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Series Concept of an Externally Excited Synchronous Machine as a Magnet-Free Option in the integrated E-Axle Platform EMR4

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ABSTRACT: Electromobility is now firmly set to become the mainstream of future mobility. The growing range of Battery Electric Vehicles (BEVs) adds more frequent long-distance highway trips at higher speeds to the powertrain requirement list. This, together with geopolitical tensions, out-of-sync supply chains, a significantly increased rare-earth cost level and the growing importance of a BEV's Global Warming Potential (GWP) has initiated a comeback of Externally Excited Synchronous Machines (EESM) for BEV powertrains. They offer a rare earth-free alternative to the Permanent Magnet Synchronous Machines (PSMs), which have become the mainstream over the past decade. Considering the growing importance of high-speed driving, EESMs offer a better efficiency at >110 km/h than PSM, and they have a lower overall GWP. Up until recently, EESMs were often seen critically as they can add manufacturing complexity and production cost. Vitesco Technologies has ten years of field-experience with EESM in series use since 2011 and has utilized this expertise to develop a new 400 V/800 V EESM series concept complete with excitation stage that combines the advantages of EESM technology with a significantly simplified and cost-optimized design for manufacturing. The magnet-free EESM rotor is readied as a new option within the modular and scalable EMR4 platform that is compact enough to address even the D-segment, but can be scaled upwards to include all passenger cars segments above.

1. INTRODUCTION

As the global trend towards sustainable mobility not only continues but accelerates in 2022, several influencing factors have begun to change. Step-by-step advancements in battery technology offer a growing energy density which helps to meet the request of electric car drivers for long-distance driving. Along with superfast charging technology, battery electric vehicles (BEVs) with more powerful batteries are be-ginning to close the range gap to vehicles with combustion engine.

This, however, leads to changing requirements to the electric machine. While the majority of BEVs are powered by a Permanent Magnet Synchronous Machine (PSM) which offers an excellent efficiency level at a certain operating point, long distance driving - typically along a highway - asks for additional properties: During long stretches of highway driving and/or large parts of the Worldwide harmonized Light Vehicles Test Cycle (WLTC) the electric motor will be run in an operating field characterized by a combination of high rpm and high or part-load power/torque.

PSM technology which has been the mainstream for BEVs does not ideally support this typical driving situation, because a PSM control strategy needs to be optimized for a specific operating point. In other words: A PSM machine is more of a "specialist". So far, this trade-off between low rpm/high torque capabilities for short and medium distance driving (urban driving mostly) and high-speed, long-distance capabilities was often decided in favor of urban driving.

Once the BEV use cases include more long distance/dynamic driving phases (e.g., >110 km/h), an electric machine with the character of an "all-rounder" has an additional strength to offer, when compared to PSM technology. Externally Excited Synchronous Machines (EESMs; alternatively referred to as: Wound Field Synchronous Machines, WFSMs) can offer this all-rounder profile. That is why this type of electric motor is coming back at the moment and widens the powertrain choices for vehicle electrification. While (fast) highway driving with frequent load changes, intermittent acceleration and high speeds is one challenge to electric driving, long-distance towing of a trailer on a highway is another. Adding the weight of, e.g., a caravan to a passenger car automatically means an high load/high rpm driving situation. The BEV’s electric machine will be run at high speeds which requires a high efficiency in this part of the map plus an effective cooling system.

Another thing that has changed over the years, is the price for rare earths such as neodymium (Nd) used in the most powerful permanent magnets. In 2022 the Nd price had already reached a 10-year high, which means an added burden to the overall cost of a BEV. What makes matters worse, is the changed geopolitical climate. It was always a matter of concern that the global rare earth mines are very un-evenly distributed on the planet, because this makes it a challenge to diversify sup-ply chains. With an increasing international competition between states for political and economic dominion, a reliable supply of rare earth materials at an economic and stable price has now become an even bigger concern. The level of volatility is alarming and asks for greater independence from rare earths. A magnet-free motor would offer this independence.

Also, a more consistent approach to sustainability, which considers everything from the raw materials for a product to its end of lifetime, is placing greater importance on the circumstances under which materials such as rare earth oxides are extracted and reduced to pure metal. A Life Cycle Analysis (LCA) that includes the mining of rare earths shows the impact this part of the life cycle has on a product's Global Warming Potential (GWP) which is a measure for sustainability. As global warming is showing its effects ever more clearly on a global scale, electrification - despite be-ing the silver bullet of future mobility - has to meet more stringent sustainability requirements.

Finally, the global COVID19 pandemic plus global conflicts along with subsequently imposed sanctions have had a massive impact on the global economy, on international trade and logistics by sea. This further increases the concern about any reliable in-time long-distance transport of materials such as rare earths.

Considering the many facets of this multi-level change, EESM technology offers an attractive mix of properties which address most of the recent challenges. Vitesco Technologies already has the backing of ten years of series production expertise with EESM motors and is now further advancing the technology to meet today's very ambitious mix of requirements.

Industrialization experience and the modular and scalable approach to axle drive technology helped to develop an EESM rotor concept which offers the well-known strengths of this technology but avoids a lot of potential downsides which are commonly attributed to it. In many cases this was achieved by detail optimization which was only possible by harnessing the many years of experience. This EESM concept is being developed as an additional option within the latest generation of highly integrated axle drive by Vitesco Technologies, the modular and scalable EMR4 platform.

2. EESM HISTORY AND FUTURE

The first generation of EESM motor for automotive Axle Drives was advanced to series production by Vitesco Technologies in 2011 for Renault, Fig. 1. Over the following years, PSM technology became the mainstream because it delivers an excellent efficiency required for the majority of typical BEV driving situations which were - and to a large degree still are - short to medium distance driving with lots of torque and power at low rpm.

Currently, EESM motor technology is coming back but it still brings quite a few challenges. The cost of manufacturing and the system complexity are often considered as major hurdles for EESM utilization. Hence, the biggest single "risk" with this technology appears to be a tendency to make the system overly complicated and thus overly expensive. The new EESM concept by Vitesco Technologies avoids overcomplicated solutions and instead uses straightforward solutions which work and limit cost.

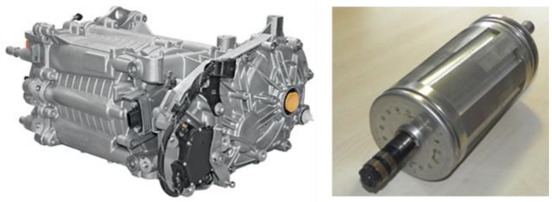

Fig. 1 The first EESM motor from 2011. Two generations of this machine were manufactured and >100,000 units of the respective EMR1/EMR2 drives were delivered.

The new EESM series concept utilizes the expertise from EMR1/EMR2, however, the EESM for the new EMR4 platform differs in many respects. The electric machine is ready for 400 V (with Si and/or SiC in the inverter) and 800 V (with SiC inverter). A customer project for an EESM inverter with 400 V provides a head start for developing the excitation stage.

One main difference to the early EESM machine is the improved and simplified rotor of the new EESM concept, Fig. 2. In particular, the new EESM concept offers an active rotor length of just up to 120 mm at a rotor outer diameter of 145 and a stator out-er diameter of 208 mm (which equals the platform outer diameter of the EMR4 motor options), Fig. 3. The concept's high power density, compactness and economic manufacturing cost level facilitates the use of this new motor type down to D-Segment models. However, the new EESM option within the modular EMR4 plat-form can be scaled up to address all passenger car vehicle segments to the very top. As a part of this, the manufacturing process is suitable for all market segments and production numbers - i.e., manufacturing is economic. With the magnetically asymmetric (single pole offset) rotor design of the EESM, a solution was found to achieve the torque requirements without rotor skewing which makes manufacturing much easier.

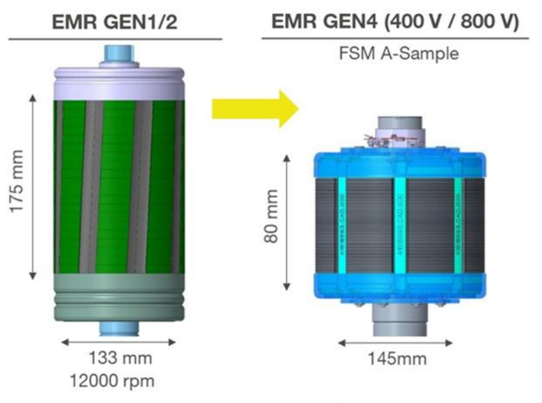

Fig. 2 The rotor for the new EESM concept was improved and simplified.

Fig. 3 The EESM series concept demonstrator in 2022.

The new improved rotor is shorter than the first two generations and does not require vacuum potting. The rotor design itself ensures a high mechanic strength. The primary target was to avoid plastic deformation of the lamination or detachment of the excitation winding at high speeds. This is the result of a multi-goal approach, bearing mechanic strength, the electric design and producibility as equally important tar-gets in mind. Therefore, the design solution realizes the mechanical design without gluing the components, Fig. 4. The excitation winding sits on the routing cap. The spacers inserted between the poles prevent the coils from shifting due to centrifugal forces. The end caps are plugged axially onto the rotor and fixed with screws [1].

The rotor is contacted via a smoothly working brush system because brushless-solutions are considered to drive unnecessary complexity and cost in EESM motors. The Vitesco Technologies brush system is field-proven in the EMR1/2 and provides reliable solution that offers several advantages: One it has proven to be a lifetime solution that does not require maintenance over the vehicle’s service life. The level of brush wear is so minimal that it has no effect on the function. Secondly, the brush system has lower efficiency losses than an inductive coupling system. Add advantage number three: With a brush system the rotor can be instantly switched to a currentless state, which is not possible with an inductive system. And finally, the brush system helps to bring the system cost level down.

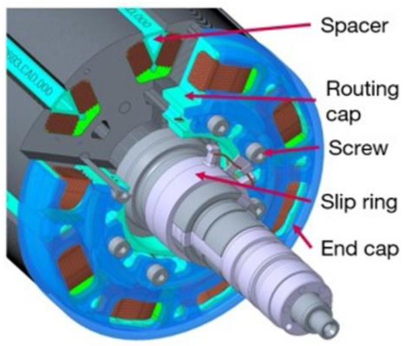

Fig. 4 Mechanic winding design for optimized high-speed strength.

Another benefit of the design without potting is an improved cooling situation. A water-cooling jacket was chosen for the sample product to dissipate stator heat. Looking to the future, the fully functional sample of the series concept is also prepared for oil cooling. This option is a part of the EMR4 platform concept and can be utilized for dissipating rotor heat via oil cooling during extended dynamic driving periods. The platform offers a generic interface, which provides the basis for developing a rotor oil cooling solution and making it an additional option of the platform should this be required. Through this cooling system modularity, the EMR4 platform concept makes it possible to meet differing OEM requirements to support load situations such as dynamic driving with many load changes. The requirements to the BEV main propulsion motor are not so different, however, the expectations to a secondary motor can vary from OEM to OEM, because the second e-motor may or may not be used for more than boosting which then requires a higher efficiency level. For instance, if a secondary motor is used frequently within a four-wheel drive concept, the secondary motor needs to have a high efficiency level. So, depending on the driving strategy, an EESM has benefits to offer to secondary motor use cases as well.

Three driving cycle simulations were used to assess the thermal capability of the EESM: This is 20 times acceleration repetition from 0 – 100 km/h and the continuous ascent of the Großglockner mountain at 60 km/h. All load cycles can be run without thermal derating and within the permissible winding temperature span of maximum 180 °C.

The absolute peak torque and peak power performance of the EESM motor concept is comparable to the EMR4 with PSM technology, however, in the higher rpm and higher power/torque field (>110 km/h), the EESM motor is more efficient, Fig. 5. Thus, bringing EESM technology to "eye level" with PSM efficiency was one of the most important development goals.

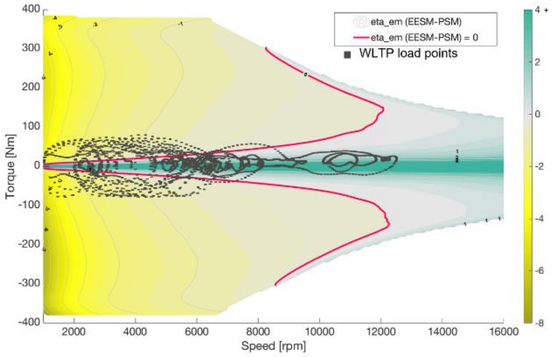

Fig. 5 Efficiency comparison between PSM and EESM machines showing characteristic strengths.

The new concept will begin to undergo testing to validate the electric motor performance during the last quarter of 2022 with a fully functional sample motor complete with SiC inverter and inverter-controlled excitation stage. Another development focus is confirming the motor design's high-speed capability up to 120 m/s, respective-ly to the magnitude of 16,000 rpm. Spin tests with up to 120 m/s at up to 160 °C have already confirmed the mechanic strength of the winding design. This will be validated via full motor testing. The Noise/Vibration/Harshness (NVH) behavior of the new EESM concept poses challenges but several suitable counter measures have been identified and confirmed by simulation. This is one of the areas where a lot of proprietary optimization works has already been done. After validating the EESM de-sign the new motor option will be integrated into the e-Axle platform EMR4. This is scheduled for the beginning of 2023.

3. AXLE DRIVE PLATFORM EMR4 WITH SYNCHRONOUS MACHINE

The drive system of a BEV has the third highest environmental impact, after battery and chassis. Within the drive system, the e-motor technology exerts a great influence on the efficiency on driving and on the overall efficiency of a BEV. Assessing the sustainability of e-motor technologies consists of two major parts: One looks at the materials extraction. This includes environmental aspects such as energy and water usage. The second part considers the use phase of the resulting product over its assumed lifetime.

3.1. EESM and PSM Comparative Life Cycle Analysis

To evaluate the GWP of different e-motor technologies, a comparative Life Cycle Analysis (LCA) was carried out and presented in 2022 [2]. “Comparative” indicates that just the technical differences and the resulting various efficiency maps between PSM and EESM were evaluated. All electrical components were considered, as far as correspondingly scalable data sets were available in the GaBi LCA database (LCA software provided by Sphera[3]). The LCA methodology was based on the lat-est CML (Centrum voor Milieukunde University Leiden) method for the impact cate-gory GWP over 100 years. The unit of the GWP is kilogram carbon dioxide equiva-lents (kg CO2-eq). To calculate the corresponding mass of kg CO2-eq, the LCA methodology, according to the standards ISO 14040:2006 [4] and ISO14044:2006 [5], were applied.

Life cycle stages are considered from cradle-to-grave excluding OEM manufacturing and end of life. The functional unit has to drive 200,000 km with a C-Segment vehi-cle repeating the speed trajectory of a specific drive cycle. The results show, on the one hand, that the EESM inverter has a higher GWP attributable to the additional module for external excitation and thus the slightly larger housing. On the other hand, the magnets of the PSM contribute to a higher GWP for the machine, Fig. 6.

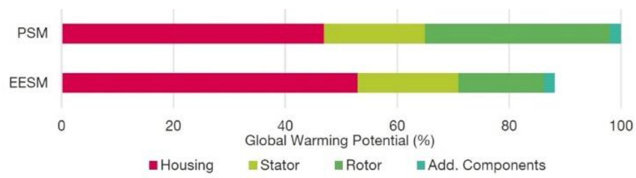

Fig. 6 The impact of rare earth extraction on the GWP.

Even allowing for the EESM's need for a slightly larger aluminum (Al) housing and the GWP impact of the added Al material, the overall GWP of the EESM is lower than that of the PSM. The rare earth magnets in the PSM rotor have such a huge impact on the overall drive system, that it overcompensates the copper windings, bigger housings, and the additional excitation module for the EESM. The GWP of the EESM is 6% lower, Fig. 7.

Currently EESM motors bring a mix of lower GWP-critical material input but higher use losses. The opposite applies to PSM motors: They require a high GWP-critical material input but have lower use losses. The recycling situation also has an influence on the GWP assessment. For Al and copper (Cu) circular systems are in place. For permanent magnets this recycling economy will still have to be installed.

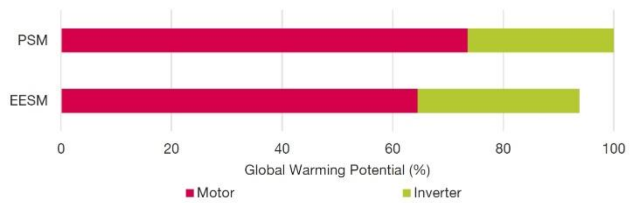

Fig. 7 GWP of the total drive system.

However, as the electricity mix gets "greener" through a growing share of sustainable energy, the use loss GWP impact of EESM can change accordingly. In any case, the electricity grid-mix for charging the vehicle has the biggest impact on the use stage. In the future, the most environmentally friendly drive system will be deter-mined by the development of the electricity grid mix in the world, Fig. 8.

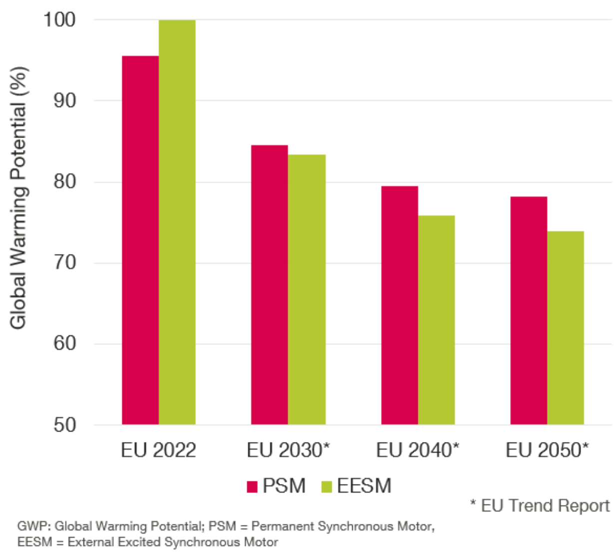

Fig. 8 Influence of the electric grid on the GWP (* indicates the EU reference sce-nario [6]).

3.2. Details contributing to optimized EESM Efficiency

As stated before, the EESM has slightly higher GWP impact in the use phase due to a lower efficiency in the WLTC. Several design optimizations have been integrated in the prototype to reduce this gap and even close it. With the asymmetric pole tip design in combination with the flux barrier the losses in the rotor were reduced and improved efficiency in all working points. This also reduced the torque ripple and allowed the manufacturing optimized skewing free design.

One thing should be kept in mind when comparing the two rotor technologies: PSM rotors are already highly optimized. There is not that much potential for further PSM efficiency improvement. EESM rotors on the other hand are in an earlier phase of optimization. They still offer much more potential for further efficiency progress as compared to PSM. The new EESM series concept, described in this paper, is currently strongly optimized towards performance. In the next development cycle the multi criteria optimization focuses on improved balance between performance and efficiency by alternating the parameters for pole tip design, winding number and flux barriers.

Besides that, the EESM technology has full access to efficiency measures from the EMR4 platform, like increased conductors per slot, reduced lamination stack thick-ness and drag loss optimized bearing system, so it can be adopted to the specific customer needs in application as main or secondary drive.

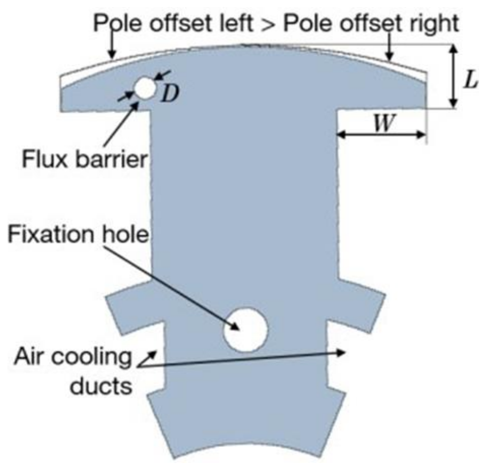

Fig. 9 Pole offset design

3.3. Field-proven Excitation Stage Technology

Compared to a PSM motor, an EESM motor requires an additional excitation stage which supplies the power to the rotor windings. As part of the streamlined series concept for the new EESM rotor, the excitation stage hardware is strongly based on the field-proven EMR1/2 excitation stage. The inverter power module is realized with an additional excitation H-bridge. However, compared to the original excitation stage, the new technology is ready for 800 V systems and uses SiC power semiconductors to achieve excellent efficiency at high voltage levels. The maximum excitation current is 20 A, the continuous current is <10 A. The EESM efficiency and functionality are provided by a new EESM control software. The switching strategy for the excitation current is optimized towards minimizing losses.

4. VITESCO AXLE DRIVE PLATFORM SOLUTION WITH EESM

The EESM series concept is designed to provide an additional option within the modular and scalable EMR4 platform, Fig. 10. While this extension to the platform is obviously more complex than just exchanging a PSM rotor with an EESM rotor plus changing the end cap, adding the excitation stage and the brush system, this is in principle exactly what the EMR4 platform facilitates. Its basic design and its modular-ity with many defined and standardized internal and external interfaces offer the potential to add an EESM rotor to the option list, Fig. 11. Only a very limited number of components needs to be changed for that. The overall maturity of the underlying platform is so far advanced that this addition can be made without touching the core design.

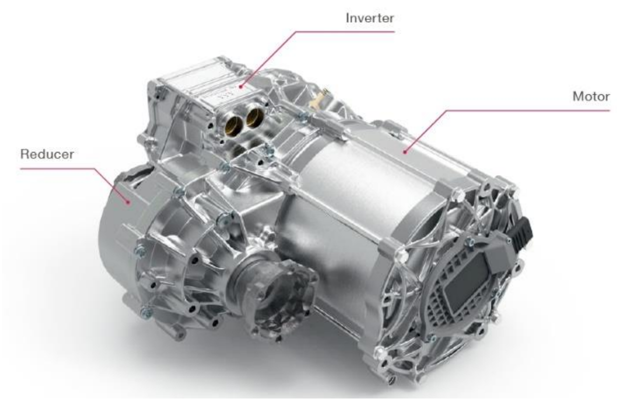

Fig. 10 The highly integrated axle drive EMR4.

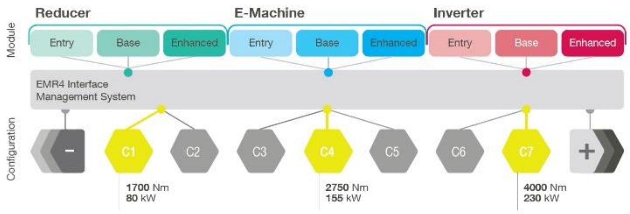

Fig. 11 The EMR4 platform's modularity and scalability allows EESM rotor as an option.

The combinatorics of the platform are ready for the EESM rotor option, brush system and excitation stage. As an example, the cooling strategy with a water-cooling jacket around the stator can be used with the EESM rotor as well. If required, an oil-cooling will also be feasible within the existing platform options. The sample hardware of the EESM machine is prepared for that. There is sufficient space for the brush system, and for integrating the additional excitation stage.

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