EVS32 Symposium
Lyon, France, May 19-22, 2019

Comparison between Permanent Magnet and Wound Field Synchronous Machines for Traction Application: Efficiency and Energy Consumption

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Summary

Electric machine and its inverter are important components of the electric powertrain with a huge impact on its performances. Various electric machines technologies allow reaching torque and power performances but their volume may lead to eliminate a technology because of the available space on board. The aim of this study is to compare two synchronous machines designs for the same specifications. Permanent Magnets offer high compactness and efficiencies, whereas Wound Field rotors are free from magnets and offer lower efficiencies except for high speeds. The machines performances impact on the consumption is investigated for various driving cycles.

Keywords: motor design, synchronous motor, permanent magnet motor, efficiency, energy consumption.

1 Introduction

Nowadays, the widespread use of Electric Vehicles (EVs) faces some difficulties due to their high prices and their limited autonomy compared to vehicles that use fossil fuels. However, with the foreseen advancements in electric motors, storage technologies and smart management of batteries energy, EVs are becoming an important actor in the transportation world. The energy transition challenges lead the automotive industry to develop an efficient and coherent offer of electric mobility solutions. In fact, the Mild Hybrid Electric Vehicles (MHEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs) cover most of the car users' needs according to their daily use and expectations. Moreover, the increasing autonomy, the smart charging involving renewable energies and Vehicle to Grid solutions offer new ways of thinking and profitability streams. One main actor of the EVs performance is the e-machine and its inverter, which need to offer the desired performances from the torque and power point of views during the constant and peak operating points as well as for low and high speeds. Consequently, an optimized efficiency needs to be ensured for the wide range of operating points (Speed/Torque) with a direct consequence on the autonomy. Otherwise, each "Wh" lost because of the machine or inverter losses will not be used for mobility purposes and will then decrease the autonomy of the vehicle. At last, the context of e-mobility brings important constraints in terms of efficiency, speed range and available space on board inducing a specific approach for the electric machine and inverter designs compared to industrial domain.

Various electric machines technologies are used in the traction domain [1], [2]. The main used technology is Permanent Magnet Synchronous Machine (PMSM) appreciated for its compactness and high efficiency: Toyota Prius, BMW i3 and i8, Nissan Leaf, Toyota Camry, Lexus, Honda Accord, Hyundai Kona, Jaguar I-

Pace. Its main drawbacks are the cost and the presence of rare earth permanent magnets with the well-known Neodymium and Dysprosium huge prices variations some years ago [3]. Ongoing studies and suppliers are developing rare earth free permanent magnets with the same magnetic and thermal performances [4]. Besides, Wound Field Synchronous Machine (WFSM) offers interesting performances from the efficiency point of view [5], [6]: Renault Zoe and BMW IX3. However, it needs additional devices to provide controlled current to the rotor, which increases the system complexity and cost. Moreover, like for induction machines, heat extraction from rotor conductors may be necessary. Contrary to the industrial domain, Induction Machine (IM) is rarely used. It is highly appreciated in the industry domain for its robustness and low cost, nevertheless its lower compactness, lower efficiency and rotor heating are important limitations in the traction domain. Tesla Motors used IM with copper in the rotor in model X but they used PMSM in model 3. Finally, reluctant machines are interesting for their low cost and manufacturing simplicity, but control needs to be improved as well as torque variations and noise. Studies are ongoing with this technology and they are not yet used in the EVs [7].

In this article, Wound Field and Permanent Magnet Synchronous Machines are designed for the same specifications. The first section describes the design optimization approach. The second one describes the synchronous machines electromagnetic designs and cooling systems. Then, the following section compares the two machines performances with a focus on efficiency and energy consumption according to various driving cycles. The objective of this comparison is to highlight the main differences between the two technologies.

2 Emotors Design Optimisation Approach

2.1 Specifications

The main specifications for electrical machine and inverter system pre-design (Fig.1.) can be summarized as follows:

- Maximum speed 13000 rpm: depends on the wheels maximum speed and the gearbox ratio.
- Maximum DC current 450 A: imposed by the battery and power electronics, it corresponds to peak torque.
- Maximum and minimum DC Voltages: imposed by the battery.
- Peak torque represented by various curves depending on speed, each one corresponding to a duration and a voltage. Parameters are occurrence, duration, base speed. The maximum value at minimum voltage is 260Nm.
- Constant power represented by various curves depending on speed and voltage. It is given for long duration and until the maximum speed.
- Maximum cogging torque and torque ripple depend on the allowed variation in the electric powertrain.
- Maximum short - circuit current.
- Maximum electromotive force harmonic distortion.

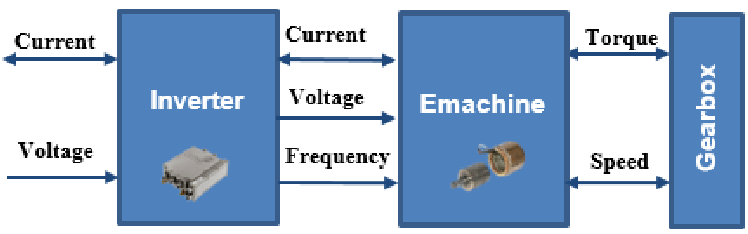

Figure 1: Machine inverter and Gearbox interactions

2.2 Optimization parameters

In the following study, the same diameter is considered for both of the machines (190mm). The aim of the optimization is to ensure the peak torque and the best efficiency while using less material for cheaper cost. It is important to notice that the available space on board is generally very constrained and may eliminate a technology because of its length. The losses that we take into account are:

- DC copper losses in stator and rotor windings (only WFSM). They depend on the winding resistance, temperature and current.
- AC copper losses in stator winding. They are due to skin and proximity effects in the winding and depend on the resistance, temperature, current and frequency.
- Magnet losses. They depend on the magnets resistivity
- Iron losses in the stator and rotor. They depend on the steel losses, the induction and the frequency.
- Additional losses due to inverter harmonics.
- Mechanical and windage losses.

On the one hand, the machine electromagnetic performance depends on stator and rotor geometries and material as well as windings definition [8]. On the other hand, the machine thermal performance depends on the machine losses and the cooling efficiency. The optimization of the electromagnetic-thermal designs is realized through optimisation loops leading to the best compromise.

2.2.1 Electromagnetic and thermal performance

The machine electromagnetic performance depends on various parameters:

- Stator geometry: slot geometry, number of slots, internal diameter, skewing.
- Rotor geometry: poles/magnets geometry, number of poles/magnets, internal diameter, external diameter, skewing
- Stator and rotor materials: steel parameters including thickness, permeability, saturation behaviour and losses.
- Number of poles
- Windings definition: number of turns, winding type, copper filling in the slot, hairpin or stranded.

The machine thermal performance depends on the machine losses and the cooling efficiency. It is evaluated on constraining driving cycles for which the machine must not reach the temperature limit neither in the stator nor in the rotor.

Decreasing losses using lower stator resistance, lower stator current or better steel for the active parts leads to a cooler machine. However, in case of an optimized design leading to the minimum losses regarding the awaited performance, the only way to obtain a cooler machine is to improve the cooling system performance. This last is impacted by the coolant liquid caracteristics, the cooling circuit localization for instance in the shaft… Besides, the thermal conductivity of the used materials (steel, copper, magnet, insulation) in each part of the machine may have an impact on the cooling performance.

2.2.2 Efficiency

Efficiency depends on the losses and thus on electromagnetic and thermal performances. During the machine design, it is possible to concentrate on a couple of operating points for which the losses need to be optimized. In fact, the driving cycles operating points may have variable importance depending on their occurrence, duration and corresponding losses.

The energy losses during a cycle is another view of the machine and inverter efficiencies for a specific driving cycle. It corresponds to the sum of energy losses for the cycle operating points including generator and motor modes. The machine and inverter efficiencies can also be represented by the vehicle autonomy for a given battery energy or by the consumption.

3 Synchronous Machine Optimized Design

Both of the machines are using M330-35 steel. Additional parameters are taken into account in the machine design, for instance short-circuit current. Stator and rotor geometries are mainly defined regarding the peak torque, the minimum losses and the torque ripple constraints.

3.1 PMSM design

On the one hand, lower number of poles induces lower torque for the same mass. On the other hand, increasing the number of poles leads to high switching frequencies and thus higher commutation losses in the inverter. Besides, previous studies showed that V magnets shape offers more peak torque [10]. Consequently, we used eight poles V magnet shape machine for our comparison.

From the stator geometry point of view, we compared 12, 24, 36 and 48 slots for the rotor definition.

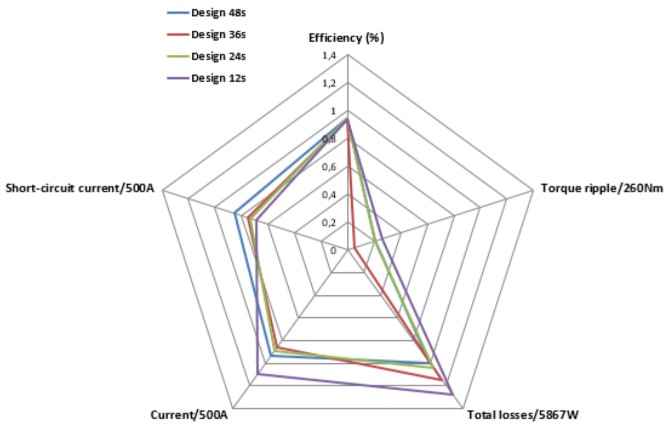

Figure 2: 8 poles, V shape magnet PMSM performance comparison for 12, 24, 36 and 48 slots in the stator

According to Fig. 2., the best compromise between losses and torque ripple leads to 48 slots stator. The stator slot geometry has been optimized for maximum torque (surface), tooth and yoke saturation as well as low cogging torque (slot opening).

Concerning the windings, four conductors hairpin winding has been selected for better efficiency despite additional AC losses. The hairpin winding is selected for a maximum filling of copper and thus improved efficiency. According to our study using increased copper slot fill of 68% for hairpin instead of 45% for stranded wires leads to efficiency increasing from 93,1% to 93,9% for base speed peak torque operating point.

The rotor geometry is defined for low magnet weight (magnet dimensions) while reaching peak torque performance. Cogging torque and torque ripple are also taken into account in the V magnet angles. The bridge thickness is chosen for the best performance while bearing mechanical stress constraint.

The PMSM ensuring the maximum torque has a length of 160mm and the rotor can be skewed (4 segments) for minimum torque ripple 3,6% at peak torque base speed point.

Stator and rotor geometries are described in Table 1.

The cooling system is based on spiral water jacket with 50% glycol 50% water coolant.

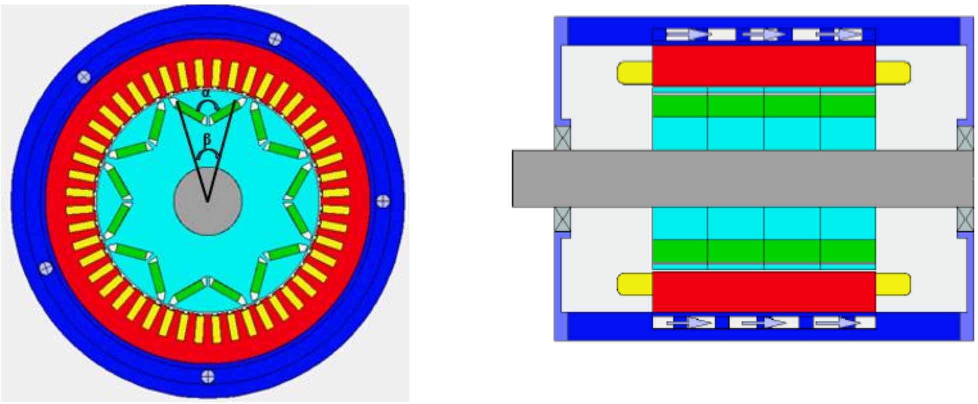

Figure 3: PMSM electromagnetic design and cooling

3.2 WFSM design

The WFSM has the same stator and PMSM. Rotor poles have been defined for maximum peak torque, minimum torque ripple and minimum losses. The rotor tip geometry is conventional. It has been defined taking into account the saturation. The stator and rotor main parameters are presented in Table 1. WFSM torque ripple is around 23%. This value can be reduced by skewing, optimizing pole shape or more innovative approaches with asymmetric pole [9].

Rotor windings have been defined for lower current at the peak torque operating point. In case of Wound Field rotor, rotor copper losses represent 16% to 25% of the machine total losses depending on the operating point. These losses lead to important heating in the rotor inducing specific cooling. Cavities in the shaft allow liquid coolant circulation allowing the calories extraction close to their source (rotor winding). The machine is cooled using the same spiral water jacket as the PMSM in addition to liquid circulation in the shaft.

The active parts length is 250mm thus 50% higher than PMSM.

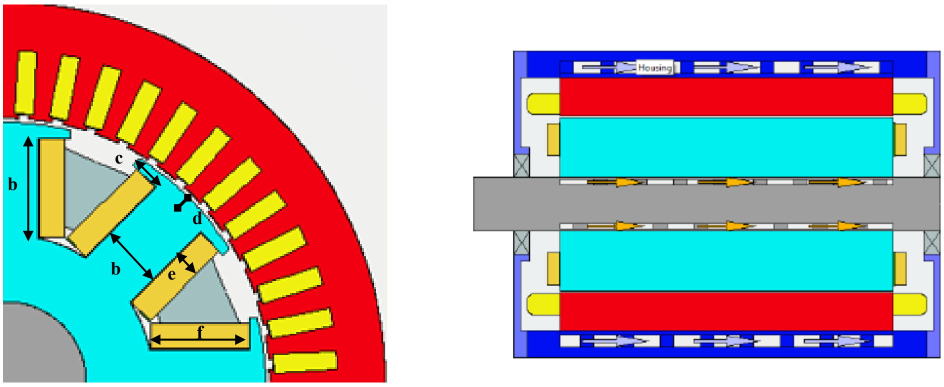

Figure 4: WFSM electromagnetic design and cooling

Table 1: PMSM and WFSM designs: geometric parameters

Stator parameter name	Value	PMSM rotor Parameter name	Value	WFSM rotor Parameter name	Value
Stator outer diameter	190 mm	Magnet thickness	5 mm	Pole width (a)	16 mm
Stator inner diameter	132 mm	Magnet lenght	18 mm	Pole depth (b)	25 mm
Slot width	4,8 mm	Bridge thickness	1 mm	Pole tip width (c)	8 mm
Slot depth	17 mm	Pole V angle (α)	120 °	Pole tip depth (d)	4 mm
Slot opening	2,5 mm	Pole arc (β)	145 °	Rotor coil width (e)	6,5 mm
Airgap	1 mm	Magnet separation	3 mm	Rotor coil depth (f)	24,5 mm

4 Performances Comparison

The following calculations are performed using Motor Cad. The DC voltage is fixed to 260V, which is the minimum value for which the performances need to be ensured. The DC current is limited to 450A. The following losses are taken into account: AC and DC losses in the stator, DC losses in the WFSM rotor winding, magnet losses in the PMSM and iron losses in stator and rotor for both of the machines.

4.1 Peak power and efficiency

At first sight, PMSM efficiency map in Fig. 5. shows higher efficiencies for most of the map operating points. However, WFSM efficiency map in Fig.6. shows good efficiencies at high speeds and low torque operating points.

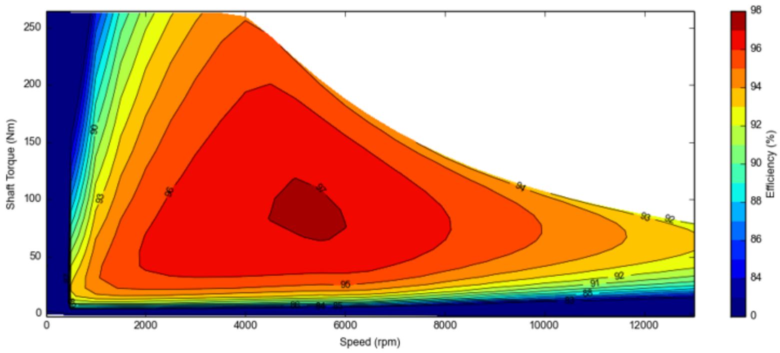

Fig 5: PMSM torque efficiency map, 260V, maximum DC current 450A

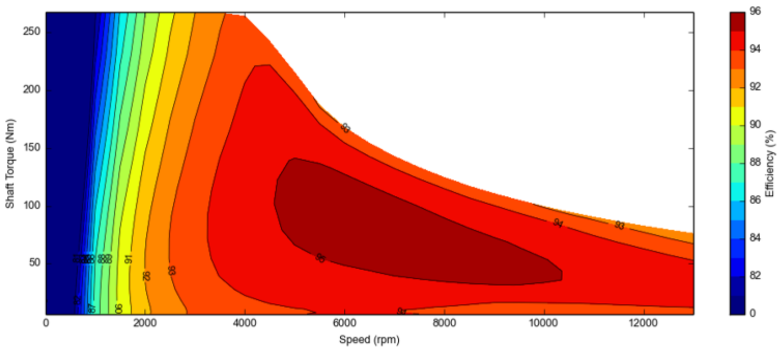

Fig 6: WFSM torque efficiency map, 260V, maximum DC current 450A

Table 3: Efficiencies comparison according to the operating points

	PMSM			WFSM		
Operating point	Speed (rpm)	Torque (Nm)	Eff (%)	Speed (rpm)	Torque (Nm)	Eff (%)
Max efficiency	5000	100	97,1	6500	67,5	95,5
Peak torque base speed	4000	260	94,9	4000	260	93,5
High speed 1	9000	110	93,2	9000	108	94,9
High speed 2	13000	49,5	92,8	13000	50	94,2

Table 3 shows the efficiencies for some points of interest. The maximum efficiency of the PMSM reaches 97,1% while the WFSM reaches only 95,5% as a maximum value. However, high speed and low torques operating points show higher efficiencies for WFSM. For instance, there is an important difference between the efficiencies for 13000 rpm operating point: 94,2% for WFSM and 92,8% for PMSM. This difference is mainly due to the lack of excitation control of PMSM and the limitation of flux weakening when the machines face a wide range of speeds. It is the case for all the machines in the traction applications.

4.2 Constant power

The constant power has been calculated using Motor cad. Maximum power is calculated for each speed while limiting the components temperatures to a maximum value imposed by the used materials. The operating point duration is 30 min and the temperatures are limited as follows:

- 180°C for both of the machines stators windings and WFSM rotor winding. This value is limited by the insulation thermal limit including insulation paper, copper enamel and varnish.
- 160°C for the magnet for PMSM. It is limited by the magnet grade and its ability to reach this temperature without demagnetizing.

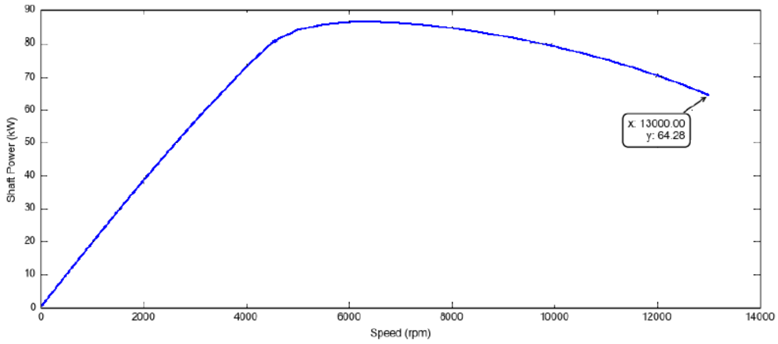

Fig 7: Constant power depending on the speed for PMSM, 260V, 30 min

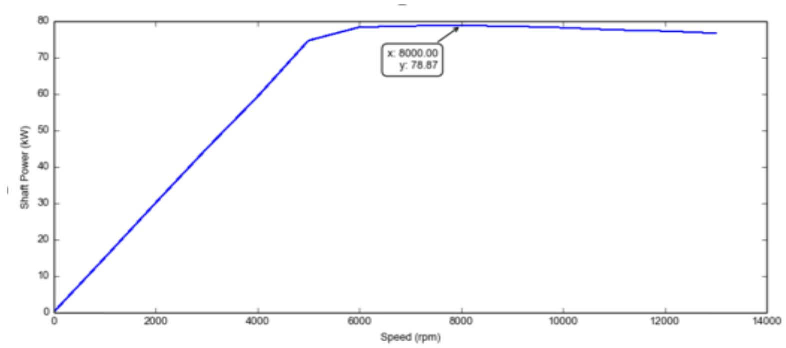

Fig 8: Constant power depending on the speed for WFSM, 260V, 30 min

The constant power variation is quite different when we compare PMSM continuous power in Fig.7. and WFSM one in Fig. 8.

PMSM shows higher maximum constant power around 6000rpm. However, WFSM shows higher power at very high speed. In fact, the WFSM power curve is flater and presents a lower decreasing when the speed increases.

Table 4: Constant power and temperature after 30 min operating points

	PMSM			WFSM		
Speed (rpm)	Power (kW)	T stator winding (°C)	Tmagnet (°C)	Power (kW)	T stator winding (°C)	T rotor winding (°C)
4000	72	180	130	58	135	180
8000	85	180	145	79	142	180
13000	64	180	160	77	148	180

Table 4. shows that WFSM offers 77 kW at 13000 rpm while PMSM offers only 64 kW at the same speed. For medium speed (8000 rpm), the PMSM remains the most interesting because it offers 7,5% more power. The magnet temperature limits the continuous power for PMSM while WFSM is limited by rotor winding temperature. Obviously, if the shaft water cooling is also used for the PMSM, it would offer more power.

Cooling has a huge effect on the constant power performance and needs to be taken into account in the comparison.

4.3 Energy cycles

The efficiency needs to be investigated at the various operating points of the driving cycles. The energy consumption in "Wh" gives a complete view of the efficiency for all the operating points of the driving cycle and takes into account the duration of each operating point. In the following section, the energy consumption (Wh/km) is calculated for PMSM and WFSM with the same gear ratio and battery. Both of the power electronics and the electric motor losses are taken into account.

Four cycles are compared with very different driving behaviors:

- High speed cycle representing highway driving
- Medium speed cycle representing rural driving
- Low speed cycle representing urban driving
- WLTP cycle which contains four phases with low, medium and high speeds, it includes the various driving behaviors.

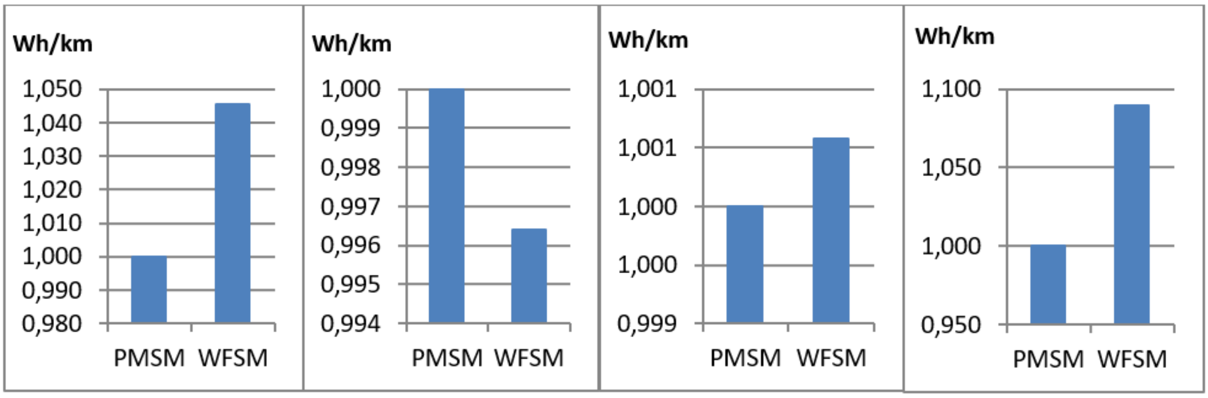

Fig 9: Consumptions for WLTP, highway, medium and low speed cycles

Table 5: WFSM and PMSM consumptions comparison for various driving cycles

Cycle	Average speed (km/h)	Maximum speed (km/h)	Consumption WFSM versus PMSM
WLTP	30	130	+4,5%
HIGH SPEED - HIGHWAY	120	145	-0,36%
MEDIUM SPEED - RURAL	70	120	+0,1%
LOW SPEED - URBAN	8	23	+8%

Fig.9. and Table 5 show the results with PMSM as reference. WFSM is as performant as PMSM for highway and medium speed cycles, whereas PMSM offers lower consumption for low speed and WLTP cycles. These results highlight the user behavior impact on the technology choice. If the vehicle is used for highway and rural cycles, the Wound Field technology is as interesting as Permanent Magnet from the consumption and thus the autonomy point of view. To conclude, WFSM may be an interesting technology for some specific users' behavior. It offers an additional parameter for controllability through rotor current but it also requires more space on board for the electric machine which is bigger. Besides, the rotor supply also induces a need of additional space.

5 Conclusion

This study compared Permanent Magnet and Wound Field Synchronous Machines for the same specifications and diameter constraint. The peak torque is reached for both of the technologies but with 50% more length for the WFSM. From efficiencies point of view, the PMSM shows higher efficiencies for most of the operating points. However, WFSM shows interesting efficiencies at high speed operating points. It offers the advantage to be controlled through rotor current which is interesting for high speeds. In fact, traction applications have a wide range of speeds which is constraining for the machines.

When the consumptions are compared for various cycles, WFSM is very close to PMSM for high speed cycles. In contrary, cycle containing low speeds like WLTP and urban show the interest of PMSM. These results highlight the importance of mastering the vehicle driving cycles before choosing the electric machine technology.

From the design point of view, there are differences that may lead to choose one of the two synchronous technologies. On the one hand, the WFSM machine is bigger (longer) for equivalent performances. Moreover, the rotor windings induce cooling in the shaft and the necessity to feed the rotor through dedicated power electronics. It leads to magnet free solution but more complexity and volume. On the other hand, PMSM is the most compact solution with low consumption for all the cycles. Nevertheless, it faces rare earth magnets prices fluctuation in addition to limitations from the temperature point of view with demagnetizing risks that need to be managed.

To conclude, PMSM shows the most interesting consumption whatever the driving cycle is while WFSM could be the best solution for some specific usages including mainly high speed operating point. The main issue is to reach interesting costs for each technology including the manufacturing processes, the materials including permanent magnets and additional subsystems like shaft cooling or rotor supply.

6 Referencing

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She developed the IE2 asynchronous machines range machines in Leroy Somer and worked on the alternators refurbishment and control in Jeumont Electric Maintenance in France. Since 2017, she has been working on the design of electrical machines for traction in PSA, France and is currently working for the joint venture Nidec PSA emotors.