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Electric Traction Chain with Segmented Power Supply

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Keywords

Non-standard electrical machine, Emerging topology, System integration, Converter machine interactions, Automotive application

Abstract

We present an electric traction chain with segmented power supply for automotive applications. The concept is to split the windings of the electrical machine into sub-windings by bundle of turns. Each sub-winding is then fed by an independent low-voltage power electronics converter. We describe here the concept in details and discuss its advantages and its drawbacks. This allows us to identify the scientific and technical obstacles that will need to be solved.

Introduction

Electric vehicles are gradually being manufactured by every automaker, pushed by the regulations to reduce greenhouse gases. Among the various manufacturers, the permanent magnet synchronous motor seems to have achieved consensus. But the architecture of the complete traction chain is not yet standardized. For example, the voltage level often differs depending on the power requirements. A first approach is to increase the voltage when the power rating increases, just like in power grids. However, above 48 V safety standards impose additional constraints that can be difficult to manage and costly. This is probably why some manufacturers opted for "low voltage" drives. The different technological choices observed today is a motivation for prospective studies about non-standard electric traction chains, such as the one discussed in this contribution.

We propose here a traction chain with segmented power supply [1]. The idea came from a discussion between an electrical machine engineer and a power electronics engineer that can be summarized by two questions:

- 1 - How to modify the coupling of the windings of a machine to optimize its convertible power? [2]
- 2 - How to segment the power electronics converter to optimize the converter-machine integration? [3]

The concept can contribute to the development of integrated traction chains. In this context, we review in section 2 the topics of machine windings reconfiguration, splitting of the phase windings, segmentation of power electronics converter and integrated motor drive. The proposed traction chain is detailed in section 3. Advantages and drawbacks of the architecture are discussed in sections 4 and 5. Then our first prototype is introduced in section 6. Finally, the scientific and technical obstacles that will need to be solved are described in section 7.

State of the art of integrated traction chains

a) Machine windings reconfiguration

Electrical engineers are familiar with the "star-triangle" start-up technique for an asynchronous machine fed by a fixed-frequency fixed-voltage grid, which enables to reduce the magnitude of the inrush currents. Similarly, the Dahlander pole-changing circuit allows for varying the speed of the motor by altering the wiring connections inside the machine. In reference [4], the authors “proposed an ac spindle motor drive with a wide constant power range by switching the winding connections of the motor”. They use the same technique as the one used to dynamically change the number of turns in the windings of a tap-transformer. In reference [5], power electronics solutions have been proposed to change the configuration of the coil. Finally, in [6] a modeling of the dynamic reconfiguration of the coils is proposed.

b) Splitting of the phase windings of the machine

The phase windings of an electric machine can be split to add redundancy to the electric drive [25] or to adapt the voltage ratings of the machine and of the power electronics [14]. Alternatively, multi three-phase machines can be obtained by splitting the different sectors of a three-phase machine [26] or by grouping the phases of multi-phase drives [27].

c) Segmentation of the power electronic converter

In reference [7], the authors “present the findings of the first global analysis of energy consumption in electric motor driven systems and the options to reduce it”. On page 56, they show that the segmented operation of the converter can bring important benefits. This is tightly related to losses in power electronics components during partial load operation [8,9].

d) Integrated motor drive

In reference [10], dating back to 2016, the authors present a comprehensive review of integrated motor drives based on 203 references. In addition, we should mention the projects of the Fraunhofer Institute for Integrated Systems and Device Technology [11] as well as the EMiLE project [12]. The Wisconsin Electric Machines and Power Electronics Consortium is no exception, demonstrating its expertise in this area in [13]. Several integration projects are under development [14, 15]. Additional elements on this part of the state of the art can be found in [16].

Presentation of the proposed traction chain with segmented power supply

To clarify the following discussion, let us define a few terms:

- *A turn* consists of one electrically conductive insulated wire wound in a certain shape (Fig. 1a).
- *A coil* is made of one or several turns connected in series and/or parallel (Fig. 1b).
- *A winding* is made of one or several coils connected in series and/or parallel. Each winding has its own two terminals by which it is supplied (Fig. 1c).

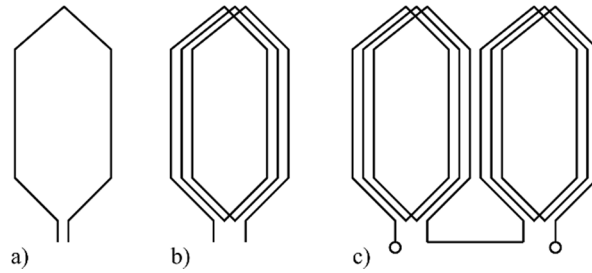


Figure 1 – Definitions of a) one turn, b) one coil, and c) one winding with its two terminals.

For illustration purpose, we consider the traction chain shown in Figure 2a). The machine is generic: the topology of the rotor is not specified. The 2-pole 3-phase electrical machine has concentrated armature windings. There are three windings (6 terminals). The windings are star-connected. Each winding is made of two series-connected coils. Each coil has three turns and is wound around a different tooth. The machine is fed by a 3-phase converter having a DC side voltage v_{dc} . It is possible to segment the power supply by splitting the windings into sub-windings.

The conventional way is to split the windings by coil [4, 12]. In Figure 2b), each winding is split into two sub-windings (the winding a is split into $a1$ and $a2$, etc.). As a result, there are 6 sub-windings (12 terminals). Each sub-winding is now made of a single coil. Note that each sub-winding is wound around a different tooth. To obtain the same magnetic state, the machine is now fed by two independent 3-phase converters having a DC side voltage $v_{dc}/2$.

The original idea proposed here is to go further and to split the windings by bundle of turns [1]. In Figure 2c), each coil is split into three sub-windings (the sub-winding $a1$ is split into $a11$, $a12$ and $a13$). As a result, there are 18 sub-windings (36 terminals). Each sub-winding is now made of a single turn. Note that several sub-windings are now wound around the same tooth. To obtain the same magnetic state, the machine is now fed by six independent 3-phase converters having a DC side voltage $v_{dc}/6$.

The proposed concept does not necessarily imply to split the windings up to the turn. This is only one option, among others. Similarly, the reduced converter DC side voltage does not imply to have a low voltage DC bus. Indeed, depending on the DC side connection of the converters, one could have a low voltage DC bus (parallel connection) or a high voltage DC bus (series connection) [14]. Finally, we underline that the concept equally applies to machines with distributed windings.

Main advantages of the concept

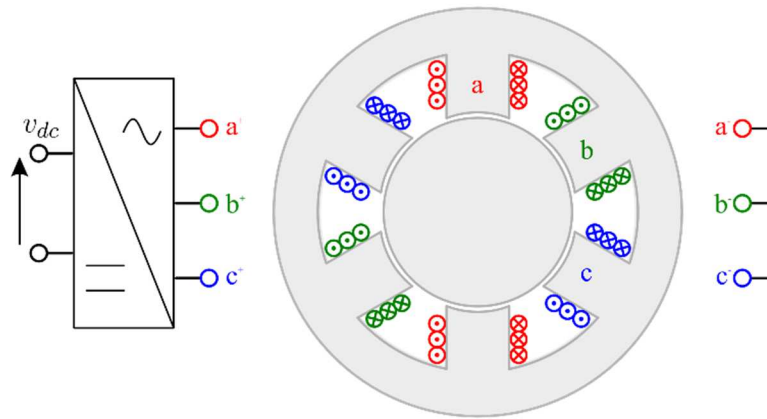
In this section, we discuss in detail several points that could be listed as advantages of the concept.

a) Low voltage traction chain

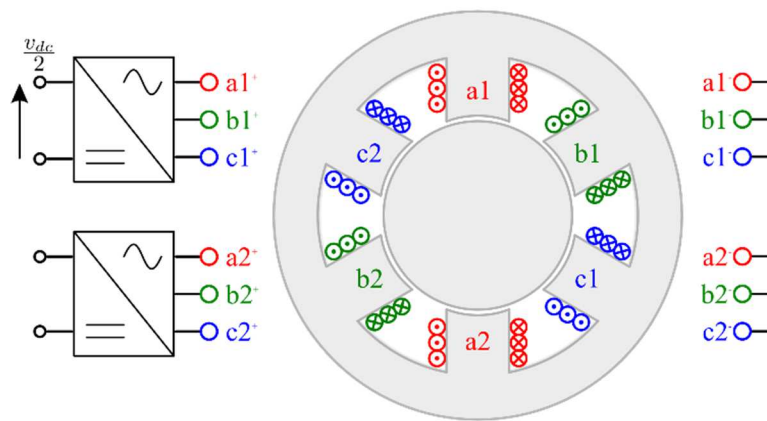
By concept, the converter DC side voltage is reduced in comparison to the equivalent standard solution. The DC bus can then be "low voltage" to limit electrical hazards, or "medium voltage" to stay under Paschen's minimum. In the previous example, with parallel connection of the converters, each winding (Fig. 2c) can now be fed from a low voltage DC source (e.g. 48 V). This is magnetically equivalent to powering the classical machine (Fig. 2a) from three times this voltage (e.g. 144 V) in order to apply the same ampere-turns. From the DC side of the converter to the electric machine, all the components operate at reduced voltage. As consequence, on the one hand it possible to use transistors that do not require to withstand high voltage and have therefore low on-state resistance, and on the other hand it facilitates the use of low-voltage battery packs.

b) Improved availability rate

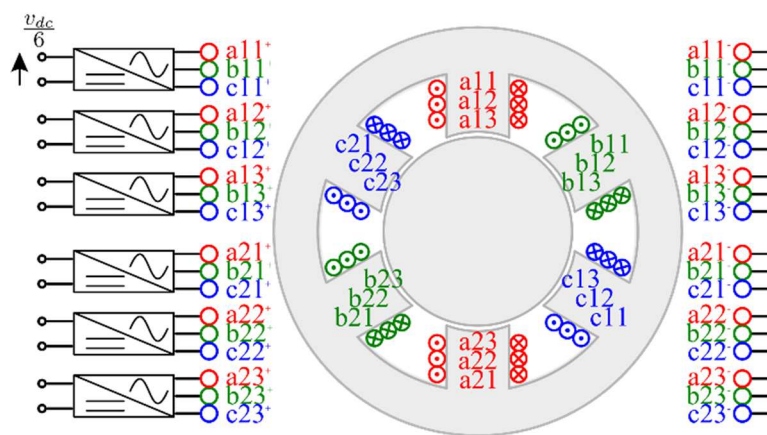
The adaptation of the structure of the electric machine to the structure of the power electronics converter can allow for a better integration and an optimized response to the specifications (cost, safety of operation, conditions of use, etc.). This directly impacts the availability rate.



a) Not split: 3-phase machine (3 windings) fed by a 3-phase converter



b) Split by coil: 3-phase machine (6 sub-windings each one on a different tooth) fed by 2 independent 3-phase converters



c) Split by bundle of turns: 3-phase machine (18 sub-windings, several of them on the same tooth) fed by 6 independent 3-phase converters

Fig. 2: Example of splitting: from a conventional traction chain to a traction chain with segmented power supply.

In addition, the resilience is enhanced by the choice of a multi-converting architecture. Indeed, the management of the degraded mode seems to be facilitated by splitting the windings. Whether it is a sub-winding or the associated converter that is failing, two strategies are possible: increase the current of the other sub-windings of the same phase to keep the same magnetic state or passivate the corresponding sub-windings of the other phases to restore a balanced magnetic state.

c) Reduced stress on the insulation

The dv/dt are better distributed within each sub-winding powered by a converter because they have few turns. This is even more important as the switching frequency is high (SiC, GaN). This reduces the stress on winding insulation.

Alternatively, the machine could be designed to maintain the same ageing, but as the voltages are lower, it becomes possible to reduce the "grade" of the insulation.

d) Multi-source power supply

In Figure 2c), the DC source is not shown. It is possible to consider the use of a DC multi-source power supply (battery, fuel cell, supercapacitors, etc.) with differentiated uses. It would also be possible to manage the energy storage of each DC source by the associated power electronics converter (BMS).

e) Additional degrees of freedom of control

The additional degrees of freedom offered by the structure could allow for a dynamic optimization of the number of active sub-windings depending on the point of operation (management of low torque/high speed operating points, etc.). Inactive sub-windings could be used as sensors to perform real-time diagnostic. In addition, certain sub-windings could be dedicated to perform specific tasks, such as active centering to limit the wear of the bearings (active magnetic bearing).

f) Low power per switch

The multiplication of low power switches does not necessarily reduce reliability. Indeed, the splitting of the power per switch is suitable for integration and large-scale industrial realization (CMS technology). This could result in better reliability through perfectly mastered processes.

g) Improved filling factor

Pushing the concept, each winding could be split into as many sub-windings as there are turns. In that case, each single-turn sub-winding ($a11$, $a12$ and $a13$ in Figure 3) could be connected directly to a printed circuit board (PCB). The placement of the single-turn coils can then be optimized, making it possible to improve the filling factor and/or the thermal design.

To illustrate this point, we performed thermal simulations for two types of windings. Considering the requirements for an electric vehicle motorization [21] using a flux switching synchronous machine with hybrid excitation [22], we carried out an initial electromagnetic sizing. We determined that the armature windings should have 5 turns. The simulations presented in Figure 3 were performed for an operating point (65 N·m, 5400 rpm) on the rated power curve (30 kW). For this operating point, the current density of the field winding is 12 A/mm² and the one of the armature winding is 8.6 A/mm². On the left of the figure, the armature windings are modeled as homogeneous domains [23]. On the right of the figure, the armature windings are split into 5 single-turn sub-windings. Each sub-winding is placed in the iron core and isolated from it by a 0.15 mm thick sheet of mica. The temperature distribution obtained by controlling the placement of the windings is more homogeneous.

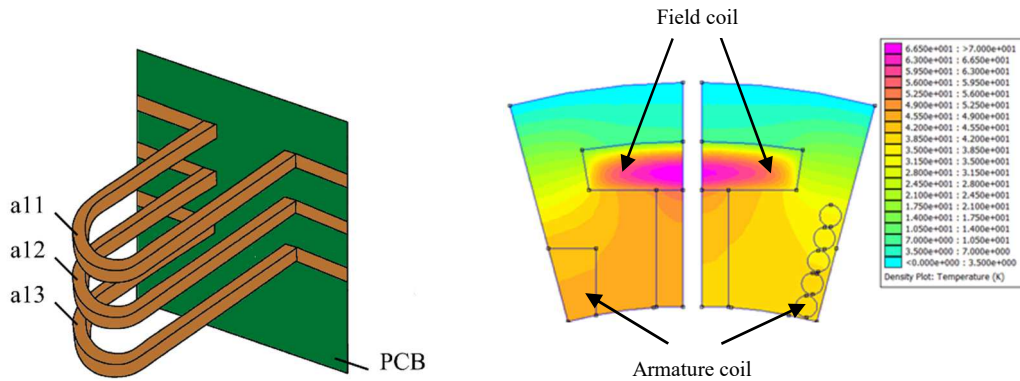


Fig. 3: (left) Splitting the windings up to the turn and attaching them to a PCB. Adaptation of the Figure 6b of the patent [1]. (right) Example of better thermal management thanks to optimized armature conductor placement.

h) Improved compactness

A "system-level design" can result in higher power densities. Indeed, as [17] points out: *"Focusing solely on the machine specific power can lead to a sub-optimal solution at the system-level"*.

i) Suitable for wide-bandgap semiconductors

Power converters using conventional semiconductors like silicon, are not suitable for the integration within an electrical machine. Indeed, the maximal operating temperature of a silicon module is much lower than the temperatures that can reign in the housing of an electric machine. It makes it difficult to mutualize the cooling systems of the power electronics and of the motor. But wide-bandgap semiconductors, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), can tolerate much higher operating temperatures. It makes it possible to reconsider a deep integration of power converters within electrical machines [16]. The power converter could then be installed directly on the back side of the PCB of Fig.3.

Other advantages related to the use of wide-bandgap semiconductors (low commutation losses and high frequency) would further improve the compactness of the concept (smaller passive components and thermal sinks) [18].

Main drawbacks of the concept

In this section, we discuss in detail several points that could be listed as drawbacks of the concept.

a) Large number of sensors

The proposed solution relies on many sensors, with their number increasing with the number of sub-windings. This can cause problems in terms of cost, real-time information processing and resilience. It will probably have to be managed by a high-performance on-board controller having many inputs/outputs, therefore complex to develop and expensive.

b) Difficulty of synchronization

One may suspect a sensitivity of the concept to the quality of the synchronization of the switching events for the sub-windings located on the same teeth. This is related to the low leakage inductance between them (since they are almost perfectly coupled magnetically). The difficulty of synchronizing all the converters and balancing the currents in the sub-windings may require different duty cycles for each inverter.

Because of the strong magnetic coupling between the sub-windings, if the inverters are out of sync or apply different duty cycles to counteract the disparities in each sub-winding, current ripples limited only by the leakage inductance appear. A trade-off must be found between the unbalanced "low-frequency" currents and the increase in "high-frequency" current ripples. This compromise will guide the choice of the structure to be adopted for the control system. A first study [19, 20] provides a better understanding of these phenomena.

c) Rethinking the control

From the previous paragraph, it will be understood that the splitting creates difficulties from the point of view of the control. This requires establishing a "good" dynamic model of the machine for its control. Such model will have to consider the splitting and the additional magnetic couplings that it implies. This will most likely lead to the design of a hierarchical control with at least 3 levels:

- *A low-level control* that will manage the synchronization of the command sent to the sub-windings.
- *A "classic" vector control-type control level* that will control the currents of the active sub-windings and the torque of the machine.
- *A supervision control level* that will have to decide in real time which elementary sub-windings are active, and which are inactive. An inactive sub-winding is not necessarily at rest, in fact it could serve as a sensor. Thus, the supervisor requires a precise monitoring of the machine in order to offer an optimized real time "dispatching" of the current references to the sub-windings, both in healthy and degraded mode [24].

The hierarchical structure of the command and the diversity of the tasks to be carried out seems to point out to the use of a SoC FPGA (System-on-Chip Field Programmable Gate Array). Indeed, such component incorporates both high-performance ARM processor cores (1 GHz) that are suitable for complex treatments (we think here of the supervisor) and a FPGA perfectly suited to the low-level control carried out in parallel [24].

d) Complex connections

The multiplication of the sub-windings leads to an increased number of connections. Non-standard solutions could be explored to reduce cost and increase reliability.

e) Electromagnetic compatibility

A high winding filling factor improves thermal exchanges but leads to an increase of the common mode parasitic capacity: the electromagnetic compatibility is therefore to be monitored.

f) Isolation of a defective cell

If a power converter or its associated sub-winding fails, the continuity of service is provided by the disconnection of the converter. This is based on the ability to guarantee that the switch will fail in open circuit and not in short circuit.

g) Consumption of copper

By design, the proposed traction chain is low voltage high current. Therefore, the consumption of copper, a critical resource, is expected to be important. Nevertheless, one can hope for an easy recycling of the windings.

h) Difficulty of recycling

An integrated system is generally considered more difficult to recycle at the end of its life.

Prototype

A prototype has been built by modifying a 3-phase synchronous machine (Fig. 4). Each armature winding has been divided into three sub-windings (9 sub-windings in total, 18 terminals). Three independent 3-phase 2-level MOSFET voltage source converters whose DC buses can be decoupled have been built to feed the machine. With the goal of later integrating the converter and the machine, all the semiconductors have been assembled on the same round shaped PCB. The system is sized for a 48 V DC bus voltage and a 10 A peak phase current. For comparison, the classic solution with a single 3-phase inverter would require a 144 V DC bus voltage for the same current.

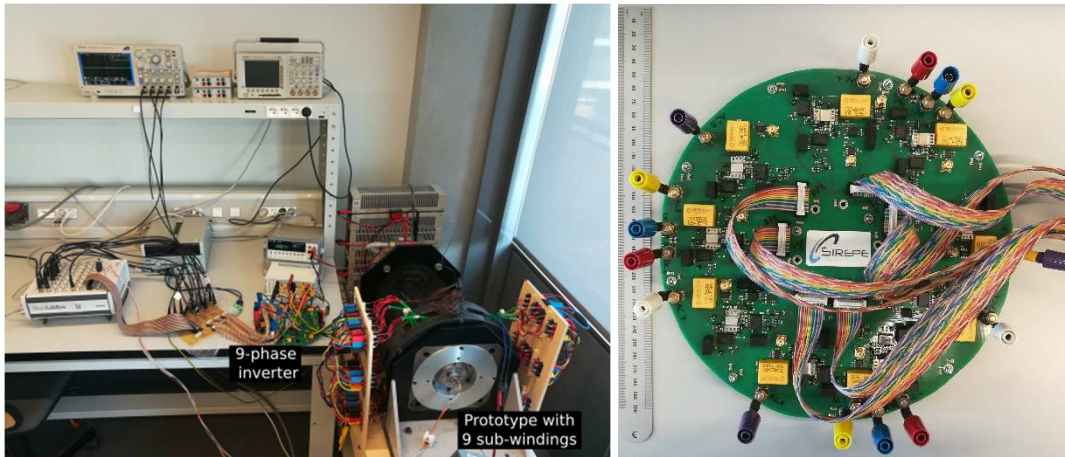


Figure 4: (left) Prototype 3-phase machine with 9 sub-windings fed by three independent 3-phase converters. (right) Prototype round-shaped PCB with three independent 3-phase converters ($\text{\O}20$ cm).

In Fig. 5, we show the measured steady-state currents of the 9 sub-windings. The three 3-phase systems have electrical disparities. As a result, we observe a current imbalance between the different sub-windings. But it does not affect the total ampere-turns in the machine. And it could be regulated by implementing a suitable control strategy.

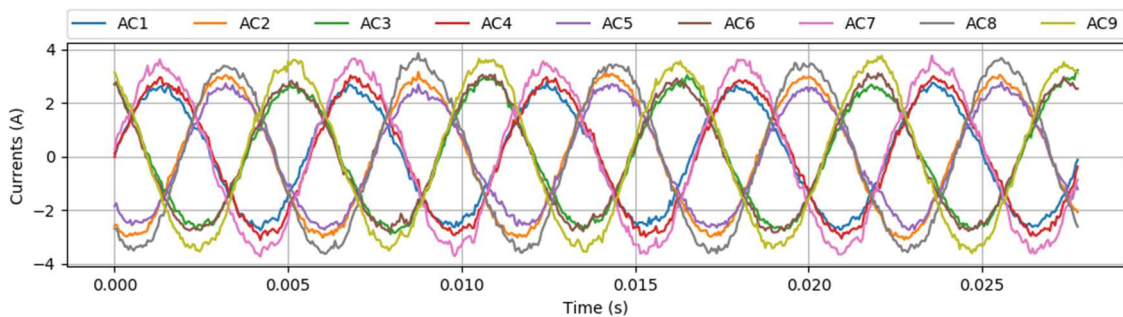


Figure 5: Measured steady-state currents of the 9 sub-windings of the prototype.

Scientific and technical obstacles

The above discussion allows us to list the scientific and technical obstacles on which it is necessary to work in order to develop the proposed concept.

a) Modeling the traction chain

First, it is necessary to establish numerical models aiming at estimating the performance of the traction chain and at controlling it. Each component of the chain must be modeled with enough accuracy to obtain a representative model of the entire chain, but it needs to be fast enough for control design purpose.

b) Implementation of the hierarchical control

Second, we need to develop the control software that would ideally be deployed on an embedded target, to ensure the best performance (torque, speed, efficiency, noise, electromagnetic compatibility...) both in healthy and degraded mode.

c) Analysis of the degrees of freedom offered for auxiliary functions

Third, the number of degrees of freedom resulting from the splitting is to be explored. Each sub-winding is not necessarily powered, especially when the full power is not required. It then becomes possible to use these sub-windings for auxiliary functions (active magnetic bearing) or as sensors to perform real-time diagnostics.

d) Study of the impact of the design and quality of the connections and sensors

Fourth, as the number of connections and sensors increases with splitting, a reflection is to be carried out on the impact of their design and quality. A sensitivity study would allow us to know which sensors are essential for proper functioning, and which ones can be removed in order to get as close as possible to a "sensorless" control. In parallel, non-standard connections could be explored to reduce cost and increase reliability.

e) Co-optimization of the converter-machine

Finally, the proposed converter-machine should be co-optimized including the architecture, the sizing and the control. The optimal system should be compared with the equivalent conventional one. The eco-design of the traction chain would be a complementary design objective.

Conclusions

This article introduces a concept for a traction chain with segmented power supply that is deemed promising for electric vehicles integrated traction chains. The concept could be applied to aeronautics applications too. After describing the proposed architecture in detail, we listed the main pros and cons. This allowed us to identify a set of scientific and technical obstacles. To overcome them, competences spanning the full spectra of electrical engineering will be required, stimulating sustained collaboration between electrical machine engineers and power electronics engineers.

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