Experimental Tests on a Spoke-Type Permanent Magnets Synchronous Machine for Light Electric Vehicle Application

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Featured Application: Light electric vehicles propulsion.

Abstract: In an attempt to limit the effects of global warming, virtually all car manufacturers have introduced in the last years Hybrid or full Electric Vehicles. The current study shows the experimental testing of a spoke-type PMSM that was developed based on the requirements of the L6e European light vehicle class. A test bench was developed for this purpose, using a DC machine fed by a bidirectional DC Power Supply that allowed the testing of the PMSM prototype both in motor and generator/brake regimes. The Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) was implemented on the control stage of the testing set-up, allowing an accurate estimation of the PMSM-based E-drivetrain performance. The test results validated the FEM-simulated results and provided an insight on the efficiency of the entire drive system (battery—inverter—PMSM) and the autonomy of the L6e light EV. The electric drive system was integrated and tested on a prototype vehicle in normal operating conditions, validating the results obtained on the developed test bench.

Keywords: electric vehicles; L6e class; permanent magnet synchronous machine; spoke-type rotor

1. Introduction

Urban air quality problems and high CO_2 levels have led to the implementation of decarbonization programs, which most countries are committed to. This will have positive effects on the climate, health, and the environment in the coming decades. Studies revealed that the emissions of passenger cars and light-duty vehicles are responsible for 15.1% of total greenhouse gas and almost 70% of transport emissions in the EU in 2018 [1,2]. Transport emissions have decreased in the last years due to decreased activity during the COVID-19 pandemic, but without the implementation of additional measures, the reduction expected will result in transport emissions in 2030 being around 10% above 1990 levels [3].

Electric vehicles (EVs) are, for now, expensive, and battery technology and charging infrastructure are far from being fully developed. The internal combustion engine will be phased out of production, being considered incompatible with climate protection. The political class aims to accelerate the transition to e-mobility, with significant amounts being allocated for incentive programs in the purchase of an electric vehicle and the expansion of charging networks. Congestion in big cities as well as poor air quality has led to a growing demand for light electric vehicles, especially in crowded cities due to their advantages, such as: (i) reduced size, which makes them easy to park in urban centers; (ii) low maintenance costs; and (iii) reduced charging times.

EVs are powered either from a battery or a fuel cell. Due to low overall efficiency, fuel cell electric vehicles application will be, for now, limited to vehicles with high daily driving usage [4]. Regardless of the energy storage technology, the electric propulsion units are
Traction motors hold a key role in the development of electric cars. The requirements they must meet (high power and torque density, high efficiency, wide speed range, and high reliability at reasonable cost) narrows the selection range. Recent years have brought to light different solutions used by car manufacturers. Induction machines offer high reliability at lower costs due to their mature manufacturing technologies acquired over the last decades in their use of different applications and electrified powertrains. Famous manufacturers such as Renault (Twizy) and Tesla (Model S) successfully integrated the asynchronous machine, despite the increased rotor copper losses, cooling requirements, and battery autonomy due to high starting current [6,7]. PM-assisted synchronous reluctance motor (PMa-SynRM) can compensate requirements of not using rare earth permanent magnets (PMs) by designing them with ferrite magnets [8]. Several studies evaluate the performances of PMa-SynRMs in different ranges of power. They also compared them with interior permanent magnet synchronous motors (IPMSM) to emphasize the advantages and disadvantages of specific driving cycles [9–12].

IPMSMs are the traction motor choice for most automotive manufacturers, despite the price insecurity and raw material limited availability. Rotors with embedded permanent magnet design have the advantage of high efficiency, wide speed range, being lightweight, and strong mechanical structure [13]. Various rotor structures are proposed with different arrangements of the PMs and their influence on the machines performance is considered in [14–16]. Different types of rotors structures for EVs are analyzed and their electromagnetic characteristics (efficiency torque output and flux weakening capability for wide operating range) are compared in [17,18]. Among these several types of IPMSM rotor configuration, the spoke-type rotor is known for its high torque density and high efficiency due to its flux concentration capability [19,20]. Many studies are performed to counteract the disadvantage of high torque ripple and distorted air gap magnetic field distribution for designing the optimal rotor structure [21–23].

Depending on the emplacement of the electric motor for the electric traction system, the degree of complexity can vary greatly, along with the cost of production, efficiency at the system level, and even the choice of topology of the electric motor. Powertrain architecture can be classified in two categories: central drive and wheel hub drive. The central drive architecture is employed in most EVs available on the market, using an electric motor connected to the wheels by the means of reduction gears and a mechanical differential. The wheel hub drive category is another attractive drivetrain, where the wheels are directly driven by electric motors, improving the overall efficiency by eliminating the reduction gear.

The current paper focuses on the full process of designing and integrating an electric motor in a light EV. The study begins with the evaluation of the most common solutions of integrating the electric motor in the kinematic chain, considering both the performances and the costs of those topologies. The next step was to determine the most advantageous PMSM structure, considering PM surface-mounted, interior PM, or spoke-type rotors. Based on these results, a PMSM was designed, modeled in FEA-based software, and optimized; a prototype was constructed. The motor parameters required for setting up a commercial inverter were determined using FEM simulations; and were experimentally validated. The test bench developed for testing the prototype is briefly presented in Section 3, along with the experimental results obtained for an operating scenario based on the WLTP drive cycle. Finally, the fully electric drivetrain, based on the spoke-rotor PMSM prototype, was integrated into a light vehicle chassis and tested in real-life conditions, validating the entire development process.

2. Preliminary Results and Research Methodology

The first step in developing a fully functional electric drive system for a light electric vehicle (L6 European class) was to determine the drivetrain topology that is best suited for this type of application. An in-depth study was performed [24], focusing on an evaluation
of the configurations already used in commercial EVs: (a) a single electric machine (EM) connected to the wheels through a mechanical system consisting of a combination of gearbox, differential, and drive-shafts; (b) two in-wheel outer-rotor EMs; or (c) two EMs directly connected to the vehicle wheels (Figure 1). The study revealed that the latter topology had the best efficiency while operating on an NEDC cycle limited to 45 km/h. However, if other factors were considered, such as the technological challenges of the in-wheel structure, the cost of the additional electronic converter required for the second EM, or the different rotational speed of the two EMs while cornering, the best solution seemed to be the former. The study also included a comparison of several PMSMs rotor topologies, considering several interior-PM structures, showing that the spoke variant had similar results to other structures that were considerably harder to build and more expensive.

A study on two variants of PMSMs suited for this application was performed [25], considering two topologies with three-phase, 15 slots, stators, and four-pole rotors with spoke and interior PM arrangement. The statoric winding is a two-layer distributed configuration, as shown in Figure 2a,b.

A multi-objective optimization, using the genetic algorithm (GA) technique available in JMAG software, was implemented with the aim of increasing the efficiency of the machines. During the optimization process, different geometric dimensions were varied in order to maximize the efficiency, to minimize the electromagnetic torque ripples, and to maintain the maximum value of the magnetic flux density below 1.8 T through the stator core, to avoid saturation. The objective function, to be maximized, is highlighted in the following relation:

$$f = \text{eff} \ast 0.4 + \frac{T_{rip}}{T_{rip}^i} \ast 0.2 + \frac{1.8}{B_{st \, teeth}} \ast 0.2 + \frac{1.8}{B_{st \, yoke}} \ast 0.2 (1)$$

Figure 1. Studied drivetrain topologies: (a) single EM with mechanical transmission, (b) in-wheel outer rotor EM, (c) EM directly connected to the wheels.
where:
- \( e_{\text{ff}} \) — motor efficiency;
- \( T_{\text{rip}} \) — torque ripple;
- \( T_{\text{rip,i}} \) — torque ripple for the initial case;
- \( B_{\text{st teeth}} \) — magnetic flux density in stator teeth;
- \( B_{\text{st yoke}} \) — magnetic flux density through stator yoke.

The optimization process was performed for a rotor speed of 4200 rpm and a phase current of 145 A. After the optimization phase was concluded, two efficiency maps, one for each machine, were obtained from simulations (Appendix A, Figure A1) considering a speed operating range from 0 to 4500 rpm.

For a better comparison between IPM and spoke-type machines, the stator geometries and PM volumes were considered identical; the results of the study (Table 1) showed that the two PMSM had similar performances. The interior PM structure exhibited better efficiency due to smaller iron losses since it used less lamination material in the rotor. Both topologies were built; however, the current article focuses on the spoke-type PMSM.

### Table 1. Comparative simulation results.

| Parameter                      | PMSM Spoke | PMSM IPM | Unit   |
|--------------------------------|------------|----------|--------|
| Mechanical Power               | 2.76       | 2.74     | kW     |
| Rotor speed                    | 4203       | 4203     | rev/min|
| Average torque                 | 6.27       | 6.24     | Nm     |
| Torque ripple                  | 8          | 8.1      | %      |
| PM Joule losses                | 7.82       | 4.34     | W      |
| Total Joule losses             | 31.34      | 34.72    | W      |
| Rotor Iron losses              | 9.23       | 6.75     | W      |
| Total Iron losses              | 129        | 77.7     | W      |
| Rotor iron mass                | 3.4        | 2.71     | kg     |
| Efficiency (mechanical losses not included) | 94.51 | 96.06 | % |

After the prototype spoke-type PMSM was built, several tests were made to determine the electrical characteristics and behavior of the machine. In Figure 3, a comparison between...
the Finite Element Method (FEM) simulated phase voltage and prototype measured phase voltage at 896.4 rev/min is presented. The voltages were almost identical, the main difference being at amplitude level, probably due to one or several of the following: higher airgap for the prototype due to manufacturing tolerances, iron core lower-quality properties, and voltage probe measurement error. This test also allowed the determination of the back-EMF constant (Ke) of the machine prototype.

![Figure 3. PMSM FEM simulated phase voltage (red) vs. prototype phase measured voltage (blue).](image)

The synchronous inductances of the spoke-type PMSM were measured using an LCR meter. It is well known that stator inductances of interior permanent magnet synchronous machines are different on $d$ and $q$ axes ($L_d < L_q$) due to the reluctance on the $q$ axis. Therefore, the measurements were performed by locking the rotor aligned positions with the two axes. For the $d$-axis phase 1 inductance, the alignment of the rotor to phase 1 was achieved by feeding the phase with positive potential, and by feeding phases 2 and 3 with negative potential. For the $q$-axis phase 1 inductance, the alignment of the rotor was achieved by leaving phase 1 floating, feeding phase 2 with positive potential, and feeding phase 3 with negative potential. A comparison of the measured and FEM determined parameters is presented in Table 2.

| Parameter                  | Symbol | Value Measured | Value FEM-Computed | Unit       |
|----------------------------|--------|----------------|--------------------|------------|
| Motor phase resistance     | $R_s$  | 0.0037         | 0.0028             | Ω          |
| Back-EMF electrical constant | $K_e$   | 0.0718         | 0.0768             | V.s/rad    |
| $d$-axis inductance        | $L_d$  | 0.000061       | 0.000067           | H          |
| $q$-axis inductance        | $L_q$  | 0.000121       | 0.000146           | H          |

A good correlation between the measured and estimated values can be noticed. The most notable difference was for the motor phase resistance, where the FEM-computed value was 24.3% smaller than the measured value. In the simulations, only the active parts or the windings were considered, without considering the connections to the terminals and longer-end windings. The differences between the other three electrical parameters (measured versus FEM-computed) can be explained by the fact that the manufactured machine could not be built exactly like the machine considered in simulations: different airgap lengths, different materials (PMs, iron core) and properties, etc.
3. Test Bench and Experimental Results

3.1. Test Bench

Two images of the test bench are presented in Figure 4a,b. The spoke-type rotor PMSM is mechanically connected to a direct-current machine (DCM), by an intermediate toothed belt. Both electrical machines should operate as motor and generator alternatively (i.e., if PMSM is motoring, the DCM is generating and vice versa). To achieve this operating mode, DCM is electrically connected to a Bidirectional DC Power Supply, model PSB 9000 3U manufactured by Elektro-Automatic, a German company with the headquarters located in Viersen, North Rhine-Westphalia, and able to feed or consume power to and from DCM.

The main elements used for experimental tests are presented in Figure 5, highlighting the power flow, the control, and measurement connections between the various components. A dedicated, commercially available, SEVCON power converter was used to power the PMSM, fed from a 48V LiFePO₄ battery. The power converter is controlled from a dSPACE board that emulates the signals from throttle and brake pedals considering that the PMSM speed should follow the reference speed. The control of the throttle/brake pedals’ signals is made with PI controllers to reduce the error between the reference and measured speed. Several current, voltage, torque, and speed sensors are used to measure the important parameters during tests. Their signals are recovered using the dSPACE board, and some are presented in the following figures. The power converter is connected to a computer, from where readings of power, speed, and estimated torque can be made. Before or between experimental tests, using DVT customer software, parametrizations of the power converter were made. The DCM acts as a generator when the PMSM is in motor mode and as a motor when the PMSM is in generator mode. Thus, a bidirectional DC power supply was used and controlled from the same 1103 dSPACE board. This power source/load will absorb the electrical energy generated by DCM when PMSM is in motor mode and will feed the DCM when the PMSM is in generator (braking) mode. Between the DCM shaft and transmission belt, a torque/speed sensor was used to measure the mechanical power between the two machines. On the other DCM shaft end, an incremental encoder is used to measure the DCM speed. In addition, a sin/cos encoder is mounted on the PMSM shaft, sending rotor position information to the SEVCON converter.

![Figure 4. Cont.](image)
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Figure 4. Photos of the test bench: (a) front view, (b) side view.

Figure 5. Schematic of the experimental test rig.

3.2. Experimental Results

Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP) driving cycle was used to test the performance of the electric propulsion machine. Figure 6 presents a comparison between the reference speed taken from a WLTP cycle and the measured speed. Overall, the two curbs are superimposed, but there are moments, highlighted with circles, when speed spikes appear. This is probably due to PI controllers tuning if the SEVCON converter responds fast enough. Figure 7 shows the measured torque on the DCM side. An interesting aspect can be observed at zero speed (red circles): the measured torque is not null; this is due to a remanence torque between the DCM and PMSM, owing to PMSM cogging torque.

A comparison between battery power and mechanical power is presented in Figure 8. Figures 9 and 10 are zoomed views of Figure 8.
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Figure 6. PMSM reference speed (in red) and measured speed (in blue).

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Figure 7. DCM measured torque.

Figure 8. Battery power (blue) and mechanical power (red).
Figure 7. DCM measured torque.

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Figure 8. Battery power (blue) and mechanical power (red).

Figure 9. Battery power (blue) and mechanical power (red)—detail for high speed operation.

Figure 10. Battery power (blue) and mechanical power (red)—detail for low speed operation.

After laboratory tests were concluded, the propulsion system was installed onto the prototype vehicle (Figure 11). The PMSM is driving the front wheels through a planetary differential transmission with a 10:1 ratio. Figure 12 shows a photo from the tests made with the prototype, and in Figure 13 it can be observed that the maximum speed obtained in the initial test with two passengers is slightly above 45 km/h, the maximum speed for this class of vehicles.
After laboratory tests were concluded, the propulsion system was installed onto the prototype vehicle (Figure 11). The PMSM is driving the front wheels through a planetary differential transmission with a 10:1 ratio. Figure 12 shows a photo from the tests made with the prototype, and in Figure 13 it can be observed that the maximum speed obtained in the initial test with two passengers is slightly above 45 km/h, the maximum speed for this class of vehicles.

Figure 11. Electric propulsion system mounted onto the vehicle prototype.

Figure 12. Photo from the prototype vehicle test run.

4. Discussion

Figures 8–10 present the difference between the electrical power measured at battery terminals and mechanical power measured at the coupling between DCM and spoke-type PMSM. It is obvious that the difference between those curves is mainly the expression of power losses on the kinematic chain: power convertor losses, PMSM losses, and toothed belt transmission losses. Measurement error tolerances can also play a small role in this difference. Considering that the SEVCON power converter has a rather high efficiency (Appendix A, Figure A2) at a transferred power of 2–3 kW (Figures 7–9) of about 98%, the remaining power losses are attributed to spoke-type PMSM and belt transmission. In Figure 9, the graph is zoomed from Figure 8, where the PMSM is at high speed. In this case, the drivetrain efficiency is between 75 and 80%. This means that the PMSM and the transmission efficiency are around 77–82%. In Figure 10 a zoom of Figure 8 was made, but for a low speed operation. Here, the drivetrain efficiency is around 90%, more consistent with the simulation results. As a partial conclusion, at high speeds, the mechanical (bearings) and transmission losses are increasing significantly. However, the PMSM iron losses and Joule losses are also important, at high speeds, due to high fundamental frequency and flux-weakening implementation. Another visible aspect that should be explained is the slight delay of the battery power curve when compared with the mechanical power curve.
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The implementation of the propulsion system on the prototype vehicle was made to validate the developed structure. Acceleration and regenerative braking pedals were used to control the SEVCON controller aside from a mechanic brake pedal. The prototype vehicle was not fitted with all the elements of a standard car (doors, windows, lights, front and rear fenders, etc.). Nevertheless, only maximum speed and autonomy could be affected in this case. Thus, one can conclude that the propulsion system was completely validated.

5. Conclusions

In the latest years, it became clearer that new solutions for passengers and goods mobility must be adopted in a final attempt to limit the effects of global warming on the planetary ecosystem. All major actors in the automotive market have taken steps in gradually eliminating the current internal combustion engines and replacing them with electric propulsion systems.

The current study shows that the process of retrofitting a light electric vehicle with a fully electric drive, starting from the requirements defined in the L6 European vehicle class and going through all the stages required to develop an EV drivetrain. The common drivetrain topologies were evaluated, resulting in a system consisting of a central EM connected to the wheels through a mechanical transmission. This was the most suitable solution and was further investigated. Several EM structures were evaluated, resulting in PMSMs providing the required performance for the given constraints set. Two vari-
ants were considered for implementation, the Interior Permanent Magnet PMSM and the spoke-type PMSM.

A prototype was constructed based on a design/FEM-simulation/optimization process, and some of the tests performed are described in this article. The FEM-estimated phase voltage is compared with the measured one, showing a very good accuracy both in wave form and value, validating the entire process. Similar results were obtained between the measured and estimated electrical parameters of the prototype, and these values were used to parameterize the commercial SEVCON power converter used for this application.

The test bench that was constructed to test the PMSM prototype was presented in Section 3 of the article, allowing the emulation of WLTP drive cycle by using a DC Machine. It worked as a load when the PMSM was operating as a motor and worked as a motor when the PMSM was functioning as a brake/generator. Test results showed good accuracy between the imposed WLTP speed profile and the measured values; the variation of mechanical power and battery power was also presented, allowing an estimation of the vehicle’s autonomy.

Once the on-bench testing validated the estimated results, the PMSM prototype was integrated into a light vehicle and tested in real-life conditions, showing that the required operating regimes can be achieved. The main novelty of the article consists of the presentation of a full development process of a drivetrain for the light electric vehicle, specifically the L6e European class. Although similar PMSM structures using ferrite magnets [26,27] were previously investigated in the literature, this paper provides a guideline for a full development process. It begins with the requirements, goes through the lengthy design–simulation–optimization–prototyping–testing process, and finally validates the procedure by integrating the drivetrain on a light EV and testing the prototype in real-life conditions.

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Appendix A

Figure A1. Simulation efficiency maps: (a) IPM machine; (b) “Spoke” rotor machine.
Figure A2. SEVCON converters efficiency with $m =$ modulation factor, $pf =$ power factor, output current $= \sqrt{I_q^2 + I_d^2}$, Size 4 converter was used during tests [this chart was obtained by the courtesy of Eng. Teodor S. Nitu from Borg Warner company].

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