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Industrial Electrical Engineering and Automation

Properties of magnetic cores of iron powder composites for electrical machines

Production experiences from research at LTH

Avo Reinap

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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The goal of powder technology and powder-based cores is the same – to enable an efficient manufacturing method for special purpose cores with low core losses. Simply put: powder-based cores can be produced by compression molding, casting or injection molding, and now increasingly by locally fusing powder particles or printing – to ensure satisfactory magnetic performance. Soft magnetic composites are ferromagnetic powder particles that are perfectly coated with a uniform layer of electrical insulation – to ensure low AC losses.

The purpose of this document is to provide a retrospective of LTH's development activities, which are focused on the production of electrical machines with moldable magnetic cores based on iron powder materials in the years 2004-2014. This document covers the following topics:

1. motives for using powder-based materials in electrical machines and research opportunities,
2. review of machine prototypes, initially focusing on SM²C as a moldable core, including stator assembly process, later development towards hybrid cores using core inserts,
3. concluding remarks and outlook.

Powder-based magnetic materials are not the main materials in the manufacture of electrical machine cores, but they offer thought-provoking challenges in the design and manufacture of electrical machines, which cannot be achieved with classic electrical steel laminated core packs, and therefore there is constantly continued interest in powder-based magnetic materials and related production processes for electrical machines. To demonstrate this, Figure 1.1 shows scientific publications from the IEEE database focusing on various powder-based materials technologies for electrical machines, including coreless (air-core) machines. Certainly, this comparison is not complete, but it is based on the following (search) conditions:

1. Coreless motors,
2. Soft magnetic composite (SMC) and electrical motors and machines,
3. Soft magnetic moldable composite (SMMC=SM²C) and low-density core motors,
4. Additive manufacturing (AM) and magnetic core not winding (as search words used in ieeexplore).

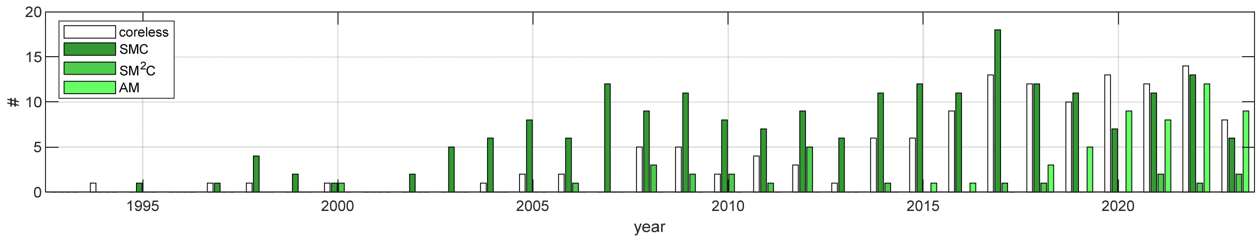


Figure 1.1 Title screening in respect to search phrases. Year of publication in the following categories: coreless, SMC, SM²C machines and additive manufacturing (of soft magnetic materials cores)

An incomplete review of publications (Figure 1.1) is presented for the purpose of generating interest rather than drawing hasty conclusions, for example, an article [41] presenting interesting new challenges in the field of energy efficiency and size reduction using powder technology (which is not included in Figure 1.1).

Acknowledgement

The author of the report is grateful to Vinnova, Energy Agency and SSF programs for long-term funding and close cooperation both within the University (Iprod and IEA) and with the project parties and their members who participated in the design of the prototype, construction and testing of several electrical machines.

1 Investigation of powder-based magnetic cores for machines

1.1 Challenges and opportunities for the adoption of powder-based cores

Given that classical electrical machine design is based on an electrical steel laminate stack, the design and manufacture of powder-based electrical machines is premised on simplicity and the resulting cost-effectiveness. Design development seeks to achieve design features related to compactness, integrability, efficiency and even performance improvements over an equivalent laminated core machine. Apparently, the production and performance of classic laminated core machines are almost impossible to surpass by powder-based electric machines, they have found an application where the machine topology requires a magnetic core that guides the magnetic flux in all three directions and not only in a plane as in the case of electromagnetic sheet steel. The adaptation of the classic laminated core to a powder core thus allows to improve the shape of the electric windings and to increase the fill factor because the winding is added before or during the assembly of the stator components and not after it, as in the case of laminated cores.

1.2 Machine topologies suitable for powder cores

There is no fundamental difference between compressed and molded magnetic cores**.** The goal of both production methods is a magnetic material with uniform material properties, the primary difference being density and relative magnetic permeability.

Soft magnetic composite SMC and compressed cores

Machine topologies suitable for SMC powder cores have the advantage that the core components and windings are built in parallel rather than in series. Compression is basically used for both magnetic cores and coils. If the magnetic performance drops, as the core fill factor decreases due to the distributed air gap, it can be compensated by increasing the coil fill factor. The integration of machine parts allows for more efficient heat dissipation, which allows increasing the magnetic and electric loads, the magnetic flux density in the core and the electric current density in the winding, respectively. As a result, a competitive electric machine compared to similar machines based on laminated cores.

Figure 1.1 visualizes different geometric choices of an electric machine and depending on the arrangement of the coils and the direction of the magnetic field or its redirection using a magnetic circuit, they also have corresponding names: radial, axial, circumferential and transverse. These multipole topologies are suitable for both stator and rotor cores. Generally, for powder-based electrical machines, permanent magnet excited and concentrated winding machines are the prime choice.

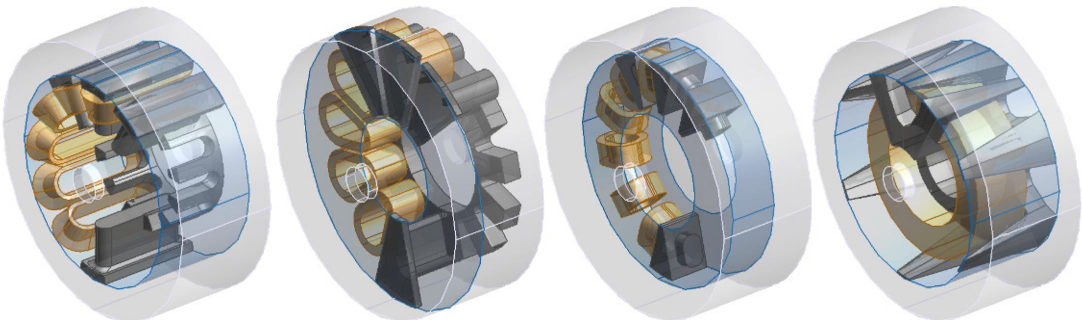


Figure 1.1 Machine topology (from left to right): radial, axial, circumferential and transverse flux machine, respectively, RFM, AFM, CFM and TFM. The classical shapes of the SMC core parts, active air-gap surface and active machine volume are shown [4].

While in conventional machines there is a maximum flux per pole connecting each pole turn, in transverse (cross) flux machines, the repositioning of the magnetic circuit allows the coil turn to be connected to the flux of many poles of the same polarity, which, figuratively speaking, increases the torque in proportion to the number of pole pairs. In conventional machines, it is assumed that the torque does not depend on the number of poles. Due to other design effects, the number of pole pairs has an optimum, allowing maximum torque for each machine topology, geometric dimensions, and shape proportions. If the magnetic circuit cannot be made of laminated electric steel or its losses are too high, then this becomes an opportunity for powder technology. Such examples could be transverse flux machine (TFM), radial transverse flux machine (RTFM) and axial transverse flux machine (ATFM). Here, this does not only mean that the coil must be a concentric ring, like TFM, but that the coil is shaped according to the pole distribution and resembles waves in its shape, as a wave coil.

Soft magnetic moldable composite SM²C and molded cores

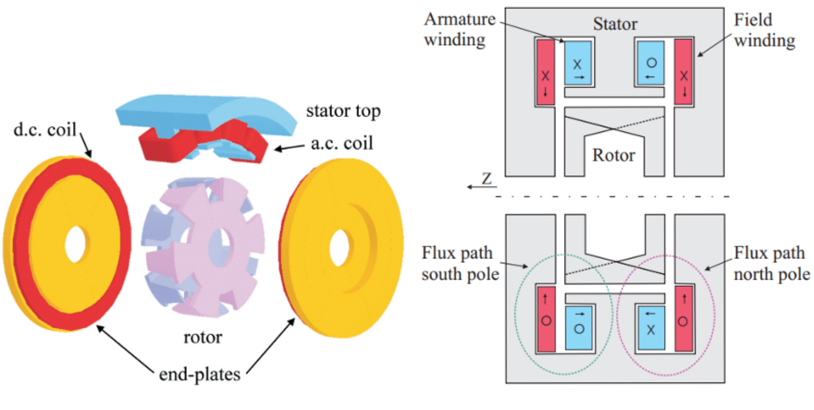
Compared to the previous compressed SMC cores, the technology based on instant forming or core molding makes an exception, as the production process changes from parallel production of stator parts to serial production, where the forming process, the manufacture of the magnetic core, is part of the assembly process. The alternative and innovative production method for electrical machines, which facilitates a high degree of integration where the injected soft magnetic composite joins the components in the mold to the complete magnetic core. Consequently, the machine windings are preferably completed and fixed in advance in the mold, and the molding is considered as a single step assembling process. Hence the fields of interests: manufacturability and design are tightly connected, and the good basis of competence and technology development becomes the success in the product realization and development. It is not an all-round success, and various experiences are addressed, and examples given in this document.

1.3 An overview of the use and development of powder-based machine cores

At the end of the document, there is a list of publications by section, and the first two subgroups are arranged in chronological order with research results for the development of powder core machines. These are presented as dissertations for SMC and research articles, reports, and theses for SM²C.

Purely SMC machines with a compressed core

References [1]-[4] are Lic and PhD theses and relate to the testing and development of SMC-based magnetic cores. Reference [1] compares laminated and powder-core in a switched reluctance motor drives, [2] presents iron loss analysis of powder-based cores and develops inductor design software, [3] demonstrates the design and prototype evaluation of electrically magnetized synchronous machine (EMSM) with stationary excitation coils fed by rectified stator currents (Figure 1.2), and [4] designs and evaluates small size claw-pole motors (Figure 1.3). The electromagnetically active size of the machines, diameter Ø (inner/outer or only outer) and height H in mm, are *Ø200-H76*, *Ø43-H23* and *Ø42/68-H11*, respectively. For diameter, the inner diameter is also given if considered necessary, otherwise only the outer diameter is given.



(a) 3-D view. (b) Axial plot.

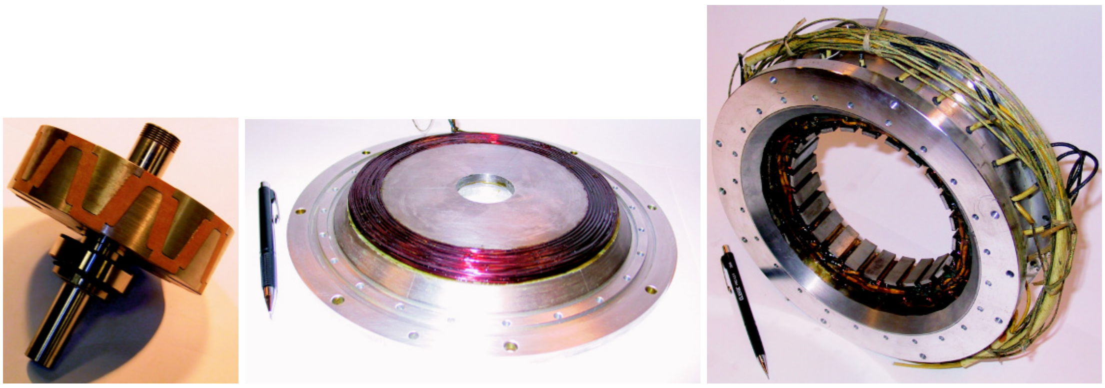


Figure 1.2 Electrically magnetized synchronous machine (EMSM) with stationary excitation coils [3]. Parts of the machine defined in the 3D FEM model and its principle in cross-section (above) and parts of the prototype machine (below).

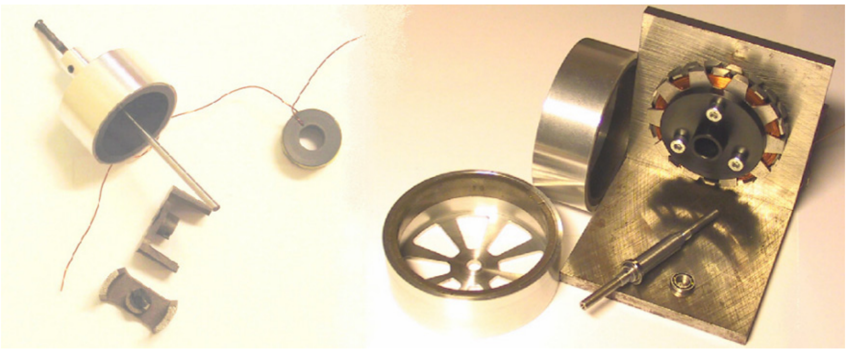


Figure 1.3 Prototype claw-pole motors: single-phase (left) and two-phase motor (right) [4].

The purpose of the electrical machine design development work outlined in theses [3][4] is to use the advantages of powder technology and develop the machine design according to the application goals. One of the advantages is that the powder-based magnetic circuits guide the magnetic flux in all three dimensions and thus a 3D finite element method based magnetic field analysis and evaluation is required. While one transverse flux machine [4] was directly related to the application's requirement for a high specific torque, the other was a more competitive solution for a fan motor, where a simple winding motor solution would have provided a structural advantage, but not ease of motor control. EMSM [3] gathers several interesting design proposals. If the transverse flux machine allows for high torque density and the choice of stator teeth in relation to the number of poles allows for reduced torque ripple, then this machine also takes advantage on magnetic flux concentration and excitation solutions, which are possible only when using powder technology. Despite the different goals and outcomes of prototyping and manufacturing, simplifying both prototypes and eventual series production became one of the many new goals of machine design and manufacturing.

Overview of prototype machines using SM²C

A material with a low relative magnetic permeability, Plastic Bounded Iron Powder (PBIP), was tested in the calculations of a single-phase claw-pole motor [4]. It was clear that the magnetic circuits must have a short flux path and as large a cross-section as possible in order not to lose the flux linkage and torque of the electric machine. Table 1.1 provides an overview of the selection of SM²C prototype machines. The table columns show following: 1) Machine name (including development number), 2) stator topology/rotor topology, 3) number of rotor poles and stator slots, 4) electric frequency (rather experimental than projected), 5) size of active volume (diameter/height), and 6) information about testing the machine.

Table 1.1 List of selected prototypes with name (1), stator topology/ rotor magnetization (2), number of poles (P) and slots (S) (3), max frequency tested (4), active size (5), Test type and drive unit for motor operation

Prototype machine	Type / M	Pole Slot	f [Hz]	Size [mm]	Test and drive unit for motor operation
1	2	3	4	5	6
Start up (D1)	TFM/SPM	20P20S	50	Ø42/68-H11	Grid low voltage-50Hz supply
Fan (D2)	TFM/SPM	40P40S	1000	Ø145/195-H9	dSpace drive
Toroid (T1)	CFM/SPM	20P60S	200	Ø135/275-H75	dSpace drive
Pump (P1)	ATFM/SPM	8P8S	200	Ø20/90-H36	Gen-test
Pump (P2)	RFM/SPM	22P24S	660*	Ø70/120-H20	dSpace drive, fmax 916Hz
Veh-Gen (G1)	RTFM/EM	20P20S	178	Ø50/176-H75	Gen-test
In-Wheel (W3)	RFM/SPM	28P30S	84	Ø240/310-H60	BLDC driver & LabWiew drive
Fan (F2)	RFM/SFM	16P18S	30	Ø90/175-H95	Gen-noload-test
Wind-Gen (G2)	AFM/SPM	24P27S	18*	Ø392/578-H75	Gen-test
Traction (T2)	RTFM/IPM	6P6S	143	Ø62/200-H224	LabWiev drive

*test speed limitation by power supply of load motor

1.4 Design-to-Manufacturing interactions

From the design-to-production point of view, two basic questions must be solved, starting with the questions of how and what - that is, for example, what is the relevant and rational production method for prototyping, that enables the expected properties, demonstrates performance, of the electrical machine. When using SMC then the practical approach is to use conventional machining techniques: turning, drilling, milling to manufacture parts for a prototype. A pre-fabricated blank, Somaloy prototyping Material (SPM) is used as the starting point for producing SMC core. SM²C can be interpreted as a joined process of molding and adhesive joining, where the first half of the process is transporting and packing the flowable iron powder into a mold using a molding or casting process and then allowing it to solidify. In the context of powder core manufacturability-oriented development, the practical measures of the design goals are related to the fabrication and assembly of the various parts. The filling factor and magnetic properties of the magnetic core are interrelated, so the molding process and its quality depend on how to place the components in the mold and how to carry out the molding process:

1. winding segment production for core molding process, and mold design accordingly,
2. eventual connection and termination of stator coils and winding segments,
3. stator core "hybridization" when selecting and introducing different types of magnetic inserts for a higher mean relative magnetic permeability,
4. introducing additional parts for integration such as sensors, cooling channels, which in turn can have impact to stator core quality.

Molding and casting

The manufacture of electric machines began with the use of an industrial injection molding machine (Figure 1.4, left), later prototype construction used two different molding /casting technologies: the so-called gravitational molding and rotocasting (Figure 1.4, middle). The difference between the iron powder packaging methods is the slightly higher relative magnetic permeability resulting from the density of the packed powder. In the first method, the flowing iron powder was poured into a mold together with the binder i.e. carrier material and left to solidify. In the second method, it is necessary to create centrifugal forces to pack the powder particles more tightly. Rotocast molding: radial and lateral linear molding depending on the position of rotating axle in respect to the mold [6][8][12][13].

Figure 1.4 Injection molding test (D1, left), rotomolded stator (D2, middle), cross-section of the molded winding (right)

1.5 Material characteristics

The properties and characteristics of the SM²C material are compared to those of the SMC because both materials are based on iron powder where the particle size and additives are selected carefully to obtain the desired manufacturing and material characteristics. Both materials use compression molding method where the difference is on applied pressure, low or high. The soft magnetic composite material (SMC) data is taken from the material developer's, Höganäs AB, website[1], and the SM²C data of rotocasted *6.5%* silicon alloyed spherical iron powder test samples is based on the article [30][38] Data from [19] is also used and included in Table 1.3 and addresses more of the research on gravitational molded machines and related evaluation samples. Since the packing of the iron powder particles is one of the challenges, PhD thesis [38] demonstrates the outcome of vibration molded powder where the relative magnetic permeability can be as high as 26 (compare to Table 1.3).

[1] https://www.hoganas.com/en/powder-technologies/soft-magnetic-composites

The Somaloy® product family is a wide range of press ready powder mixes, which is the outcome of Höganäs development work addressing different manufacturing and electromagnetic performance features. SMC's development work is based on years of experience, and it has a clear structure that is divided into three different performance (P) categories (Figure 1.5):

- Somaloy 1P Baseline
- Somaloy 3P Mechanical strength, permeability
- Somaloy 5P Lowest losses

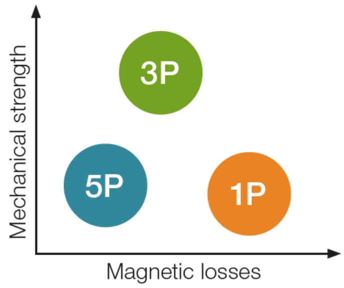


Figure 1.5 Somaloy® material performance (P) levels

Table 1.2 Manufacturing related data for powder core based materials

	700__ 1P	700__ 3P	700__ 5P	SM²C
Additives	0.4-0.5% Kenolube	0.3% 3P Lube	0.3-0.4% 5P Lube	Epoxy
Compaction pressure [MPa] and die temperature	800 + room	80	100	
Heat treatment	530 Air	530 Steam	650 Nitrogen	-

Table 1.3 Material properties for powder core based materials

	700__ 1P	700__ 3P	700__ 5P	SM²C
Density, ϱ [g/cm³]	7.45-7.45	7.57-7.52	7.52-7.50	4.74-5.18-5.5
Resistivity, r [μΩm]	400-1000	200-600	90-700	
Hysteresis coef. K_h	0.096-0.097	0.099-0.101	0.065-0.063	0.0716
(**Large**) Particle coef. K_{ep}	2.7-2.7e-5	2.7-2.7e-5	2.7-2.7e-5	-
Permeability, μ_{max}	540-440	850-770	720-600	11.5-14-18.5
Coercitivity, H_c [A/m]	210-225	217-225	124-120	
Losses 1T1kHz, p [W/kg]	152-136	183-147	217-106	101-189
TRS [MPa]	40-35	125-120	65-60	
Th. conductivity, k [W/mK]	25-25	25-25	21-21	2.2
Sp. heat capacity, c [J/kgK]				510-545

Table 1.3 shows the range of values given in the data sheets for SMC and SM²C data presented in [19] [30] and [38]. Cells with missing data are left blank, and data ranges may not correctly account for the characteristics of different SMC premixes and process parameters.

Magnetic characteristics

The same color combinations have been used for the presentation of BH characteristics of 1P, 3P, 5P and SM²C series, which are given in the headers of (Table 1.2 and Table 1.3). There are two SM²C materials presented: gravitational molded iron powder ($\mu_{max}=12.5$) and rotocasted iron powder ($\mu_{max}=17.5$).

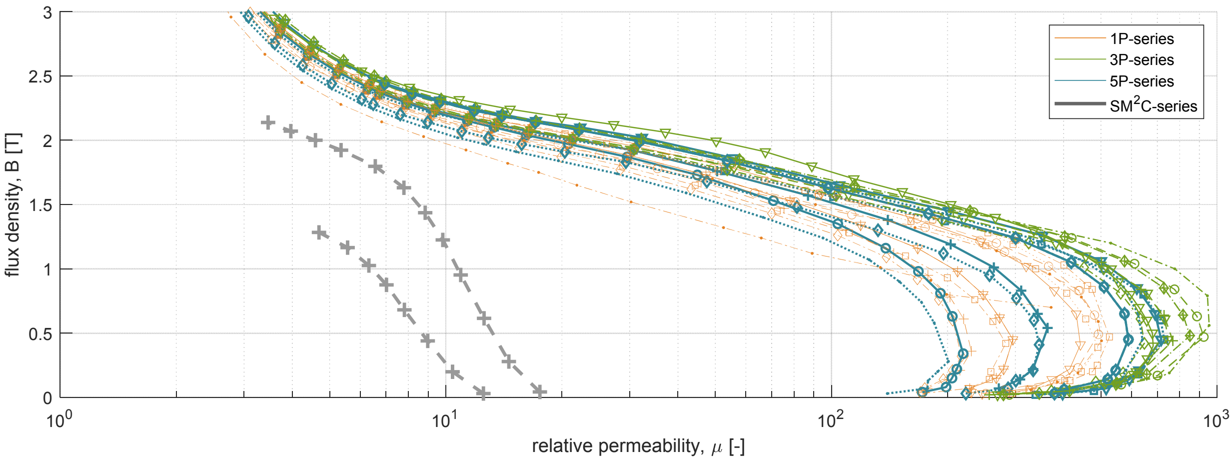


Figure 1.6 Realtive magnetic permeability as a function of flux density for powder core based materials

Core losses

The following mathematical expressions proposed by material developers are used to characterize iron losses, for SM²C:

$$P_{tot}\left[W/kg\right] = K_h f^{\alpha} B^{\beta} \qquad 1.1$$

where K_h hysteresis loss coefficient and exponents a and β are used to fit measurements to mathematical expression, and for SMC:

$$P_{tot}\left[W/kg\right] = K_h f B^{1.75} + K_{ep} f^2 B^2 + \frac{d^2 B^2 f^2}{1.8\rho \cdot r \cdot 1000} \qquad 1.2$$

where K_h hysteresis loss coefficient, K_{ep} in particle eddy current coefficient, d smallest cross section of component [mm], f frequency [Hz], B flux density [T], r resistivity [μΩm]. Reference [30] demonstrates factor *1.87* between SMC and SM²C losses at *0.1T* and *1kHz*, which means that core losses are not non-existent or vanishingly small for SM²C. Furthermore, the exponent a in [30] is rather similar for SMC and SM²C. The continued study in [38] shows that when trying to increase permeability, by vibrational molding, then the measured loss characteristics remained nearly the same, but function fitted loss coefficients (Eq. 1.1) gave larger variation on expected power losses. When using loss density coefficient $k=394$ [30] and mass density of $5.5\ g/cm^3$ then the recalculated specific loss coefficient becomes *0.0716* with the exponents of $a=1.05$ and $\beta=1.76$. When using the data given in [38], $k=212$ $a=1.22$ $\beta=1.9$ and $k=133$ $a=1.23$ $\beta=1.77$, the corresponding numbers of specific loss coefficient becomes *0.0385* and *0.0242*, respectively. Furthermore, when selecting an operation point at *1T* and *1kHz* then the expected specific loss, the power loss per unit of mass [W/kg] is, *189* and *110*, respectively (Table 1.3). A comparison of material losses and load points reveals an interesting fact, namely that SM²C iron losses are considered low, which is of course correct, but there is also a very rare situation where the magnetic flux density in the material turns out to be high.

2 Moldable magnetic cores for electrical machines: challenges and design opportunities

In the case of moldable magnetic cores for electrical machines, the manufacturing of the magnetic core and the assembling of the accompanying components become the same. The distinctive feature of the obtained material is very low frequency-dependent energy losses as well as low magnetic permeability. The mechanical fixation obtained as the result of the process is taken for granted. The main challenge of integration is increasing the performance of the electromagnetic component under development. Based on the almost non-existent dynamic magnetic losses of the magnetic core, the efficiency can be high, but the low magnetic permeability makes the device literally weak. The guidelines of electromagnetic design for electrical machines and components are simple: 1) make the magnetization path short, 2) increase the frequency, and 3) keep the design simple. Depending on the starting point of the design, in a situation where a machine with a classic laminated magnetic core could be used, a machine based on a pure SM²C core will always have a lower specific torque [Nm/kg] and specific power [W/kg]. If the starting point is electric machines with an air core, the situation is reversed, especially if the air core can be replaced by a core with low magnetic permeability.

This chapter provides an overview of different electrical machine topologies that have been fabricated and tested and highlights the challenges. From the point of view of the material and production technology development work, it is expedient that the construction of the prototype is related to the existing test or production equipment. From the point of view of the development work of powder-based electric machines, it was natural to continue with a transverse flux machine, where 1) the coil geometry and manufacturing method is extremely simple and 2) the magnetic core (or circuit) becomes complex and is not practical to make of laminated electrical steel.

2.1 Transverse flux machines

The advantage of transverse flux and claw-pole machines is their specific torque, which is several times higher than any other machine topology. The disadvantage of the machine is the low power factor, which decreases with the relative magnetic permeability. One of the biggest challenges from the machine's development point of view is the cogging torque, which can often be several times greater than the electromagnetic torque provided by the machine itself. This situation is clearly presented in the bar chart, where the colored bars characterize cogging when using different magnets and the black bars indicate the electromagnetic torque.

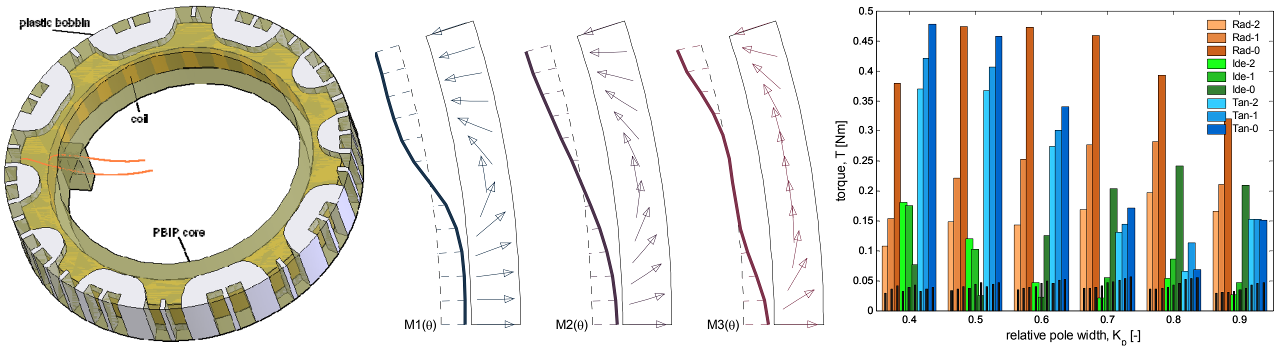


Figure 2.1 D1:Shifted claw-poles for cogging reduction (left), analysis of the influence of magnetization pattern (middle) and cogging to driving torque comparison (right) [5].

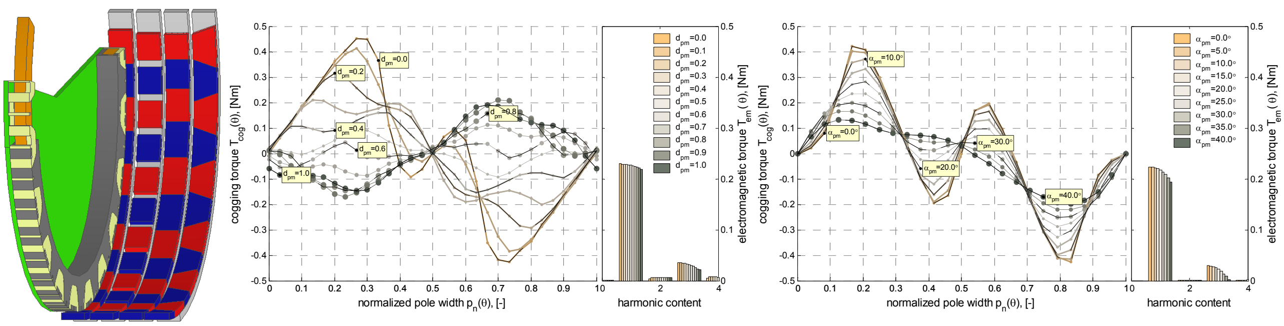


Figure 2.2 D2:Section view of stator with PM ring configurations and their waveforms: displaced magnets with varying pitch (middle & PM-ring 3), and trapezoidally shaped magnets (right & PM-ring 4) [9].

If claw pole machine D1 rearranges stator claw-poles to reduce cogging, the claw-pole machine D2 rearranges rotor magnets. The latter separates the challenge of core material and production development since unequal fill rate gives additional impact to unequal magnetic reluctance paths and therefore has high probability to increase cogging. However, the claw-pole stator core for radial flux outer rotor machine is a perfect candidate for SM²C machines as it can be perfectly produced either using injection or rotocast molding (Figure 2.3). The challenges related to cogging, starting, and driving torque can be dressed in the design phase when developing control [7] and testing the machine.

Figure 2.3 Claw-pole stator cores with SM2C: injection molded D1[5](left) and rotocasted D2 (righ) [9].

The preferences for choosing a transverse flux machine are: 1) a simple geometry that facilitates production, 2) the expected higher specific torque as a feature of this type of machine topology, 3) is well suited for a ring or a disk type machine. TFM oriented research also led to more thorough analyzes and experiments in the manufacture of permanent magnet circuits and obtaining the desired magnetization pattern [16].

Both radial-transverse flux machine and axial-transverse flux machine take advantage of 3D printed structures that define non-electric non-magnetic volumes inside the mold and in the stator. From the point of view of the design of the axial-transverse flux machine, the optimization of the torque was an interesting challenge, where a larger current conductor cross-section lengthened both the magnetization path and increased the magnetic coupling between the phases. The stator of the machine is a 3D printed plastic shell that had a place for coils and magnetic circuits. From the point of view of experimentation, it was not necessary to solidify the core in order to fix it, and various additional magnetic inserts that strengthen the magnetic coupling could be tested, from iron bars to U-cores made of iron wire. The geometric simplicity of the electric machine also allowed testing different PM magnetization solutions. Regardless of various tests and solutions, the performance of the electric machine was not good enough to be further developed.

Figure 2.4 Parameterized machine (left) and bottom view of the machine where the iron powder flux paths that are defined by PM excitation are shown.

2.2 Circumferential flux machine

The design of electric machines with an air core directly follows the law of physics, which describes the electromagnetic forces acting on a current conductor in a magnetic field. This is how a radial axial flux machine could be described, where, for the sake of the motor design, as much of the winding as possible is placed near the permanent magnet, allowing both a higher torque and the shortest magnetization path. A toroidal or torus machine is an excellent example of an SM²C molded core machine with attractive output as seen at least in fine surface finish (Figure 2.5) and machine performance. In this case, the performance becomes almost incomparable since the core cannot practically be produced using any other type of magnetic core. For example, in the case of an SMC machine, this would require not only a selected number of stator segments on which the coil is wound, but also stator teeth of rather inappropriate dimensions and proportions, which are possible to manufacture but far from rational. The design of the SM²C toroid machine and mold, as well as a very comprehensive description of the production process are given in [8] and the test results of the machine are presented in [10].

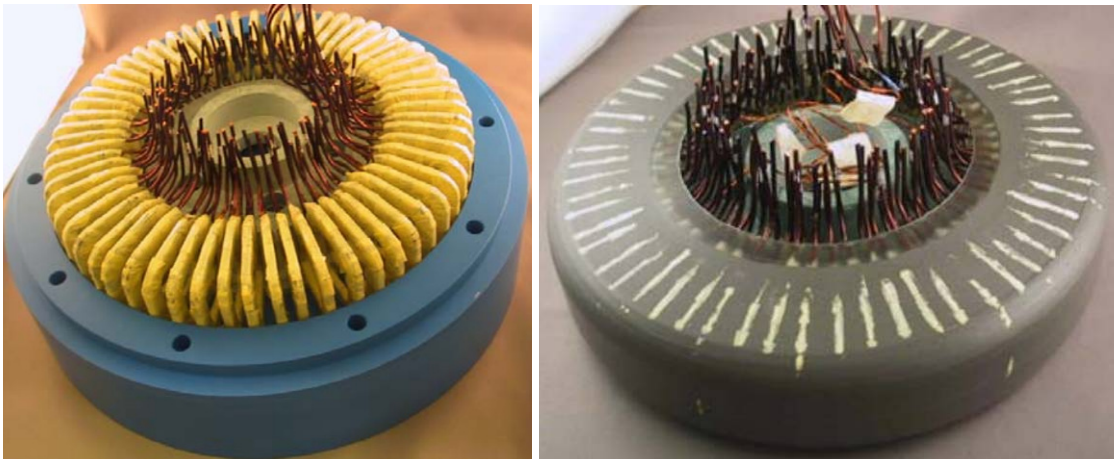


Figure 2.5 Toroid machine [8], bottom half of the mold together with the mounding disk for the coils and the coils (left), and rotocasted stator core (right).

2.3 Torque quality improvement

If the number of poles of the machine is the same as the number of teeth, then it is almost inevitable that it will be accompanied by a large amount of cogging. There can also be exceptions where the magnetic forces are apparently balanced when the magnet is, for example, aligned to the stator tooth or between two teeth. Changing the tooth and magnet width is the only way to reduce the cogging torque in such a situation (Figure 2.1 and Figure 2.2). Since cogging is one of the biggest disadvantages of transverse flux machines, and any machines where the number of poles N_p equals number of slots N_s, a way must be found where, for example, three stator teeth achieve balancing forces on the two magnets, and thus change cogging with the choice of poles and teeth. The other criteria to be followed is if the pole-to-slot configuration provides pairs of modular coils like *16P18S*, *22P24S*, *28P30S* (Table 1.1) or alternatively *20P18S*, *26P24S* and *32P30S* so that $N_s=N_p\pm 2$ and Ns is multiple of *3*. $N_s=N_p\pm 3$ is fine selection as it gives zero net force that is not the case with $N_s=N_p\pm 1$ (Figure 2.7). A next criterion is to keep number of poles and supply frequency preferably lower.

Distributed concentrated winding is preferred as it gives a shorter end-turn that can be embedded into a stator core and as a result allows making a more compact machine along the rotating axis. Not all combinations of the number of stator slots (*Ns* or number of teeth $N_t=N_s$) and the number of rotor slots can establish an electromagnetic coupling and a symmetric three phase system: A figure below indicates the strongest electromagnetic coupling (darker regions with value closer to 1) and the possibility to establish the symmetric three phase system ⊕.

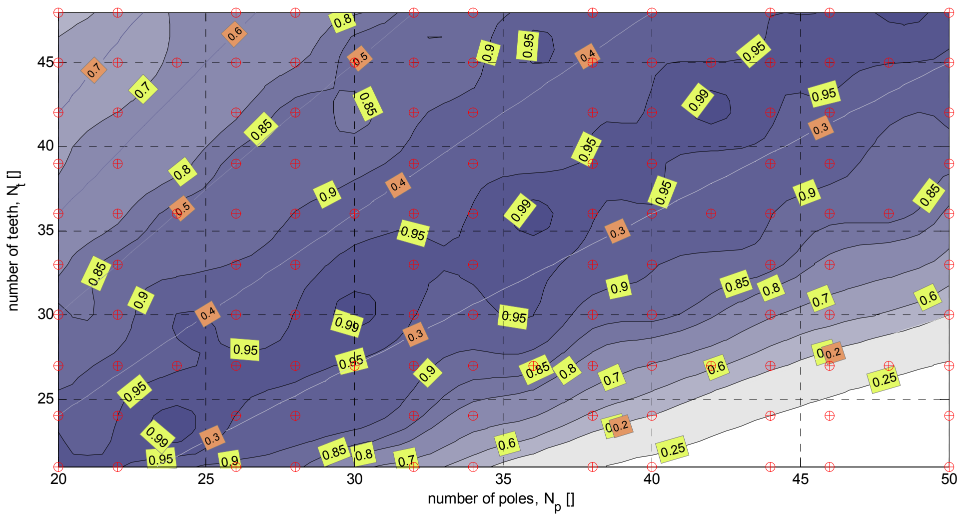


Figure 2.6 Pole-teeth selection and winding factor: 16P18S, 22P24S, 28P30S primarily focused and used for prototypes

Practical experimentation with a radial flux permanent magnet synchronous machine with SM²C core has shown that:

a. Cogging torque becomes (much) higher than expected and the reason is the SM²C filling that can cause "dominating pole-pair" so that all the magnets "are presented" when turning the shaft. In case of W3 machine with SM²S core, the cogging became about *15-20%* of nominal torque compared to expected value below *1-2%*.

b. SM²C core has a weak shielding ability due to low permeability and this means that the core leaks through the back (and sides!).

The figure gives an example of the winding distribution, an example of modular coils where the phase coils are divided into two opposite pairs, and the machine construction solutions, where a common concentrated coil is compared with wave coils. Wave windings are presented in two variants, which are single- and double-layer windings. In both cases, the thickness of the winding is doubled in its winding head (end-turn), which slightly complicates the geometry of the core.

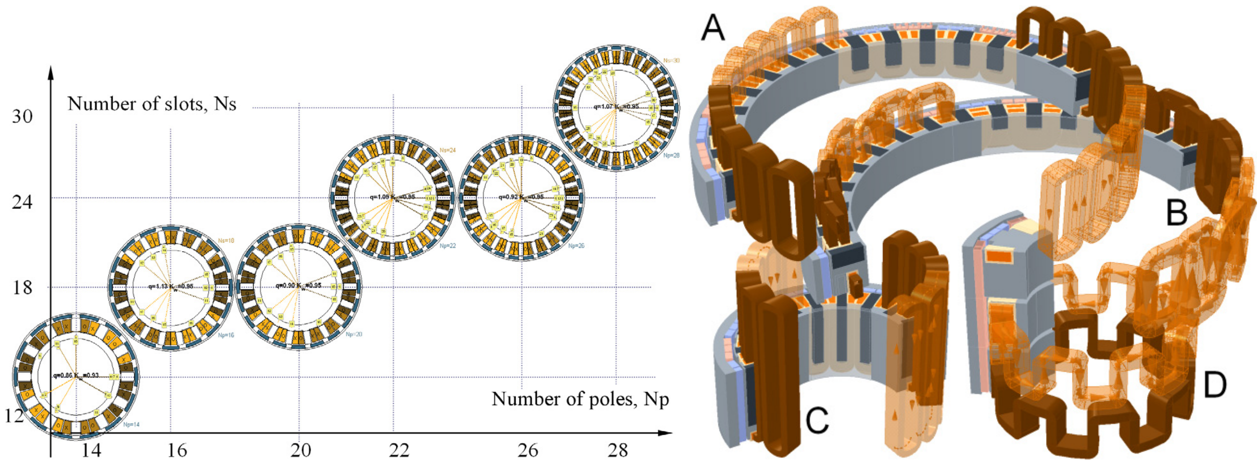


Figure 2.7 The preferred arrangement of distributed concentrated winding when the phase windings are symmetrically divided into two sections (left). Outer rotor PMSM with concentrated distributed winding (A and C), and circumferentially distributed double-layer (B), and axially distributed single-layer (D) three-phase wave-windings. Core inserts (dark grey blocks) and two phases are shown from the winding arrangements (right) [28].

2.4 Effect of magnetic permeability on electromagnetic torque and power

When designing a machine with a molded core, the magnetic properties of the core can be varied by the choice of molding technique and inclusion of magnetic inserts that purpose is to increase magnetic flux linkage and torque capability. Therefore, it is useful to look at the effect of the magnetic properties of the material on the machine design, as this way the performance of the molded core after its manufacture is also evaluated. When choosing characteristics with lower magnetic permeability, the core may therefore turn out to be better than expected.

Figure 2.8 shows a calculation example where the size of the stator slot and the material of the stator core are changed step by step and its effect on various parameters and properties of the electric machine is presented. This calculation example is given for a W3 machine *28P30S Ø240/310H60* in the article [23]. Calculations are performed in 2D FE and 3D FE computational environment. In the first case, the design space of the selected design parameters is examined, in the second case, the effect of the choices made is examined more precisely. For example, Figure 2.9 shows the magnetic loading for three different core designs: 1) SM²C core, 2) SM²C core with SMC magnet field strengthening blocks, and 3) pure SMC core.

The same 2D FE calculations are extended [28] to explore the design space, including different combinations of rotor poles and stator teeth, stator core material choices, and different machine sizes to gain insight into the impact of SM²C material choice compared to other materials.

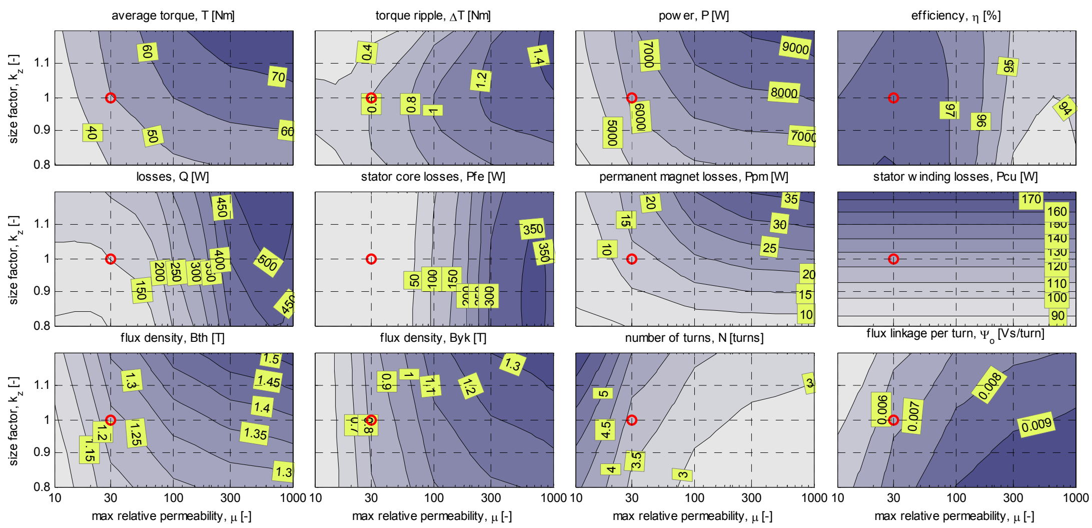


Figure 2.8 Maps of machine parameters as a function of maximum permeability of the core and the size of the slot (where slot tooth and yoke width is gradually changed).

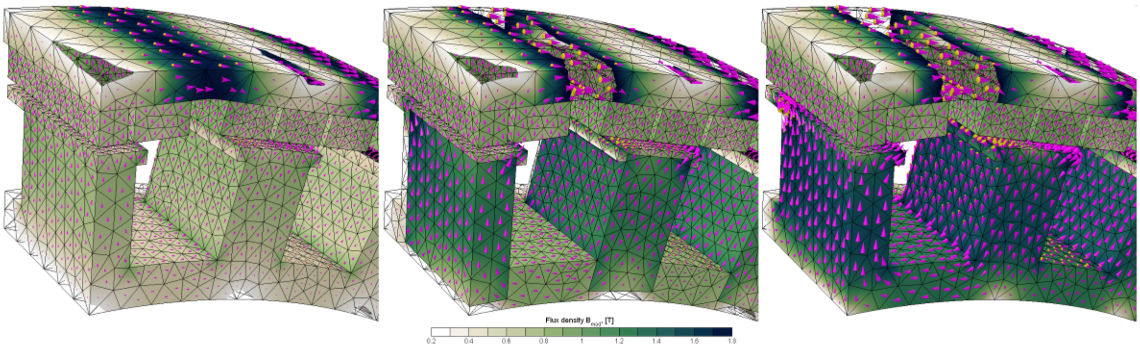


Figure 2.9 Flux linkage distribution for SM²C stator core (left), the same stator core with SMC inserts, and the core made of SMC.

If looking material selection and machine performance options in more generally (Figure 2.10)[28], then it is clear that the electrical machines with SM²C cores need to provide sufficiently inexpensive production that they remain to be attractive with their specific low torque capability compared to the other cores and solutions. It seems that SM²C machines can be more efficient at higher frequency and speed but still higher permeability couples more high frequency field that low permeability material is not able to attract (Figure 2.10). However, the high frequency leakage field can easily produce power losses in the other structures and the whole solution is not as efficient anymore.

Table 2.1 Machine dimensions used in calculations (Figure 2.10)

Size of the machine	Design-W3 "Short & Wide"	Design-F2 "Long & Slender"
Active length, mm	60	112
Outer diameter, mm	310	175
Inner diameter, mm	240	100

The sizes of the machines used in the article are slightly different (Table 2.1) compared to the prototypes (Table 1.1). Namely, the smaller diameter machine is slightly longer in the calculations, so the large and small diameter machines have the same active volume.

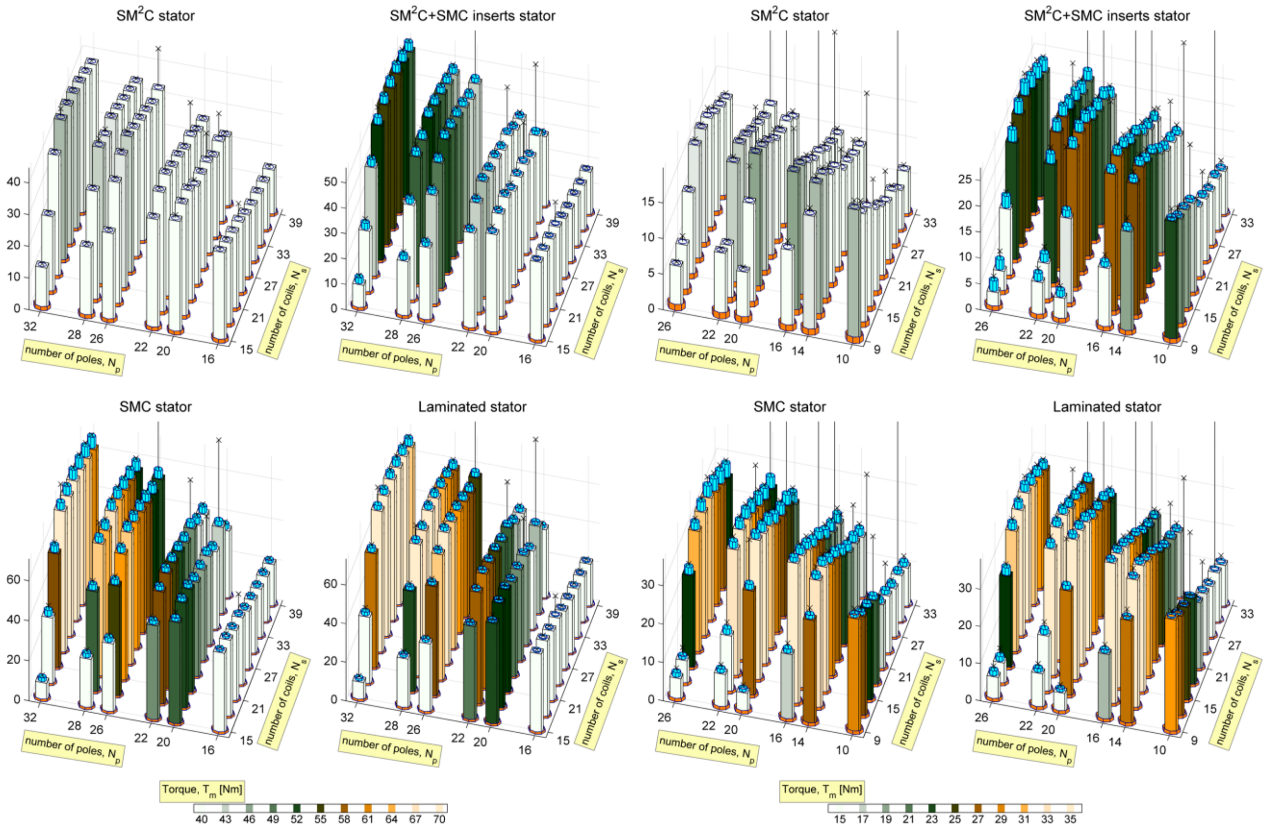


Figure 2.10 Average torque, ripple and losses as a drag torque over speed of four different stator of the Short & Wide machine (left) and Long & Slender machine (right).

The calculation (Figure 2.10), which is carried out in 2D FEA where the field-controlled machine is modeled, estimates the average torque, the torque ripple and the corresponding losses in the stator. The power losses in the windings are presented as a load torque at *900 rpm* and the power losses in the core are at *9000 rpm* [28]. The different speeds are selected to make the power losses more distinguishable as additional "internal load torque". The following materials are included in this stage:

1. Soft magnetic moldable composite (SM²C) with maximum permeability of *16*,
2. Compressed soft magnetic composite (SMC) in teeth regions and SM²C in the yoke,
3. Whole stator core made of SMC (Somaloy-P5) with maximum permeability more than *500*,
4. Laminated stator (M250-35A) with maximum permeability more than *5000*.

A quick summary of Figure 2.10 is that the machine performance is 1.6-2 times higher when using laminated or SMC core than using SM²C, and in this example the larger diameter machine had a better chance of using SM²C because of the lower expected torque drop. The relative increase in losses as torque loss in this graphical comparison is of only secondary interest.

2.5 Moldable windings

The prerequisite to produce moldable magnetic cores is that the coils are easy to manufacture and do not change shape or deform before setting up the mold and during molding. One of the many possibilities was to redesign the solenoid coil with a simple geometry so that the coil would have new contact points as well as bearing surfaces towards the mold walls and a magnetic circuit with lower reluctance could be achieved. Figure 2.11, center and right, shows wave coils made by hand and industrially using a winding machine. During the development of the design and production of the coil, investigators has come to a solution where the coil is made from a strip of electrical conductor such as aluminum or copper where the material is removed for the stator teeth, and which aligns when the strip is rolled up. A narrow space can be deliberately left between the insulated electrical conductor, which can be then used for direct cooling of the coil. As a result, a direct-cooled winding, or a laminated winding, named after the shape and manufacturing method of the conductor, is produced [22][31]. By redesigning the coil, it is possible to produce a magnetic core that contains both transverse flux and radial flux cores. However, the number of core teeth and excitation poles is the same, which also results a high cogging and torque ripple.

An alternative solution is a distributed concentrated winding, which allows coils to be grouped into the same phase. The challenge in manufacturing this coil is the large conductor cross section left in the prototyped machines due to the high number of poles, speed, and low supply voltage. The left image in Figure 2.11 indicates that the connections between poles and groups require skillful placement and methods and tools that facilitate the manufacturing process. For larger machines, it is possible to fabricate and design modular winding segments with tooth-tips and stator teeth, shown as cavities on the left and filled cores on the right in Figure 2.12.

Figure 2.11 pre-formed coils: 22P24S distributed concentrated winding (left [14]) and wave windings (middle [19] and right [25])

Figure 2.12 Inclusion of hall sensors (left) and their location after molding and machining (right)

Figure 2.12 also shows the placement of three digital Hall sensors in the center of the coil for BLDC control and two linear sensors to replace the resolver-based synchronous machine control input.

3D printing technique has been successfully used for the manufacture of magnetic circuits and early experimental evaluation of the coil, where the coil is printed out of plaster or plastic (Figure 2.13) and measuring coils are added to it on four sides, or on the lower and upper sides when viewed from an air-gap. Such a method makes it possible to estimate the topology values of the proposed machine with relatively simple means, to estimate the core production and the product based on 2D and 3D FE calculations [29].

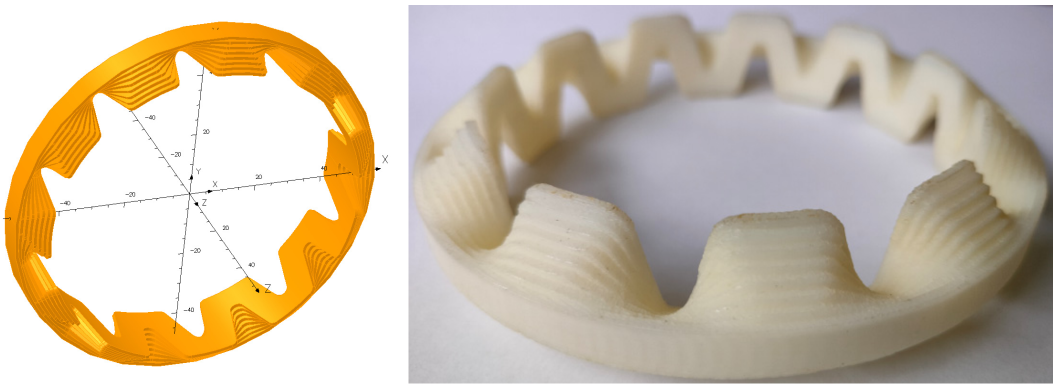


Figure 2.13 Winding design (left) and dummy 3D-printed winding (right).

2.6 Radial flux machines

Radial flux machines are one of the most tested types of machines that use both SM²C magnetic core and distributed concentrated windings. The initial focus of development work was on the *22P24S Ø70/120-H20* pump motor [14][15], which grew to the *28P30S Ø240/310-H60* in-wheel motor [23][24] and then to the *16P18S Ø90/175-H95* fan motor [34].

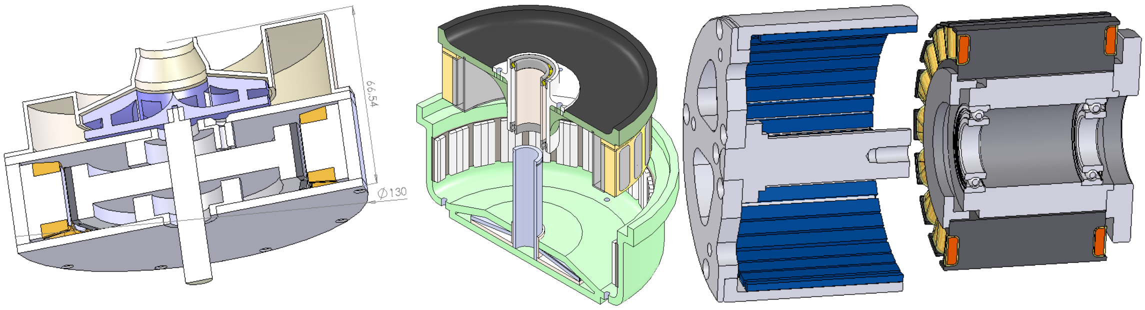


Figure 2.14 CAD drawings of the radial flux machines that take advantage of distributed concentrated windings

Pump motors

In this document, two pump motors have been show, which have been more thoroughly studied and tested, including various modifications and samples. Concerning the radial flux machine [14], is the selection and manufacturing moldable winding structures [15][29] and molds accordingly. One of the challenges of the pump motor was implementing a rotocasting method for uniform and complete filling of the powder core. The rotation axis of the casting machine does not align with the axis of the machine because the diameter of the stator is too small or alternatively the rotation speed is too high to achieve the required filling pressure and fill rate, the lateral linear molding was used. The repetition of molding process for improvements was influenced by the fact that the manufacture of the moldable coil was a long and time-consuming process. One of the possible goals of production efficiency was to find more suitable machine topologies that simplify the production of coils.

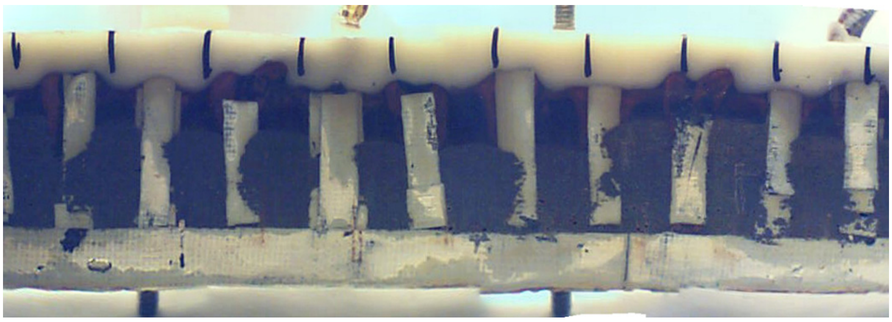


Figure 2.15 A fragment of the inner periphery of the stator indicating uneven filling of the teeth

One notable advantage of the pump motor was that its size made it easy to practically experiment with different winding distributions to match the 22-pole rotor. Different winding distributions and no-load voltage waveforms and their analysis are given in [15][31].

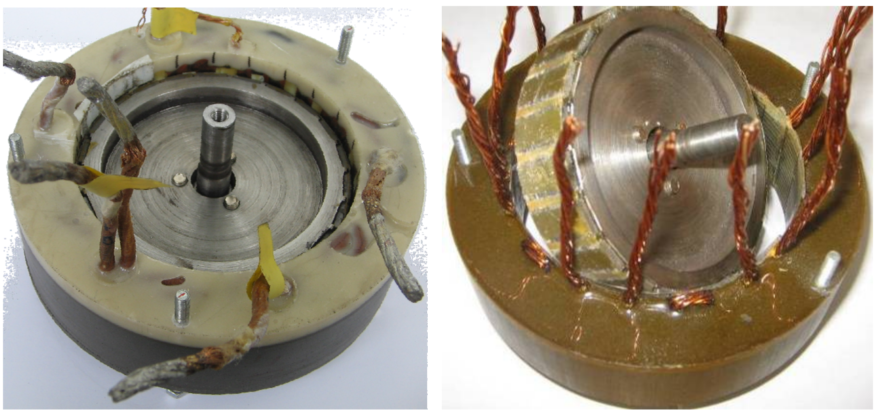


Figure 2.16 The first pump motor stator made with the rotocast method (left) and the later test stator made with the settling method for a different winding (right). A transparent plastic film with measurements printed on it has been used to evaluate the test sample.

Wheel motors

There are 4 different design generations with the following number of poles (P), slots (S) inner to outer diameter [mm] ratios for electromagnetically active volume [33] where the goal was to find simple solutions for the manufacture of the motor and not to give up the desired performance of the electric machine:

1. 22P18S Ø160/270 changed dimensions to Ø120/256,
2. 22P18S, 26P27S, 28P21S and 32P27S Ø180/260,
3. 28P30S Ø240/310 that uses a balanced modular winding 5 coils per segment,
4. 22P22S Ø120/190 that uses two segments with direct cooled wave / laminated windings.

A comparison of manufactured stators and flux linkage is summarized as follows: Four complete stators are built (Table 2.2 and Figure 2.17) where for SMC Somaloy-3P is used. The stator core and coil data are provided in Table 2.3 and coil packing compared in Table 2.4 provides calculated values of magnetic flux linkage peak value per windings turn.

Table 2.2 Stator core specification

Short description of stator	Yoke	Teeth	Head
St1: Modular winding segments in SM²C core	SM²C	SM²C	SM²C
St2: Single tooth coils molded into SM²C core	SM²C	SMC	SM²C
St3: Modular winding with SMC inserts	SM²C	SMC	SM²C
St4: Modular winding, inserts and wound yoke	Fe-Wire	SMC	SM²C

Figure 2.17 Stator prototypes[24]

Table 2.3 Stator types and winding specification[23]

Stator configuration	Strands & wire [mm]	Number of turns per tooth	Flux linkage [mVs]
St1: Modular winding segments in SM²C core	17x0.8	12	2.16
St2: Single tooth coils molded into SM²C core	3x1.0	5x30	3.73
St3: Modular winding with SMC inserts	70x0.65	3	3.48
St4: Modular winding, inserts and wound yoke	70x0.65	3	3.87

By citing conclusion in [23] the following is stated about the magnetic performance of the cores based to magnetic flux linkage evaluations: Based on the calculation and experimental estimation of flux linkage it can be stated that the results comparing quite well. Still the discrepancy becomes bigger with SM²C core alone, which can indicate that the molding process can cause larger difference in geometry and material properties inside the molded core. However, inserts improve the design with the cost of reduction on energy conversion efficiency. The wound insert (St4) has relatively low flux linkage, which is likely due to additional reluctance between the ferrous (yoke) core and SMC insert.

From a construction point of view the SM²C core is attractive for high frequency applications that give single step assembling with high integrity. As a matter of fact, the low permeability causes low torque capability, which in turn depends on geometric complexity and fill rate (further visualized in Figure 2.12). The high permeability inserts increase the torque capability with multi-step production.

Table 2.4 FE-based flux linkage values

Stator core description and	2D FE	3D FE
Whole core SM²C no inserts	2.61	2.66
Short Somaloy-3P @ 1.1GP inserts	3.47	-
Long Somaloy-3P @ 1.1GP inserts	3.71	3.49
Core Somaloy-3P @ 1.1GP inserts	4.42	-
Yoke Somaloy-3P @ 1.1GP inserts	3.04	-
Whole core Somaloy-3P @ 1.1GP	4.58	4.57
Short Somaloy-5P @ 0.8GP inserts	3.48	-
Long Somaloy-5P @ 0.8GP inserts	3.67	3.45
Core Somaloy-5P @ 0.8GP inserts	4.40	-
Yoke Somaloy-5P @ 0.8GP inserts	3.03	-
Whole core Somaloy-5P @ 0.8GP	4.55	4.53

Details related to hub motor vector control and also position feedback are described in [17].

To produce moldable cores, it is important not only that all the necessary integrated components, such as the coils, are placed correctly in the mold but also the manufacturing process parameters such as forces or temperatures are considered properly.

Fan motor

This machine uses modular windings, but the winding is not made before the stator core is made. Instead, a 3D printing is used to first print out the coil to evaluate the molding process, followed by evaluation of the magnetic core. After the first magnetic circuit is fabricated and evaluated, a new stator is produced using a nylon 3D printed insulation system shell that separates core (region) from the slots and end-turn regions for windings (Figure 2.18, leftmost image). A brief overview of the manufacturing of the fan motor prototype is given in the following figures, where the first of them focuses on the manufacture of the stator core and the second on the rotor PM assembly and evaluation tests of the rotor [34].

Figure 2.18 The mold with the main insulation system (left), the exchange process (left from the middle) and the ready stator from top and side view[34]

Figure 2.19 Air-gap between rotor and the stator, mounting process of permanent magnets and machine parts in prior to stator core evaluation[34]

Based on the test results, the performance of the magnetic core is estimated to be better compared to the 3D FE calculation and the (conservative) BH characteristic of the material selected in the calculations. A simplified production cycle to make a complete distributed 3-phase winding increases the attractiveness of the machine, but also the expected performance if the winding integration allows direct cooling.

Vehicular generator

One of the goals of the development work of this *20S20P Ø50/176-H75* electric machine was to investigate the possibility of combining RFM and TFM, and use a wave coil [19]. Consequently, in the case of a three-phase machine, there are three identical segments arranged axially side by side with a spatial phase shift [31].

Figure 2.20 Stator core consisting of 3 axially distributed segments (left) and single phase prototype machine where different stator core prototypes where tested (right) [31]

One of the challenges of the machine's topological choices was electrical magnetization, which would require a higher-than-usual excitation current for a stator with low relative magnetic permeability. The theoretically higher torque obtained by using the wave coil [19] is overshadowed by the limitations of practical tests [26]. The impact of the unbalanced axial flux due to the machine topology on the machine design was not recognized as a challenge. The fabricated stator segments are perfect, allowing for the desired precision on all component surfaces as desired by the designer. Influenced by the production developments of this machine, both the idea and a dozen practical laminated coil prototypes were born [22][31].

Traction motor

This machine is designed under the conditions of a prototype built for a heavy-duty machine, and the purpose of the machine is to demonstrate the efficiency of a direct-cooled coil. The selection of the SM²C stator tooth/pole is related to material availability and relatively efficient manufacturing process rather than magnetic properties. Thanks to the relative ease of manufacturing the SM²C-based core part, it was possible to test machine designs that were even more difficult to manufacture, such as installing an anodized coil that would meet the requirements for both electrical isolation and direct cooling.

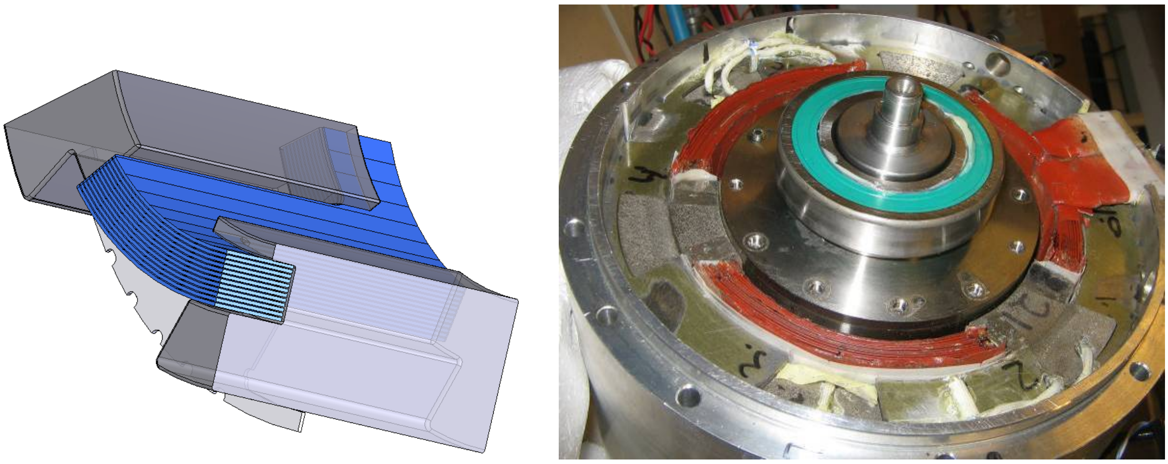


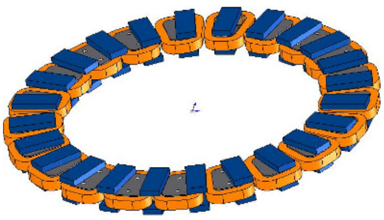
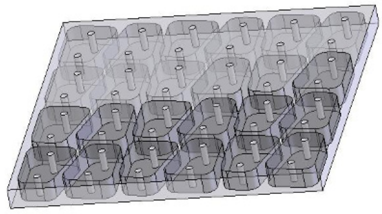
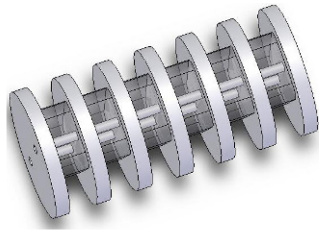
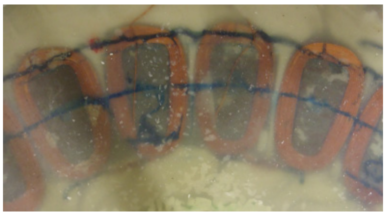
Figure 2.21. An electric machine that uses laminated stack in the stator yoke and SM²C poles for the stator teeth.

This *6P6S Ø62/200-H224* radial flux machine with axially distributed phase segments has a no-load voltage difference of about 4% between phases but had relatively high total harmonic distortion. Considering the expected characteristics of the electric machine [27] and using the same 2D and 3D FE methods for machine recalculations with SM²C, the test results become acceptable. Since the performance of the machine was more affected by the application of direct cooling and its efficiency, the tests and evaluation focused on conjugate heat transfer calculations [32][37] rather than a thorough evaluation of the machine's electromagnetic properties.

2.7 Axial flux machine

The original *Ø392/578-H75* machine is an air-core machine, while the introduction of the SM²C brings at least two advantages: 1) more than doubles the power and 2) introduces low content of torque ripple and radial force pulsation. The manufacturing process or the axial flux machine stator is shown in Table 2.5. The design related goals are presented in the first row and some outcomes of the process outcomes are presented in the second row. The most demanding design step is to specify the number of coils and proportions between the core and the coil (a). Once the shape of the stator core is specified, the SM²C block size, production and tracks for waterjet cutting are specified (b). This step is processed in the sequence of determining the manufacturing steps for producing the coils (c). The stator poles are cut out from molded SM²C block (d) and have fine surfaces and tolerances. These poles are used as the core for bobbin when manufacturing the coils (e). These coils are placed into a new mold, where the molding of non-magnetic and dielectric material is used to assemble the coils and establish the mechanical strength needed (f).

Table 2.5 Manufacturing process of stator cores and coils

Stator	Stator core	Coil
 A	 b	 c
 F	 d	 e

The full report [35] compares AF and RF machines based to magnetic share stress, compares several RF designs by using 2D FEM, evaluates a number of options for redesigned AF machine by using 3D FEM, demonstrates prototyping and evaluation of the new *24P27S* stator.

3 Conclusions and critical assessment

Molded magnetic cores are perfect for motor cores that have short magnetic paths and require high frequency operation, since particular to SM²C it has low core losses and low relative magnetic permeability. Evaluating a core based solely on the magnetic properties of the material, core fabrication, or electrical machine performance is incorrect, and this complex evaluation must be viewed together. The magnetic permeability of SM²C cores is low and this is a distinctive property that directly reduces the torque and power density of the machine, but it should be properly considered in the choice of machine topology and subsequent design. Thus, meeting the performance requirements and geometric constraints of an electric machine application can be a real challenge early in the design process if the choices of machine building materials do not allow for the desired torque and power density. Playing around with parameters such as compensating lower flux density with higher current density or replacing torque with higher rpm, to get the same power, changes mainly the "load point" and characteristics but not the performance.

The order of presentation of prototype machines in the evaluation table (Table 3.1) has been slightly changed compared to Table 1.1 for better grouping the components connecting the machine topologies. The columns of Table 3.1 are: 1) name of the machine, 2) topology, 3) type of magnet used for excitation (☺ blocks of NdFeB, 😐 plastic bonded NdFeB, ☹ plastic bonded Ferrite), 4) type of winding (☺ solenoid, 😐 formed or slotted solenoids, ☹ modular coils), 5) active volume, 6) torque based on test results, 7) torque density. The table also provides references to Lic and MSc Thesis, articles, and technical reports where information related to the design, or the control, of the machine is given. For example, reference [31] presents the SM²C engineering experience more broadly than just prptotype G1.

Table 3.1 List of selected prototypes with name with evaluation icons and calculated numbers

Prototype machine	Type / M	PM	WIN	Volume [dm³]	Torque [Nm]	T/Vol [Nm/dm³]	References
1	2	3	4	5	6	7	8
Start up (D1)	TFM	😐		0.0247	0.01	0.40	[5][11]
Fan (D2)	TFM	☹	☺	0.120	0.1	0.83	[7][9]
Pump (P1)	ATFM	☹☺		0.217	0.023	0.11	
Toroid (T1)	CFM	☺	☺	3.38	95	28.1	[8][10]
Wind-Gen (G2)	AFM	☺	☺	10.6	47.6	4.49	[35]
Pump (P2)	RFM			0.149	0.3	2.0	[14][15][29]
In-Wheel (W3)	RFM	☺	☹	4.50	36**	8.0**	[17][23][24][33]
Fan (F2)	RFM			1.68	15**	8.93**	[28][34]
Veh-Gen (G1)	RTFM	😐	😐	0.559*	0.32	0.57	[19][22][25][26][31]
Traction (T2)	RTFM	☺		6.36	20	3.14	[27][37]

*one axial segment, electric excitation at 4 A

**The torque and torque density values marked in gray are assumed values calculated based on the design data and assume a conductor current density of 5 A/mm²

Some clarifications regarding magnetizing circuits, coils and thermal margins:

- Permanent magnets are classified according to remanence (*1.2, 0.6, 0.2 T*), which means that a stronger magnet allows greater flux density and torque. The electrical excitation of the G1 is also rated at the same level as powder-based NdFeB magnets
- The evaluation of windings is mainly based on the winding type and its effect on the production of the core. The production of individual coils with a simple shape gives the best score. The coil that needs to be deformed or machined to achieve the appropriate final shape gets a lower score. The modular windings are considered the most complex here, because there is a need to consider both the connection between the coils and the placement options of other phases, which in turn complicates the manufacturing of the winding and can affect the molding of the core and its result.
- The torque in the table is selected based on the results of the load test, which showed the highest value. In the case of machines for which more detailed load tests were not carried out, design data is provided. Regardless of the results, this document does not make any assessment of the heat load or its margins neither if the load torque is taken from thermally transient or steady-state operation.

Does the interest in electric motors and machines made based on SM²C disappear simply because the low magnetic permeability does not allow sufficient specific torque and specific power? The critical assessment is not based solely on complaining about the low specific torque and power, but rather on highlighting the values of the production concept.

- The manufacture of the electric machine core and the assembly of the related components have been converted into a single production step and this enables the coil to be sourced separately, leading to a focus on improved fill factor, electric insulation or/and direct cooling.
- The manufacture of the AC core of an electric machine and the integration of coils or windings and additional components (such as magnetic parts, cooling circuits and sensors) change the concept of the construction of electric machines, affect the performance of the magnetic core and the production-oriented design. The focus is the analysis and evaluation of different production options and effects is well exemplified with prototype W3.
- In the manufacture of SM²C machines, the mold is usually designed in such a way that it allows maximum filling of SM²C material during the molding process, and that also in the situation where the mold is filled with complex coils and additional components. By designing and using molds, it is possible to obtain an almost uniformly filled magnetic circuit and surface finish on important or even all core surfaces (G1, F2).
- Both in the case of more complex windings and the use of magnetic components with higher magnetic conductivity, a contradictory effect may occur where the filling of the magnetic material may be incomplete or the filling factor may be uneven, and it also depends on the molding method applied during the filling process (P2, W3).
- Rotocast molding allows for the highest mass density and relative magnetic permeability of the SM²C core and is perfect for toroid/torus and (outrunner) claw pole type machines where it is not possible to make a laminated core as well as an SMC core due to large aspect ratios and small dimensions (D1, D2, T1).
- Despite the shortcomings of the magnetic properties, the relative ease of fabrication of the SM²C core allows the production of complex shaped core parts necessary for the construction of a prototype machine and the realization and testing of interesting concepts (P1, G2, T2).
- Shouldn't machine core molding be treated the same as additive manufacturing of soft magnetic cores and identify it as a "technology of choice" because its added value cannot be achieved with any other manufacturing technology [39]? The production of a magnetic core in laser powder bed fusion (L-PDF) chamber or by packaging a flowing iron powder into a mold are incomparable and even if they strive towards the same goal, high torque-per-volume (and weight) over wide speed range. One has the advantage of high relative magnetic permeability [40] while the other has seemingly low power losses.

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