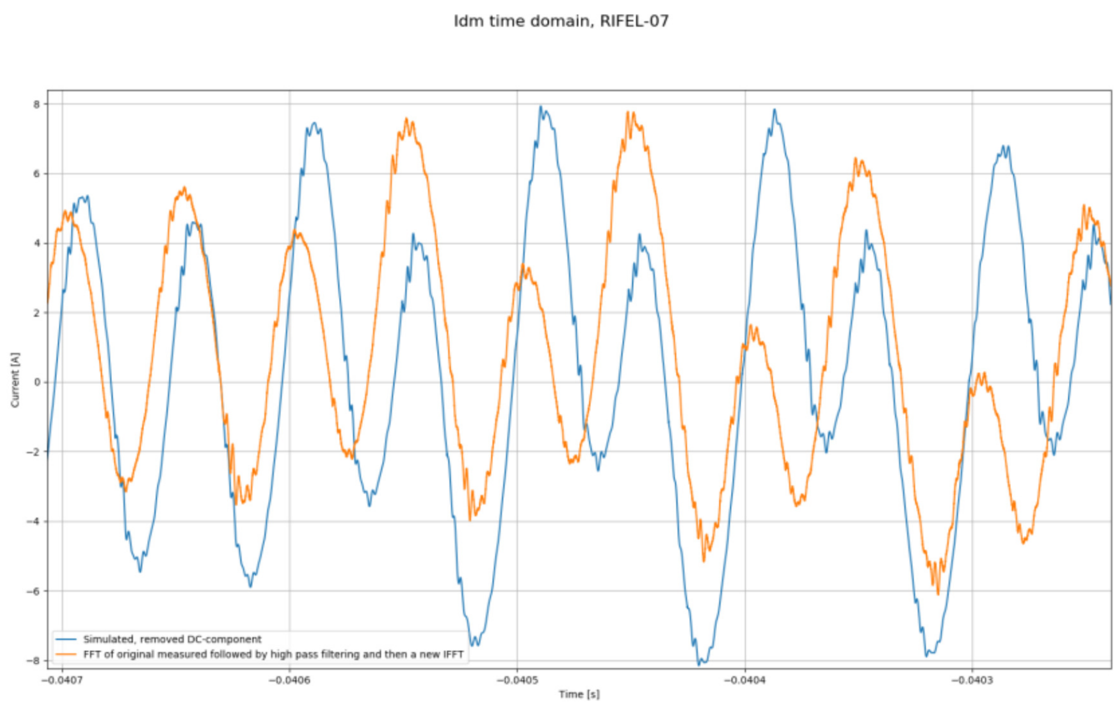
RIFEL

Ripple and Electromagnetic Fields in Electric Vehicles

Public Summary for Vinnova

Full report can be downloaded from Chalmers (https://research.chalmers.se) as Technical report 2018:2 – "Ripple and Electromagnetic Fields in Electric Vehicles"



Project within: Electronics, Software and Communication

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Date 2018-05-29

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1 Summary

The electrical system in an electrified vehicle consists of high voltage (HV) components interacting in a complex way. The switching interaction in the power electronics results in ripple causing electromagnetic fields, disturbing other electronics and degradation of components. An overview of this can first be obtained when a physical system is built which could lead to unintentional over- or under dimensioning of HV components. This lack of information within the electrical system can lead to late verifications in the project causing substantial cost if changes are needed.

This project aim at improving early evaluation of new concepts, create tools and build the necessary competence for a virtual system model that includes the key HV components: battery, electrical motor and power electronics, a simple load along with cable and connectors. This virtual model shall be able to simulate voltage and current ripple generated by the power electronics, initially in a frequency range up to 100 kHz. Results from the simulations shall be presented both in time and frequency domain as well as be expressed in RMS values for easier comparison to measured results.

Some of the more important findings are briefly summarised below;
For the high voltage battery, the electrical characteristics up to a frequency of roughly 1000 Hz was well determined using an impedance spectroscopy instrument at cell level and then multiplied by the numbers of cells. However for finding the impedance behaviour for frequencies above 1000 Hz, the determination must be done on the battery pack level since bus bars and other component in the complete battery pack will be dominating in this frequency range.

From measurements of differential mode impedance in high voltage cables it is found that it is important that the mutual inductance between the centre conductor and shield is included in the model to describe cable impedance below 10 kHz properly.

The control of the inverter is very important for the overall behaviour and in this project SVM was used which has been shown to give the lowest current and voltage ripple of the traditional switching schemes. And for the machine model, the temperature variations must be taken into account since the machine parameters has been found to vary with ~20 % over the specified temperature range.

The system model is found to agree well with rig measurements well up to 1 MHz with regards to both currents and voltages at the DC and AC sides. Furthermore, measurements in a real car match those in the rig. For time domain simulations, it was decided to use Ansys Simplorer since it can handle the inverter and the electrical machine simulations very well and for frequency domain simulations, it was decided to use LTspice since it is freeware, has support for AC-sweeps, improved switching compared to other SPICE-simulators, and is easy to use.

Magnetic field simulations have been calculated and compared to measurements in the driveline rig at Chalmers. It was a good match across the investigated frequency range 10 Hz to 100 kHz.

In this project, only internally developed component models were considered. To expand the functionality of the system modelling tool, international interface standards such as the Functional Mockup Interface (FMI) need to be investigated. Consequently, it would be a good idea to include additional automotive OEMs as well as suppliers and software vendors in future research collaborations.

2 Sammanfattning på svenska

Det elektriska högvoltssystemet i ett elektrifierat fordon består av flertalet komponenter som samverkar på ett komplext sätt. Switchningar i elektroniken ger upphov till ström- och spänningsrippel som kan störa annan elektronik på grund av externa elektromagnetiska fält samt degradera ingående komponenter såsom kondensatorer. Det är också svårt att få en överblick över ripplet innan det fysiska systemet är byggt och fullt ut förstå konsekvenserna för de egenskaper som ska uppnås vilket kan leda till oavsiktlig över eller underdimensionering av komponenter. Denna brist på tidig information om det elektriska systemets funktion kan leda till ofullständig eller sen utvärdering av nya elektrifieringskoncept samt sena ändringar i projekt vilket kan föra med sig stora kostnader.

Detta projekt syftar till att förbättra tidiga konceptutvärderingar, skapa verktyg och bygga nödvändig kompetens genom att ta fram en virtuell modell på systemnivå beståendes av de viktigaste högspänningskomponenterna: HV batteri, elmaskin med tillhörande kraftelektronik, enklare laster samt kablage och kontaktdon. Den virtuella modellen skall klara av att simulera spännings och strömrippel genererat från kraftelektroniken, initialt i ett frekvensområde som sträcker sig upp till 100 kHz. Simuleringsresultat skall visas dels i tids och frekvensdomänen men även som RMS värden för att mer överskådligt kunna jämföras med verifieringar i fysisk rigg.

Projektet är uppdelat i fem arbetspaket och med tre olika intressenter. Arbetspaket 1 leds av Volvo Cars och hanterar projektledning samt resultatspridning och de övriga hanterar respektive delsystem. Arbetspaket 2 leds av Volvo Cars och fokuserar på högfrekvent modellering och validering av HV batteriet. Arbetspaket 3 leds av Chalmers och undersöker simuleringsmodeller för olika kraftelektroniska enheter och elektriska maskiner i systemet och arbetspaket 4 leds av RISE och fokuserar på kablagemodellering samt dess inverkan på systemnivå. Resultaten från dessa arbetspaket kommer sedan att kopplas samman till en systemmodell i arbetspaket 5, som leds av Volvo Cars, för att skapa en fungerande modell med hög detaljgrad. Systemfokus är projektets kärna och för att för att tidigt kunna definiera sammankopplingen och vilka interface som kommer att användas genom projektet kommer arbetspaket 2 till 4 att ha tidiga leveranser till systemmodellen. Projektet har definierade milstolpar där bland annat 3 offentliga seminarier samt ett antal publikationer och presentationer ingår.

Några av de mer intressanta resultaten beskrivs kort nedan;

För högvoltsbatteriet räcker det att karakterisera cell nivå impedansen och sedan beräkna det totala resultaten för antalet celler i batteriet för frekvenser under 1 kHz. För att göra liknande beräkningar för frekvenser över 1 kHz måste hela packnivån inkluderas, främst för att bus bars och andra komponenter kommer bli dominerade i detta frekvensområde.

Genom mätningar av den differentiella impedansen i högvoltskablarna framkom att det är viktigt att den gemensamma induktansen mellan ledare och skärm är inkluderad i modellerna för att beskriva kabelimpedansen korrekt vid frekvenser under 10 kHz.

Hur omriktaren kontrolleras är väldigt viktigt för de generella rippel resultaten och i detta projekt användes SVM som anses ge de lägsta rippelnivåerna av de mer traditionella switchningsstrategierna. Elmaskinens temperatur måste tas med i beräkningarna för att få ett bra resultat då vitala parametrar kan variera upp till 20 % vid olika temperaturer vilket påverkar resultatet.

Systemmodellen stämmer överens med mätningar i rig upp till 1MHz vad gäller både ström och spänningsrippel, både på DC och AC sidan. Verkliga mätningar i bil stämmer också överens med riggmätningar i samma mätpunkter.

Ansys simplorer användes för att göra simuleringar i tidsdomänen eftersom programmet bland annat har stöd för omriktare och elmaskiner. För simuleringar i frekvensdomänen användes istället LTspice eftersom det är gratis, har support för AC svep, har bättre stöd för omslagsmodeller än andra SPICE simulatorer och att det är enkelt att använda.

Magnetiska fält beräknades och jämfördes med mätningar i den elektriska drivline riggen på Chalmers och visade sig stämma bra i det uppmätta frekvensområden 10 Hz till 100 kHz.

I detta projekt användes bara internt framtagna modeller av högvoltssystemet. För att utvidga systemmodelleringsarbetet och dess funktion hade internationella interface standarder, till exempel Functional Mockup Interface (FMI) kunnat användas. Det hade också varit fördelaktigt att inkludera andra OEM:er, leverantörer och mjukvaruutvecklare i framtida forskning inom detta område.

Projektet har även bidragit till FFI genom att stödja följande programmål:

- Teknologier som möjliggör reducering av fossilberoendet

Projektet har fokuserat helt på elektrifierade fordon och förbättringar av deras design och utvecklingsprocess. Genom att minska ledtider och utvecklingskostnader samt att förbättra kvalitén kommer användningen av elektrifierade fordon att öka och därmed kommer CO_2 emissionen i fordonsflottan att minska.

- Främja den svenska fordonsindustrins konkurrenskraft

Kortare ledtider är en nyckelfaktor i att bibehålla och öka svensk fordonsindustrins konkurrenskraft. Detta projekt har bidragit direkt till detta genom att tillhandahålla virtuella och validerade systemmodeller i tidiga faser och därmed minska utvecklingsledtiderna.

- Stärka forsknings- och innovationskapaciteten i Sverige

De utvecklade systemmodellerna och den kompetens som byggt upp i projektet kommer utgöra viktiga verktyg för både industri (Volvo) och akademi (Chalmers och RISE) efter projektets slut. Modelleringskunskapen kommer att bidra till målet att stärka forskning och innovation genom att möjliggöra snabb återkoppling på nya koncept innan hårdvara finns tillgänglig.

- Främja samverkan mellan industri och akademi

Projektet har utförts i samarbete med Volvo, Chalmers och RISE. Kunskapen har också att delgivits genom en seminarieserie där även andra parter såsom Volvo AB, Scania, BorgWarner, CEVT med flera har medverkat i. Från tidigare erfarenheter vet vi att samarbete mellan akademi och industri ger en bra grogrund för innovationer och ökar den gemensamma kunskapsnivån på en nationell nivå.

Projektet syftar även till att ge nya verktyg för att bygga kompetens och brygga ett kunskapsgap inom programmet för ”Elektronik, Mjukvara och Kommunikation”. Inriktningen är huvudsakligen programbeskrivningen med syftet att ”Utveckla nödvändig basteknologi för att realisera funktioner. …” och ”Etablera världsledande metoder och verktyg för fordonsutveckling”.

Utveckla nödvändig basteknologi för realisering av ”green functions” innebär i detta projekt att frekvensområdet mellan 1 kHz till 1 MHz studeras extra noga eftersom modellerna blir betydligt mer komplicerade här då många olika mekanismer samverkar. Det finns ett kunskapsgap inom systemmodellering eftersom det krävs validerade högfrekventa komponentmodeller samt tydliga gränssnitt när olika komponenter skall kopplas samman i ett system. Även om projektet från början skulle leverera verifierade modeller upp till 100 kHz så har mätningar visat att systemmodellen klarar att leverera valida resultat i ett högre frekvensområde, upp till 1MHz.

Projektet möter också Verification/Validation i programmet genom att öka den virtuella förmågan till att inkludera HV DC-systemets elektriska miljö med fokus på högfrekvent rippel och störningar. Virtuella metoder har skapats som i ett tidigt utvecklingsskede kan analysera nya koncept eller nya kravställningar i befintliga konstruktioner vilket i sin tur kan leda till minskad utvecklingsledtid, ökad flexibilitet samt högre kvalité.

3 Objective

Ever since Volvo Cars started to discuss voltage and current ripple in hybrid vehicles, the major question has focused on requirement levels and unwanted effects caused by ripple. The lack of knowledge in this area lead Volvo Cars into the idea to start a separate project, including both industry and academy to gain maximum results. It was decided to apply for an FFI (Fordonsstrategisk Forskning och Innovation) project with Chalmers and RISE as partners with the aim to develop a virtual model of the HV system that should be able to simulate voltage and current ripple. Without the support from Vinnova, it is very unlikely that this project had ever started since the resources needed for this type of investigation could be hard to secure, since the ripple issue was not causing immediate problems.

The project lasted for a little bit more than 2 years during which it evolved from being a theoretical idea to a verified prototype that can be used for multiple purposes. Numerous meetings and workshops has been performed, some very creative and some more confusing. In the end, this system model prototype performs much better than ever could be thought at project start.

We would also like to thank Vinnova for making this project possible via your contribution for FFI, it is very important that these kind of support is available for the industry.

4 Background

The increasing demand to lower CO_2 emissions together with a decreasing cost for high-voltage batteries has led to a large interest in electrification of vehicles within the automotive industry. There is also an increasing customer demand for electric and hybrid vehicles, which drives the interest in electrification further. This has led to a beginning shift in technology, from traditional internal combustion engines towards electrified powertrains, where one or more electric machines are introduced, alone or in combination with an ICE. In addition to the technology shift, there is also an ambition to develop more of the control software in-house, as well as a constant aim to shorten time to market. For the automotive industry, the coming decade will be a very exciting as well as uncertain time. The introduction of new technology, more complex control software, and the shorter time to market will, maybe more than ever, require accurate, flexible, and validated methods for virtual testing and verification of vehicle systems and subsystems. An effect of Volvo Car Corporation’s commitment to electrification is that there will be some kind of electric powertrain in all vehicles in the near future. Issues that need to be addressed in this aspect include verification of system functions, electromagnetic compatibility and possible health hazards related to radiated electromagnetic fields, and the increasing amount of software code.
When it comes to verifying the system functions, it is important that this can be done in every phase in the product development process. To achieve this, there is a need for virtual

methods that are flexible so that they can be adapted to different development phases, as well as to different configurations of the electric powertrain. There might, e.g., be alternative configurations of number of electric machines, placement of components or battery size depending on the size of the vehicle or price segment. Normalization of electric powertrains will lead to a modularized way of working when it comes to hardware. This must be mirrored for the virtual engineering in order to make sure that there are reliable simulation models at each phase in the product development process.

The HV system, here defined by HV battery, power inverter, electric machine, and electric wiring, is an expensive part of electric and hybrid vehicles and there is a need for methods to efficiently dimension the system. Furthermore, the introduction of a HV system in a vehicle increases the risk of disturbances in the form of high-frequency current and voltage ripple. This could lead to degradation and performance loss for the HV components. In addition, this could also affect other critical components in the vehicle or the environment surrounding the vehicle, leading to bad electromagnetic compatibility performance. In this regard, Volvo Car has initiated the research project RIFEL (Ripple and Electromagnetic Fields in Electric Vehicles) in order to investigate virtual methods for analysing the HV system.

The main goal of the project is to model voltage and current ripple in the HV system. This is important in order to understand the effect of ripple on EMC, dimensioning aspects, and components in an early phase of the product development process, where there is no hardware available.

5 Purpose, research questions and method

5.1 Purpose & Research questions

The power quality of an electric grid is an area that has attracted enormous research interest throughout the years. However, the focus for this issue has almost completely been on the 50/60 Hz grids. As DC-grids become more and more common where one important example is the electrification of vehicles, more knowledge has to be developed also for this area. While the AC-grids have a large number of standards describing the power quality issue, the standardization work regarding dc-grids has reached the stationary voltage levels. However, the transient and dynamic frequency ranges still awaits to be covered in standards. The goal is to design a power system where the chain ‘generation-propagation-component immunity’ reaches its ‘best combination’. With ‘best’ is here meant that the cost function of the various components, as well as efficiency, robustness, cost of electromagnetic immunity, etc., reaches a favourable combination. In order to design such a complex system with a virtual tool, adequate modelling both on component and system level is needed. The models needs to be sufficiently accurate in detail but still be computationally efficient so that an analysis can be done in a reasonable time. The method of how such a model can be extracted is also of interest to investigate; the model shall preferably be possible to develop early in the project phase, i.e. based on virtual tools, but also possible to validate by measurements on a subsystem level as an individual component.

A very high research value would be to study how a DC power system in a plug-in hybrid electrical vehicle could be designed, based on a physical-based modelling approach. The dynamic electrical environment needs to be determined on a system level where the main DC-link is the focus of this investigation. In order to perform this task, the components needs to be modelled accurately and their interaction with the system has to be investigated. Accordingly, the high voltage battery, inverter, electric machine as well as the connecting cables need to be incorporated in the system simulation model. Of extreme importance is that the theory behind each subsystem model must be verified with measurements in order to ensure that not only the main component but also the parasitic components have been accounted for since they can affect the results to a very large extent.

5.2 Model architecture

In order for the model to be useful in the project and for future investigations, it is important that it is flexible both in terms of fidelity and modularity. If there are different levels of fidelity for each component model and the system model is flexible in terms of choosing between the components models, the system model can be tailored to the right overall fidelity level for a certain purpose. Furthermore, in order to make the system model reusable in future projects, it needs to be flexible in terms of which components are included and how they are connected. This leads to a modelling approach that mirrors a modular approach to product development.
When it comes to the technical details of the model, it should be defined in time domain and use an acausal modelling approach to effectively model transient physical behaviour in the electric powertrain. The transient properties of the model are, e.g., important to capture the behaviour of the switching of the IGBTs in the inverter in order to correctly simulate the high-frequency behaviour of the system. When it comes to using a casual (e.g. Simulink) or acausal (e.g. Dymola or Ansys Simplorer) modelling approach, acausal modelling has a lot of advantages when it comes to simulating physical systems. One of the main reasons is that it is relatively easy to change the model in response to a topology change in the physical system when using an acausal modelling approach. For casual modelling, the entire system model might have to be recreated in order to reflect the change in the physical system.
However, it is important to be able to couple the acausal physical plant model to controller software. In this project, the focus is on modelling the physical system, but in order to run simulations, the actual controller software needs to be represented in the model. In addition, for future use of the model, it might also be relevant to use the plant model for virtual software testing, and then it is crucial that the controller software can be coupled to the plant model in an easy manner. Since controller software is inherently casual and physical models are acausal, the model architecture needs to support coupling of casual and acausal models
In order to fulfil the demands on the model architecture, an investigation of different software tools for physical modelling was conducted in the beginning of the project. Properties that affected the choice of software tool were, among others, ability for fidelity flexibility, predefined models of components, coupling to 3D models, and coupling to

controller software. Another important issue to consider is the use of the system model in a larger context. There is a general ambition in the automotive industry to simulate complex systems and in order for the model in this project to fit into a larger picture, it is important to consider interfaces to external models. An example could be to use software tools that adhere to international standards of model interfaces, such as the Functional Mockup Interface (FMI).

6 Results and deliverables

Regarding the impedance modelling of the battery cells and the validity of this impedance to module and pack level, clear results were found. The electrical characteristics up to a frequency of 1000 Hz was well determined using an impedance spectroscopy instrument, Gamry Reference 3000. This means that the influence of temperature and SOC level on a battery can be determined using a single cell and just add the cells together. Regarding the impedance behaviour for frequencies above 1000 Hz, the determination must be done on the battery pack level. The reason is that the inductance in a battery cell is extremely low, so it makes it impossible to determine it on the cell level. In addition, internal bus bars in the battery will be the ones that are important for the determination of the inductance. Also the resistance for frequencies above some kHz, needs to be determined for the whole package, results obtained using a cell measurements are not very accurate. Very satisfying was that the Gamry measurements were compared with results using the Bode 100 instrument, and the results in the frequency range 100-1000 Hz agreed very well between the two instruments.

When dealing with the inverter and the electric machine there are many different aspects that need to be taken into account. For the actual switching events in the inverter, an idealized simulation model of the IGBT is sufficient. Actual switching events will only increase the simulation time drastically. The control of the inverter is very important for the overall behaviour and in this project SVM was used which has been shown to give the lowest current and voltage ripple of the traditional switching schemes. Also, no data of the control structure was given which required a great deal of reverse engineering. For future projects, more details about the inverter control loop is needed.

For the machine model, the temperature variations must be taken into account since the machine parameters has been found to vary with ~20% over the specified temperature range. Also, the traditional PMSM-machine model is not enough since is does not give access to the y-point of the machine and does not account for the stator and rotor common mode (CM) impedance. This impedance is one of the most important components for the CM-currents and must be accounted for in the system simulation model. Therefore a more detailed machine model is necessary, and in this project it was realized in VHDL-AMS. This model also includes a simple implementation of cogging torque which has been shown to affect the current and voltage ripple on the DC-link.

The system model is found to agree well with rig measurements up to 1 MHz with regards to both currents and voltages at the DC and AC sides. Furthermore, measurements in a real car match those in the rig. Some aspects of the model are ad hoc, for instance the actual implementation of the control system is not known and it could have an impact on the results. When it comes to components, some parameter values are found from component measurements and there are many cases where it would be desirable to know these properties without access to physical hardware. In some cases, equivalent circuits are reconstructed from frequency domain measurements. If the circuit elements do not represent physical objects, a more compact and convenient approach might be to use state space models rather than equivalent circuits. Furthermore, the frequency domain approach may be a more convenient tool than the time domain approach in some cases.

The selection of simulation tools in this project were mainly based on the functionality of circuit simulations for the inverter and the electric machine. Another important aspect was the possibility to co-simulate different simulation domains and the possibility to link the selected tool to other simulation tools within Volvo. For time domain simulations, it was decided to use Ansys Simplorer since it can handle these requirements very well. In addition to this, it is easy to use, gives fast simulation time, support multiple simulation domains, supports FMU, and has previously been used within Volvo. The main drawbacks are the cost, installation, licensing, and poor control handling capabilities. For frequency domain simulations, it was decided to use LTspice since it is freeware, has support for AC-sweeps, improved switching compared to other SPICE-simulators, and is easy to use. The main drawbacks are poor control handling capabilities, no official support since it is freeware, and no electric machine modelling.

For shielded cables, such as high voltage cables in vehicles, the problem has to be divided into two parts, one inner problem and one outer. The reference for the inner problem is the shield, and for the outer the chassis of the vehicle. From measurements of differential mode impedance it is found that it is important that the mutual inductance between centre conductor and shield is included in the model to describe cable impedance below 10 kHz properly. The induced current in the cable shield can be quite large if the shield loop impedance is small and depending mainly on contact resistances for the shield connection in the cable ends. The resistive losses in the cable shield will give the cable a low pass filter characteristic for ripple currents. The potential high shield currents are because forward and return currents are shielded separately. A configuration with forward and return current conductors with a common shield, the shield current magnitude can be much smaller.

Magnetic field simulations have been calculated and compared to measurements in the driveline rig at Chalmers. It was a good match across the investigated frequency range 10 Hz to 100 kHz. The procedure for magnetic field simulations can shortly be summarized as follows. The system model of the driveline is used to provide currents on the cables. The electromagnetic simulation model provides actual magnetic fields, taking into account 3D CAD and shielding effects of metals. This means the same method can be used to simulate magnetic fields inside and outside a car. To get correct simulated magnetic fields at low frequencies it is important to choose an electromagnetic simulation software that can handle thin steel plate (permeability and conductivity), as is used in the car chassis. One such electromagnetic simulation software is e.g. COMSOL.

When it comes to the model architecture, it is important that the chosen solution supports flexibility in terms of component variants and fidelity level. Even for a specific system as was the case in the RIFEL project, the number of possible system model configurations grows rapidly when component model variants are introduced. In order to be able to switch between different component models easily as well as to keep track of combinations used in the system model, it is preferable if these features are available in the software tool. This is very important for traceability and confidence level for the system models.

6.1 Deliveries to FFI Goals

This project contributes to the goal of the FFI program by:

6.1.1 Technologies that make it possible to reduce fossil dependency

This project has focused on electrified vehicles and their improvement in design and time to market. By decreasing the development cost and increasing the quality, the usage of electric vehicles will increase hence reducing the CO2 emissions within the vehicle fleet. This project will also make earlier verification possible hence reducing the lead times and development cost.

6.1.2 Promote the competitiveness of the Swedish automotive industry

Shorten lead times is a key factor in maintaining as well as increasing the Swedish competiveness within the vehicle industry. This project has enabled such competiveness by offer validated virtual system models in early phases hence shortening the lead times.

6.1.3 Strengthen research and innovation capacity in Sweden

The developed system models and the increased competence will be important tools for both the industry (Volvo) and the academy (Chalmers and RI.SE) after the project end. The knowledge how to develop and execute system models will strengthen research and innovation by giving feedback on new concepts before HW is available.

6.1.4 Promote collaboration between industry and academia

The project was performed in collaboration with Chalmers and RISE. Knowledge gained within the project was spread at 3 different seminaries with participants from varying companies such as Volvo AB, Scania, BorgWarner, CEVT but also from the academic side. Based on previous experiences it is known that collaboration between industry and academia will increase the knowledge at national level as well.

This project supports the “Electronic, Software and communication” goals through creating and building new competences and tools. The vision to “Develop necessary base technology to realise functions…” and “Establish world leading methods and tools to the automotive industry” are described below.

Develop the necessary base technology for the realization of “green functions" includes to study the frequency range between 1kHz and 1MHz thoughtfully since different physical phenomenon will be dominating at different frequency which makes these models quite complex. The project sought to investigate these phenomenon and clarify the somewhat diffuse knowledge in this area. Even though the models first should be validated up to 100kHz it has been shown that they can perform effective results in a higher frequency range as well, up to 1MHZ.

The project also supports the Verification/Validation within the programme through increased virtual availability to include the HV DC systems electrical environment with focus on ripple. These virtual methods can be used for analysing new or changed concepts in the early phases of a project which will lead to shorter development times and higher quality.

7 Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	
Be passed on to other advanced technological development projects	X	Will be continued in research project Virtual Electric Propulsion System
Be passed on to product development projects		
Introduced on the market		N/A
Used in investigations / regulatory / licensing / political decisions	X	

7.2 Publications

Below is a list of publications and conference presentations associated with the project:

[1] Alexandra Nafari, Robert Eriksson, Continued High Voltage System Development, EEHE – Electric & Electronic Systems in Hybrid and Electric Vehicles and Electrical Energy Management, 8-9 June 2016, Wiesloch, Germany

[2] Virtual methods for investigating system-level ripple and EMC in electrified vehicles, Per Jacobsson, Anders Bergqvist, John Simonsson, EEHE – Electric & Electronic Systems in Hybrid and Electric Vehicles and Electrical Energy Management, 12-13 June 2018, Würzburg, Germany

[3] Peter Ankarson, Urban Lundgren, Modelling and Simulation of a High Voltage Car Electric Drive Line to See Ripple on HV DC and AC cables for Different Cable Routings

– Measurements vs Simulations, EMC Europe 2018 Workshop Automotive AMC, August 27-30 August, Amsterdam, Netherlands

[4] Andreas Henriksson, Impedance Modeling for Accurate Estimation of DC-Link Current and Voltage Ripple in Electric Vehicles, International Electric Vehicle Symposium, Sep 30-Oct 3, 2018, Kobe, Japan.

8 Conclusions and future research

In this project, only internally developed component models were considered. To expand the functionality of the system modelling tool, international interface standards such as the Functional Mockup Interface (FMI) need to be investigated. Consequently, it would be a good idea to include additional automotive OEMs as well as suppliers and software vendors in future research collaborations. Another important focus for future research projects could be flexibility and usability. With a simulation tool that is flexible in terms of component fidelity, the tool could be used throughout the product development process and updated in an agile manner. This would allow the tool to be used in early phases for concept studies as well as in late stages as a high-fidelity digital twin. Flexibility in terms of system configuration is also important for using the tool for new designs. In the RIFEL project, a system model validated both on component and system level for a specific vehicle platform has been created. The next step is to use the existing framework to set up new system configurations and use them for system performance predictions.
Another aspect of the system model that needs to be explored further, is the use of currents in the system model as sources for an external electromagnetic field simulation. Building on preliminary investigations, an aim for future projects could be to create reduced order models for radiated electromagnetic fields based on 3D or 2D field simulations.

9 Participating parties and contact persons

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