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High speed brushless PMSM for in-fan application

Damia-2 application status report

Avo Reinap

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

High speed brushless PMSM for fan application

This is a reviewing document (a progress report on Damia-2) on design and evaluation of an outer rotor surface mounted permanent magnet synchronous machine for fan drive application. As the matter of fact, the machine design has been influenced on the achievements on the design and manufacturing of:

1. Outer rotor machine for In-wheel application
2. Development and realization of wave-windings for electrical machines

The specific outcome to the machine design and manufacturing of the machine has resulted to

1. Systematic 2D FEA scan trough of the distributed concentrated windings and core material combinations for the specified size of the machine
2. 3D FEA comparison between distributed concentrated windings and axially distributed wave-winding with a few material combinations
3. Machine prototyping with the unique approach of molding the insulation system in prior to core analysis and the final specification of the winding

1 Manufacturing, design and target specifications

The advantages of not repeating the potential traps in the design and manufacturing process turned to be disadvantages to the complete evaluation of the high speed brushless PMSM for fan application. Namely the design realization of the electrical machine for in-wheel application showed that even if it is easy to mould the SM^{2}C core around the mechanically locked windings there are much more concerns on

1. preceding manufacturing of the modular winding or the chain of the concentrated coils, especially for high fill factor and low number of turns
2. Establishing the main insulation system around the winding, between the package of wires and the molded core, there a few tests showing that the main insulation does not hold insulation voltage reguirements
3. Not acceptable tolerances of the components, especially coils and windings, that has to be placed into the mold in prior to molding
4. Last but not least the molding process, feedstock preparation, the mould design and production is not completely developed that can be adapted to various sizes and specially designed cores with inserts

As a result, the selection of the manufacturing approach for this machine is not the repetition of the preceding course of actions; if not innovative then the new process is unconventional and adds to the design for manufacturability knowledge of the machines with molded AC cores. The steps and the motivation behind is as following

1. Starting from the design and the electromechanical energy conversion it is believed that the modular winding is the most suitable for the core with low magnetic permeability
2. Instead of trying to solve the production of the high fill factor modular winding with appropriate insulation system that gives (very) good tolerances and high dielectric strength the main insulation is inserted to the mould and the core is molded to the "right side" of the insulation system.
3. The insulation system is 3D printed from the CAD drawing and dielectrically reinforced by coating with the layer of epoxy
4. Pure SM^{2}C rotomolded core is selected and no magnetic or mechanical reinforcement system is added. It is known that the torque capability is low and this could be improved by adding simple geometries of magnetic inserts but this would make the manufacturing process much more complex according to previous experiences. In extreme it would exclude SM^{2}C completely, use laminated core and reduce electric loading considerably for the same torque level that the machine gives with SM^{2}C. As a matter of fact but this is considered to be out of the project scope as the goals are to explore the moldable soft magnetic composites, molding processes and their suitability for machine cores.
5. The predefined core with insulation system is contra revolutionary as it is the traditional way of making machines. The advantage of the premade core and the insulation system is that there is the exact structure to form and to wind the winding, thus there are no additional steps to build bobbins, patterns or constructions to produce windings or add the premade segments together. The only troublesome production step is to succeed hand made high fill factor windings inside the slotted structure of the stator core.

1.1 Size and power specification

The predecessor PMSM with SM^{2}C core for in-wheel application has appeared with various diameters in order do adjust to the specific features of the core that have inherently low permeability and low power loss. The most manufactured size is $D_o/D_i\text{-}H_{act}$, $310/240\text{-}60$ mm. The high speed brushless PMSM for fan application has quite strict size specification $D_o/D_i\text{-}H_{act}$, $175/90\text{-}100$ mm.

The outer radius has slightly increased from the initial specification and the resulting active length H_{act} is the outcome of the mechanical design and construction to respect actual space limitation. The inner radius is basically the size related parameter only that the electromagnetic design could influence. The machine should be able to deliver 10 kW at 6000 rpm and the driver voltage is as high as 600 V. The machine supposes to be "naturally cooled". As a matter of fact, the machine is part of the fan application, where the machine is part of the forced cooling that it supposes to provide.

1.2 Machine topology specification

The specific features of SM^{2}C core establish a number of natural choices for machine topology specification:

1. Permanent magnet excitation – permanent magnet have even lower permeability than SM^{2}C i.e. significantly larger magnetic air-gap for surface mounted machines, PM can perfectly magnetize air-core machines so they are even better for the machines with magnetic core. The high energy density and low excitation loss density (expect the material cost) is the only and right choice for electrical machines that work at relatively low magnetization speed
2. High number of poles means shorter magnetization bath and higher frequency, both these are perfect match for SM^{2}C. The consequence with high number of poles and magnets is the reluctance forces between the core and the magnets that results as a high cogging.
3. Distributed concentrated winding that is grouped per phase so that the build up a modular winding (Figure 1.1) is the next natural choice and also the challenge for production. It is the simplest to produce a solenoid, and bit more advanced to form the shape of the single solenoid to become a chain of coils in the modular winding.

Some examples of concentrated coil arrangements that compose a modular winding is shown in Figure 1.1.

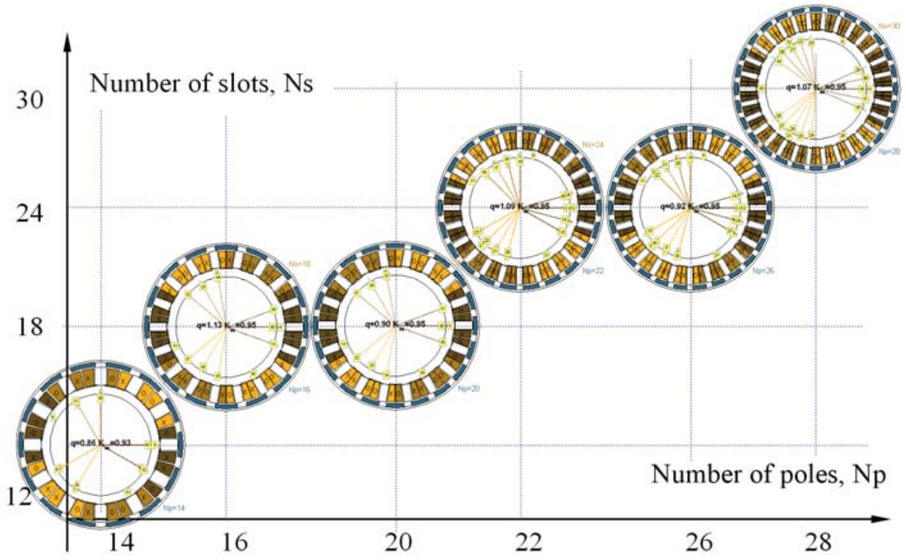


Figure 1.1 Rough dimensioning of a radial flux machine (left) and axial flux machine (right)

The next section shows the design process that provides the design for the application.

2 Design process

The design process focus on outer-rotor surface mounted permanent magnet radial flux machine and consists of following steps

1. initialization where the machine dimensions are roughly selected for the given space
2. Winding specification determines the number of poles and type of the winding
3. The proposed design is compared to another machine topology with wave-windings
4. Finally the construction for prototyping is specified with the expected characteristics

2.1 Initialization

There are a number of machine parameters that can be estimated and a number of design parameters that can be changed. One of the most meaningful design parameters are the number of poles and the proportion between the magnetic core and the electric winding that is expressed by a slotting factor. Higher slotting factor means more conductor area for the same K_f=60% fill factor within the insulated slot and thinner stator teeth. Thinner teeth are not able to carry the flux and machine looses ability to produce more torque. Lower slotting factor facilitates magnetic flux to link to the stator due to the wide teeth but reduces the current area to produce torque.

The calculation results are grouped on three figures of a number of parameter maps:

1. Example geometry and performance values in Figure 2.1
2. Magnetic loading, weight and power losses in Figure 2.2
3. Winding parameters and quality features such as specific torque and power in Figure 2.3

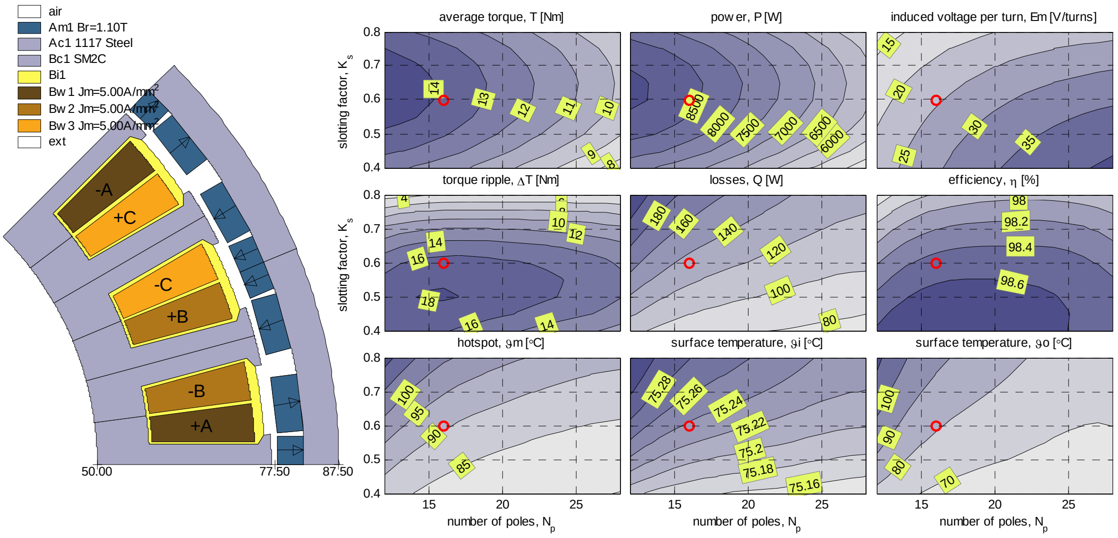


Figure 2.1 Machine construction that is behind the calculation is marked as a red dot on the maps. These 9 parameter maps reflect most of the machine performance as a function of number of poles and slotting factor.

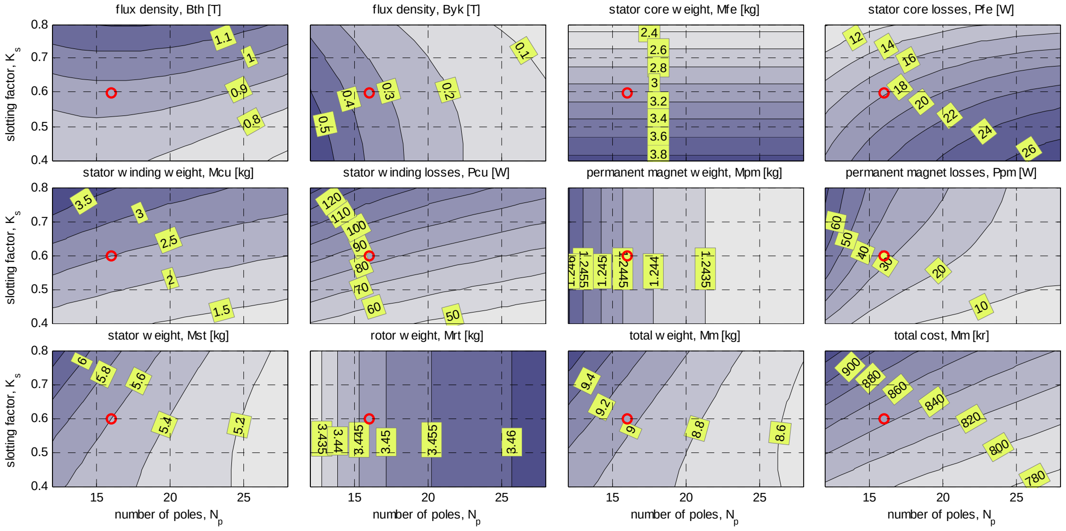


Figure 2.2 These 12 parameter maps reflect most of the machine magnetic loading, weight and power losses as a function of number of poles and slotting factor.

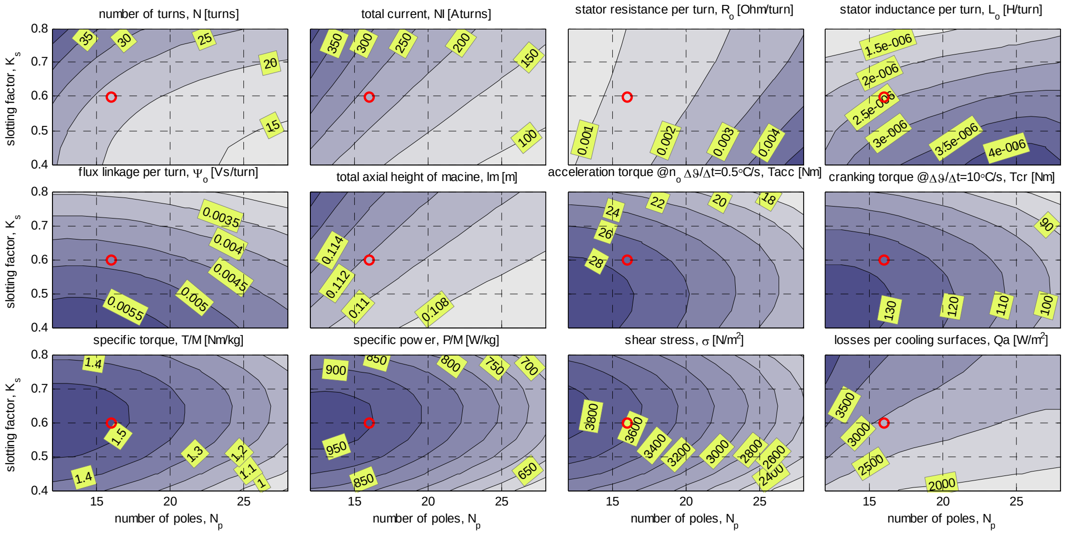


Figure 2.3 These 12 parameter maps reflect most of the winding specification and the design evaluation results as a function of number of poles and slotting factor.

The machine suppose to provide at least 16 Nm torque on shaft and the initial design shows that the number of poles shall not be too high, likely less or equal to $N_p=16$ poles.

2.2 Concentrated winding specification

Even though the main concern in this design step is to determine the number of poles and winding configuration according to that it is also analyzed the importance of the core selection based on the material properties. 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

The calculation (Figure 2.4), 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* [1]. The different speeds are selected in order to make the power losses more distinguishable as additional "internal load torque".

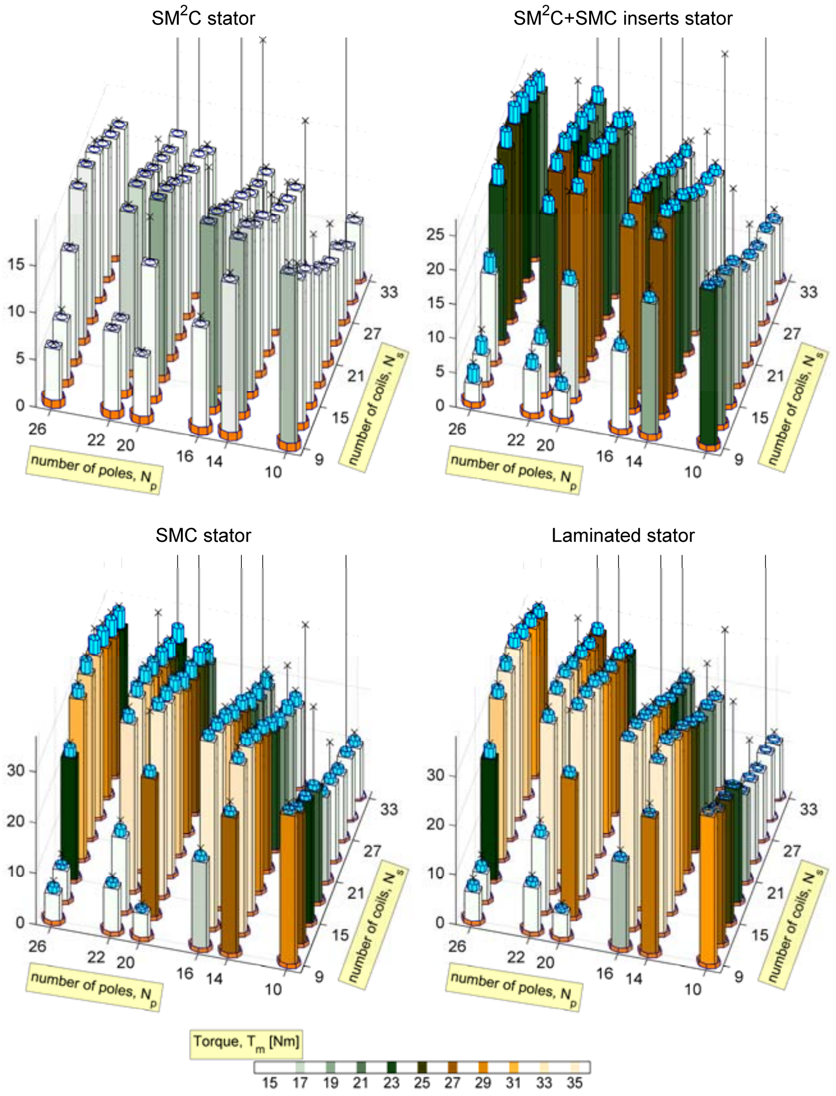


Figure 2.4 Average torque, ripple and losses as a drag torque over speed of four different stator of the Long & Slender machine.

From this analysis it is clear that the electrical machines with SM²C cores need to provide extremely 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 2.4). High frequency leakage field can easily produce power losses in the other structures and the whole solution is not as efficient anymore.

From this study it is clear that the machine has to be specified either as 20-pole and 18-coil or 16-pole and 18-coil.

2.3 Comparison between wave-winding and distributed concentrated winding

From manufacturability point of view the wave-windings have caught a lot of attention as during the project (Damia-2) there are number of successful results produced that has to be included in return into the machine design process. By starting from the round wire to profiled rectangular and even further to the planar sheet of the conductor, the various production methods based on deforming 1) a solenoid or 2) a single wire, or alternatively 3) gutting all segments of planar sheets or 4) cutting and rolling it together gives a variety of options for the production [2]-[4].

From magnetic construction (or concern) point of view, the wave-winding looks like a remarkable improvement of a simple planar solenoid in a transversal flux machine, which has the main field direction in the axial direction and thanks to the high permeability core it is modulated towards an air-gap that makes it as a transversal axial flux machine or transversal radial flux machine. On the contrary the wave-winding can be seen as a badly unbalanced coil when comparing to the modular winding. Some concern that is obvious with this kind of (transversal) machines

1. Cogging – usually there is same amount of excitation poles as the stator poles that makes the filed alternation possible. High number of poles may result more to the cogging than to the coupling
2. Power factor – is the problem for all transversal flux machines and becomes more in evidence with reduced of permeability in the core.

Nevertheless of the magnetic concern, a perfect sample of segment molding with a good pole formation is experimentally tested and evaluated [2]. Based on this production achievement for a simpler machine construction an extensive effort of 3D FE simulations are processed in order to show the potential of the topology and the risks related to material selection. 2D FE optimization routine is used to predefine the 3D FE geometry.

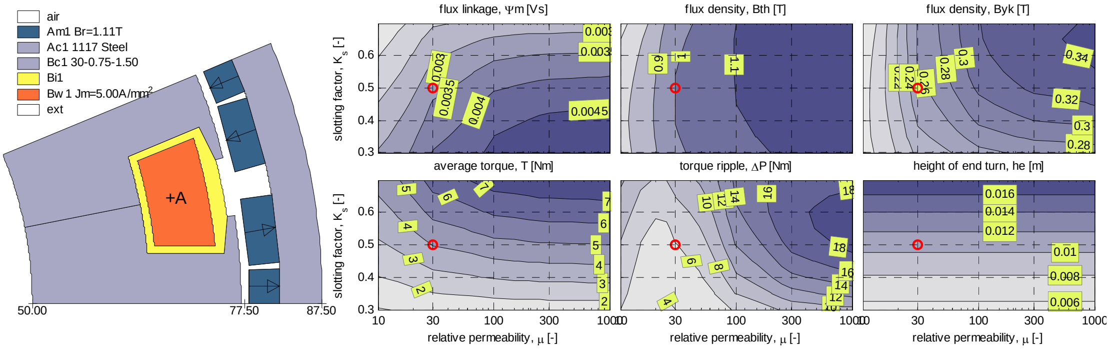


Figure 2.5 2D FE simulations used to provide optimal dimension for the winding and consider also the magnetic permeability of the core.

Figure 2.5 shows the interesting character for the magnetic core, where the magnetic permeability determines the braking point when the core looses extensively the ability to carry the field and to couple the machine parts magnetically. For this geometry and material specifications the relative magnetic permeability of the core has to be more than 30 so that the permeability of the air-gap becomes more dominant and the flux is less influenced by the permeability of the core.

Figure 2.5 is used do determine whether the coil or the stator tooth has parallel sides and constant width. By considering the same cross sectional area in the slots and in the end turns, the overhang of the trapezoidal shaped winding area is larger than for the rectangular shaped winding area. The target designs of 1) the rectangular coil area axially stacked wave-winding, 2) the trapezoidal coil area axially stacked wave-winding, and 3) distributed concentrated winding are shown .

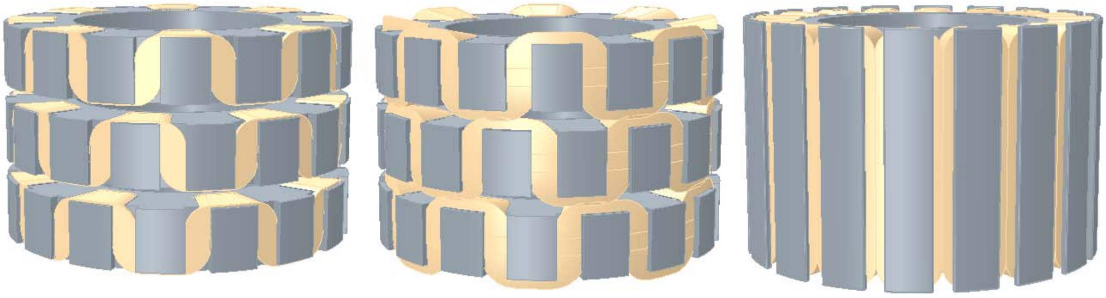


Figure 2.6 Stator topology description: (left) the rectangular coil area axially stacked wave-winding, (middle) the trapezoidal coil area axially stacked wave-winding, and (right) distributed concentrated winding

From manufacturing point of view, a different amount of efforts is needed when producing the coils or windings for the electromagnetic part of the stator (Figure 2.6). Figure 2.7 shows the wave-winding and the modular winding segment that belongs to a single phase. In this figure the winding volume includes main insulation, conductors and the insulation between the conductors. The fine net shape and the tolerances of the winding or the winding segment are usually the challenging part that complicates the mold design and molding the SM^2C core.

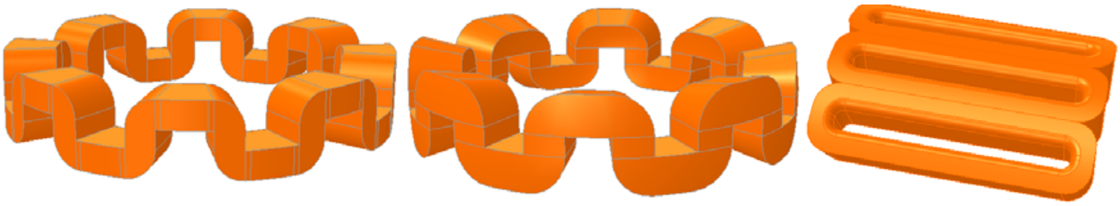


Figure 2.7 Wave-winding with rectangular (left) and trapezoidal (middle) cross-section, and phase segment of a modular winding (right)

The main concern in the electromagnetic design is the torque capability of the electrical machine. The 3D FE model set up for the axially stacked wave winding and distributed concentrated winding as well as the field results are shown in Figure 2.8 and in Figure 2.9, respectively, the torque waveforms as a function of rotor position in Figure 2.10 and the outcome is presented in Table 2.1 [1]. It is important to notice that the calculation does not consider the finalized dimensions for the design target and the dimensions used behind these calculations are presented in [1].

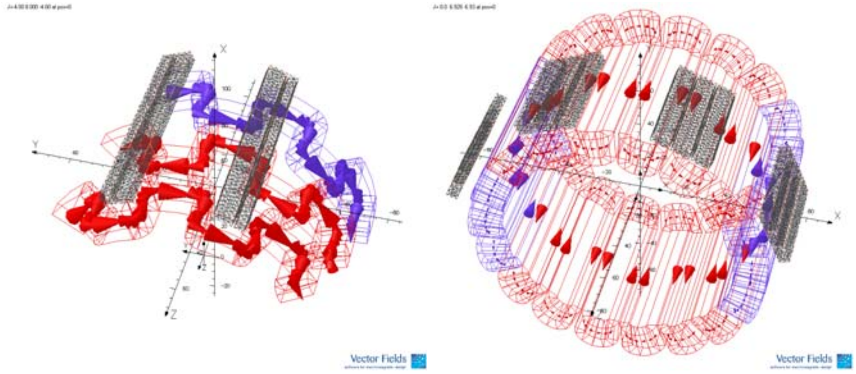


Figure 2.8 Winding and current definitions in the 3D FE model where N-magnets are only shown

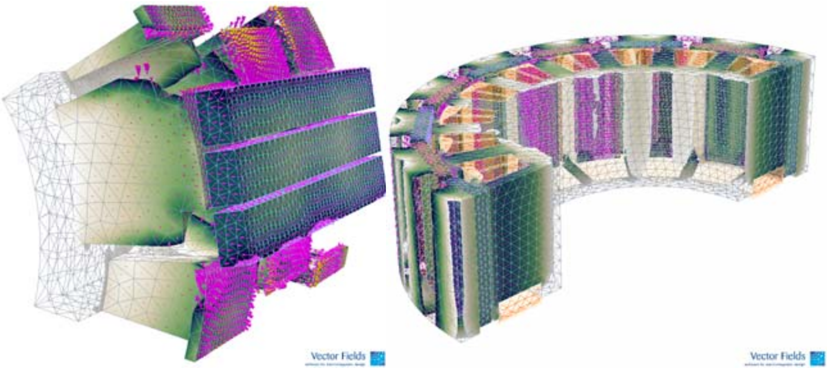


Figure 2.9 flux density distribution of the different machines at loaded conditions

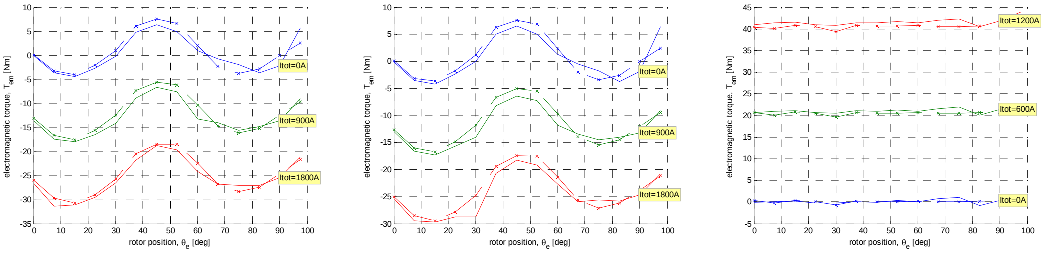


Figure 2.10 Electromagnetic torque as a function of position calculated by different methods in 3DFEA and shown for wave-windings with rectangular(left) and trapezoidal (middle) cross section and for the distributed concentrated winding (right). Torque is applied in different direction and at different current levels by assuming that the wave-winding can hold considerably higher fill factor than the conventional coil winding.

Table 2.1 Comparison between the machine topologies that have distributed modular winding respective axially stacked wave-windings. Recalculated value of total current is used to make 2D and 3D comparable..

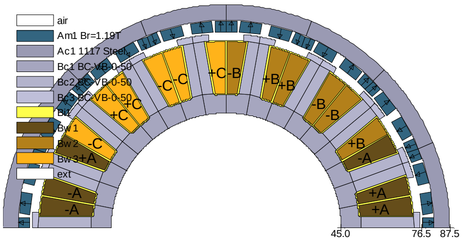
	Distributed concentrated winding		Axially stacked wave-windings	
	SM²C	SMC	SM²C	SMC
Torque (2D), Nm	21.3	45.3	-	-
Torque (3D), Nm	22.4	49.2	11.3	29.8
Torque ripple, %	1	1	30	>30

The outcome of 3D magnetic analysis shows that the machine configuration with axially distributed wave-windings has considerably higher cogging, which peak value is 15 Nm, and considerably lower electromagnetic torque *11.3 Nm* at the same current loading than the machine with modular windings. This is due to fact the machine configuration with axially distributed wave-windings has shorter active height of the machine due to 3 times wider end-turn volume (which is backed to the same stator volume) and additional axial space between the phases in order to compromise the magnetic balance. More cogging and less driving torque, even if the production would be extremely smart it is not decided to continue with this concept directly, but if time left the rest of machine parts can be used to verify the concept in the production as well as in the energy conversion.

There are a lot of 3D FE computation hours behind the design another axially stacked three phase machine design in order to support 2D FE design and get valuable input to the prototype in order to learn topology that requires considerably higher permeability than SM²C can provide the axially stacked wave-winding [5][6].

2.4 Machine characteristics

The machine construction is optimized in 2D FE simulations where the most realistic SM^{2}C material parameters is used and the optimization target is the maximized torque per given volume. The geometric layout and the material selections are shown in Figure 2.11.



Region	A, [cm^2]	ΣA, [cm^2]	V, [dm^3]	material	ρ, [kg/m^3]	M, [kg]
Am1	0.36	17.22	0.16	N35	7400	1.21
Ac1	2.04	32.59	0.31	1117 Steel	7600	2.35
Bc1	0.64	23.01	0.22	BC-VB-0-50	5500	1.20
Bc2	0.90	32.34	0.31	BC-VB-0-50	5500	1.69
Bc3	0.16	5.58	0.05	BC-VB-0-50	5500	0.29
Bi1	2.82	7.84	0.07	insulation	1200	0.09
Bw1	1.19	7.15	0.05	copper	8900	0.47
Bw2	1.19	7.15	0.05	copper	8900	0.47
Bw3	1.19	7.15	0.05	copper	8900	0.47

Figure 2.11 Machine layout and material specification

The cooling conditions are not updated in this optimization. The cooling requirement is specified at the maximum loading condition. Figure 2.12 shows the magnetic loading or the flux density distribution at maximum current of *10 A/mm^2* and torque. Figure 2.13 shows the thermal loading or the temperature rise in the machine as the reference temperature at the inner periphery is selected 0ºC and the natural convection is applied to the outer periphery of the rotor, the only heat sources applied are in the windings *766500 W/m^3*. The estimated machine data at the maximum loading point is presented in Table 2.2. Figure 2.14 shows the circle diagram and the torque speed characteristics

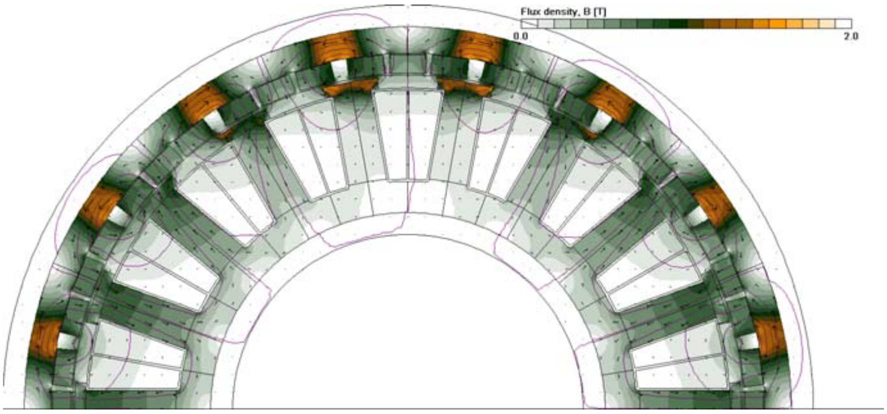


Figure 2.12Flux density distribution at maximum current loading and maximum torque conditions

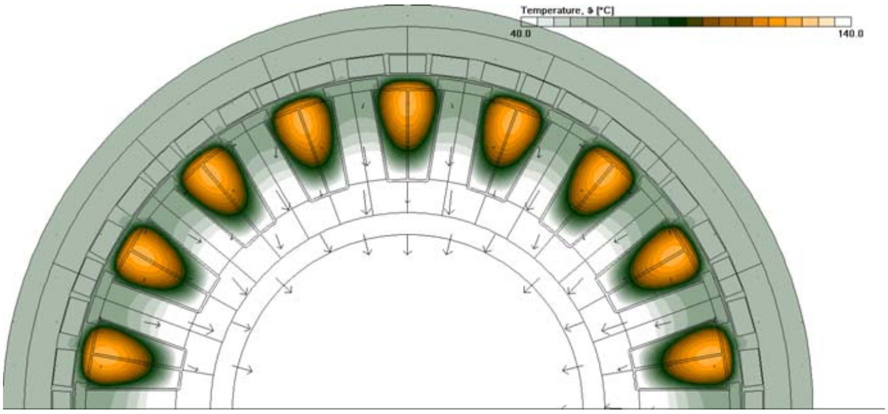


Figure 2.13 Temperature distribution at maximum current loading for a given reference temperature in the inner periphery and convection on the outer periphery

Table 2.2 Estimated machine data

quantity	symbol	value	unit	quantity	symbol	value	unit
outer radius	ro	87.5	mm	number of turns	Nt	23.0	turns
inner radius	ri	45.0	mm	rms phase current	I	22.0	A
active length	lact	95.0	mm	rms phase voltage	U	300.0	V
actual length	ltot	119.8	mm	rms back emf	E	289.6	V
air-gap length	g	1.0	mm	resistance	Rs	65.6	mOhm
number of poles	Np	16.0	-	direct inductance	Lsx	838.3	µH
number of slots	Ns	18.0	-	quadrature inductance	Lsy	913.2	µH
weight of stator core	Mstfe	3.2	kg	nominal torque	T	30.2	Nm
weight of stator winding	Mstcu	1.4	kg	moment of inertia	J	26.3	gm/s^2
weight of rotor magnet	Mrtpm	1.2	kg	copper losses	Pcu	380.0	W
weight of stator	Mst	4.6	kg	core losses	Pfe	24.5	W
weight of rotor	Mrt	3.6	kg	rotor losses	Prt	3.6	W
total weight	Mtot	8.2	kg	nominal power	Pout	19.0	kW
winding fill factor	Kf	0.6	-	estimated efficiency	η	97.9	%
teeth flux density	Btm	1.2	T	magnetic shear stress	MSS	8659.6	N/cm^2
yoke flux density	Bym	302.6	mT	specific torque	T/M	3.7	Nm/kg
current density	Jcm	10.0	A/mm^2	specific power	P/V	2327.3	W/m^3
total current	NIm	1.4	kAturn	estimated material cost	cost	2328.2	kr
flux linkage	Psimo	3.5	mVs	specific cost	cost/M	285.4	kr/kg
base speed	no	6.0	krpm	torque ripple	ΔT	2.8	Nm
dc link voltage	Udc	600.0	V	cogging torque	δT	2.7	Nm
hot-spot temperetaure	ϑmax	122.9	°C	load angle	δ	16.9	deg
inner surface temp	ϑin	1.2	°C	max speed @ 0.9Pmax	nmax	9.0	krpm
outer surface temp	ϑout	56.2	°C	core loss @ nmax	Pfem	NaN	W
inner cooling	Qai	11294.3	W/m^2	saliency ratio	ξ	0.9	-
outer cooling	Qao	259.4	W/m^2	acceleration torque	Tacc	30.2	Nm
inner heat transfer	hai	92.8	W/Km^2	cranking torque	Tcr	NaN	Nm
outer heat transfer	hao	3.9	W/Km^2	acceleration current	Iacc	22.0	A

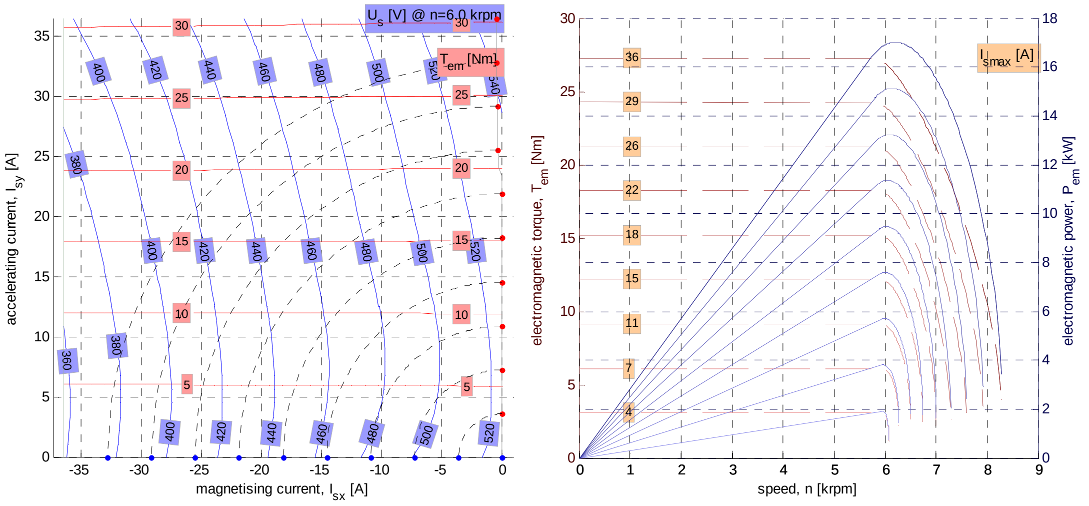


Figure 2.14 Circle diagram with torque and voltage map and torque speed diagram of the machine

Figure 2.14 shows the circle diagram where the torque and the voltage maps are presented. The voltage map is calculated from machine flux and resistive voltage drop across the windings at *6000 rpm*. The torque speed diagram is constructed from the circle diagram where the 9 circles of the current are shown. Each current level corresponds to an integer number of current density in the coils. Therefore the first circle is with $1\ A/mm^2$, the second with $2\ A/mm^2$ and so forth and so on. The power losses in the rotor is only the estimation of eddy current losses in the magnets and not in the rotor core when following the flux variation at different rotor position and operation points of stator currents.

3 Manufacturing and assembling process

The earlier efforts on molding SM²C core around the windings have established some concern that directly influenced the manufacturing the prototype. By inspired of the good design and manufacturing experience, which should be repeated, there are a number of "small obstacles" that should get more attention before the new prototype is processed. By taking the manufacturing in prior to design, which is for the sake of the goal to provide a good design for manufacturability and likely not the best design for the performance, there is a tree of events to be considered:

1. Ideally the stator core is molded i.e. assembled in a single process step. In practice it is always optimized towards that. The rotocast molding is preferred to (low pressure) injection molding so that the better and more compact core can be achieved, not least the change of relative permeability around 11 to 16 when comparing injection molding to the rotocast molding,
2. In order to achieve single step molding the mould and the components in the mold such as coils, pieces of higher permeability core, insulation, mechanical support or/and cooling system, etc have to be carefully designed and manufactured. If this condition is not fulfilled then either the molding process fails – there is no homogeneous core inside all the intentional cavities of the stator, or the machine performance is reduced due to various failures
    - Geometrical tolerances: insufficient tolerances cause failure in montage, 1) insufficient fill rate in tooth-tips, teeth etc, or 2) incorrect fill in the gaps and gravities where should not to be any core, but where the core material enters during molding. Typical concern here is geometrically well defined coils and windings. This task gets even harder when high fill factor is desired in order to compensate somehow the low permeability of the SM²C core.
    - Introduction of new concepts such as establishing main insulation system by 1) tipping the coils or windings or even 2) extra molding of the dielectric insulation. This causes directly the final component tolerances. The innovative process comes together with uncertainty, which cause failures in the dielectric system.
    - Geometric or geometry alteration due to various process related loads. Understandable example here is that the component in the mold may move due to the forces applied in the molding process or the dimensions of the mold can change due to temperature. There are number of aspects that influence the molding process and the outcome of the process. The outcome of these aspects can lead to increased complexity such as it can result more components into the mould, such as fixation structures, and also splitting the single step process to a few processes.
    - Mechanical and electrical termination is usually not as vital in practice as it could be imagined, neglected and solved later
3. The disassembling process has to be considered too when designing the mold

3.1 Machine parts

Based on the magnetic design and the geometry and material specification (Figure 2.11) the cad drawing of the machine is made. Volvo AB has prototyped the machine housing and provide with the bearing i.e. all light grey parts in Figure 3.1 are provided by Volvo AB.

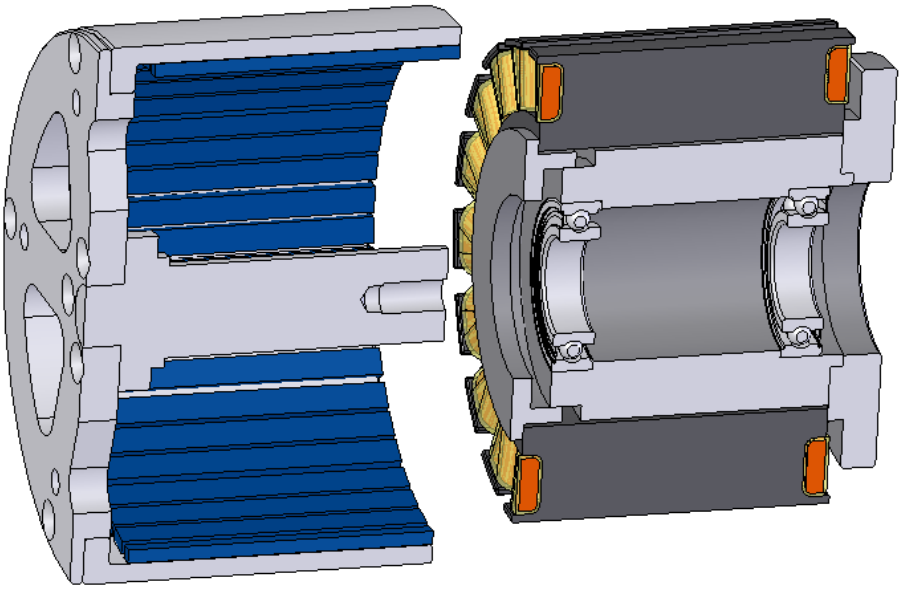


Figure 3.1 CAD drawing of the prototype target

3.2 SM^{2}C core molded around temporal support structure

The first rotocast molding of SM²C for the stator core uses a temporal support structure so that the removal of the structure would define the exact shape of the core. There are the following intensions with this manufacturability study:

1. Studying the molding process and process parameters: 1) preparation: material composition, selection of carrier substance and temperature, 2) rotocasting: feeding material and removing carrier substance, processing time and temperature, and 3) finishing process: hardening and disassembling the molded core
2. Investigating the quality of the molded core: 1) fill rate and the filling quality of various core parts, 2) final measures and tolerance specification based on the molding process and 3) determination of possible improvements or risks in prior to next molding.

Figure 3.2 Molded core after disassembling from the mold (left), view to the whole core and to the core section

Experience from the molding and the quality of the molded core (Figure 3.2)

1. Relatively low temperature, low viscosity of the SM²C feedstock and the compaction pressure resulted more than satisfactory filling of the teeth and tooth-tips
2. The material exchange (SM²C into the mold and light carrier substance out) during the molding allowed getting good finished surfaces along the inner periphery and edges that are used to mount the core.

3.3 SM^{2}C core molded around the main insulation system

The next molding is processed on the verifications from the pre previous experience. Figure 3.3 shows the main insulation system in the mold, the exchange process where the more dense iron settles, air backs away and also the carrier substance collects to the uppermost part of the mold. The finished product from the top and the side is shown in Figure 3.3. The manufacturing tolerances of the mold are not perfect so that the insulation system is not clearly seen between the tooth-tips.

Figure 3.3 The mould with the main insulation system (left), the exchange process (left from the middle) and the ready stator from top and side view

3.4 Machine assembling

The machine assembling is started with tolerance analysis and mounting 240 magnets where Loctite 480 is used to fix the magnets to the rotor cylinder (Figure 3.4).

Figure 3.4 Air-gap between rotor and the stator, mounting process of permanent magnets and machine parts in prior to measurements

The centering process in prior to mounting is shown in Figure 3.3 and the test windings around the teeth in Figure 3.4. The test windings are used to validate magnetic coupling and apart from that the cogging is roughly measured. There are some mechanical work to do in order to adapt the height and the mechanical fixation of the stator to the support system. All the continuation and experiments so far are reviewed in the next section.

4 Evaluation process

There is not too much focus on the production process or the material characterization rather than the design. Nevertheless there are a number of evaluation process steps that are related to the completion of the design and manufacturing. The following completion process steps are stated according to the design plan:

1. Evaluation of the magnetic circuit in order to specify the winding. For this test a number of test coils are assembled and the induced voltage measured at different speeds. From this measurement the flux linkage is estimated
2. In order to specify the winding, the driver or drivers has to be specified. An available 2-quadrant BLDC speed driver is specified (48ZWSK30-B-803) for the first experimentation. The different dc-link voltage levels (100V) 200V or 300V and 600V specifies the number outputs or strands per phase that establish the symmetric supply
3. Apart from the coil terminals, the number of turns the specified wire diameter of 0.65 mm determines the number of parallel strands and the fill factor.
4. 3 hall sensors and 2 temperature sensors are specified to use

First tests, after the magnetic parts of the machine is assembled, is to evaluate mechanical balance and eccentricity (due to stator basically), vibration and normal forces between the stator and rotor and cogging. The cogging is roughly measured and assessed to be in the range of 1 to 2 Nm, which if correct is quite good match to the predicted results. Observed but not measured there is nothing unexceptional of vibration and sound that comes with cogging. The rest of the structure is well balanced and has periodic character that is directly defined by magnets and stator teeth. The measurement sample of induced voltages over 4 consecutive teeth and the extracted peak flux linkage per teeth at different (low) excitation frequency is shown in Figure 4.1.

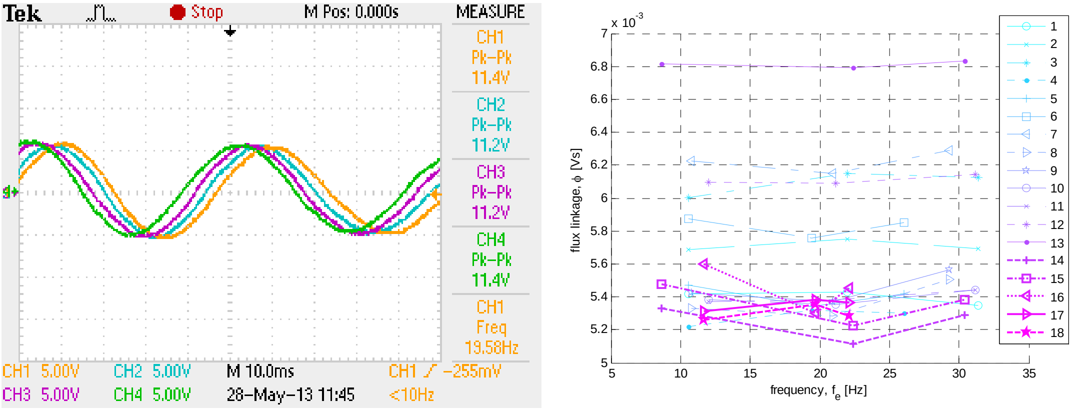


Figure 4.1 Induced voltage measurement sample (left) and the extracted flux linkage

According to the expectation based on the material characterization and 2D FE simulations the flux linkage in the bottom of the teeth is *0.41 mVs* and in the top *0.64 mVs*, which is somehow more skeptic than the measurements provide. Unfortunately the coils are not accurate enough to give better possibility to characterize the material and see the variation due to different packing and the core material utilization.

5 Conclusions and future work

The ultimate goal of this work in Damia-2 has not reached to the end as the drive unit is not completed but the essential goal is accomplished. The central goal of this work is achieved as

1. Stator core with rotomoulded SM²C is built and the crucial parameters such as 1) flux linkage, 2) cogging torque and 3) not least the manufacturing process is experimentally verified
2. The new unconventional way of building machine core – innovative but not rational has the focus on the main insulation system. This is important contribution to this project as the insulation system may have lack of attention when having focus on a number of other vital issues. The shell of the insulation system is placed into the mould and the soft moldable composite is feed into the mould and rotocasted into the cavities of the insulation system where the core has to be. The other cavities for the winding are leak free due to a proper tightening.
3. For the case of manufacturability, this prototyped stator shows the new level of geometric complexity with good results as 1) the tooth-tips were properly filled, and 2) the molding process gave fine finished surfaces as there is a special concern of replacing the carrier substance with iron powder so that there is minimum overflow of the carrier substance and maximized utilization of the iron content for this low pressure compaction process used. The challenge is the hand made windings.
4. For the case of electromagnetic design, there are not too many choices left to compensate the drastic reduction of magnetic permeability when turning a conventional core to a molded core. Usually the reduction of air-gap and improving the winding, taking advantage of embedded coils in order to reduce the overhangs or increase the active axial height H_{act} has small effect against the overall reduction of torque capability. If the machine construction takes advantage of core-less principle or if the magnetic core obviously suffers under the high core losses then the soft magnetic moldable composite could probably be a good alternative.
5. The essential part of this project is related to manufacturability for design, where usually the simple arrangement for production does not establish a good design for electromechanical energy conversion. The originality of this (Damia-2) project is the reversed order for the electrical machine production, where the windings with insulation comes first and moulding is used as an assembling process to compile the pieces into a mold into a single piece, brings up many new ideas, establishes a broad basis of design and manufacturing experience.
6. The design and manufacturing of the high speed brushless PMSM for fan application, prevents previous manufacturing complications and tries to get the best out from the SM²C material, but likely not for overall efficient production process or/and for the most energy/volume efficient solution for the application.

The future work is 1) to complete the winding for the specified driver and 2) to verify the machine performance.

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Self references related to research

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