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NGHVT –
Next Generation High Voltage Topology

Research programme: FFI - Elektronik, mjukvara och kommunikation.

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1. Summary

Within this project, NGHVT, have components and system for the electric drive train in an electrified vehicle been studied, focusing on the power electronic components as well as the electric machine and the high-voltage system (400V) originating from the hv battery. Model building of these components as well as modelling on system level has been important activities with verification towards existing prototypes/products. Method development has been a central part, for instance regarding the determination of the electric machine circuit equivalent parameters, where the main machine design program Maxwell was controlled by a supervisory software in order to get a flexible and efficient calculation flow. The contact with the research front as well as the industrialization front has been secured through a large numbers of supplier visits as well as participation on important industrial and academic conferences. Furthermore have courses with the main calculation software supplier been arranged, which apart from the instructions also gave a possibility to demonstrate for the supplier the problems existing in the multiphycics simulations. This has lead to that the need of that the software should be able to cope with certain calculation problems have been added to the to-do-list for upcoming software program version.

Thoughts about platform adaptation as well as commercialization has been important aspects apart from the pure technical ones such as power density, efficiency and functionality, and of course, cost. Based on new techniques such as new semiconductor materials, power electronic and machine topologies, new solutions have been investigated and their performances determined.

To sum up, the project has resulted in an improved competence regarding the high voltage electrical system as well as its connected power electronic components and the electrical machines. Apart from the direct results, the project has contributed to strengthen the position in relation to the suppliers. Using results from the project, the possibilities of new technology has been shown to the suppliers and driven them to take up the technical possibilities that has been developed within the NGHVT project.

2. Background

Volvo Car Group (VCG) embraces a vision to enable customers to buy and use premium cars with the best possible "environmental consience". The term premium cars concerns cars with a high level of comfort and driving experience. Environmental conscience refers specifically to reduced CO_2-emissions and in general a low environmental impact.

One important step towards our goals is to identify commercially viable and industrialised system solutions that fulfil technical requirements on vehicle electrification. Of special interest are units capable of fulfilling demands on mass production, cost and durability that complies with automotive component specifications. Electrification, in this context, is the use of electrical components and systems for vehicle propulsion and related grid charging.

Examples of such components are electric machines, power electronics and batteries, operating at a voltage around 400 V.

Efficient procurement of related components involves an active role in the collaboration with suppliers and development partners. A key to successful participation in the process, both in internal an external development, is a strengthened competence base in corresponding scientific fields. Presently, this is done by carrying out three projects partly financed by Vinnova. One of them is NGHVT, which is focused on more effective power electronics and electric machines in passenger cars.

3. Purpose

The main purpose of the project is to prepare for the next generation of components that are part of a hybrid electric vehicle powertrain. It includes the establishment of verified component models like electric machines and converters, but also batteries as a part of the electric power system on board. Apart from the technical properties, like efficiency, functionality and performance, there are further interesting topics to be investigated. Examples of such topics are platform compatibility and commesialisation of respective component.

4. Objective

The main activities of the project are:

- Technical survey.
- Functionality and design of the electric traction power system.
- Investigation of the electric drive system performance, specification, thermal properties and noise generation.
- Alternative design of on-board chargers and DC/DC converters.

5. Work package 1 – Technology survey.

Several conferences were attended. Both research oriented and more industrial focused events. On some occations, VCC presented results from the ongoing work. Table 1 summarises the activities on external monitoring.

Table 1: Activities on external monitoring.

Conference/activity.	**Date and place.**	**Notes.**
Supplier visits and fares.	2011-2012 Göteborg, Germany.	
SiCPEAW.	2013, 10-12 june, Stockholm.	SiC technology is getting more mature. The issue of durability related to the gate seems to be solved. Module packaging is still difficult to industrialise.
Advanced E-Motor Technology.	2013, 18 – 20 februari, Nürnberg, Germany.	Prototype inverters equipped with SiC transistors are available. One was on display. Integrerated drive systems, combining inverter and electric machine, are expected in a not too distant future.
Swedish Hybrid Centre, annual conference.	2013, Göteborg.	Results from VCC´s project activities were presented. The name of the presentation: ”Utmaningar för högtemperatur SiC i Fordon”.
EPE ’14 ECCE, The 16th European Conference on Power Electronics and Applications.	2014, 26 -28 august, Lappeenranta, Finland.	PCB integration is getting more common. Multi level inverters using cascaded H-bridges are becoming popular in power system applications.
ICEM XXI, International Conference on Electrical Machines.	2014, 2 – 5 September, Berlin, Germany.	Double rotor machines are popular research objects. Machines with fractional slot pitch 10/12 poles/slots are also subject to increased research. Switched reluctance machines are getting more attention. Thermal modeling, efficiency analysis and fault tolerant systems are also popular, as usual.
Supplier visits: Microsemi, Rohm, Cree, Infineon.	2014, 2015 Göteborg.	Packaging is a common problem. Demands on current levels used by automotive industry seems to cause problems. The specific chip properties are usually proprietary.
SiCPEAW.	2015, 26-28 june, Stockholm.	It is believed that another five years will pass before commercialisation has its brake-through. Material defects in the substrate is no longer an issue. Parallell connected chips is troublesome. Chip size 1 cm^2 are functioning.

		The module packaging problem still remains, as well as the durability issue.
EPE '15 ECCE, The 17th European Conference on Power Electronics and Applications.	September 2015, Genéve	A prototype converter with GaN transistors was shown; a 1.6 kW dc/dc. A SiC module rated 1200 V/800 A, which is sufficient for many car applications was presented by Mitsubishi.

Further studies of competitor vehicles were conducted within the workpackage, comparing the power electric system architecture and Noise and Vibration Harshness (NVH). Summarising the workpackage, it can be concluded that the NGHVT related activities have been well synchronised with the latest progress in research and industrialisation.

6. Work package 2 – System analysis.

This work package treats how various components affect and is affected by the voltage on the DC-link. Thus, the power quality of the dc-link is generally in focus. The activities made were

- Studies of how the voltage on the dc-link were affected by the various components connected to the dc-link through their current injection/consumption. Model building was an important task in the work effort.
- Studies of various combinations of components and voltages, below such a study will be presented.
- Battery modelling. Usually the inductance in the battery cell is not very much in focus, however, due to the high-frequency current and voltage pulses in the system, it was needed to also include the battery inductance.

Extended driving range – increasing the number of cells

The main components for the propulsion of an electrified vehicle can be seen in Figure 1. In case of a hybrid-electrical vehicle, also one additional electric machine converter system is added, placed next to the ICE, with a slightly smaller size, and also connected to the main battery.

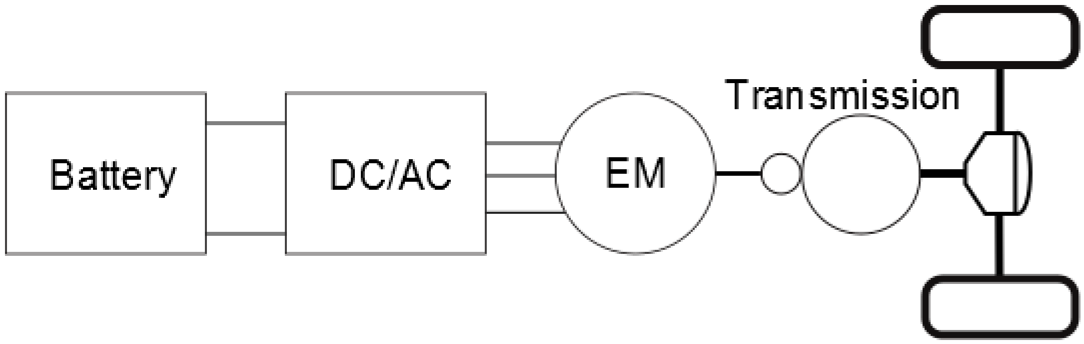


Figure 1: Main circuit components for electric propulsion of a vehicle. Battery, converter, with its dc-link capacitor and 6 transistors, gear and wheel pair.

In order to obtain the best cost effectiveness it is important that all components are utilized to their full extent, i.e. that we shall not exceed any voltage or current limits, but on the other hand we want to be as close to the limits as possible, otherwise the costs will be high. If a 400 V battery system is considered, i.e. 400 V at full charge, then we want to adjust our converter and electric machine for this voltage. For the converter 650 V transistors are suitable for a 400 V dc-voltage, in order to ensure that the transistors are not damaged by high voltage spikes originating from the switching of the transistors, both instantaneously as well as during the whole life-time of the system. Let us use a safety margin of 100 V in this example and that leaves us room for 150 V spikes caused by the switchings.

In figure 2 the vehicle is operating followig a certain drive cycle, and three voltages can be observed here. The battery voltage, the blue one, is what exist on the cable between the inverter and the battery. For the red one, the switching transients, depicted as green are also present. Thanks to the dc link capacitor, as well as an EMI-filter on the dc connection of the inverter, only very small amount of swtiching transients are emitted out towards the 400 V dc bus.

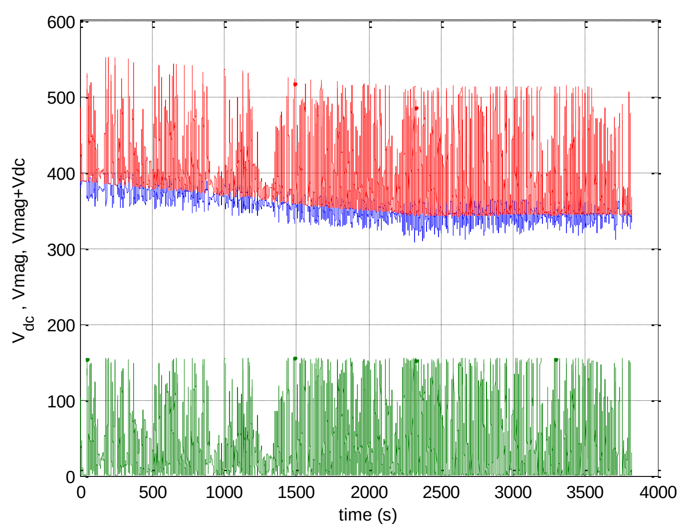


Figure 2: Battery voltage, blue, dc voltage in the inverter, red, size of switching transients, green, for the drive cycle operation.

It can be observed that the dc-link voltage in the converter now reaches 550 V, and thus we have found a good economic balancing with the voltage being as close to the limit as possible.

A battery is composed by a number of cells that have a certain Ah-strength and the commonly used Li-Ion technology, has typically a 4V/cell voltage. 400 V can thus be achieved by putting 100 cells in series. Unfortunately is the vehicle market never continuously stable, so changes are always needed to be done. A typical request can be to reuse the electrical system in a more heavy vehicle without too much changes, while keeping the electrical range constant. Easy would have been to just buy cells with a slightly larger Ah capacity, in order to compensate for the shorter driving range that follows when propelling a heavier vehicle. Unfortunately the battery cell suppliers typically has a limited number of Ah selections, moreover by using different cell variants, the benefits of large scale production is reduced, and price would increase. A simple way could then be to add some extra cells in series, however, then the dc-voltage is increased. In figure 3 an example is given where the driving range has been increased with 12 % through the addition of additional cells. It can be observed that now the upper limit of 550 V is frequently exceeded which means that something needs to be done in order to limit these events.

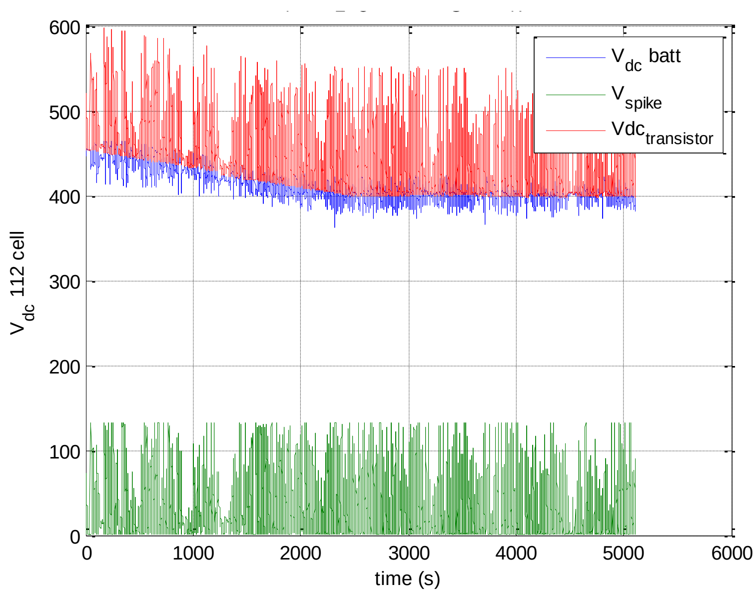


Figure 3: Battery voltage, blue, dc voltage in the inverter, red, size of switching transients, green, for the drive cycle operation, with 15 % more battery cells.

A solution to overcome this problem would be to reduce the speed of the switchings, however, this will lead to increased losses in the IGBT's. That means that the maximum allowed current level in the transistors has to be reduced in order to not overheat the transistors, i.e use derating. There are two consequences of derating of the current ability. First, the propulsion torque/power is lowered and during regeneration we have to limit the maximum power that can be recycled back to the battery. In figure 4, the battery voltage during driving and regeneration can be noted. Due to the battery resistance the voltage is increased even more due to the regeneration, and accordingly, it is in this operation where the voltage problem will be as largest.

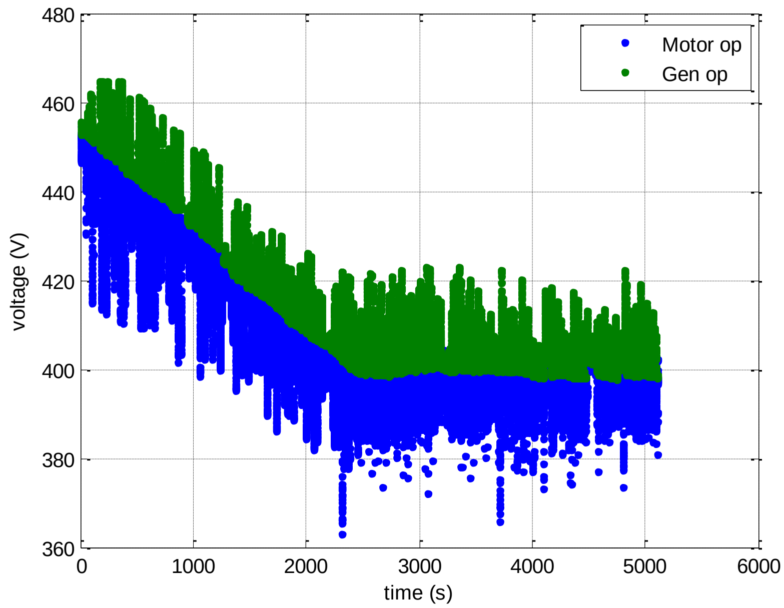


Figure 4: Battery voltage for a drive cycle operation, with 15 % more battery cells.

An example of a derating event is shown in Figure 5. This was the worst situation that occurred during the drive cycle. The blue line shows the derated case and the green shows what can be achieved due to the derating caused by the increased number of battery cells.

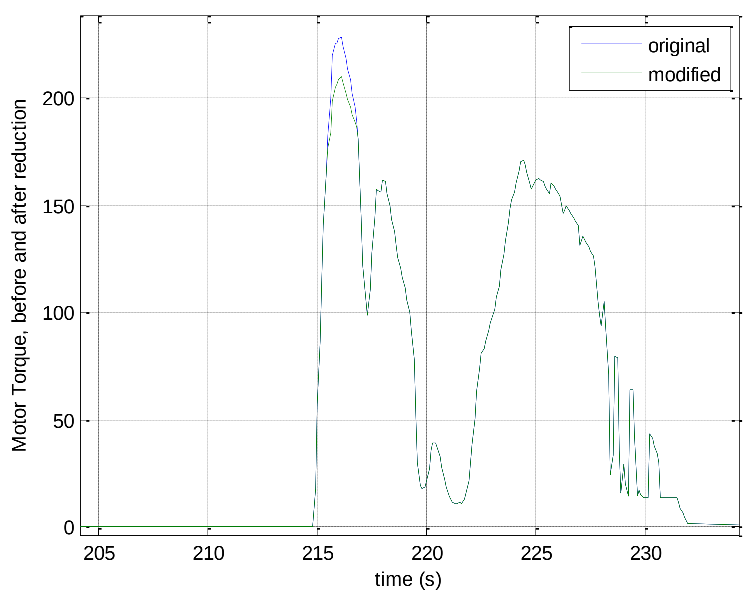
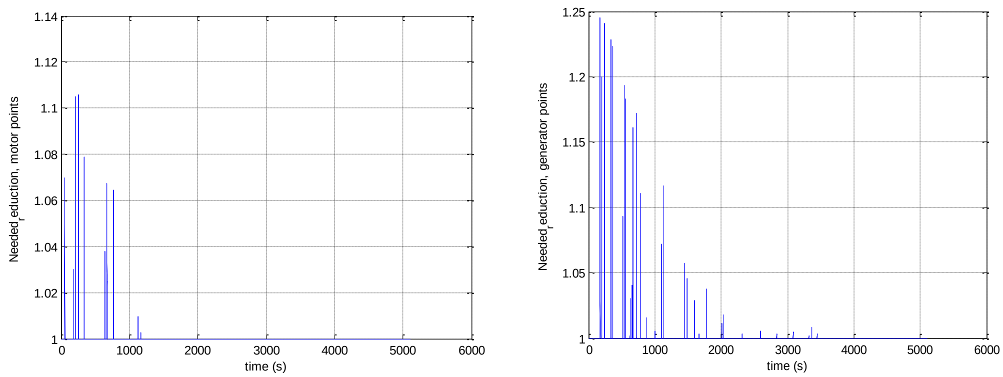


Figure 5: (Torque) derating at a propulsion event during the drive cycle..

In figure 7 it is shown how often derating occurs during the whole cycle.



Figur 6: Derating at motoric (left) and regenerating (right) operation in order to avoid over voltage.

It can be noted that when it comes to the propulsion, there are very few occasions when derating is needed, moreover it can be observed that the maximum derating level is 10 %. When it comes to the derating during regeneration, these events come much more frequently, and the derating needs are larger. However, the right picture in Figure 6 gives a too negative picture. In reality it is only 0.5 % of the regenerated energy that is lost, which is an insignificant value

To sum up, if a 10 % reduction of the acceleration ability is accepted for a few occasions when the battery is fully charged, then it is possible to increase the driving range with 15 % without changing anything regarding the hardware. Also other drive cycles were tested and for all of them were the lost regenerated energy was less than 1 % and the maximum propulsion torque reduction was 13 %.

7. Work package 3 – Electric machines.

Strategic collection of knowledge in the field of electric machines has been the grasping goal of the work carried out. Development of tools for analysis and dimensioning of both conventional and innovative machine topologies is also considered as a knowledge based path towards a more insightful product development, in cooperation with partners and suppliers. By a successive increase of the models complexities, and simultaneous verification of calculated results, methodological changes can be implemented stepwise in investigations, procurement processes and evaluation of various suppliers offers. Therefore, the origin of the workpackage has been a physical machine, enabling the forementioned verification.

The procedure was conducted for a few known electric machine designs from both industrial suppliers and academic studies. The main attention was brought to permanent magnet machines, but also topologies without magnets have been studied, such as synchronous reluctance machines, see Figure 7, and induction machines. As a consequence, these machine types can be analysed and modified to adapt to plausible applications in the product programme, aiming for a reduced cost influence from the permanent magnets.

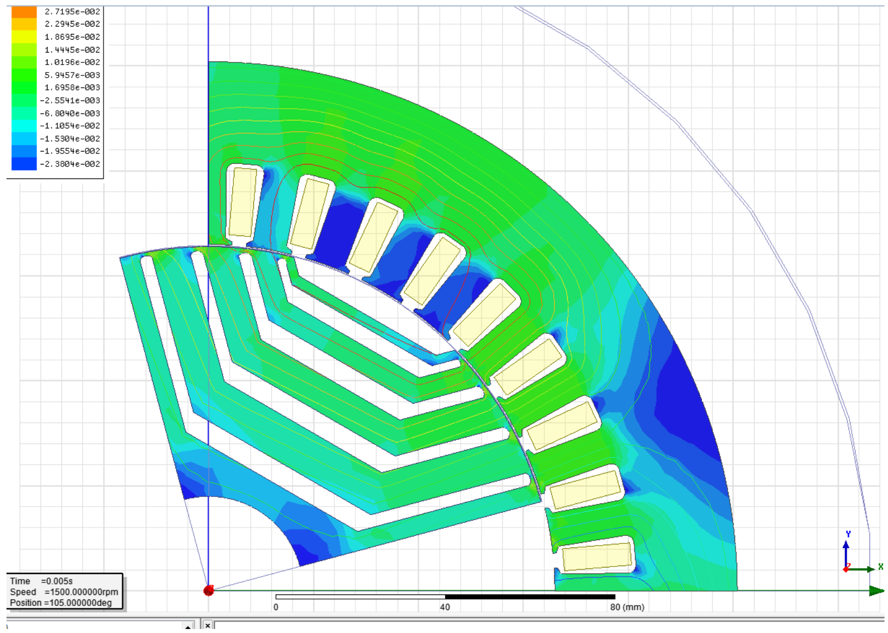


Figure 7: Cross-section of the synchronous reluctance machine model.

Table 2: Calculated results; reference machine (KTH) and Volvo's model implemented in Maxwell.

	Reference machine	Maxwell Implementation
Ld	26.4 mH	24.4 mH
Lq	2.9 mH	2.6 mH
Torque	153.4	141.75 Nm
Torque ripple	21 %	26 %
Max B in airgap	1.083 T	
Total Iron Losses @3000 rpm	1413 W	1450 W

Calculated results of one of the PM-machine models were coupled to ANSYS/Fluent (CFD) to analyse the thermal behaviour of the machine [4]. It turned out that the meshing of respective part solver (electro-magnetic and fluid mechanic) is incompatible and therefore cannot be automatically generated. At present, the meshing requires manual hands-on intervention which is considered as unacceptable in the overall process. It is regarded as more resource effective to fall back to less sophisticated methods for thermal analysis. An increase in coupled FEM-based calculations requires improvements of the software tools, which was initiated during the project, in cooperation with the software supplier.

In addition, an investigation on coupled electro-magnetic and acoustic calculations was made. Noise generated through electro-magnetic forces on specific machine parts is a shared interest with the NVH-group. As a part of the collaboration, an evaluation of methodology concerning magnetic forces and vehicle noise was conducted as a pilot study. Results from electro-magnetic calculations are being analysed by the NVH group and correlated with on-board measurements of acoustic noise. Conclusions from the work remains to be clarified and presented along with acoustic measurements of the electric powertrain to be used as a basis for validation. Future work in the field is being planned and coordinated.

As the work with electric machine modelling has progressed, it has become clear that the parameterised models of included materials may have a significant influence on the calculated results. As an example, the number of defined points on the magnetisation curve, how they are connected and extrapolated, may influence the calculated performance in a strong manner. In addition, the resulting airgap flux is influenced by locally altered material properties, caused by manufacturing processes, like punching. Achievement of good results is therefore depending on experimentally validated parameters using compensation for various discrepancies. As a consequence, the implemented method for calculating iron losses cannot deliver reliable results. Instead, an exchange of information with electric sheet manufacturers and electric machine suppliers is required to obtain relevant data.

As mentioned previously, the possibility to use coupled FE-calculations of electro-magnetic and thermal analysis was investigated. The task of integrating these calculations, aiming for a complete analysis tool, was conducted in a new environment, as far as Volvo is concerned. A step wise evaluation of a combined software package was carried out to determine feasibility and maturity of the coupled FEM calculations [1-3]. As a complement to the new FEM-based environment, a more traditional method for thermal analysis was implemented. A reduced thermal network was studied, implemented and tested for prediction of critical temperatures in an electric machine. Of special interest are the end winding and the permanent magnet temperatures. The coupling with the electro-magnetic analysis is done by transfering geometrical and material data as well as calculated losses to a thermal network that is solved by means of ordinary numerical methods [9].

A study of inductance computation by FEM was carried out in order to strengthen in-depth knowledge of methodology [5]. A common method based on time-stepping transient solution of the field, using a frozen permeability approach, was compared with an alternative method based on magnetostatic solutions. The magnetostatic method has the advantage of faster computation, which has a potential to speed up the design procedure. However, a disadvantage is the requirement of a well defined return path for the stator current, which in some cases yields a twice as large geometric model. The increased number of elements may be a drawback for the method, which was expected to be significantly faster. The methods were compared using a well known reference machine, and the results show that the magnetostatic method agrees well with the built-in transient one.

The investigation of electric machines suitable for hybrid electric vehicles has, based on literature studies and external monitoring, have been focused on reduction of heavy rare earth elements. Permanent magnets suitable for vehicle applications are depending on strongly cost driving additives, which motivates the investigation to reduce the usage if such elements. It is mainly Dysprosium (Dy) and Terbium (Tb) that are used to obtain temperature stability and coercivity desired for the applications. Furthermore, the production of the materials is concentrated in China, which has shown to be volatility in terms of market price and availability. It is therefore considered as worthwile to find solutions with lower content of critical elements, and, in addition, potentially reduce the environmental impact from extraction and production of such elements. Figure 8 displays various rotor topologies for permanent magnet machines, where type f) was selected for further investigation.

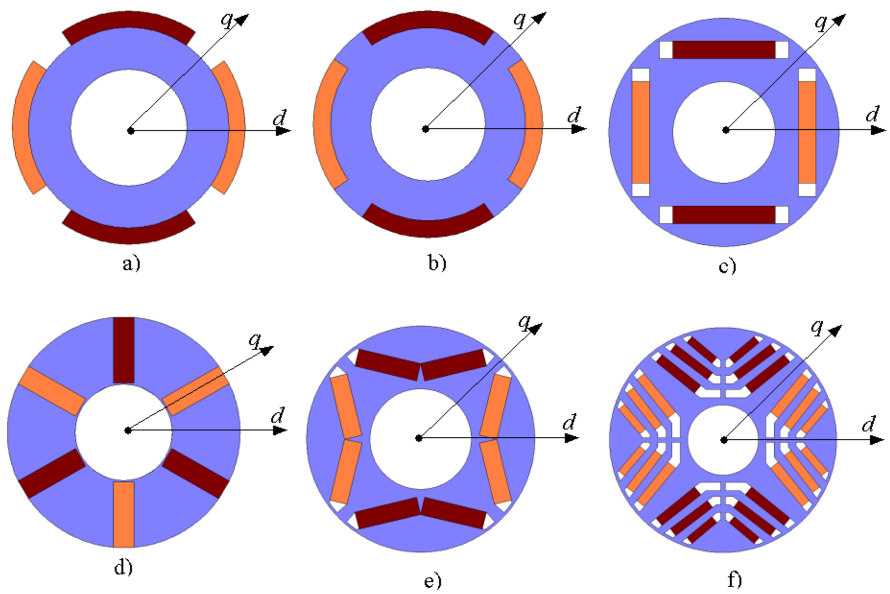


Figure 8: Rotor topologies for permanent magnet machines with varying degree of saliency.
a) surface mounted magnets (SPM), b) inset magnets (INSET), c) interior magnets (IPM),
d) spoke topology (SPOKE), e) v-shaped magnet IPM (V-IPM), f) PM-assisted SyRM/multi-barrier PM.

8. Work package 4 – Power electronics.

Work package 4 was comprised by the following activities:

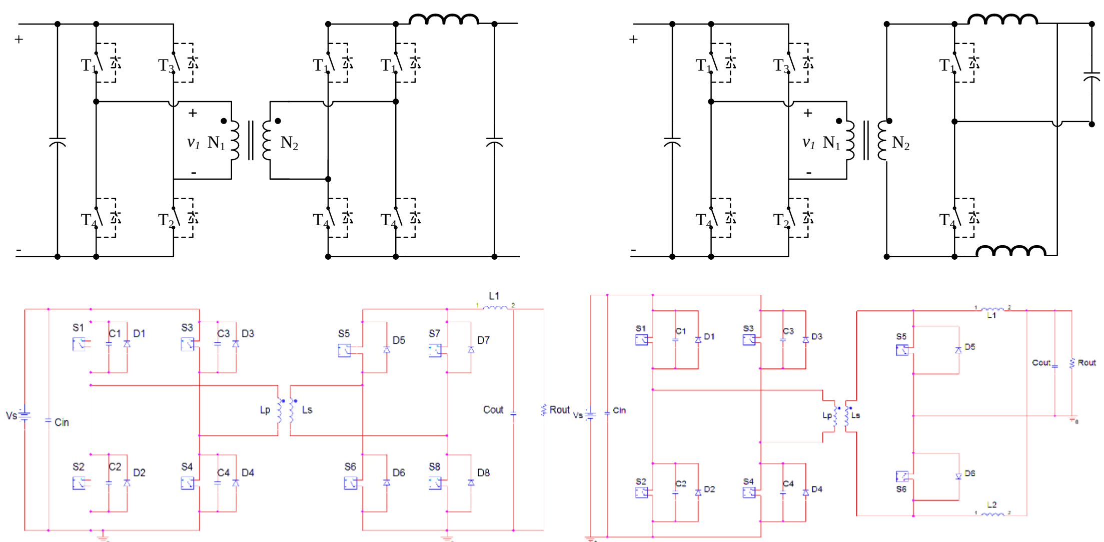
- Modelling and implementation of a three-phase converter for prediction of load currents. Implementation was done in Matlab.
- Modelling and simulation of a MOSFET switch to predict transient behaviour. Implementation was done in Matlab.
- Thermal networks of power electronic converters and tools for conversion between Cauer and Foster circuit layouts [7].
- Studies of SiC implementations in converters for application products available today.

- Studies of on board charger concepts for improved efficiency, but without galvanic separation of primary and secondary sides [11].
- A study of EMI influence from grid connected chargers [8].
- Investigation of topologies of the secondary side of DC/DC converters. Efficiency improvement was a primary target for the study.

Topology study of the DC/DC converter

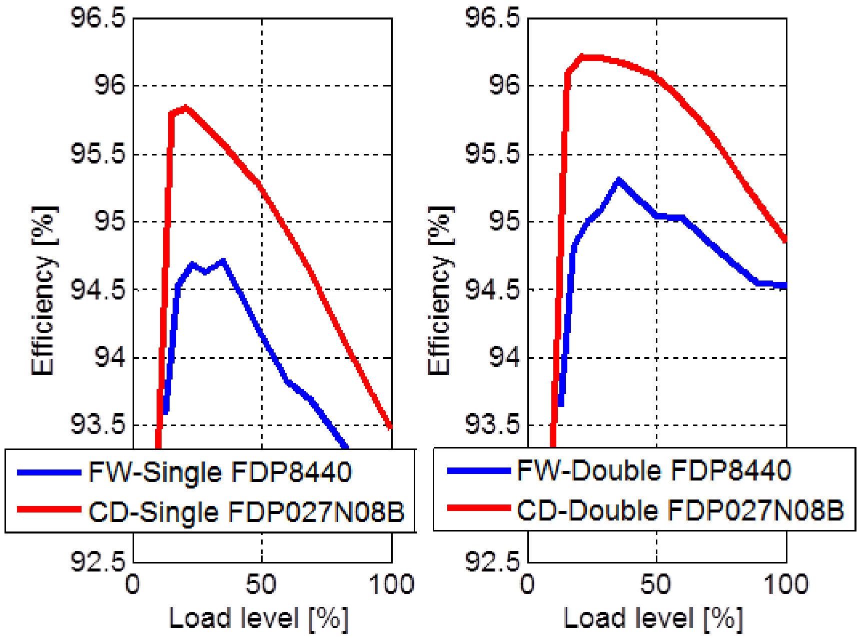
The DC/DC converter converts the higher battery voltage to the 12 V system level and replaces thereby the generator used for electric supply of auxiliary units in conventional cars. Important features of the converter are good cost effectiveness and high efficiency. The conversion of electrical energy should have low losses for two main reasons: Electric operation range and component cooling requirements.

Figure 9 shows two converter secondary layouts: A full bridge topology and a current doubler.



Figur 9: Secondary side converter topologies: On the left, a full bridge layout and on the right a current doubler.

In figure 10 the result of an efficiency calculation of the two topologies with a single and double set-up of power semiconductors on the secondary side of the transformer is shown



Figur 10: Efficiency of the two topologies, blue fullbridge converter red, current doubler, left, single power semiconductors, right – double semiconductor components on the secondary side.

It can be noted that the current doubler configuration has a substantially higher efficiency. The reason is that there are fewer semiconductors though which the current needs to flow.

We can note that the efficiency increases with 0.5 % around the point of maximum efficiency and up to 1.5 % at the highest load point if we double the number of semiconductors on the secondary side. The fact that it is rising the most at the higher load is natural since it is at this occasion that most current is flowing. From a cooling point of view it is extra valuable with the considerable improvement at high load, since at this high load point it is the case where we have the highest losses, and this is what to a large extent determine the size of the design.

Moreover, the consequence of having double amount of semiconductors on the primary side was also investigated. In this case, the energy benefits were less important. On the primary side the voltage is high and this leads to that semiconductors having higher switching losses must be used. If the number of Mosfet transistors is doubled, then the switching losses remain the same.

If only the case with doubling the transistors on the secondary side is utilized, then the energy savings are 9 kWh per year in case of using the fullbridge concept and 6 kWh per year when using the current doubler topology. During 15 years of operation this means 134 and 89 kWh respectively for the two topologies. With an electricity price of 1.72 kr/kWh (this is a low value, the electricity price on board a vehicle could be much higher than that) then 230 respective 153 SEK cost savings is achieved. The cost is 226 and 91 SEK for the transistors

(OBS, for a larger number of components, the price can be lowered). Accordingly, cost can be saved, and moreover, the reduced cooling need could lead to further cost savings. This must then be traded towards the increase space requirement of the extra transistors.

9. Work package 5 – System evaluation methods.

Prediction of viable electrification of selected vehicles requires cost analysis of the electric propulsion system and its components. A scalable component brake-down was created and implemented as a spreadsheet to support the cost and performance evaluation of the system and related components. Figure 11 displays the interface for the analysis tool for an example electrical machine.

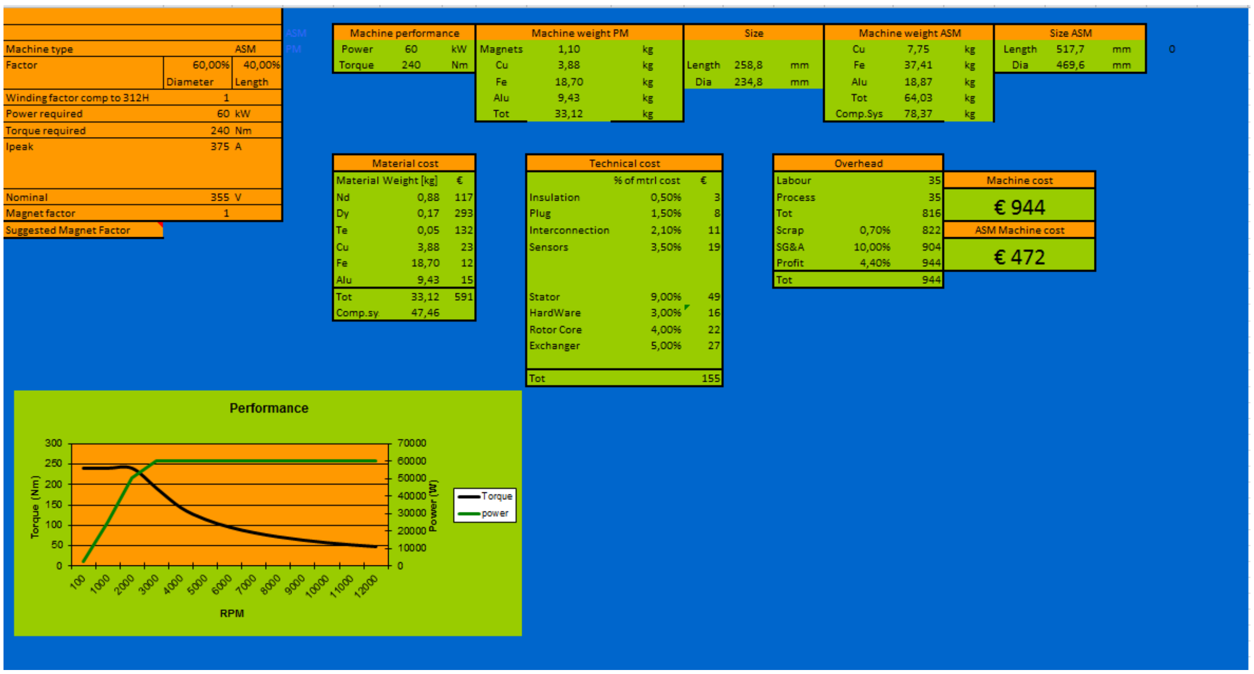


Figure 11. GUI for the electric machine evaluation tool.

By analysing cost sensitivity of different compositions of hardware solutions, identification of various improvements could be done and prioritised. A comparison of two generations of hybrid systems, in accordance with the project plan, shows improvements at a component level regarding cost, power density, weight and volume. These aspects are sometimes in conflict with each other.

Efficiency is in conflict with torque and power density, torque and power density is in conflict with cost. An important aspect has been the efficiency. With the price unchanged the losses in the machine was lowered by 15 % from the early project. When it comes to power electronics, then the technique was far less mature compared to the electric machine. The result was that the price per kW for the onboard charger could be reduced with 40 %, while keeping the efficiency. The weight could be reduced with 20 % and the volyme with 40 %. In the early variants the dc/dc converter supplying the 12 V system was a separate unit while in later versions it is included in the converter, so an easy comparison cannot be made. However, here could approximately a 50 % price reduction be observed, a reduced volume while maintaining the efficiency.

10.

10. Dissimination and publication.

The content of several work packages was discussed with Chalmers University of Technology. An example is work package 2 where Ph.D. Ali-Rabiei, who worked within the National Energy Administartion program ”enegy efficient vehicles”, conducted efficiency analysis of converters for vehicles. Furthermore, in WP4, the contact with academy was frequent due to the diploma works that were carried out by students from the Masters programme in Electric Power Engineering at Chalmers.

Results from VCC´s project activites were presented at ”Utmaningar för högtemperatur SiC i Fordon”. The occation was the annual conference of the Swedish Hybrid Centre 2013.

Within WP3, the progress of FE-calculations was discussed in a contact group where representatives from Volvo Cars, Volvo AB and Chalmers gathered. The contact group is called ”Västsvenska Maxwellsällskapet”, which deals with electric machine design and performance analysis based on Ansys/Maxwell.

Courses concerning Ansys/Fluent and Ansys/Mechanical were held, aiming for acoustic prediction and coupling with electro-magnetic calculations done in ANSYS/Maxwell. The participants affiliations were Chalmers, VCC and Aros Electronics. VCC were able to bring specific problems important for the vehicle industry to the discussions, and thereby giving feedback to the software developer. One important aspect was co-simulation using Fluent and Maxwell to predict thermal behaviour and acoustic noise generation.

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12. Conclusions and future work.

Activities within the NGHVT project relates to a number of diciplines concerning power electronics and electric machines. One important result is that Volvo Cars was able to collaborate with suppliers and drive development in a direction suitable for the next generation of electrified vehicles. The main reason being the in-depth studies conducted, giving way for a more proactive approach in the relations, which would not have been possible without the project. This is also true regarding the software developer Ansys, whose multi-physics calculation suite was partly rewieved during the events proposed and conducted in the project. Furthermore, it has been of great importance to participate at scientific events through the NGHVT project. Relevant and up to date knowledge was thereby transferred to VCC.

Examples of other significant results are systematic and rapidly executed parameterisation of electric machines by the use of FE-calculations (ANSYS/Maxwell), as well as efficiency analysis of three-phase inverters and DC/DC converters using new transistor technologies. In addition, part of the NVH analysis that was initiated within NGHVT was developed further in two industrial Ph.D. projects [14, 15].

Coupled electro-magnetic, thermal and fluid mechanical calculations will hopefully proceed once the computational inconveniences have been solved. Until then, the electric machine design initiative is carried on with improved methods, thanks to this project.

13. Participants and contact persons.

NGHVT has been a project conducted solely by Volvo Cars. The contact person for the project is Martin Ask, dept. 97312.