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POTENTIAL FUTURE FOR SRM AND SYNCRM IN AUTOMOTIVE APPLICATIONS

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Abstract: The global warming is affecting the life of all of us. Several sectors are contributing to the greenhouse emission. One of the larger contributors is the transportation, in which the road transport accounts for the CO_2 emission with a significant percentage. In order to reduce the CO_2 emission vehicles are becoming hybridized, electrified. Currently in the electrical vehicles the Permanent Magnet Synchronous Machines (PMSM) outweigh other types of electric motors. The application of the electric machines with rear-earth material is becoming more and more difficult, and costly. Also, the technological improvements of other types of electric machines make them potential candidates to replace the PMSM. As a potential alternative the Switched Reluctance (SRM) and the Synchronous Reluctance Machines (SyncRM) can be considered. The application of such electric machines without permanent magnet would further contribute to the reduction of the greenhouse emissions considering the well-to-wheel cycle. The goal of the following review is to summarize the sectors that have major impact on the CO_2 emission, summarize the current trends followed in order to reduce the CO_2 emission in the road transport sector, review why the currently preferred PMSM electric motors might have limitations in automotive applications in the future, and review why and how the SRM and SyncRM could be alternative solutions for the PMSM, which is finally summarized in a datum method based comparative evaluation.

Keywords: *environmental pollution, electric vehicles, electric motors, Switched Reluctance Machine (SRM), Synchronous Reluctance Machine (SyncRM)*

1. INTRODUCTION

As a result of the environmental pollution global warming poses a huge challenge for the entire world. The deteriorating atmospheric condition along with the global warming mainly caused by the high CO_2 emissions has triggered international initiatives to reduce the global CO_2 emission. The new directives and regulations set strict targets for the emission level itself, and also define certain dates when the regulations go into effect. The road transport has a major portion in the energy consumption, and through that in the CO_2 emission. Based on statistical data transport contributes to more than 30% to the final energy consumption (https://ec.europa.eu/eurostat/web/main/data/database).

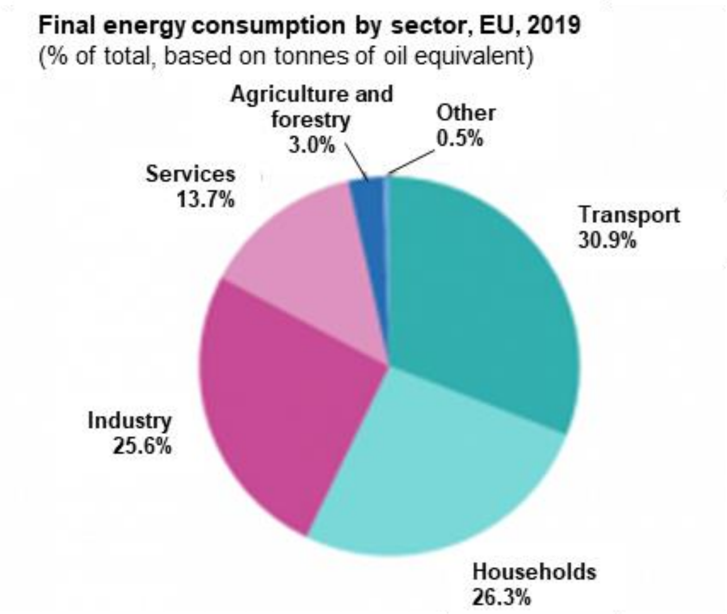


Figure 1
Final energy consumption by sector in the EU

According to the statistics of the European Environment Agency road transport accounts for more than 70% of the total greenhouse gas emission caused by the transport sector (https://ec.europa.eu/eurostat/web/main/data/database).

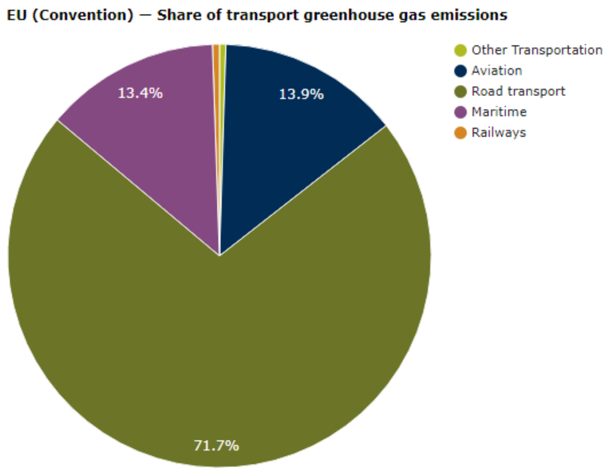


Figure 2
Share of transport greenhouse gas emission in the EU

Further breaking down the road transport greenhouse gas emission it becomes visible that more than half of the road transport emission is caused by the cars (https://ec.europa.eu/eurostat/web/main/data/database).

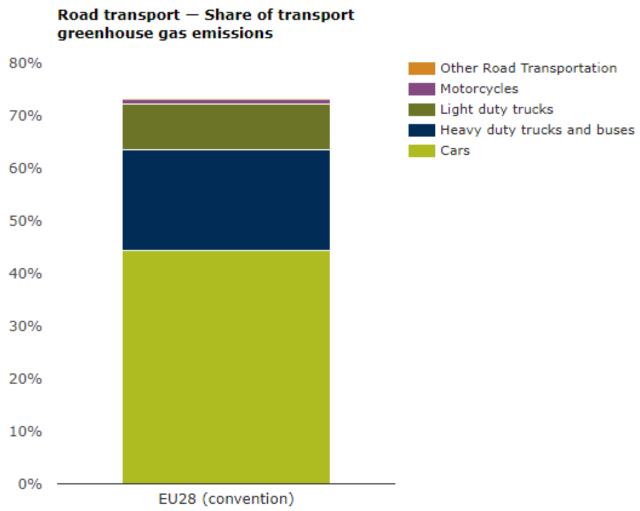


Figure 3
Road transport share in the EU

The electrification of the cars offers a huge potential to reduce the CO_2 emission. The required sharp decrease on CO_2 emission of new vehicles on fleet level forces the car manufacturers to increase the volume of the electrified vehicles in their fleet. In addition, governmental incentives are also fuelling the purchase of electric vehicles (https://ec.europa.eu/eurostat/web/main/data/database).

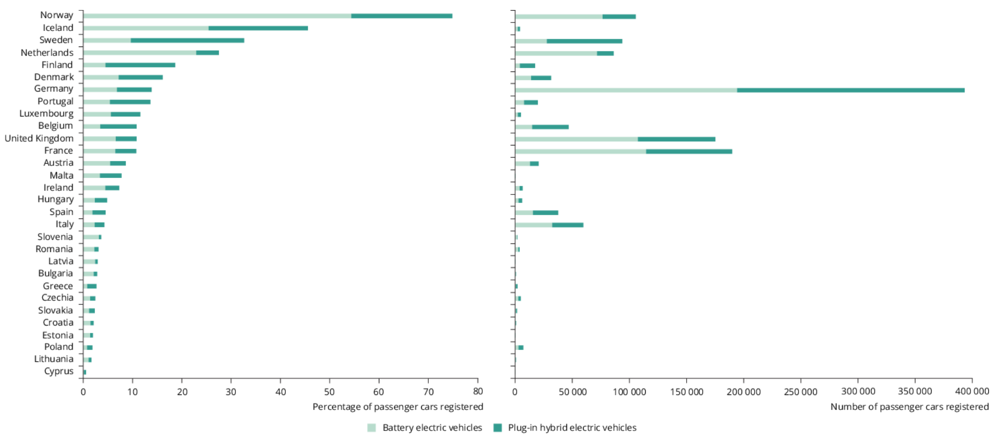


Figure 4
Newly registered electric cars in EU27, Iceland, Norway and UK in 2020

Electric vehicle sales forecast shows a rapid growth in the upcoming decade [1].

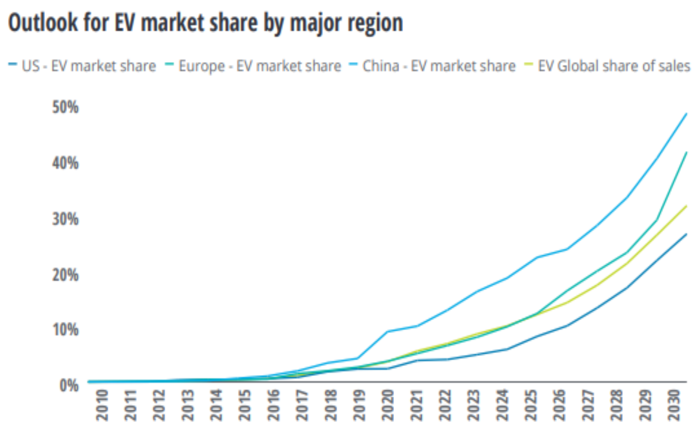


Figure 5
Outlook for EV market share by major region [1]

2. OVERVIEW OF ELECTRIC VEHICLES HEV, PHEV, BEV, FUEL CELL

The electrification of the cars can be achieved in multiple ways. Hybrid electric vehicles (HEV) combine the Internal Combustion Engine (ICE) with Electric Machines (EM). They offer fuel consumption advantages compared to the pure internal combustion engine vehicles. This results from the ability to downsize the engine and to operate it nearer to optimal conditions and, in some driving conditions, the ability to recover kinetic energy during braking [2]. Literature and studies show that downsizing the internal combustion engine, shifting the operating point and combining with regenerative braking can result in significant fuel consumption reduction. According to different literatures, the reduction can be up to 45%.

A step forward in the vehicle electrification is the Plug-in Hybrid Electric Vehicle (PHEV). This type of electric vehicle has also an ICE and an electric motor. However contrary to the HEV, where the electric motor is mainly used for boost, the PHEV offers a shorter range of electric driving. Depending on the design the electric driving distance can be up to 50 km. In the PHEV charging is not just by regenerative braking, but also possible by external electric sources via a charging port. Due to the electric driving capability PHEVs have a larger battery than the HEVs. In comparison to the HEV, PHEV offers 10% fuel consumption reduction additionally.

Contrary to HEV and PHEV, which are partially electric vehicles, Battery Electric Vehicles (BEV) are fully electric vehicles. BEVs don't have a secondary source of propulsion. The electrical energy used by the electric machine of the BEV is stored in battery packs. Due to the technology improvement in the past years, which resulted in efficiency increase of the overall drivetrain, and improved battery design, and depending on the battery size the electric range of the electric vehicles can reach over

400-500 km. A high-level topological comparison between the ICE, HEV, PHEV and BEV can be seen in *Figure 6* (https://europe.midtronics.com).

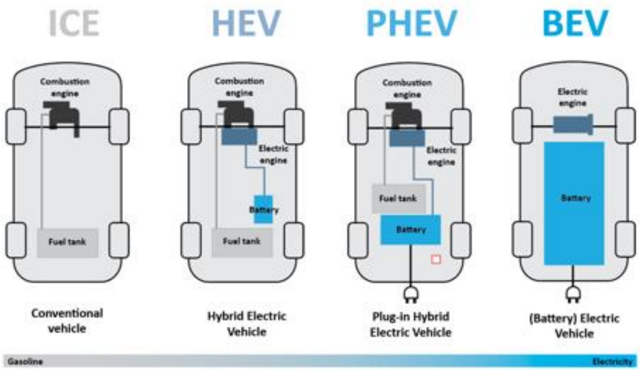


Figure 6

Topological comparison between ICE, HEV, PHEV and BEV vehicles

3. ELECTRIC MOTORS IN DIFFERENT ELECTRIC VEHICLES, E-DRIVES

Regardless whether partial or full electric vehicle, they are common in the usage of at least one electric machine. In the hybrid and full electric vehicles not all types of electric machines used. The electric machines used in the hybrid and electric vehicles must fulfil certain performance and commercial requirements. They must have high efficiency, high starting and rated torque, overload capacity, high reliability, high power density and specific power, wide operating speed range, and of course all this at a feasible cost. Based on today's electric motor technology the induction and synchronous electric machines can fulfil these requirements.

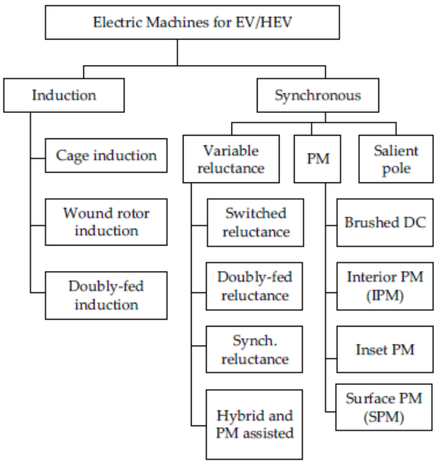


Figure 7. *Motor types available for hybrid electric/electric vehicles* [3]

In the hybrid and electric vehicles, the application of the induction machines (IM) and the permanent magnet synchronous machines (PMSM) outweigh the application of other machines. The following table provides a high-level overview on the application of electric machines in different electric vehicle makes.

Model	Year	Motor Type	Peak Power [kWp]	Peak Torque [Nm]	Max Speed [rpm]	Poles	Peak Specific Power [kW/kg]	Peak Power Density [kW/L]
Roadster	2008	IM	215	370	14800	4	4,05	–
Tesla S60	2013	IM	225	430	14800	4	–	–
Model 3	2017	PM	192	410	18000	6	–	–
Prius	2004	PM	50	400	6000	8	1,1	3
Prius	2010	PM	60	207	13500	8	1,6	4,8
Prius	2017	PM	53	163	17000	8	1,7	3,35
Accord	2006	PM	12	136	6000	16	0,53	2,83
Accord	2014	PM	124	-	14000	8	2,9	2,93
Spark	2014	PM	105	540	4500	12	–	–
Volt	2016	PM	111	370	12000	12	–	–
Bolt	2017	PM	150	360	8810	8	–	–
Leaf	2012	PM	80	280	10390	8	1,4	4,2
Leaf	2017	PM	80	280	10390	8	1,4	4,2
Camry	2007	PM	70	270	14000	8	1,7	5,9
Camry	2013	PM	70	270	14000	8	1,7	5,9
Lexus	2008	PM	110	300	10230	8	2,5	6,6
Sonata	2011	PM	30	205	6000	16	1,1	3
BMW i3	2016	PM	125	250	11400	12	3	9,1

Figure 8
Motor types used in electric vehicles and their specification [3]

As it can be seen the permanent magnet synchronous machine has been the preferred solution. The reason is that the PMSM machines have a very high torque density, high efficiency, however in order to have these advantages a permanent magnet has to be in places either on the surface of the rotor, or integrated inside the rotor. In order to have high torque/power density, high efficiency, and also be resistant to demagnetization during field weakening high-energy rare-earth magnets are used in permanent magnet machines.

4. PERMANENT MAGNET COST, UNEVEN DISTRIBUTION OF RARE-EARTH MATERIAL PRODUCTION, SUPPLY

The permanent magnets have high cost, and they take up a significant portion of the total cost of a permanent magnet machine, even though they represent a small portion of the total weight of the motor [4]. Depending on the application the rare-earth permanent magnets can take even more than 50% of the total cost of the electric machine.

The rare-earth magnet supply chain can be divided into five stages: (a) mining, milling and concentration of the ore, (b) separation into individual rare-earth oxides, (c) rare-earth metal production, (d) alloy or powder production, and € magnet manufacturing [5]. Out of the five stages the production is concentrated among few countries, which tends to result in a monopolistic situation, seriously affecting other industries. China dominates the rare-earth production, even though they hold only about half of the known world reserves [6]. As it can be seen in *Figure 9*, China holds 84% of the world production [4].

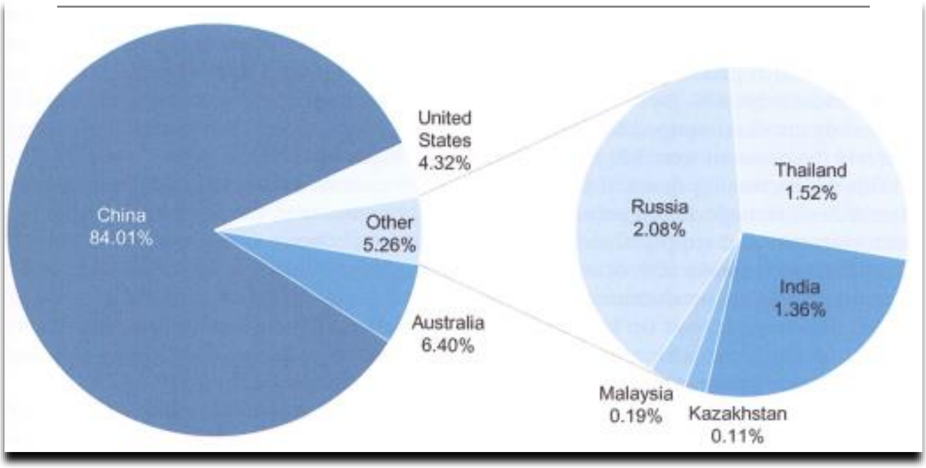


Figure 9.
World mine production of rare-earth materials by country [4]

As China is the largest producer of the rear-earth materials, they have a significant control over the availability and the price of the material. Through export quota regulations the market would further be distorted.

In addition to the higher cost and uneven distribution of the rare-earth material production, in the past time serious supply issues happened with the rare-earth materials due to shortages in the production. Rare-earth materials are not just used more and more in the automotive industry, but it is also used in application of other industries, like PC, cell phones, batteries etc. Due to the increase in the demand in all the industries, on one hand the shortage further increased the price, on the other hand it slowed down or stopped completely vehicle production lines.

Because of these serious issues, disadvantages an alternative electric machine solution should be applied in the hybrid and electric vehicles in order not to be exposed to price volatility, supply chain issues and shortages. In order to mitigate the risk, the alternative solution could be another synchronous machine, the switched and synchronous reluctance machines.

5. Application of SRM and syncRM

The Switched Reluctance Machine offers a low cost, robust and simple construction, combined with reliable operation, which is suitable for usage in high speed and high temperature applications. Its simple design includes a stator made of stamped silicon steel with salient, inward projected poles. Depending on application the stator can have different number of poles, but most of the motors on the market have 6 or 8 stator poles. The stators also carry coils, which on the opposite poles are connected in series. The rotor has a similar salient, but outward projected pole design, they do not carry coils, and opposite to a PMSM they do not have any permanent magnets. The shaft of the SRM is a simple turned steel, while the winding is of copper. *Figure 10* compares the construction of the SRM to the PMSM, visualizing the main differences.

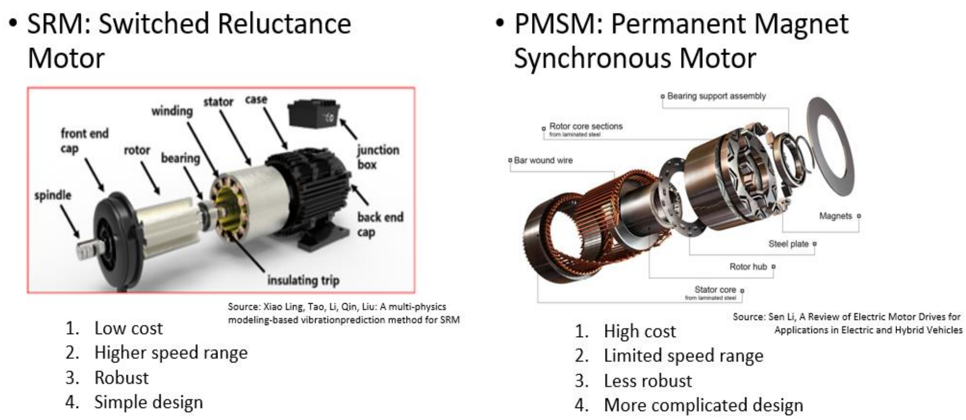


Figure 10

Comparison of the SRM and PMSM construction [7, 8]

The lack of permanent magnet (rare-earth material), simpler, less complicated design, simple manufacturing offer significant advantages in terms of cost, independency from rare-earth material, and supply chain security.

Additional advantages of an SRM over a PMSM are the simple rotor design, which due to the lack of magnets, windings offer higher achievable operating speed, better acceleration. Because of the lack of rear-earth magnet, the machine can withstand higher operating temperature, which allows a less sophisticated, simpler cooling design in the automotive applications. In the automotive applications additional significant advantages of an SRM are the potential usage in harsh environment, and the so-called limp home capability. In case of fault in any of the windings in an SRM application the SRM can still work at reduced load, allowing the vehicle still to limp to the nearest service station. The SRM has high efficiency over a wide speed and load range, however it can be seen that the higher efficiency is available from the mid-range speed. A comparison of the efficiency maps between an SRM and PMSM are shown in *Figure 11*.

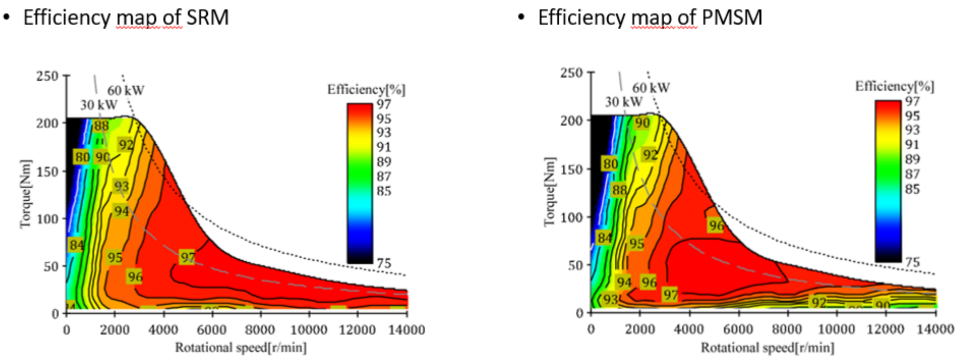


Figure 11
Efficiency map comparison of SRM and PMSM [9]

It is visible, that at low speed, below 2,000 rpm the PMSM offers a slightly better efficiency, however between 2,000–5,000 rpm the SRM efficiency matches that of the PMSM, and above 5,000 rpm the SRM is clearly provides better efficiency.

Disadvantages of an SRM are the higher torque ripple and higher acoustic noise. *Figure 12* provides a high- level summary on noise and vibration sources for electric motors.

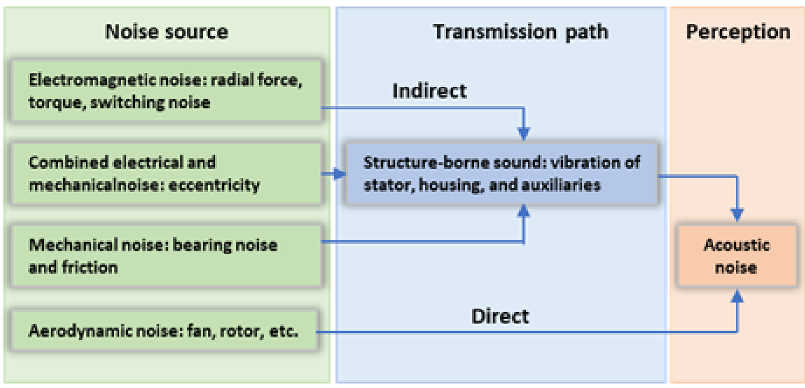


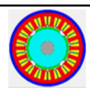
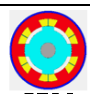
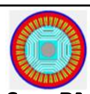
Figure 12
Noise and vibration sources for electric motors [4]

Due to the salient pole construction of SRMs, when a phase is excited with current, the flux penetrates into the rotor, mostly in the radial direction, and generates radial forces [4]. The radial forces deform the stator core, which results in airborne borne noise. This airborne noise can become audible around the electric motor directly. The acoustic noise can be optimized by active (i.e. additional ribbing on the stator) and passive (i.e. encapsulation of the SRM) countermeasures, reducing the impact of this disadvantage on the overall evaluation.

A very similar construction to the SRM is the Synchronous Reluctance Machine (SyncRM), however in case of the SyncRM the stator does not have salient poles, and the rotor has either a radially or axially laminated core. Keeping important advantages of the SRM, like low cost, simple design, application in high speed and high temperature environment, the SyncRM offers additional advantages in terms of less torque ripple, less acoustic noise, higher efficiency, simpler inductance waveform, and less expensive power electronics as the SyncRM requires lower phase currents. Comparing the different propulsion types for hybrid and electric vehicle applications, one can summarize the characteristics showing importance in automotive applications. One potential approach, which is based on the datum method is shown in *Table 1*.

Table 1

Comparative evaluation of PMSM, SRM and SyncRM for automotive applications

Propulsion type	 **PMSM**	 **SRM**	 **SyncRM**
Characteristics			
Power density	5	3,5	3
Efficiency	5	3,5	4
Controllability	4	3	3,5
Design complexity	3	4	4
Speed range	3,5	4	4
Temperature resistance	3,5	4	4
Supply chain security	3	5	5
Reliability	4	5	5
NVH	4	3	3,5
Cost	3	4	4,5
Total:	**38**	**39**	**40,5**

In the datum method the evaluation criteria are listed vertically, which are the characteristics in this particular case. The PMSM has been selected as the datum, and the SRM and respectively the SyncRM have been selected as the potential alternative solutions. Instead of the general "+"/"–", numerical (1–5) evaluation has been used, where "1" is the worst, and "5" is the best. Considering the subjective evaluation results, it is visible that the SRM and SyncRM can be competitive with PM which is dominantly used in today's hybrid and electric vehicle applications, and depending on the development preferences the advantages of an SRM and SyncRM could even be a better option for the automotive applications.

6. Conclusion

Researches have recently been focusing already on the SRM and SyncRM. Further study, analysis and development of SRM and SyncRM for automotive applications seems to be reasonable, as depending on the preferred characteristics the SRM and especially the SyncRM can indeed be considered as a potential candidate to replace the PMSM. Some characteristics of SRM and SyncRM are comparable, some characteristics of the SRM and SyncRM are even better than the PMSM characteristics. In addition to the cost and supply chain security, reduction of dependency on limited the number of rear-earth material producers are all pushing for alternative EM solutions. Simple design and manufacturing of the SRM and SyncRM are also important aspects. Disadvantages like higher torque ripple and higher acoustic noise can be improved with active and passive countermeasures. Additional advantage of the SRM and SyncRM that they can still work at reduced load in case of fault in any of the windings, which allows vehicle to reach the nearest service station in a limp-home mode.

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