High-performance compact in-wheel electric motors for future electric mobility

Luka AMBROŽIČ

Abstract: The automotive industry is moving in the direction of electric cars and seemingly bringing a new hope for humanity being able to make amends with the environment. In the meanwhile, behind the scenes, a battle of e-technologies is taking place. Still an underdog among the many contenders is the vehicle designer's favorite: the in-wheel motor. Arguably the simplest and the most refined concept of them all, but technically speaking certainly a worthy challenge for engineers, scientists and entrepreneurs.

Keywords: electromagnetic topology, electric vehicles, electric motors, permanent magnet synchronous motor, in-wheel, direct-drive, high-efficiency, regenerative, electronically commutated

1 Introduction

Vehicles require most of the available torque as they are starting to move or when accelerating, making electric motors perfect for use in cars as they produce the maximal torque already at startup. With the race for energy-efficiency becoming more and more important, placing the propulsion source closer to where it is needed is becoming a great way to optimize, while also allowing manufacturers more control for implementing advanced features, increased safety and truly smart propulsion systems. In-wheel motors are electric motors that are incorporated together with the bearing on the hub of a vehicle. Thus, they are often also named as wheel hub motors. In their general form for utilization in automotive applications, they fit inside a regular rim and drive the wheels directly, without mechanical transmission.

2 History of in-wheel motors

Many first designs of in-wheel motors began appearing towards the end of the 19th century and one of the first of many in-wheel motor concepts was conceived in 1890 by Albert Parcelle. This was to become to first so-called « traction motor »

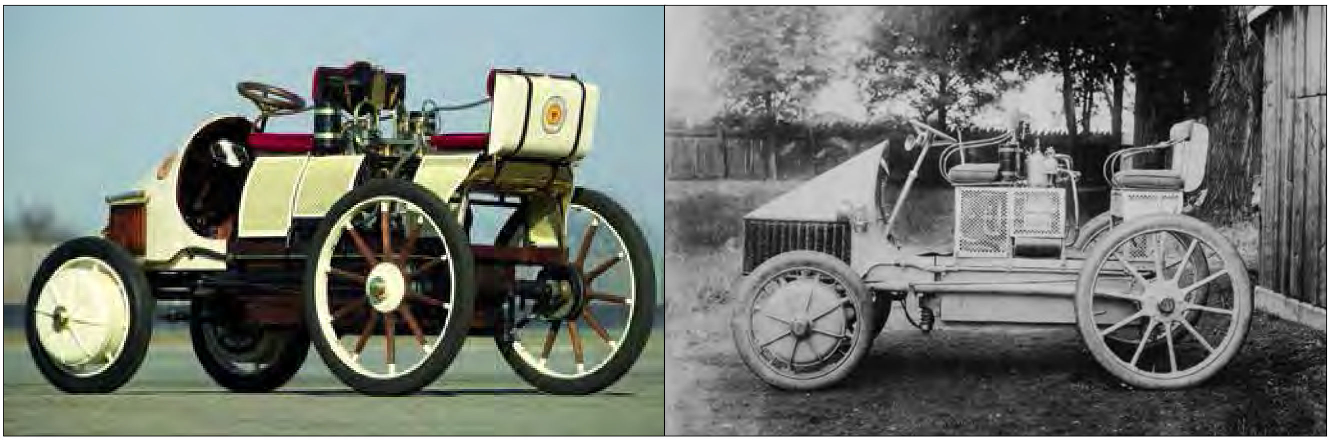

Figure 1. *Semper Vivus, a Lohner-Porsche hybrid electric vehicle (right) with front in-wheel motors, which was presented at the Paris World Exhibition in 1900.* **Right:** *original.* **Left:** *a modern recreation. Photo: Porsche Cars North America*

Luka Ambrožič, univ. dipl. inž., Elaphe Propulsion Technologies Ltd., Ljubljana, Slovenia

which was designed to be fully incorporated in the wheel hub. Many more wheel motors were under development between 1890 and 1900, and not all were electric. Ferdinand Porsche began his automotive career by engineering electric vehicles, whereby his first racing creations were driven by in-wheel motors that ran on batteries.

As the internal combustion engine (ICE) became more and more efficient and powerful and oil discoveries were increasing rapidly, the gasoline engine overtook the electric motor as the primary source of propulsion by the late 1920s, mostly due to power and range considerations, while the ICE was and still is far from reaching the energy-efficiency of the electric motor. Despite being invented for vehicle propulsion systems, most in-wheel motors are nowadays used in industrial applications, driving assembly line wheels. In modern times, the in-wheel motor became popular again with the advent of electric bicycles, facilitated by the development of light and powerful batteries.

3 Why in-wheel motors?

Since electric motors produce full torque immediately at startup, they are a perfect combination to use for vehicle propulsion, where torque is required mostly when initiating movement. Currently, the appearance of our automobiles is characterized by the traditional drivetrain layout (internal combustion engine, gearbox, power transmission, and exhaust system). The majority of the drivetrain is placed in front and below the passenger compartment, which severely limits the space available to designers for user-centric design (space for passengers and luggage). For the most part, requiring power transmission systems and gearboxes adds losses of up to 15% to overall efficiency of a vehicle [1]. Moreover, IC engines have by themselves high thermal losses due to heat dissipation (i.e. an ICE has approx. 20% efficiency, depending on the size). Electric motors generally show unbeatable efficiencies, which is especially true for Elaphe in-wheel motors, having an energy-efficiency of over 93%. By using direct drive in-wheel motors, many complex systems which are expensive to manufacture, like the drive shafts, gearboxes and differentials become redundant, which results in an overall decrease of weight and a more efficient vehicle.

Figure 2. *Elaphe M700 in-wheel motor cross-section. The motor fits inside a regular 16" or larger rim and is integrated with standard off-the-shelf parts like the hub bearing and friction brake. Windings are part of the inner stator and the magnets are attached to the inside of the outer rotor shell.*

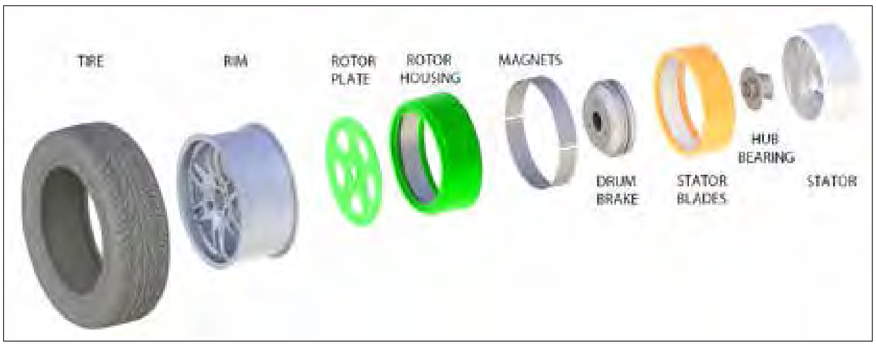

Figure 3. *An exploded view of the SMART 2nd Generation in-wheel electric motor assembly to the vehicle hub bearing.*

Another important feature in the battle for increasing efficiency is harvesting the energy of energy from braking, which is otherwise dissipated through heat. The recuperated braking energy can be stored either as mechanical (in a variation of a kinetic energy recovery system - KERS) or electric energy (directly in the batteries). An in-wheel drivetrain requires the least energy conversion steps of all available technologies and consists of components that all work at high efficiency, resulting in a high overall well-to-wheel efficiency. Aside from the advantages of energy recuperation, propelling the vehicle by an electric motor offers other advantages over an ICE vehicle: the torque generation is extremely quick and can be controlled much more precisely with a shorter control period. The torque response is in the order of several milliseconds, which makes it about 10 to 100 times faster than an ICE with a conventional braking system [2]. All this results in improvement of control systems, compared to those found in ICE vehicles (up to 7% faster response for ABS/ESP and up to 3% faster response for TCS [3]). By having the opportunity to control each wheel independently, the vehicle also comes close to having maximally stable dynamics.

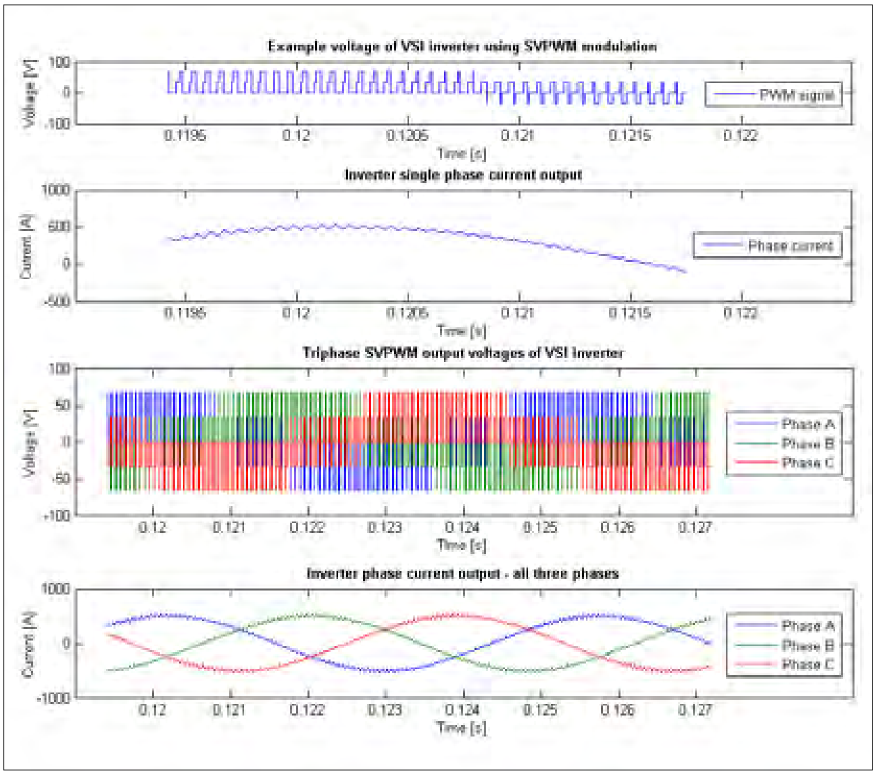

Figure 4. *Top two graphs: A cutout example of SVPWM inverter voltage output with corresponding phase current waveform shown below. Bottom two graphs: Phase output voltages of VSI inverter using SVPWM modulation (upper) and the resulting PMSM in-wheel motor phase current waveforms (below).*

4 How in-wheel electric motors work

The majority of in-wheel electric motors are in their core brushless electric motors, where a rotary electromagnetic field, generated by electric current flowing through the windings, provides the electromagnetic force to drive the rotor. Most high-performance in-wheel motors are AC permanent-magnet synchronous motors (PMSM) optimized for fitting inside vehicle rims. An in-wheel motor can be constructed in different ways. The so-called pancake motors (axial-flux) use stator windings placed between sets of magnets where the magnetic field acts in the axial direction and are considered as the least practical of all forms. Radial-flux motors are more popular, and have magnets incorporated in the rotor, where the magnetic flux flows radially, from the center outwards.

Radial flux motors come in two variations, based on which part is attached to the axis of rotation. An inner-rotor type is the common style of motor that most people know. These PMSMs have a stationary outer shell (stator) with windings on the inner side and an inner rotor with permanent magnets attached, driving a central shaft similar to any other electric motor.

A more suitable configuration for mounting vehicle rims over the motor is the outer-rotor type, such as the Elaphe M700 (*Figure 2*). In this configuration, the stator and the

Figure 5. *A selection of vehicles using Elaphe electric motors as the propulsion system of choice. (1 -Steinbock HX1 all-terrain vehicle with 4 in-wheel motors, 2 – VW Sharan through-the-road hybrid, with 2 near-wheel motors, 3 - Smart pure-electric car with 2 in-wheel motors in the rear, 4 – Chebela, a pure electric Slovenian concept car with 2 in-wheel motors.*

windings are on the inside, and the stator is attached to the hub together with the hub bearing. Due to a very compact active part (containing windings and magnets, where the EM force acts to turn the motor), the inner part of the stator is hollow with space for installation of the mechanical brake. The rotor outer shell and the permanent magnets (inside the shell) are the spinning parts and are attached to the distant end of the hub bearing, just like a normal rim with a tire would be (See *Figure 3*). In this case, the rotor of the in-wheel motor acts as a coupling between the bearing and the rim.

Like regular AC motors, in-wheel motors rely on the interaction of magnetic fields to generate torque (and motion). They are unique, however, in the way they manipulate their torque-producing electromagnetic fields by performing commutation electronically, requiring the use of inverters. The main functionality of inverters is the generation of AC output waveforms from a DC power supply (i.e. a battery). Generally speaking, these inverters are composed of a number of semiconductor switches, which turn on and off to produce quasi-sinusoidal waveforms, made of discrete values where the shape is controlled by using pulse width modulation (PWM, see *Figure 4* top).

To achieve high dynamic performance in a PMSM in-wheel motor, a field oriented control (FOC) strategy, a form of vector control, is applied. By controlling two stator currents (i_{ds}, I_{qs}), which are mathematical transformations of the phase currents, it is possible to directly control the electromagnetic torque. To achieve this, measurements of rotor position and stator currents are necessary. The position can be obtained by using a position sensor, such as an encoder (Elaphe M700 uses RLS RM44S absolute encoders) or three independent Hall sensors installed onto the windings themselves, while the stator currents are measured by current probes inside the inverter circuit.

5 Conclusion and further development

The success of passenger cars such as the Nissan Leaf and Tesla Model S shows that the automotive industry is embracing electric drives as the propulsion system of the future, but the most radical changes have yet to conquer the market. Elaphe's patented electromagnetic topology is the kind of fundamental innovation which enables design and manufacture of extremely compact, lightweight and supremely powerful in-wheel drives that use no power transmission, leave plenty of space on the chassis for passengers and batteries, and increase safety on the road by utilizing advance torque vectoring methods. The design that stems from the revolutionary Elaphe EM topology also brings about other hidden advantages, such as minimizing material costs.

The core driver behind Elaphe in-wheel motor innovations is the mission to use them for advancing the users' daily travels. Future concepts for passenger cars will significantly differ from the current ones and in-wheel motors are one of the disruptive technologies which are opening a whole new field of possibilities and opportunities to revolutionize the car concept of the 21st century. Throughout the company development cycle, Elaphe persistently strives to be involved in industrial vehicle development projects, and the bottom line are more than 10 different, fully functional vehicles – used on mud, gravel and snow – where Elaphe's kow-how and solutions have been utilized (see *Figure 5*).

6 About Elaphe Propulsion Technologies Ltd.

Elaphe has been in full throttle since the early days of the new electric revolution, developing a revolutionary EM topology which enables the motors to have an extremely compact and lightweight active part. We built our technology and experience from the bottom up – starting with testing the innovative active part topology on small, ultra-compact electric motors for robotic applications and in-wheel drives for electric scooters. Then we created one of the most powerful compact in-wheel drives in the world. We got to this point by relying on our team of amazing young engineers, counting on the agility and flexibility of our response to the call for innovation. But, honestly, we also do it because it's fun.

References

[1] D. J. L. Brett, P. Aguiar, N. P. Brandon, R. N. Bull, R. C. Galloway, G. W. Hayes, K. Lillie, C. Mellors, C. Smith, and A. R. Tilley, "Concept and system design for a ZEBRA battery--intermediate temperature solid oxide fuel cell hybrid vehicle," J. Power Sources, vol. 157, no. 2, pp. 782–798, 2006.

[2] Y. Hori, "Future vehicle driven by electricity and control-research on four-wheel-motored' UOT Electric March II,'" Ind. Electron. IEEE Trans., vol. 51, no. 5, pp. 954–962, 2004.

[3] R. Vos, "Influence of in-wheel motors on the ride comfort of electric vehicles," Eindhoven University of Technology, 2010.

We are always looking for bright minds to join our team and help us make a sustainable and fun future for driving … and if you like what we stand for and love having fun, contact us and we can change the world together.
We are expecting your introductory e-mail at *customer@elaphe-ev.com*.

Zmogljivi kolesni električni motorji za električna vozila prihodnosti

Razširjeni povzetek: Avtomobilska industrija se vse bolj osredotoča na proizvajanje električnih avtomobilov in tako izpolnjuje prikrito hrepenenje človeštva, da se odkupi okolju. Medtem pa se za kulisami bije boj med različnimi e-tehnologijami prihodnosti. Še vedno so med manj zastopanimi tehnologijami, a glavni favoriti oblikovalcev vozil, kolesni elektromotorji. Utemeljeno najbolj preprost in prefinjen in najbolj prefinjen koncept izmed vseh oblik pogonskih sistemov so kolesni elektromotorji še vedno tehnično zahteven izziv tako za inženirje in znanstvenike kot tudi za podjetnike in inovatorje.

Začetek vožnje terja od pogonskega sistema vozila največji navor ravno pri speljevanju, za kar so pri klasičnih avtomobilih z motorji na notranje zgorevanje potrebni mehanski prenosi in menjalniki. Po drugi strani pa električni motorji lahko proizvedejo celoten navor že takoj ob zagonu, brez mehanskih prenosov in so pisani na kožo uporabi za pogon avtomobilov. Tudi zgodovinsko so bili električni motorji razviti kot pogonski sklopi prvih avtomobilov (ki so bili električni), čeprav jih je kasneje zaradi različnih razlogov izpodrinil motor z notranjim zgorevanjem. Dandanes narekuje videz avtomobilov prav klasični pogonski sistem, ki je sestavljen iz motorja na notranje zgorevanje, menjalnika in diferenciala ter izpušnega sistema. Večji del pogonskega sistema je v prednjem delu vozila in pod potniško kabino, kar oblikovalcem vozil praktično onemogoči oblikovanje, ki bi se osredotočilo na uporabniško izkušnjo potnikov. Skupaj z razvojem baterij in naprednih kolesnih elektromotorjev pa se lahko tradicionalna oblika pogonskega sistema drastično spremeni, saj pri uporabi kolesnih električnih motorjev postanejo menjalniki, centralni motor ter ostale komponente mehanskih prenosov popolnoma odveč, pri tem pa se dosežejo izjemno velik izkoristek energije – preko 90 % - nižjo težo vozila in veliko povečanje nadzora nad dinamiko vozila ter izboljšanje varnosti.

Ključne besede: električna vozila, pogon prihodnosti, v platišču, sinhronski motor s permanentnimi magneti, neposreden prenos, visok izkoristek, regeneracija, elektronska komutacija, EM-topologija