1. Publishable Summary

:: Summary Description of Project Context and Objectives

Road transport plays a crucial role in actual society, however pollution (including noise) generated by circulation has become a serious impediment to the quality of life and even the health of urban populations. Moreover, energy consumption by urban transportation has dramatically increased the dependency on petroleum. Progressive vehicle electrification is considered one of the main ways to promote efficiency and to meet broad environmental concerns; yet its greener version, i.e., pure electric vehicle (EV), has not been extended so far due to the insufficient energy density of batteries to provide the desirable autonomy and power. In recent years a technological breakthrough has occurred on this issue: largely driven by the explosion in consumer electronic demand (laptops, digital cameras, etc.) lithium-ion battery technology is reaching energy densities approaching 200Wh/kg (see Figure 1) and even more due to ongoing research (including current EU funded projects HELIOS, AMELIE and EUROLIION), which makes EVs with practical ranges of >130 km become physically possible while respecting reasonable vehicle size/mass/cost limits.

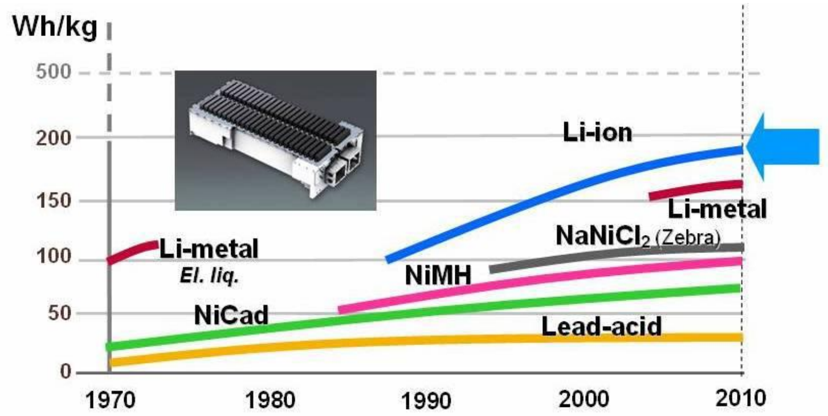


Figure 1. Battery Technology - Energy Density Evolution[1].

Now the strong growth potential of the technology's consumption faces a challenge in that it is reliant on some material (lithium) that has been in short use to date. Even though there is some controversy on whether lithium carbonate suppliers will be able[2,3] or not[4] to accommodate the growing demand occasioned by a growing electric car market in the future, the truth is that the countries with extensive, relatively low-cost, lithium brine deposits are Argentina, Bolivia, Chile, China, and the United States, with the only presence of Portugal among European countries in the list of significant producers.

However the raw material dependence problem of the EU is even more worrying when it comes to the electric motors themselves rather than their batteries. Currently, the most powerful and efficient electric machines use permanent magnets composed by rare-earth materials such as neodymium and dysprosium. The problem is that in the past decade 95% of the global supply of these materials was provided by China only[5] which puts at risk a mass introduction of EVs in Europe if the current motor technology is exclusively embraced. Just how dependent the entire world is on Chinese rare earths became very clear at the end of 2010 when China threatened to restrict supplies. The

[1] D. Twohig, Large-scale deployment of electric vehicles, Proceedings of the ITRN2011, IR, 2011.
[2] Chemetall, Lithium applications and availability: Chemetall statement to investors, July 2009.
[3] P. de Solminihac, Sociedad Química y Minera de Chile S.A.: a statement to investors, September 2009.
[4] W. Tahil, The trouble with lithium 2, Meridian International Research, May 2008.
[5] M. Humphries, Rare Earth Elements: The Global Supply Chain, CRS Report for Congress, R41347, US, June 2012.

subsequent Chinese embargo against Japan verified these worries and alerted the Western world. The spike in rare-earth prices was very dramatic - up to 3,000% for some of them.

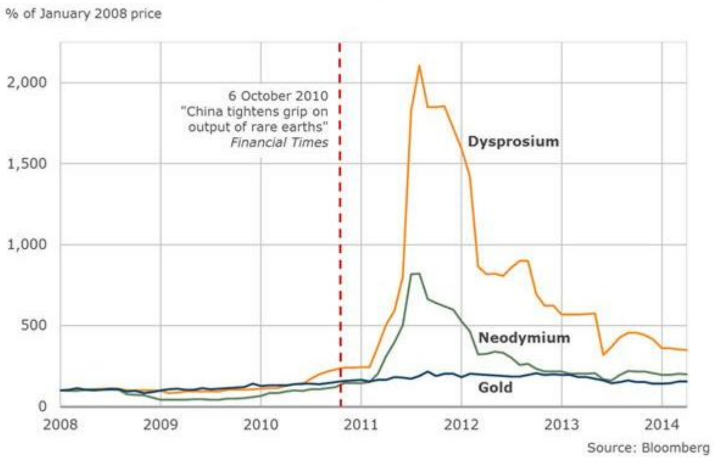


Figure 2. Dysprosium and Neodymium prices compared with gold (source: Boomberg).

Prices for most of the elements have declined significantly since 2012, but China had successfully demonstrated the power that comes with monopolistic control of an important raw material class. The shock was enough to prompt companies to begin to explore producing and refining rare earths elsewhere in the world. According to the last data from U.S. Geological Survey[6], rare earth production share in China has dropped to 84.8%, while production of Australia, USA, Russia and Thailand accounts for 8.1%, 3.3%, 2.0% and 1.6% respectively.

The big question remains on the future availability and price of rare earth magnets. Many experts foresee a supply deficit of Terbium and Dysprosium in the next future, as demand over time is expected to exceed the industry's ability to produce these rare earth elements. In fact, China announced on Oct 18 2016 that it will limit its annual mining of rare earth within 140,000 tonnes by 2020[7] (it currently produces 105,000 tonnes).

It should be noted that during export shortage period, the material cost of PM motors spiked up to around 75% of the total cost (see Table 1a, gross margin excluded), with magnets comprising around 45% of such material cost (see Table 1b). This implies that around 34% of the total estimated cost of a motor being due to the magnets. Under this circumstance, motor manufacturers without privileged access to neodymium and dysprosium as fundamental components for their permanent magnets (PM) find themselves at a competitive disadvantage.

Table 1. Permanent-magnet motor: (a) estimated OEM cost[8]; (b) material content and cost of components[8].

(a)

Cost Contributor	Cost ($)	Avg. Cost ($)	Avg. Share (%)
Material cost	390	390	62.2
Assembly and testing (20-30% of mfg. cost)	97-167	132	21.1
Total mfg. cost	487-557	522	83.3
Gross margin @ 20% of mfg. cost	97-111	104	16.7
OEM price	584-668	626	100.0

(b)

	Mass		Cost		
Component	(lb)	(%)	($)	(%)	($/lb)
Stator core	24.0	27.4	68[a]	17.4	2.83
Stator winding	11.0	12.6	22	5.6	2.00
Housing	21.0	24.0	50	12.8	2.38
Rotor	16.0	18.3	26	6.7	1.63
Magnets	3.5	4.0	175	44.9	50.00
Attachment band	0.5	0.6	6	1.5	12.00
Shaft	5.5	6.3	3	0.8	0.55
Miscellaneous	6.0	6.8	40	10.3	6.67
Total	87.5	100.0	390	100.0	4.46

[6] U.S. Geological Survey. Mineral Commodity Summaries 2016

[7] http://www.china.org.cn/china/Off_the_Wire/2016-10/18/content_39515617.htm

[8] R.M. Cuenca et al., Evaluation of Electric Vehicle Production and Operating Costs, Center for Transportation Research, Energy Systems Division, US, November 1999.

In order to establish a successful large scale EV manufacturing industry in Europe a new necessity arises: finding an efficient and power dense alternative to permanent-magnet machines in order to provide a technological alternative to European motor manufacturers to continue in the EV motor market. The year 2015 saw the global threshold of 1 million electric cars on the road exceeded, closing at 1.26 million (see figure below). This is a symbolic achievement highlighting significant efforts deployed jointly by governments and industry over the past ten years.

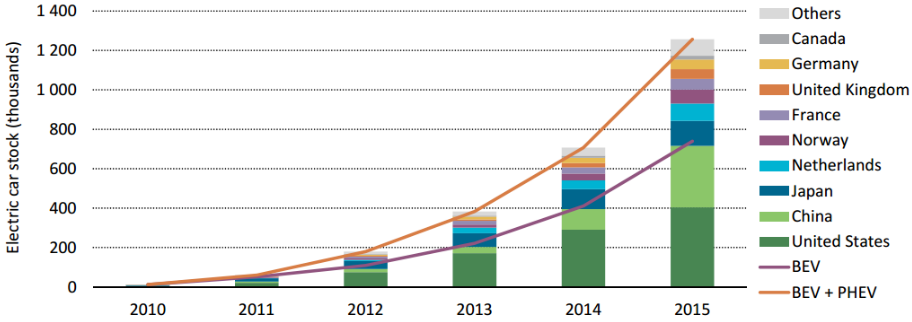


Figure 3. Evolution of the global electric car stock, 2010-15[9].

EV car fleet is predicted to grow significantly in the following years, especially after 2020 when scale economies are supposed to start taking place. By 2050 EV, PHEV and fuel cell vehicles are projected to dominate the market[10].

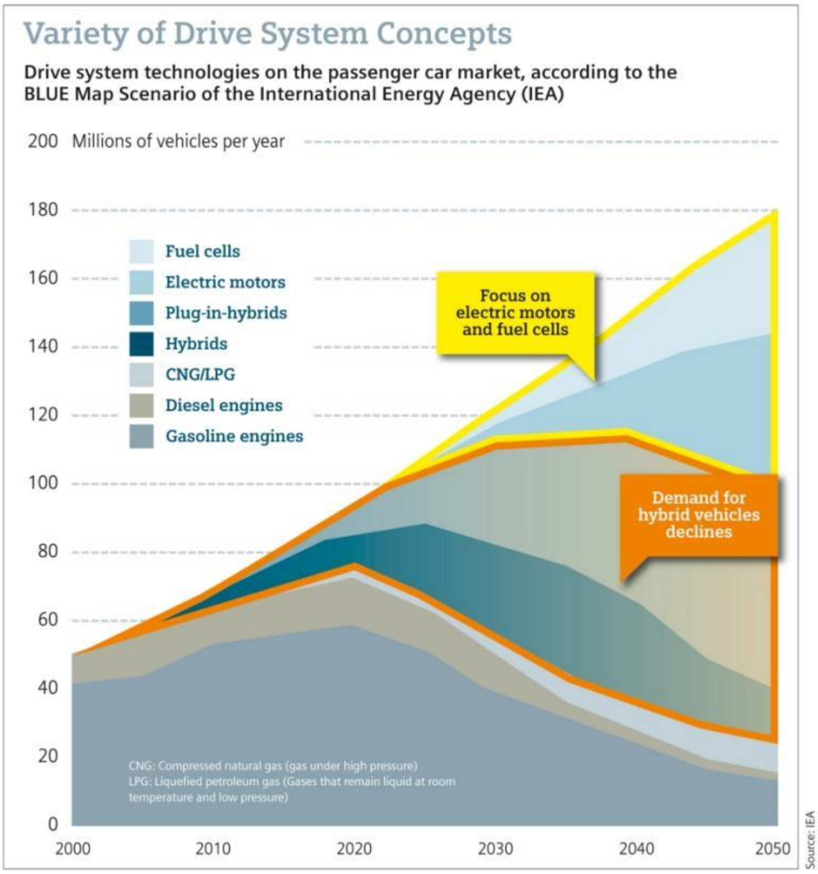


Figure 4. Forecast of car sales evolution by technology type for the upcoming decades10.

[9] Global EV Outlook 2016, OECD/IEA 2016
[10] International Energy Agency, Transport, Energy and CO_2, EU, 2009

In this context, the development of high efficiency motors using a limited amount of permanent magnets or completely new magnet-free motor designs is crucial. A promising option for this new generation of electric motors could be reluctance technology, which has been left out of the first line up to now due to its lower power density when compared to PM motors. On the other hand, the use of axial-flux configurations has proved recently in PM motors that power density can be increased in a relatively cost-effective way. The combination of both approaches, reluctance motors in axial-flux configuration, could lead to power densities comparable to those of PM motors in current EV-s while minimizing (PM assisted synchronous reluctance motors, PMSynR) or avoiding (switched reluctance motors, SRM) the usage of scarce magnet materials. The aim of this project is:

- To develop both axial-flux AFSRs and AFSynR motors in parallel (meeting EV power density requirements), exploiting their commonalities and synergies in the design and prototyping phases, to further opt for the most suitable solution to be integrated in commercial EV-s.
- To develop a completely novel approach for EV applications considering the combination of reluctance technology and axial-flux configuration.
- To obtain a cost-effective and high efficiency motor & drive design, considering a potential large scale manufacturing and industrialization of this new generation of motors.

:: Performed Work Description since Project Start and Main Results Achieved

In the next pages, the work performed in VENUS Project is described in five sections:

- Design of VENUS Motor Prototype. VENUS Motor has an original electromagnetic configuration. For that reason, specific electromagnetic design and calculation tools have been developed, as well as advanced thermal models. In addition, the novelty of the VENUS AFSR motor configuration makes its mechanical design to be completely different from common radial-flux machines. The power electronics has also been developed: a new inverter consisting of a control board, an interface board, a driver board, an IGBT module, a cooling system, a DC-Link capacitor and aluminium housing. For the control system, a SRM model has been implemented with non-linear flux linkage.
- Manufacturing of VENUS Motor Prototype. Manufacturing of each component and the full assembly of the motor has been carefully done to attain the maximum accuracy of the prototype. Multiple tests have been carried out in a specifically prepared test-bench.
- Vehicle Integration of VENUS Motor Prototype. VENUS motor and inverter have been fully integrated in an Azure Transit Connect van.
- Design of Marketable VENUS Motor. Original VENUS motor was designed to be suitable for a pre-established platform (Azure Transit Connect van), which was not the most appropriate for the new motor topology. For a more marketable second version of the VENUS motor a market opportunity for L-category vehicles was identified and thus a new design was carried out: this design considers solutions for the limitations encountered with the first prototype.
- Industrialization Analysis. Exploitation of VENUS motor has been comprehensively studied, including cost evaluation, manufacturing processes and required investments.

Four strategic objectives were defined for VENUS Project. The level of implementation of those objectives is summarised in next points:

1. Weight reduction and power density increase. Power density of VENUS motor is 10% better than Letrika Iskra (Renault Twizy motor), which is the benchmark for motors without permanent magnets in L-category and low-powered vehicles. However, even if a figure of merit for a switched reluctance machine, a power density equivalent to PM magnet machines (which was the original plan) was not achieved.
2. Replacing or greatly reducing rare earths content, or innovative magnet-free designs. VENUS motor is magnet-free, so the objective is satisfied.
3. Smart packaging of power electronics and integrated thermal management. VENUS inverter can provide the highest power per litre in the market: 19 kW/l (320 kW in 16.8 litres), suitable for other type of motors, not only for SR motors. At the end of the VENUS project, a prototype near of the final product has been achieved.
4. Optimised design and processes for manufacturing. In the first motor design, this objective was not fulfilled because the manufacturing cost for the motor was clearly above the market. In the second design, the sale cost would be in the same order of magnitude as most competitors. The performance of VENUS motor is lower than the best permanent-magnet motors. However, in a context of high rare-earth prices, VENUS motor could be quite competitive.

Design of VENUS Motor Prototype

Electromagnetic Design

Due to the novel electromagnetic configuration of the VENUS AFSR motor specific electromagnetic design and calculation tools have been developed to find the best design possible for the project specifications: an electromagnetic design tool (based on analytical formulation), and a 3D finite element method (FEM) based model.

The electromagnetic design process for VENUS motor prototype has consisted in four main steps:

1) Definition of specifications.
2) Search for the best motor designs without restricting the number of phases
3) Search for the best motor design with 3 phases and selection of the final motor configuration
4) Design refinements for the selected 3 phase 12/8 motor predesign

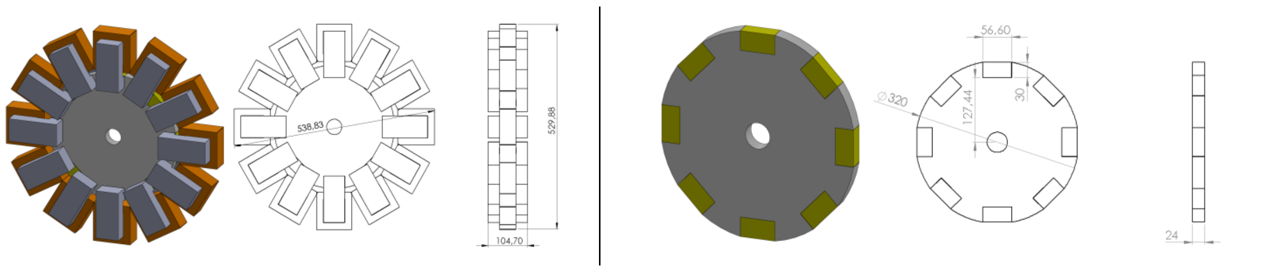
The analytical design tool developed is used to search for all possible electromagnetic motor predesigns with any number of poles that fit the specifications, and selecting the best ones considering different criteria: torque and power capacity, and torque and power densities.

During the motor design process the number of phases has been finally forced to be 3 in order to use power electronic modules closer to market product level. Higher number of phases would require non-standard power electronic modules, thus less reliable, which introduce more uncertainties for the prototype development and testing. Additionally the number of poles has been forced to be even (multiple of 2). The reason is making easier the parallel connection of coils in order to have the option for switching between series and parallel connected winding and increase motor speed range because this is expected to be a limitation. Selecting an odd number of poles would make impossible parallel connection of coils, so each coil should be divided and connected in parallel, which requires many more electrical connections.

The selected 3-phase 12/8 motor predesign was them further analyzed and refined, interacting with mechanical design, thermal analysis and control. To summarize, the process is divided in four steps:

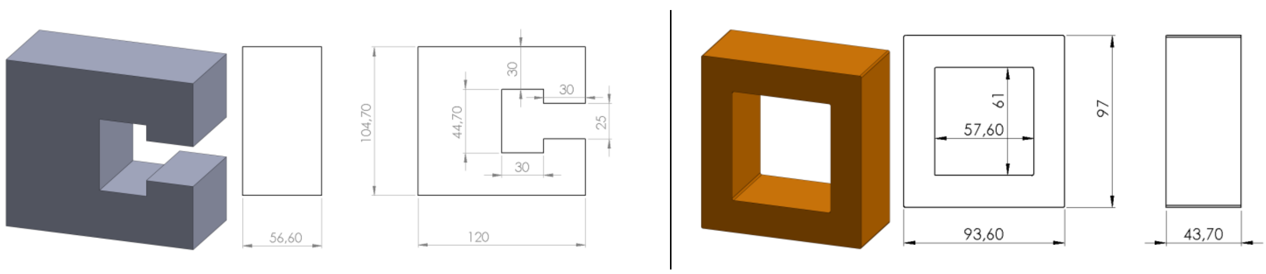
1) Further analysis on the first motor predesign to detect some problems and needs.
2) Reduce magnetic saturation to avoid uncertainties due to electric steel's real magnetic properties, and reduce copper losses to reduce motor temperature.
3) Reduce motor diameter for integration in the vehicle.
4) Reduce phase inductance to improve electrical dynamic behaviour.

The process is iterated several times until reaching the final VENUS prototype design.



(a) (b)

Figure 5. (a) 3D view of the active parts of the motor; (b) 3D view of the rotor (open slots).



(a) (b)

Figure 6. (a) 3D view of one C-core; (b) 3D view of one coil.

Thermal Design

Thermal models have been developed using analytical and numerical methods. The analytical models are based on lumped-parameter thermal network (LPTN) method. The main advantage of LPTN method is fast computational speed, which is very useful for sensitivity analysis of machine cooling design, to identify the critical parameters that could affect the machine thermal performance. The numerical models are based on Computational Fluid Dynamics (CFD) method. Due to the complexity and novelty of the machine, the CFD method is useful to predict the convective heat transfer coefficient inside AFSRM and housing water jacket, and also the pressure drop in the housing water jacket. CFD models can also provide calibration to the LPTN models. A Portunus thermal model for Axial-flux Switched Reluctant Machine (AFSRM) has been developed to meet the electromagnetic, manufacturability and assembly requirements.

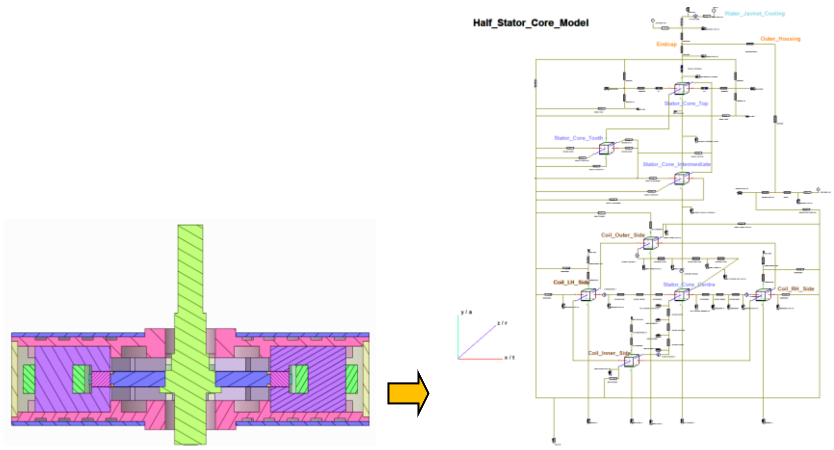
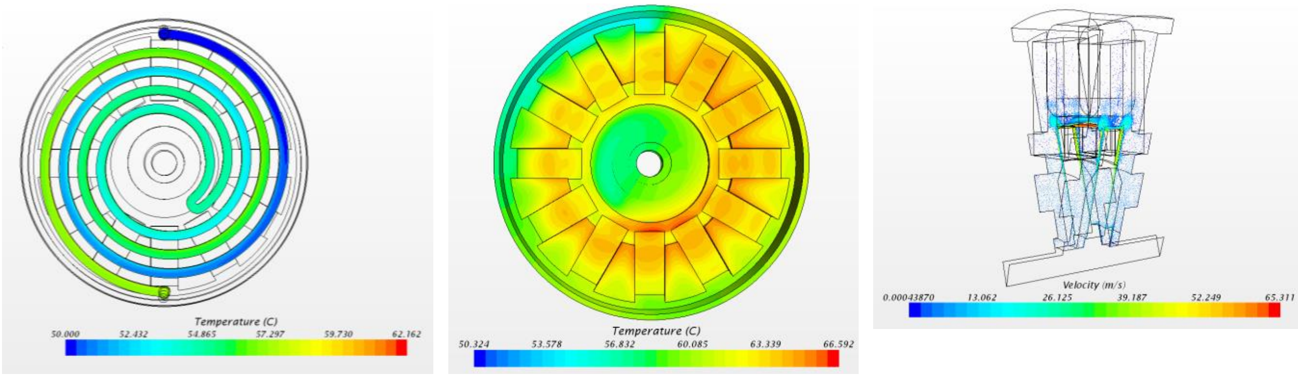


Figure 7. Improved Portunus thermal model.

Co-simulation is performed for the thermal analysis and two different types of CFD models were developed. The first type of CFD models are used to determine the performance of water jacket designs. The second type of CAD models are used to investigate the convective cooling performance due to circulating air inside the machine. This can save the computational cost considerably by dividing the thermal model of the complete machine into a number of smaller thermal models. Also, CFD models can provide calibrations to the Portunus thermal model.

Since the water jacket is formed by assembling inner endcap and outer endcap together, only one end of the housing was modelled in three dimensions due to machine axial symmetry for simulating flow and heat transfer. Alongside the fluid domain, the solid domain representing the inner endcap, outer endcap, outer housing, inlet and outlet pipes were also included to calculate power dissipation with conduction.

Polyhedral and prism layer meshers were employed. The mesh in the fluid region is denser because of the advection term in the flow equations, which is more difficult to resolve than pure conduction in the solid domain.

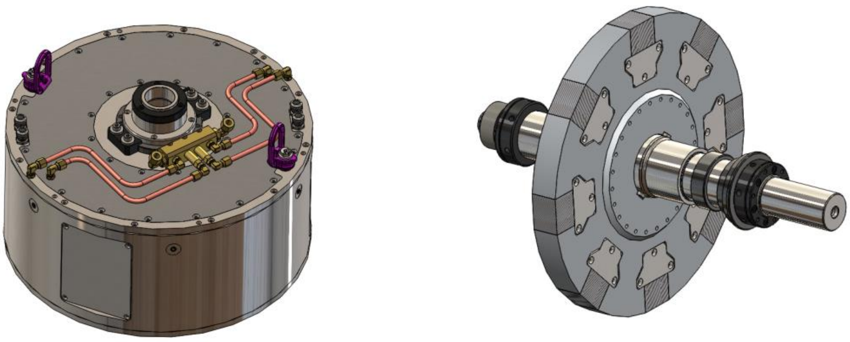


(a) (b) (c)

Figure 8. (a) Coolant temperature rise of 8mm channel height water jacket; (b) Endcap temperature rise of 8mm channel height water jacket; (c) Flow field inside machine induced by rotor at 3500rpm.

Mechanical Design

In addition to the rotor poles, stator poles and coils that are considered in the electromagnetic design, other elements are required to complete the motor. The novelty of the VENUS AFSR motor configuration makes its mechanical design to be completely different from common radial-flux machines, for which the current motor industry is oriented. However, to make easier the prototyping of the VENUS motor, common manufacturability and assembly criteria are applied where possible.



(a) (b)

Figure 9. (a) VENUS motor design; (b) VENUS rotor design.

In most of the cases the accuracy that can be achieved with prototype manufacturing processes is higher than more usual processes in mass production. However, in case of the laminations where for mass production the stamping is employed, the accuracy of the mass production is higher than the accuracy of processes that can be used in prototyping (Laser cutting, WEDM). That is why the mounting has to be carefully planned to compensate the accuracy errors of the pieces produced by prototyping. In the rotor some mounting pieces have been designed for the correct compensation of these inaccuracies.

The stator assembly concept of VENUS AFSR motor is very different from existing industrial motors. Due to winding requirements, each of the actuators of the stator is an independent workpiece. In the final assembly, all these C-cores must be placed firmly and with some precision.

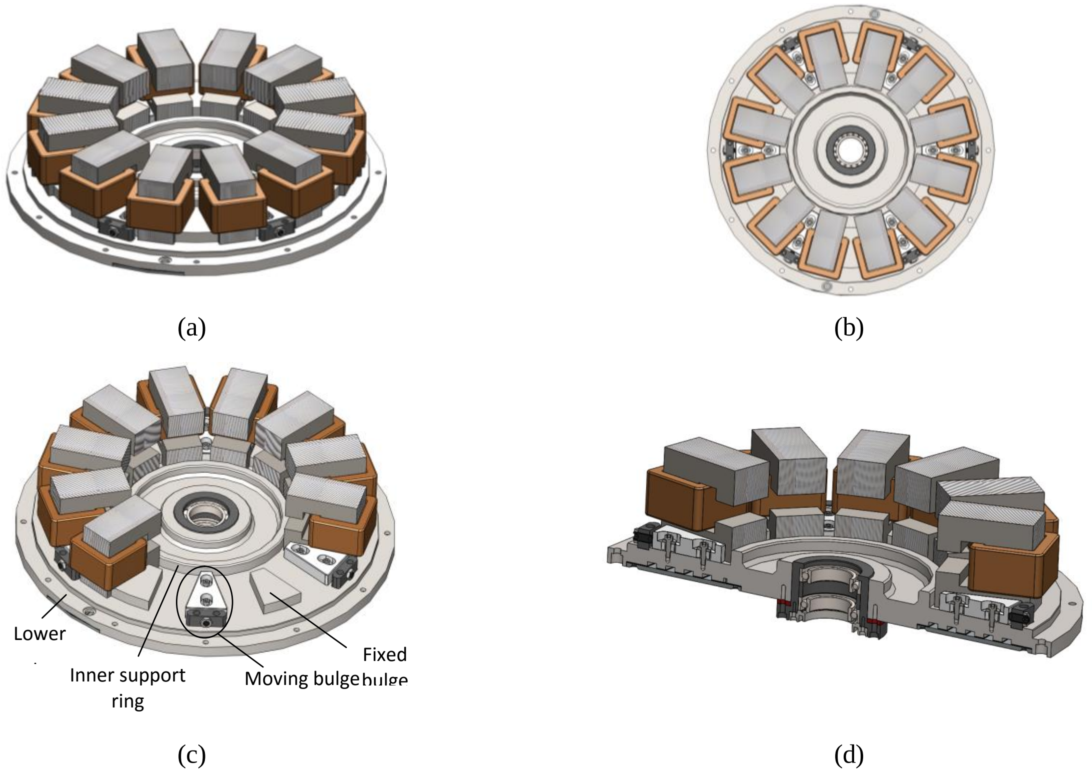


Figure 10. Stator assembly (upper end-cap omitted) and C-cores assembly.

Power Electronics Design

A new inverter consisting of 7 parts has been developed:

- Control Board: is the part in charge of controlling the system.
- Interface Board: the function of this board is to drive two Driver Boards (and therefore two IGBT Modules) from just one Control Board. There are some jumpers that have been used for testing purposes in the development phase but will be removed in the final product.
- Driver Board: the Driver Board is the part of the inverter that drives the IGBTs controlling the motor rotation.
- IGBT Module: these are the elements that provide the power to the motor.
- Cooling system: aluminium component to provide the water cooling to the IGBT Modules. Screwed directly to the IGBT Module provides direct cooling for pin-fin base plate
- DC-Link Capacitor: is the interface between the HV battery and the system. It is specially needed when high currents during short times are required, as the HV battery cannot provide such currents often (battery life drops with each cycle).
- Housing: a 3 mm aluminium housing box has been manufactured, except in the base (4mm). It also includes the connections to the rest of the system (HV battery, LV battery, CAN of the vehicle and the motor).
- Control algorithms and software: autosar, iso26262, applications, functionalities, traction and adherence control, energy saving and efficiency.

The next figure shows the interactions/interfaces between the different elements in the inverter in a graphical manner as well as the looks of the new inverter.

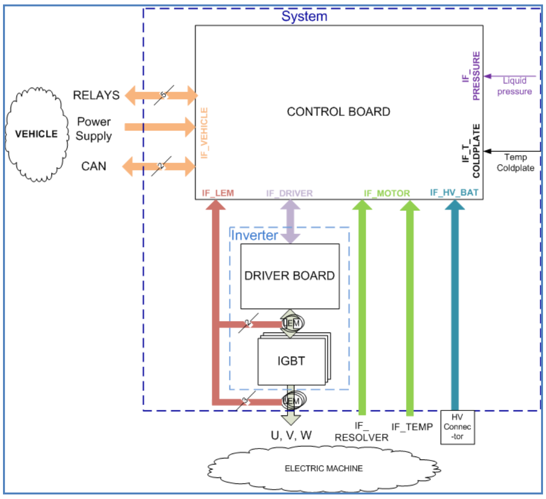


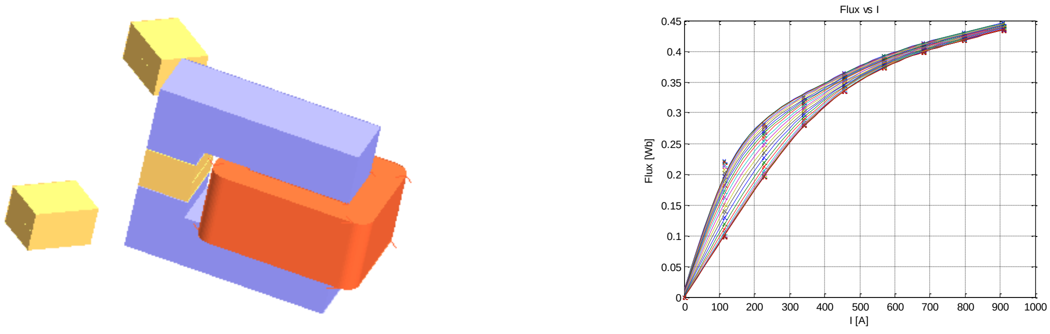
Figure 11. Inverter interfaces

Figure 12. VENUS Inverter design.

Control System Design

An SRM model has been implemented in Matlab Simulink with non-linear Flux Linkage. This SRM model includes the power electronics domain and the electromagnetic domain. The electromagnetic model is based in a torque and current map. FEM-3D simulations are needed to get these torque vs. current and position and current vs flux and position maps for the AFSRM motor developed in VENUS. By including these maps in the electromagnetic model it is possible to have a SRM machine model including the non-linearity. In the project the different aspects of the control have been simulated using an advanced parameter based model.

The model has been obtained first by FEM 3D simulations and then using specialized tests with this objective. The control developing platform is fed at different developing stages by the parameters obtained from simulation and/ or by experimental results in order to have the most accurate approximation to the fine desired performance.



(a) (b)

Figure 13. FEM-3D simulation, b) Flux vs current and position

The control is based on two main stages with an optional third one with which the torque loop may be closed. The dynamic torque control gives the signals for the different branches of the converter. This control needs the speed feedback, but also the current command (I*) and activation (θ_{on}*)/deactivation (θ_{off}*) angle commands, so that the converter signals can be generated. These commands depend on the torque command (T*) and angular speed (ω), and are created with a flux level strategy. Using a torque and flux estimator the performance of the machine can be increased, improving the flux level strategy with the torque and flux feedback.

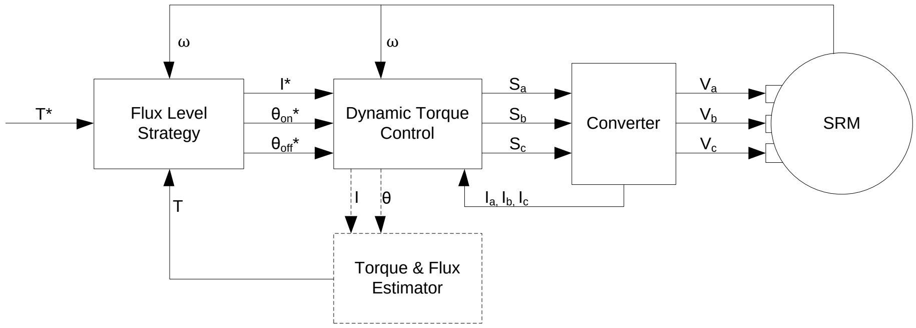


Figure 14. General view of the motor controller block diagram.

A complete dynamic simulation platform has been then developed and implemented in Matlab/Simulink to validate the following aspects:

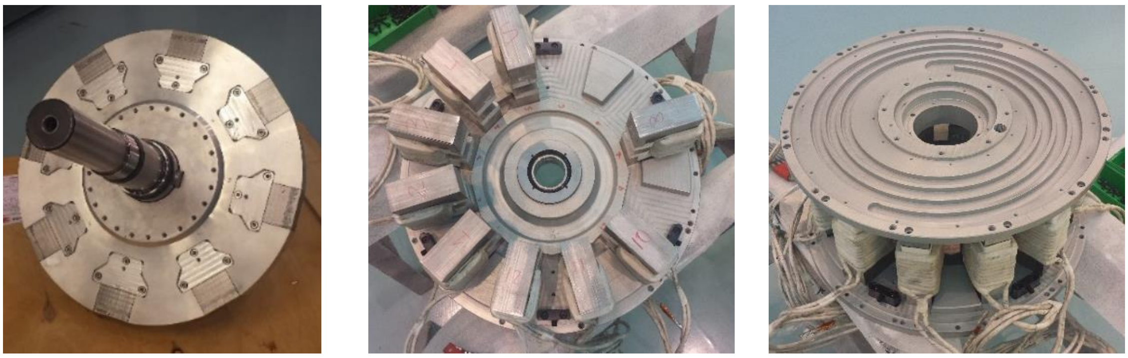
- The dynamic behaviour of different AFSRM designs
- The dynamic performance of the developed control system

The simulation platform allows motor operation at different modes:

- Constant speed or speed varying according to the dynamic of the vehicle
- Torque control or current control
- Constant DC BUS or DC real supply (with battery model & inverter capacitor)

Manufacturing of VENUS Motor Prototype

Each part of the VENUS motor has been carefully manufactured and assembled to maintain the maximum accuracy in the prototype. The sub-assemblies have been measured one by one to assure the correct manufacturing of the pieces and the assemblies. The different poles of the motor are assembled using pieces specifically designed to press and locate correctly the lamination poles in the rotor. In the case of the stator, the C cores have been assembled one by one using positioning pieces.



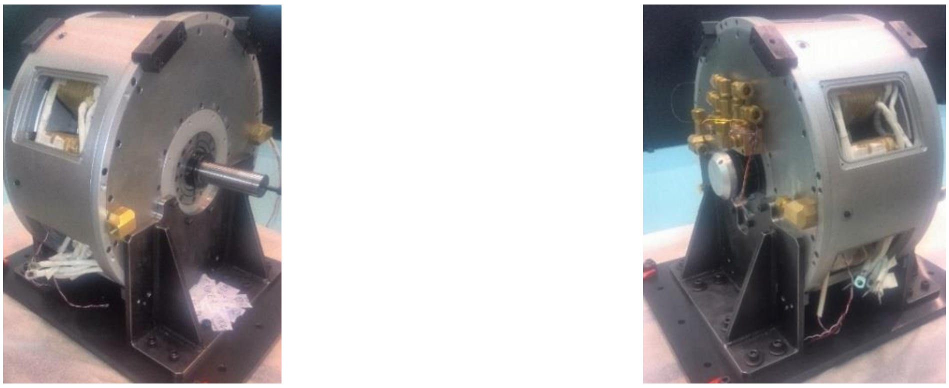
(a) (b) (c)

Figure 15. (a) VENUS Rotor; (b) VENUS Stator; (c) Cooling Tape.

The motor has 12 physically independent coils, each one with two, thus 24 coil terminals overall, and one connection box with 6 terminals, 2 per phase. Coil terminals of poles of the same phase must be interconnected and distributed inside the motor and finally connected to the corresponding terminal in the connection box, but the motor geometry is unusual, which requires a previous analysis to decide the more suitable way to proceed.

(a) (b)

Figure 16. Assembly process pictures: (a) C-cores preliminary positioning (one side); (b) C-cores preliminary positioning (both sides).



(a) (b)

Figure 17. Assembled motor pictures.

Once the motor has been completely assembled and mounted, multiple tests have been carried out in a specifically prepared test-bench. The VENUS motor is controlled in torque using the new control algorithms developed during the project. The load is generated by controlling in speed a different motor that is working in opposition to the VENUS motor. In this manner the performance of VENUS motor at different working points is evaluated.

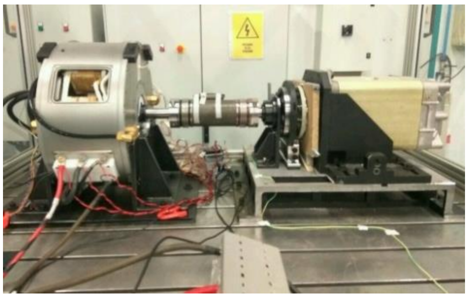
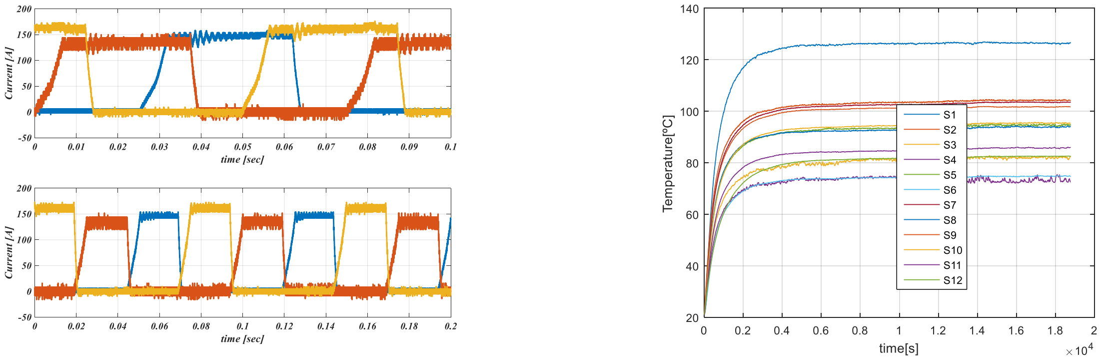


Figure 18. VENUS motor in test-bench.

This testing frame, allows to test different current control strategies and to assure the correct performance of the motor including long tests such as thermal tests.



(a) (b)

Figure 19. Tests in test Bench: (a) current in different phases of the motor; (b) thermocouple measurements at different locations.

Vehicle Integration of VENUS Motor Prototype

The VENUS motor and inverter have been integrated in an Azure Transit Connect van.

Mechanical Integration

The steps followed to integrate the motor and inverter in the vehicle are:

- Initial packaging in CAD software
- Development of a new cooling system
- Development & implementation of vehicle modifications

(a) (b)

Figure 20. (a) Azure Transit Connect van; (b) Available space for the integration of new elements (original motor & inverter shown in blue).

Suitable positioning and clamping systems for the new components (motor and inverter) on the vehicle engine compartment were defined. The most challenging task was to locate the new motor in a way that it matches the gearbox and the original engine mounts points of the vehicle. Unfortunately, this was not achievable because the dimensions of the original and VENUS motors are very different from each other (original motor is considerably longer but has a lower outer diameter). Therefore, the new motor and the original gearbox were mounted off-axis and a coupling mechanism was designed to connect both systems.

A new cooling system was developed defining the right paths for the required hoses in the available space.

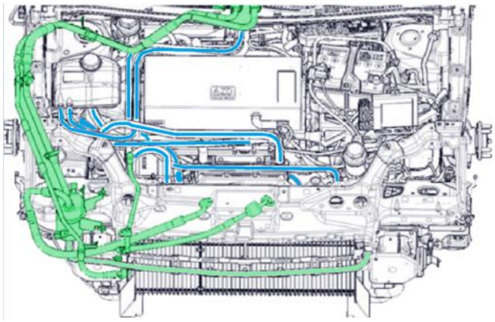


Figure 21. Cooling hoses (not modified in green; modified in blue).

Additionally, it was necessary to implement new engine mounts, changes in some elements (e.g. half shaft bearing, etc.), a new mounting plate for the inverter, etc.

Figure 22. Full assembly of the new VENUS powertrain in operating condition.

Electrical Integration

The main two tasks required to electrically integrate the VENUS powertrain comprised in the Azure Ford Transit Connect were:

1. Implementation of CAN communications between the new inverter and the Vehicle Control Unit (VCU) according to Azure protocol. There is no additional need to communicate the motor with the vehicle since the original motor did not have any kind of CAN interface with the vehicle.
2. Execution of electrical connexions among the motor, inverter and all the vehicle components following the usual safety standards for this kind of operations.

The main task was related to the communication procedure between Vehicle Control Unit and the rest of the elements of the vehicle, like the new inverter, the battery pack, the air conditioning module, etc. The communication follows a specific CAN protocol developed by Azure to allow the correct operation of the vehicle. Since the original inverter of the vehicle had been removed, the new inverter had to accurately replicate the same frames at identical rate in order to be recognised by the vehicle as the original one

Once the messages sent and received by the Inverter were identified, they were implemented in the software code (state machine) of the inverter. The next step consisted in checking if the software of the inverter was correct. The software would be correct if the output messages of the Inverter bus CAN reply the vehicle bus CAN behaviour regarding the input messages. To do this kind of check, the inverter was firstly connected to a virtual vehicle model instead of the vehicle, in order to safeguard the integrity of the inverter and the components of the vehicle. The virtual vehicle model emulates the messages of the vehicle, specifically the switch-on sequence, forward and reverse commands and torque command. The vehicle virtual model was developed in Matlab-Simulink environment

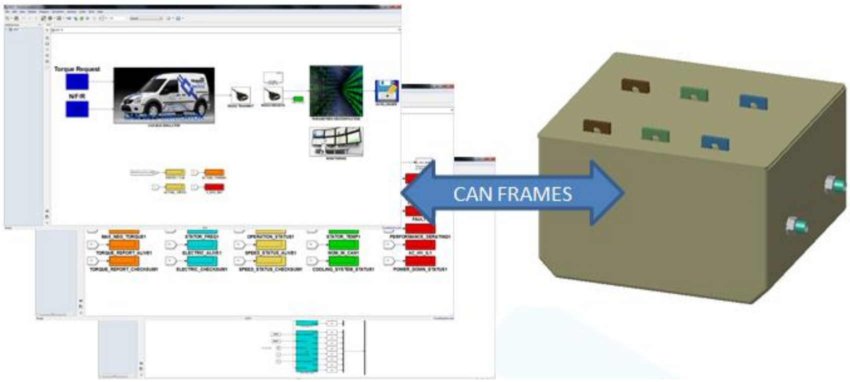


Figure 23. Vehicle virtual model.

Once the communication issues were solved the electrical integration of the motor and inverter in the vehicle was relatively straightforward. The positive and negative terminals from battery pack were connected to the inverter through the Junction Box. The three phases of the motor were then directly connected to the inverter without further requirements.

Figure 24. Motor and inverter integration finished (cover of the inverter is removed for display purposes).

<u>Design of Marketable VENUS Motor</u>

The fact that the VENUS has to be integrated in a pre-established vehicle platform (Azure Ford Transit) with fixed transmission and battery characteristics has limited the achieved motor prototype design. It should be noted that the Azure Ford Transit is designed for (induction) radial-flux motors. The most sensible trade-off has been considered according to the technology, the platform limitations and the fact of this being the first prototype of its kind. The table below shows the limitations of the first version of the prototype version of the VENUS motor and solutions for a second (closer to market) version of the motor. Optimally the best approach would be to define a platform planned to integrate such a motor (i.e. full drive-train design instead of just focusing on only the motor).

For a more marketable second version of the VENUS motor a market opportunity for L-category vehicles was identified and thus a new design was carried out: this design considers solutions for the limitations encountered with the first prototype.

Table 2. First VENUS motor limitations and orientation for a more market oriented version.

VENUS version 1	Reason	Version 2
Torque and speed limitations (Power limitation)	Use of a 3-phase motor: ○ Closer to an automotive solution. ○ Wider market apart from VENUS.	**4** ~~or 5~~ **phase motor.** **Smaller motor niche.**
	Limited battery voltage and current in Azure Ford Transit.	Investigate **other battery limits and gearbox ratios**.
	Given gearbox ratio in Azure Ford Transit.	
	Keep performance and controllability uncertainty under control: not work in excessively saturated regimes.	~~Investigate~~ **Use higher saturation level, but not significantly higher.**
Peak torque limitation	Design optimized to maximize power density in S1 service.	**Optimize design from S2 service operation point of view**.
Torque ripple	Use of a 3-phase motor.	**4** ~~or 5~~ **phase motor**.
Weight	Thick housing and aluminium made rotor: to keep structural risk under control.	~~Composite made rotor.~~ **Reduce housing walls thickness.** **Remove non-active material.**
Motor diameter	Gearbox set by integration platform	**Explicitly selected gearbox integrated in motor.**
Winding	Complex winding process of C-cores (not divided in two parts to avoid more uncertainties regarding losses and mechanical design)	Split C-cores and winding the coils outside before inserting into C-core.
Cooling system design	Due to space limitations in Azure Ford Transit, water-jacket is at the end-caps not in contact with coils, which is much less efficient.	~~Water jacked at the perimeter.~~ ~~OR~~ **Air-cooled for smaller motor niche.**
	Due to prototyping needs (repeated assembly/disassembly), potting material is not considered, which makes heat transfer poorer.	~~Potting material for better cooling in proven well performing prototype.~~

Electromagnetic Design

For the electromagnetic design of VENUS motor 2 the tools developed within the project have been used: firstly the analytical/numerical tool (implemented in Matlab software) have been used to search for the motor configuration that best suits the performance specifications and geometry restrictions, and secondly the finite element based model (Flux software) to validate and refine the design.

The specifications for the design of VENUS motor 2 are shown in next table.

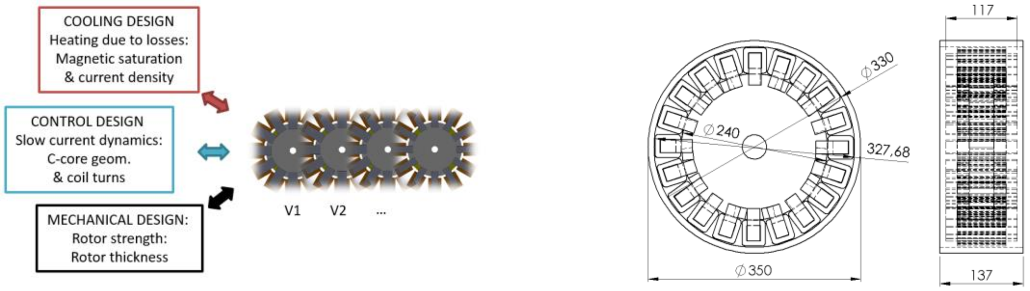
Table 3. Specifications for VENUS motor 2 design.

Parameter	Value	
Cooling	Air cooled	
Weight	< 37 kg	
Volume	Diameter 350 mm, Length 150 mm	
Voltage	48 Vdc	
Current	400 A	
Power, Torque	S1:	8 kW, 21 N·m
	S2-60s:	12 kW, > 33.5 N·m

The design process starts off by defining and exploring a big amount of motor designs with the help of the analytical/numerical design tool developed and implemented in Matlab during the project. The best motor configuration is sought considering 3, 4 5 and 6 phase motor configurations. Also, all possible stator pole and rotor pole combinations were explored. This implies the analysis and evaluation of several thousands of motor designs which is only possible if explicit analytical design tools like the ones developed are used.

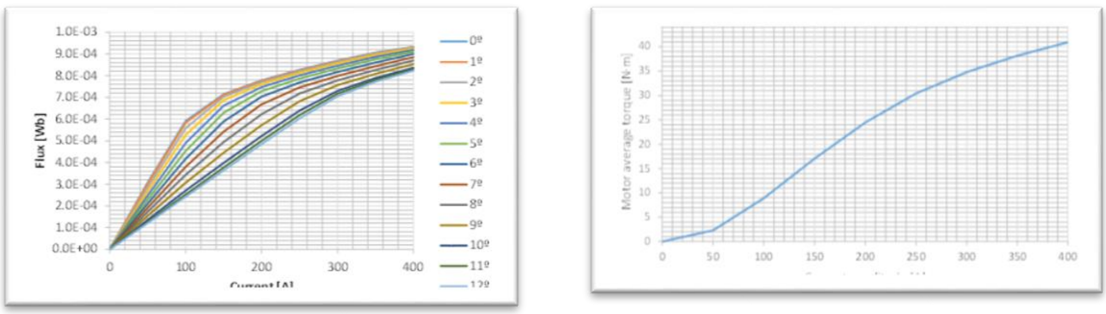
It was found that the best motor candidates were the 4-phase designs. Based on this a more refined search was carried out over 4-phase configurations while increasing a bit the motor saturation to 1.8-2.0 T to obtain the best motor candidate. It was found that the best results in terms of power density and torque density could be obtained with a 4 phase with motor with a 20/15 stator pole and rotor pole configuration.

Subsequent design steps were dedicated to design refinements in terms of geometrical and winding characteristics. This implied optimizing the adjustment of the slot size and the coil size, reducing the C-core coil column in order to reduce the motor diameter and carrying out multiple sensibility analysis to increase the torque (e.g. by varying the rotor thickness & rotor pole width).



(a) (b)

Figure 25. (a) Iterative process for VENUS design; (b) Electromagnetic design for new VENUS motor.



(a) (b)

Figure 26. Characteristic curves: (a) Flux linkage vs Current & position; (b) Average torque vs. Current.

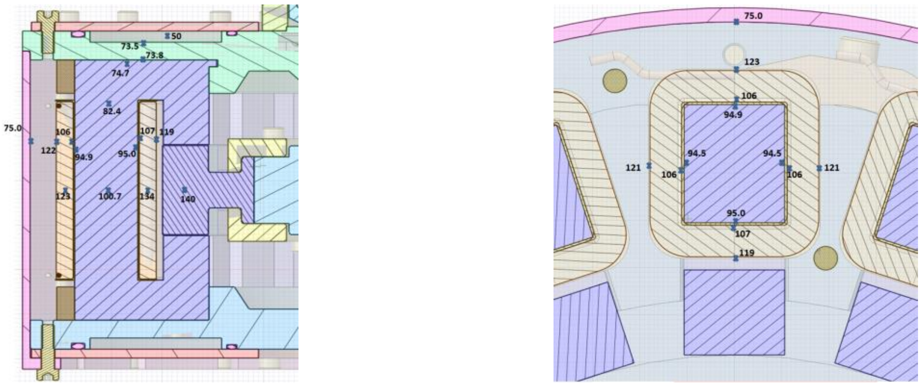
Thermal Design

As there is a trade-off between the cost and the machine performance, the thermal analysis results were used for a comparison in terms of electromagnetic, mechanical, reliability, machine lifetime and go forward with the most suitable selection for the second version of the VENUS motor. The thermal models developed in the project (lumped-parameter thermal network method for fast and accurate thermal calculation) have been used.

Air-cooled and water-cooled versions of the VENUS motor 2 have been analysed. The air-cooled was considered in the section so that VENUS motor 2 can compared effectively with the benchmark competition motor which is air-cooled as well. The option of water-cooled was considered in the thermal analysis as well as it provides higher cooling power relatively than air-cooled. This can improve the power density of VENUS motor 2. The power losses of the VENUS motor 2 for nominal and peak torque operations were used for thermal calculation.

Both cooling methods (i.e. air-cooled and water-cooled) demonstrate that they are capable of cooling the machine temperature effectively below the temperature limit of 180°C (insulation – H class) for nominal torque operation continuously and even S2 service for peak torque operation.

- For air-cooled design, fins are required on the endcap and housing to increase the heat transfer area for natural convection and thermal radiation. The fins design should provide at least the same surface area to that of proposed in the earlier sensitivity analysis.
- For air-cooled design, both natural convection and radiation dominate the heat dissipation processes from machine outer surfaces to the ambient. As radiation is strongly influenced by the emissivity, the machine outer surfaces need to be black-colour-painted or coated with dark material to give emissivity of 0.9 approximately.
- For water-cooled design, the machine is predominately cooled by the water cooling channels in the endcaps. The design fluid flow rate is 8 litre/min and thus lower flow rate may give less cooling. In reality, a fluid flow is driven by a differential pressure (generated by a pump) and restricted by system flow resistance. However, the cooling system of a vehicle consists of a number of components, e.g. power electronics, radiator, etc. Therefore, the actual flow rate must be further analysed in system level analysis.
- By comparing the air-cooled design and water-cooled design, the water-cooled design provide lower maximum coil temperature, i.e. 134°C versus 173°C. Hence, the water-cooled design provides significant room for electromagnetic performance improvement.
- The path from the stator core to the endcap/housing path is the primary heat transfer path (conduction) where the thermal resistance have to be minimal. The internal circulating air aids the heat flow from coils/rotor poles to the outer endcap and housing. The convective heat transfer is estimated using heat transfer correlations developed using Computational Fluid Dynamic (CFD) method.
- The thermal capacitance of VENUS motor 2 is rather large; the machine temperatures are low for air-cooled and water-cooled design for S2 service operation point.



(a) (b)

Figure 27. (a) Temperature distribution in axial cross section; (b) Temperature distribution in radial cross section.

Mechanical Design

A new mechanical design of the VENUS motor 2 has been carried out focusing on cost reduction and easy manufacturing. Additionally several mechanical calculations have been carried out in order to check that the designed electrical machine does not have any mechanical risk. Three mechanical risks will be considered in the calculations:

1) Structural resistance of the rotor.
2) Lateral stiffness of the rotor in the rotor poles. The objective of this calculation is to check that the negative stiffness of the rotor due to magnetic forces is lower than the lateral stiffness in the rotor poles. As result of the calculation, a minimum width of the rotor is calculated in order to avoid the risk of collision between the rotor and stator due to deformation.
3) Dynamic behaviour of the rotor. Natural frequencies of the rotor will be computed in order to check that there will not be any vibration problem in the rotor during operation.

To check the dynamic stability of the system, a finite element model has been built and a natural frequency analysis has been performed. Beam elements have been used to model the shaft and shell elements have been used to model the rotor.

Also, in addition to the typical rotordynamic problems, as each actuator can generate an axial force due placement tolerances, axial modes in the rotor have to be considered. In fact, each actuator acts in the shaft five times in each turn, so rotordynamic problems are checked at 1x as usual, and axial modes are checked at 5x. As the maximum speed is 10,000 rpm, flexure modes should be far upper than 167 Hz, and axial modes should be over 833 Hz.

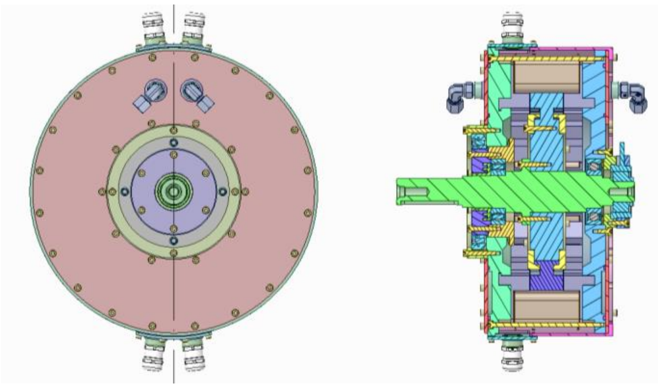


Figure 28. Internal cross section of VENUS motor 2

Industrialization Analysis

During the analysis of exploitation possibilities of the VENUS motor, it soon arose MONDRAGON Automocion is seriously considering the growth potential for next years of the L7 & N1 vehicle category market. Polaris (US company) is a clear example of this growth which is already taking place. Polaris produces special vehicles (off-road vehicles, snowmobiles, motorcycles) as well as small L6, L7 and N1 vehicles. They have recently acquired GEM, Goupil, Aixam Mega (L6, L7, N1 manufacturers) and between 2010 and 2014, their total sales increased from 1,991M$ to 4,480M$. This is twice the sales of MONDRAGON Automocion, thus the strategic movement MONDRAGON is making towards this segment.

As a first entry to the market, the planned strategy is to introduce the VENUS motor in the vehicles that MONDRAGON is currently producing. A competitor benchmark was carried out and Letrika motor was identified as a reference motor model for low powered motors in L-category vehicles. At present Comarth (member of the MONDRAGON Group) has decided to equip their future vehicles with a Letrika Iskra AMV7118 motor (also Renault Twizy 80's motor) and a Comex gearbox. The plan is to substitute such motor with an evolved version of the VENUS prototype. This would be a smaller, less powered motor oriented to L-category vehicles, with a strong focus on cost reduction. This strategy will allow testing many motor units in vehicles operating under real working conditions before offering it to other customers. It should be noted that the Letrika Iskra motor sets a strong cost target mark, thus the need of a strong industrialization analysis in order to bring costs down to a comparable level.

This section connects the developed VENUS motor technology with its industrialization. Based on the requirements set by the design team, VENUS motor attributes have been defined such as performance specs and part drawings for a prototype. However, in order to effectively introduce the technology in the market further work is needed in terms of design refinement for cost reduction, adaptation to most suitable target market, production requirements, etc. and essentially motor manufacturing definition at the smallest cost while ensuring product quality. The work covered includes the necessary decisions at initial conception and design level in order to orient the work towards a sensible (eventually marketable) outcome

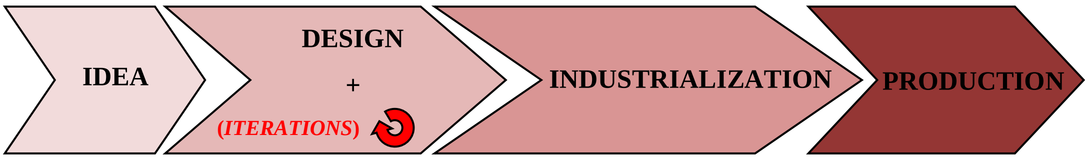


Figure 29. Steps from idea until a marketable product.

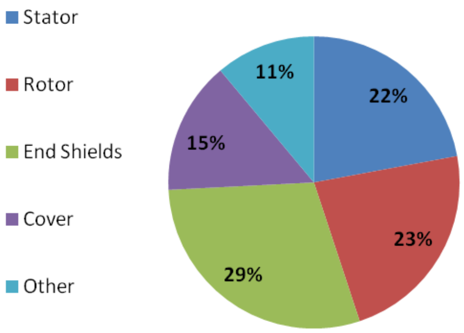
A costs analysis for the new motor design has been carried out. The calculation of the main time of processing is based on a high performance CNC machining centre. The volume is also essential to estimate costs. It was assumed that the volume is between 10,000 and approx. 50,000 motors per year.

The maximum possible cross section was used to determine the copper input in order to reduce copper losses as much as possible. For the raw materials steel and aluminium costs were assumed: structural steel approx. 400 €/t, aluminium approx. 1400 €/t. A surcharge for alloying has been added to the material costs for higher grade steel and aluminium alloys. According to the cost estimations, the total motor cost is shown in next table.

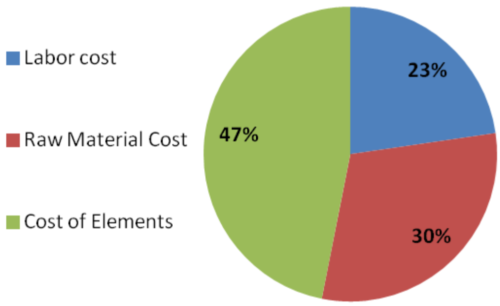
Table 4. Total motor cost.

MOTOR		
	Water-cooled Cost [€]	Air-cooled Cost [€]
Stator active material	75.70	75.70
Rotor	77.98	77.98
End shields	123.73	100.32
Covers	50.22	50.22
Screws and mounting	64.90	58.10
Motor production cost	392.53	362.32

It should be noted that this is a good starting ground for such a novel motor topology as there are several manufacturing solutions ad-hoc thought for the new motor and it is expected that as the process settles the costs can be brought down even further. The following figure provides a visual representation of the cost distribution among the motor elements:



(a)



(b)

Figure 30. (a) Cost comparison per element for the new VENUS motor; (b) cost comparison between labour, raw material and purchase of elements.

As it can be observed, the main motor parts contributing to the cost are the active parts (the rotor and the stator) and the end-shields. Also, labour costs are less than a 25% of the total costs for the manufacturing plan put in place for the new VENUS motor design. From the motor manufacturer's perspective, further cost reductions would be oriented to getting lower quotations from suppliers for the different elements that are being used in the motor.

According to these cost estimates there would be a significant gain in both the motor performance and its cost respect to the motor selected for inclusion in upcoming Mondragon vehicles.

Industrial Manufacturing

A schematic summary of the manufacturing process considering manufacturing of active stator components, manufacturing of active rotor components and rotor and complete assembly would be:

<u>Manufacturing of active stator components</u>:

- Punching of C-cores by progressive dies
- Lamination gluing (Glulock method)
- C-core insert-moulding with plastic material reinforced by glass beads
- Conductor fabrication: stranded parallel wires with individual varnish layers

- C-core winding
- Insulating sleeve pushing over the lead-in conductors
- Impregnation of windings

Manufacturing of active rotor components and rotor:

- Punching of rotor laminations by progressive dies
- Lamination gluing (Glulock method)
- Casting of rotor disc
- Rotor disc machining (first clamping): holders for electrical steel blocks
- Rotor disc machining (second clamping): turning and boring
- Insertion of rotor blocks (adhesive fed) in disc: fixed by screwed rings
- Shaft machining from thick-walled steel tube: fine turning of bearing seats
- Joining of rotor disc and shaft by screws
- Drive end side bearing mounting: pressed with inner ring and secured by labyrinth disc
- Casting of outer standing labyrinth ring
- Machining of outer standing labyrinth ring (turning)
- Fixing of outer ring in fixed bearing by screwing sliding ring and outer standing labyrinth ring
- Pressing of non-drive end bearing on shaft

Complete assembly:

- Casting of end-shield
- Machining of end-shield
- Rotor insertion in end-shield (not fixed yet)
- Insertion of wound C-cores over rotor
- Air-gap verification and adjustment by thrust ring and fixed by locking ring
- Fixing of C-cores by fixing brackets (injection of epoxy resin adhesive from outside if required)
- Insertion of non-drive side end-shield
- Fixing of bearing cover on non-drive end side by screws (pre-stressing of loose bearing at outer ring by cup spring)
- Position sensor mounting
- Mounting of cooling covers, o-rings and sealing rings; fixing by screws
- Coil connection
- Casting of hood by lost-form method
- Insertion of hood (sealed by rubber cords in the edges)
- Insertion of cable bushing and fixing by screws

The manufacturing activities that will be carried out in-house and the activities that will be outsourced have been defined. Additionally the working times required by each-part have been calculated. This is used as a basis for defining the number of machines necessary to produce all the parts. A 50,000 motor/year production is considered. It is assumed that 1700 h/year shifts will be implemented in the manufacturing plant with 3 shifts per day, so that the utilization of the machines is maximized. Depending on the activity an efficiency of each process has been considered so that down-times can be covered. In general a higher efficiency has been considered for highly automated activities while a lesser efficiency has been attributed to more manual operations.

The above data serves as a basis for defining a conceptual manufacturing plant as well as the necessary direct operators to produce the required motor volume (50,000 motors/year). The number of work-stations and number of employees necessary for production of the new VENUS motor has been estimated:

Table 5. Work-stations and employees.

Work-station	Total Required Operators	Required Operators (per working shift)
Winder Machines Impregnating Machine	3	1
Post-winding Testing	3	1
CNC Machining Center #1 (shaft)	3	1
CNC Machining Center #2 (disk)	3	1
CNC Machining Center #3 (side plates and locating bearing units)	3	1
CNC Machining Center #4 (front/rear plates)	3	1
CNC Machining Center #5 (retainer plates)	3	1
Motor Assembly	49	16
Motor Connecting and Testing	11	4
TOTAL	**81**	**27**

Suppliers have been also sought based on proximity (suppliers which are geographically close are preferred instead of distant suppliers) and previous relationship and performance (product quality and supply reliability). For example the insulation pieces for the C-cores have to be mounted directly onto them; therefore the selected supplier has to have experience in this process (e.g. PVS). While some elements can be purchased from several vendors (e.g. bearings from SKF or FAG), there are several supply sources that are critical for the VENUS motor. Among them the most important players in the VENUS supply chain would be: Kienle + Spiess for the laminations, Ederfil for the stranded wires and Fagor Ederlan as casting supplier.

Necessary investments have been also analyzed. The considered machine costs represent a band width with a mean value. Depending on the supplier a quotation of 800,000 € may vary from 600,000 € to 1,100,000 €. On the other hand it is not worth to invest in a punching machine for the C-cores for example; it is a typical purchase part as well as the cast bodies for the end-shields. However direct tooling costs for punched and cast parts should be considered, which would be around 1,000,000 €. Additionally it would be necessary to budget a 30% extra cost approximately on top of the machine costs for ad-hoc devices and tools to be incorporated in the CNC machining centers. The following table summarizes the investment required on machinery for the production of the new VENUS motor.

Table 6. Investment required on machinery for new VENUS motor production.

Machine Type	Investment [€]
Winder	2 x 300,000
Impregnating system	1 x 300,000
CNC machining center	5 x 800,000
Devices and tools for CNC machining center	5 x 240,000
Direct tooling costs for punched and cast parts	1,000,000
TOTAL	7,100,000

A total of 7,100,000 € initial investment in machinery is considered to be necessary. Depending on the selected machinery supplier(s) and the corresponding negotiation process the investment range could oscillate between 5,800,000 € and 8,400,000 €.

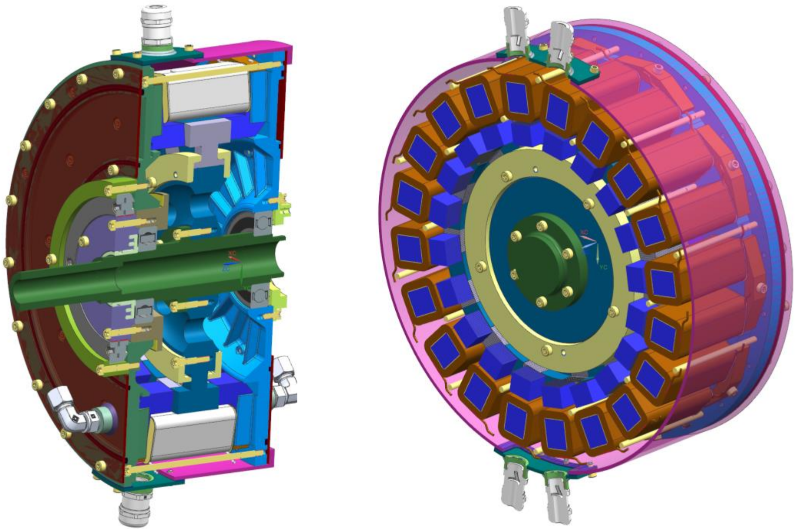


Figure 31. Industrializable VENUS version 2 motor.

:: Final Results and their Potential Impact and Use

In the next pages, the main exploitable results are described:

- VENUS motor, a magnet-free axial-flux reluctance motor for L-category vehicles. This product provides similar performance/price ratio compared to other motors in the market, but without rare-earth magnets in the motor, meaning that no supply shortage will ever occur in key components during mass production. A comprehensive Business Plan has been developed to analyse the exploitability of the product in different scenarios.
- Power electronics for VENUS motors. At the end of the VENUS project, a prototype near to the final product has been achieved. This inverter is an easy product to manufacture, both mechanically and electronically. With small configuration changes, the inverter can provide the highest power per litre in the market: 19 kW/l (320 kW in 16.8 litres), suitable for other type of motors, not only for SR motors. This constitutes a platform for different configuration of inverters providing a high range of different applications.
- VENUS driven EV-s. The market of electric quadricycles and small electric vehicles is going to grow in a very significant way in the next decade according to most forecast analyses. VENUS project results are particularly interesting for the market of low-powered electric vehicles and the possibilities for manufacturing VENUS driven EV-s have been examined by the industrial partners of the project.
- Methods/tools for design of VENUS motors. The new motor configurations require new tools to allow their design: specific electromagnetic formulation, analytical/numerical programs to rapidly evaluate the performance of one particular design, etc. These tools have been generated, tested and used during VENUS project and can be exploited by the R&D members of the project.
- Methods/tools for thermal analysis of VENUS motors. The special topology of VENUS motor requires new tools for thermal analysis that have been developed in the project. These tools could be extended and applied to other axial-flux motor configurations.

Exploitable Result 1: VENUS motors

The first exploitable result is the main outcome of the project, i.e. the VENUS motor: a magnet-free axial-flux reluctance motor for automotive applications.

Innovativeness introduced compared to already existing Products/Services

In the VENUS project, two types of motors were analysed: a SR motor and a PMSynR motor. The goal of the developed designs was to improve performance and power density of these motor options (by using an axial-flux configuration). After comparison and discussion, the SR motor was chosen over the PMSynR motor due to the following reasons: i) SR motor is easier to manufacture; ii) PMSynR motor is very difficult to take to series production; iii) SR motor offers the possibility of dual coil and further improvements.

The final version of VENUS has three important advantages compared to its competition:

1. It can provide similar performance at a competitive price.
2. It can provide similar performance at a somewhat reduced size (an important feature to simplify packaging issues in the development of vehicles).
3. The absence of rare-earth magnets in the motor means that no supply shortage will ever occur in key components during mass production.

Market Trends/Public Acceptance

One of the main problems in the HEV-EV motor market is the dependence on rare-earth materials. This causes magnet prices (and consequently motor prices) to oscillate when exporting policies vary in rare-earths producing countries. Even if there are already some motors (IMs) that do not employ rare-earths, they have some disadvantages that make interesting the development of new motors free of rare-earths.

As far as current automotive solutions go, PM brushless motors and IMs are currently the favourites of car manufacturers. SRM is an option that is slowly appearing, particularly in academia. While they have some inherent disadvantages such as EMIs and torque ripple, a design that overcomes them has the potential to become a winner in the automotive motor market.

Considering the limitations and advantages of VENUS motor, the main potential customers are:

- L-category vehicle manufacturers. Potential customers in this target market include GEM, Goupil, Alkè, Ligier, Tazzari, Volteis, Micro-Vett, Aixam and Reva. Additionally, most large automotive OEMs are currently developing or will soon start developing many models in this category. For an initial entry to the market there is also the possibility of supplying motors to MONDRAGON group, either through Comarth manufacturer (50% owned by Fagor Ederlan) or through another company that may be established by MONDRAGON in the future.
- Niche & special purpose vehicle manufacturers. There is a growing market of electric vehicles for specific purposes. Several examples can be found in the postal service (e.g. Paxster), all-terrain vehicles (e.g. Polaris), hotel-resort vehicles (e.g. MotoEV) and a wide range of other devices, like in-plant machines, milk-delivery floats, etc.
- Large automotive manufacturers. Most compact versions in M-category vehicles, like small City Cars or Japanese Kei Cars, require motor performance levels similar to the evolved version of VENUS. In addition, new small OEMs, like Tazzari, employ 15 kW motors in their M-category automobiles.

Competitors

Getting the VENUS motor into the EV motor market is a challenge due to the competency of well-established motors manufacturers, like ZF, Siemens, Toshiba, Remy, Bosch, Letrika, Hohomer, Curtis, etc.

In order to compete with these players using relatively well-known motor topologies, high purchasing quantities are needed (i.e. high volume production). Competing only in terms of price is in general very difficult due to the fact that the main costs of a motor are currently material costs. Therefore, an advanced design like VENUS is the suitable business path.

Feasibility analysis

VENUS motor production cost is estimated at 362 euros (air-cooled version) or 392 euros (liquid-cooled version) for 10,000 units/year. This estimation includes material costs and assembly costs (counting as well the depreciation of the investments).

Under the scrutiny of a comprehensive Business Plan, three scenarios are contemplated:

- OPTIMISTIC Scenario. In this Scenario, motor sales start at good level and continue growing steadily in five years. Average price per unit provides significant margin and does not require reductions in five years while production costs decrease 2% per year as a result of the gained experience in the company.

- REALISTIC Scenario.In this Scenario, motor sales start at a moderate level and grow at slower rate in five years. Average price per unit is lower than in previous Scenario and is stable during five years. Production costs decrease 2% per year.
- PESSIMISTIC Scenario. In this Scenario, motor sales start at relatively low level and grow up at an even slower rate in five years. Average price per unit is lower and decreases steadily in five years due to strong competence. On the other hand production costs do not decrease during this period.

The main details and conclusions from this analysis are being studied by MONDRAGON Automocion in order evaluate the cost to enter into the electric motor business and potential outcomes of the initiative. MONDRAGON Automocion is currently manufacturing components for internal combustion engines and, if forecasts are accurate, this current business will be at risk in the future. Therefore the strong interest of the group to enter into the electric motor business, especially if we consider the growth potential in this sector.

Exploitable Result 2: Power electronics for VENUS motors

While price and being free of rare-earths the main advantages of SRM-s, a proper companion inverter is still necessary. Therefore the marketable product is a powertrain pack (motor + inverter) and apart from motor manufacturers, inverter manufacturers will also have a business opportunity.

The inverter developed during this project can also be sold alone without any motor and also can be adapted easily for other type of motors enlarging in this way the objective market.

Description of the Result

At the end of the VENUS project, a prototype near of the final product has been achieved. This inverter is an easy product to manufacture, both mechanically and electronically. Anyway, in future projects with customers, mechanical and electronic customization tasks will be necessary to answer to customer requirements.

Figure 32. VENUS Inverter.

This inverter consists basically of 7 parts:

- Control Board: is the part in charge of controlling the system.
- Interface Board: the function of this board is to drive two Driver Boards (and therefore two IGBT Modules) from just one Control Board. There are some jumpers that have been used for testing purposes in the development phase but will be removed in the final product.
- Driver Board: the Driver Board is the part of the inverter that drives the IGBTs controlling the motor rotation.
- IGBT Module: these are the elements that provide the power to the motor.

- Cooling system: aluminium component to provide the water cooling to the IGBT Modules. Screwed directly to the IGBT Module provides direct cooling for pin-fin base plate
- DC-Link Capacitor: is the interface between the HV battery and the system. It is specially needed when high currents during short times are required, as the HV battery cannot provide such currents often (battery life drops with each cycle).
- Housing: a 3 mm aluminium housing box has been manufactured, except in the base (4mm). It also includes the connections to the rest of the system (HV battery, LV battery, CAN of the vehicle and the motor).
- Control algorithms and software: Autosar, ISO26262, applications, functionalities, traction and adherence control, energy saving and efficiency.

Regarding the manufacturing process for this inverter, the 3 boards (Control Board, Interface Board and Driver Board) manufacturing processes will be implemented within Fagor Electronica S. Coop premises.

In the case of the IGBT Module and the DC-Link Capacitors, they are commercial components.

The aluminium heatsink will be provided by Fagor Electronica's current heatsink suppliers.

Finally, final assembly and test process will be performed, again in Fagor Electronica S.Coop premises. In this process the assembly of the different elements will be completed. Cables, copper strips and final elements are added manually to finish the assembly.

Innovativeness introduced compared to already existing Products/Services

This inverter, with small configuration changes, can provide the highest power per litre in the market: 19 kW/l (320 kW in 16.8 litres) suitable for other type of motors, not only for SR motors. This constitutes a platform for different configuration of inverters providing a high range of different applications.

Another important point is the software architecture used in the Inverter. AUTOSAR (Automotive Open System Architecture) standard software is used in the Inverter, which is a very important point in automotive applications.

Exploitable Result 3: VENUS driven EV-s

Once the VENUS motors reach the automotive market, vehicles using these new generation motors (or special versions of them) are another business opportunity.

The market of electric quadricycles and small electric vehicles is going to grow in a very significant way in the next decade according to most forecast analyses. For that reason, MONDRAGON Automocion developed a new business in this area: the design & manufacturing of electric vehicles. To increase its penetration in the market, one of the companies of MONDRAGON Automocion bought in 2013 50% of Comarth, a company that manufactures and sells L6, L7 & N1 electric vehicles (see next figure). Apart from this company, MONDRAGON Automocion is currently planning other actions to try to take advantage in this sector for the next future.

Figure 33. MONDRAGON - Comarth vehicles in the market.

VENUS project results are particularly interesting for the market of low-powered electric vehicles. The evolved version of VENUS motor is very well suited for this application because of its reduced size and the potential price/performance ratio that it has because of its particular topology. The planned strategy is to introduce the VENUS motor in Comarth vehicles and/or in other vehicles that MONDRAGON Automoción may be producing in the future. As it has been shown in D6.3, this motor can compete with the current reference for low-powered vehicles, the Letrika Iskra AMV7118. On the other hand, the absence of rare-earth magnets in the motor implies that no supply shortage will ever occur in key components, so this will also be an advantage for these vehicles.

Additionally, the properties of VENUS motor, together with the capabilities in chassis components of MONDRAGON Automocion, means that a Universal Rolling Platform could be developed in the future as a new business opportunity. This platform could be sold to multiple quadricycle manufacturers to achieve a cost reduction for them through an economy of scale production. The launch of this new business is also under study in MONDRAGON Automocion, although a decision has not been taken yet.

<u>Exploitable Result 4: Methods/tools for design of VENUS motors</u>

In order to design alternative versions of the VENUS motor(s), special design methodologies that have been developed in the project would be helpful. This knowledge can be exploited in consultancy projects or even further developed to be packaged in software form.

Description of the result

The new motor configurations (new axial-flux switched reluctance motor) require new tools to allow their design: development of specific electromagnetic formulation, analytical/numerical programs to rapidly evaluate the performance of one particular design, etc. These tools have been generated, tested and used during the VENUS project.

In particular these electromagnetic design tools include:

- Several analytical/numerical programs implemented in Matlab code:
  1. Axial-flux SR motor predesign program, which is based on an algorithm that creates multiple motor designs exploring different configurations (number of phases and pole combinations) and geometries, and finally selects the motor designs that fulfil the specifications.
  2. Axial-flux SR motor calculation program, which estimates the electromagnetic performance of the motor
  3. Axial-flux SR motor design optimization programs with several functions, such as make sensibility analysis of motor parameters and show the effect in the performance.

- The finite-element based model of the AFSR motor implemented in Flux software, parametrized so that it can be updated to every geometry can be easily which is used to verify the results estimated by the analytical tools, and for further refinements and optimizations.
- Excel templates to calculate the motor performance from the results got by the partial finite-element model:

Apart from the tangible design tools mentioned above, improved know-how related to the design of electric motors with the new axial-flux switched reluctance topology as well as on SR motors in general has been gathered during the project. This includes consolidated knowledge for electric drive dimensioning assessment based on functional requirements.

Innovativeness introduced compared to already existing services and Competitors

Being this a totally new motor configuration, these are the only available specifically developed design tools. However for other motor topologies that are more widely known/applied the available options are multiple. In the case of switched reluctance motors which fall closest to the topology developed in the VENUS project, the main design tools available in the market are general purpose finite-element method based software packages.

It should be noted that some manufacturers could opt for these kind of rough/generic SR motor calculation tools to pursue designs of the new topology, even if they are not suited for this particular configuration. The benefits and drawbacks of the VENUS specific design tool solution as compared to generic solution are (i) fast computation and (ii) design flexibility. These are key features of the implemented electromagnetic design tools, which are of utmost interest to find optimum designs for each application and constraints.

Exploitable Result 5: Methods/tools for thermal analysis of VENUS motors

The special configuration used in VENUS requires new tools for thermal analysis that have been developed in the project. These tools could be extended and applied to other axial-flux motor configurations.

Description of the result

The new motor configurations require new tools to allow their thermal design: development of specific thermal models that can be quickly evaluated during the design stage of a new motor. These tools have been generated, tested and used during the VENUS project.

The thermal modelling tool of the AFSR motor built in Portunus software, and the new thermal modelling tool is fully parameterised with Excel VBA so that the Portunus thermal model can be updated easily and quickly in terms of machine geometry, materials, heat sources and cooling to estimate the steady state and thermal transient performance for a design. The existing thermal models are restricted to totally enclosed design, liquid cooled by cooling channels in the endcap, natural and forced convection cooling from the outer housing. However, the thermal modelling tool can be further extended its capabilities to other cooling options easily.

Due to the topology of new axial-flux switched reluctance machine, the knowledge gathered during the project improves know-how related to the thermal design of similar machine topology that are manufacturable and implementable especially for EV-s.

Both thermal modelling tool and knowledge can be used as expertise benchmark for similar consultancy projects.

Innovativeness introduced compared to already existing services and Competitors

As the motor configuration is new, these are the only available specifically developed thermal models based on lumped parameter thermal network method. When compared to the thermal models based on the numerical methods, the thermal models of AFSM motor allows machine designer to effectively analyse the thermal performance of a switched reluctance motor design that has similar topology to that of in the VENUS project in the design stage. This could considerably save the cost and time required from design to production. Also, the thermal design tool provides machine designers insight into thermal constraints and way to achieve the optimum designs.

The experience gained during the VENUS project helps to guide thermal design in projects of similar motor configuration.

:: Address of Project's Public Website

www.venusmotorproject.eu