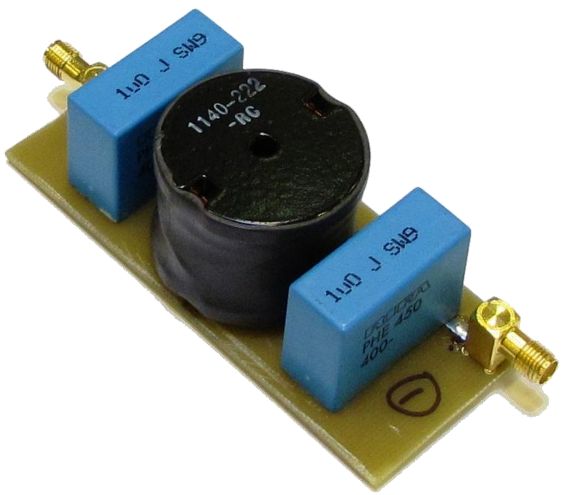
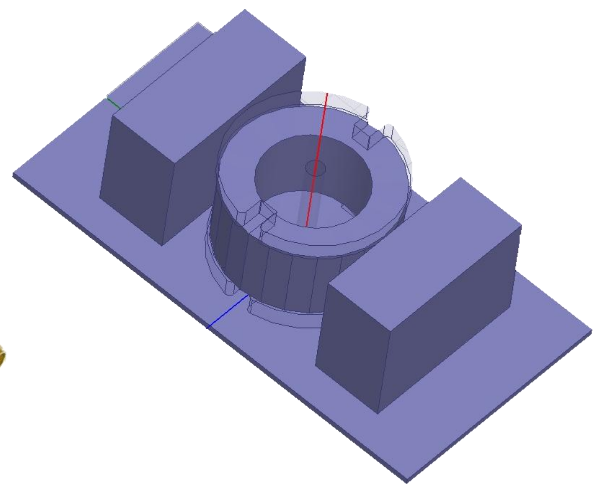
Reduction of Electromagnetic Interference from Switched Converters in Vehicles





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Project within Vehicle Development - 2008-04101

Contents

1. Executive Summary 3

2. Background 3

3. Objective 4

4. Project Realization 4

5. Results and Deliverables 5

5.1 Deliveries to FFI-goals 8

6. Dissemination and publications 9

6.1 Knowledge and Results Dissemination 9

6.2 Publications 10

7. Conclusions and Future Research 11

8. Participating Parties and Contact Persons 12

1. Executive Summary

This project (registration number 2008-04101) addresses the detailed design of switching converters and how they can be designed in an advantageous manner for the benefit of a good electromagnetic environment. The overall goal of this project is to attack the sources of interference directly at its origin and thereby reduce the need for external filter components. To achieve this objective, three sub-goals are identified, an evaluation of component models and the required level of detail to achieve and an accurate interference profile. The second sub-goal is an evaluation of a new method (referred to as Active Gate Control) to reduce the level of harmonics in a switching converter, and the final sub-goal is to investigate how modern simulation tools (Ansoft Q3D, SIwave, Maxwell 3D) can be used to identify the parasitic elements within the converter and thus get a more accurate picture of the generated disturbance profile. The main results that emerged from the project showed that more detailed component models are often required to simulate the correct switching behavior and that the simulation tools that have been evaluated helps to obtain a more complete picture of the converter's emission profile up to a certain frequency (~10MHz). The frequency range was found to be a reasonable balance between the level of detail of the component models and reasonable simulation time. In addition, it has been shown that the developed method to reduce the level of harmonics in the converter operates both theoretical and practical up to a given switching frequency (~ 2 kHz). The interested reader is encouraged to read the thesis, "EMI From Switched Converters - Simulation Methods and Reduction Techniques" (ISBN 978-91-7385-568-6), presented at Chalmers University in September 2011.

2. Background

Electrification of modern vehicles means that many traditional mechanically driven loads are being replaced with electrically actuated ones instead. In addition to this, the traditional combustion engine that still coexists in a hybrid vehicle needs to be intermingled with a drive system for electric propulsion. This electrification also leads to new demands on the electrical equipment that is brought into the vehicle since it must be able to interact with each other without disturbances that can propagate and interfere with surrounding equipment; a concept known as electromagnetic compatibility. A hybrid vehicle is just one example of an environment in which electric converters with high power must coexist with sensitive radio receiver in a very limited space. In order to get all electronic devices to interact, careful design of all its subsystems is required, and a detailed system design work to define the maximum allowable interference levels. This project deals primarily with details of the design of the switching converter and how these can be designed advantageously to benefit a good electromagnetic environment.

3. Objective

The overall aim of the project is to examine how to reduce electromagnetic noise from a switching converter by using various simulation tools to identify the mechanisms that contribute to increased interference. When the dominant mechanisms are defined, its origins are identified and a design process is then initiated to minimize them. The method proposed in this project is thus based on that electromagnetic interference shall be minimized at the source to minimize the need for external components such as filters and shielding. The design methods which are mainly intended to be treated is optimal component location in order to maximize filter action, switching means to minimize the level of harmonics in the voltage and currents, and by means of different simulation tool to identify and quantify the sources of interference.

4. Project Realization

The project has been carried out at Chalmers University in Gothenburg together with industry partners with Volvo Cars, AB, Ericsson AB, SAAB AB and Haldex AB and is a continuation of the previous Vinnova Project "Reduction of EMI from switch-mode power conversion devices." In the previous project the foundation was laid was laid for the work on the reduction of electromagnetic interference and the main work has been performed by a graduate student (Andrew Karvonen) that September 12, 2011 defended his doctoral dissertation. The defense was successful and the presentation itself attracted great interest not only among all project partners but also from outside the project team and other departments at Chalmers. To assist them in their daily work, the PhD student had a reference group with members from all participating companies which have contributed resources and come provide ideas and suggestions for relevant studies for each stakeholder. In addition, a large number of thesis projects performed in both at the participating companies as well as within Chalmers. The breadth of degree projects have been great, but they've all had the common denominator of electromagnetic fields and switch-mode power converter.

5. Results and Deliverables

The main results from the project can be divided into three major milestones; demands for greater detail in the component models, development and experimental verification of the method for reduction of harmonic levels of in a pulsed signal, and requirements for optimal component placement for enhanced filter effect.

The first milestone is based on simulation of interference levels from switched-mode power converters. In order to analyze the electromagnetic interference, all components must be characterized more accurately than conventional simulation models often account for. The elements that with traditional simulation tools have been not been possible to quantify, the so-called parasitic elements, can now be quantified using modern simulation tools (Ansys Q3D Extractor and SIwave). These simulations are based on field calculations of e.g. the PCB and by implementing the results from these tools together with a traditional electrical circuit simulator, can be more satisfying interference levels obtained from the simulation model. Furthermore, it was shown in the thesis that both active and passive components must be characterized in terms of their high frequency dependence, which is often disregarded when traditional models are used. As for active components, the simulation models supplied by the manufacturers sometimes inadequate because they do not always are intended to simulate a converter on the degree of detail required to estimate correct interference levels. An example of a component which has been proven difficult to model is the classical diode. The static behavior is often sufficiently well described, but the dynamic events are rarely described with sufficient detail (especially the so-called reverse recovery process that occurs when a diode is switched). As for the switches used for lower voltage levels (MOSFETs), it was found that the models provided by manufacturers are often sufficiently detailed and can be implemented directly in an electrical circuit simulator with satisfactory results. However, it is significantly worse when components for higher voltage levels (IGBTs) are analyzed. The dynamic behavior of the standard models is often quite misleading, and manufacturers are rarely can provide sufficiently detailed models. Ansoft Simplorer proved to be the only identified program that could simulate the switching behavior of an IGBT with sufficient detailed manner. However, a considerable amount of manual work is required, which means that the extraction procedure is slow but provides satisfactory simulation results.

Milestone two deals with a method to reduce the level of harmonics in a switching converter, mainly by implementation of a technique called Active Gate Control. The technology relates to minimize the level of harmonics in the square pulsed current flowing through the switch by replacing the sharp transitions are with sinusoidal transitions. The pulsed current is directly controlled by controlling the switch via the gate voltage, and to do this from a proper control engineering point of view, a new MOSFET-model had to be derived. The technique was verified both with simulations and practical measurements and was shown to work. However, the demands were high for the regulator which meant that only switching frequencies up to about 2 kHz could be achieved.

Milestone three showed that the input filter affects the interference levels to a large extent, not only by its damping characteristics at low frequencies, but also by the unavoidable parasitic elements that arise in the filter. These connections can in extreme cases make the filter ineffective at higher frequencies. The main parasitic elements that contribute to the high-frequency properties within a filter have been found to be the mutual magnetic coupling between the various filter components. This factor is often overlooked in traditional simulations, mainly because of the difficulty in quantifying its value. Thanks to the finite element software (Ansys Maxwell 3D) and a cosimulation with an electrical circuit simulator, these couplings can be determined their impact on an electric circuit can be accounted for.

To verify the simulation models developed during milestone one, and to verify how well these models can simulate the interference levels generated by a converter, several prototype boards were developed during the project. The main purpose of these prototypes was to verify the previously developed simulation models by measurements. One of these converters which was developed in collaboration with a master thesis project was a 3-phase inverter (500W) for operation of BLDC motors. The converter was used, among other things, to evaluate different component placement of the input filter and how the cable that connects the inverter and the motor affects the interference levels. The results showed that the cable layout and placing affects the interference levels to a large extent and that the overall simulation model of the converter must be very accurate in order to simulate a drive system. Since the control of the 6 switches in the inverter affects the interference levels in a significant way, the associated drive circuits of the switches must also be very detailed. For a low power flyback converter (15W), accurate diode modeling was combined with magnetic transformer modeling in the simulation software Ansoft Simplorer. The study showed how the reverse recovery phenomena in the diode affect the conducted disturbances. It also pointed out the need to model the transformer and switching elements together with the input filter in a detailed manner so that the conducted emission levels can be predicted. The simulations including these factors showed that the proposed simulation model is valid up to about 10MHz. The final converter, which also was designed in collaboration with a mater thesis project, was a synchronous step-down converter. Measurements on this converter also served as a basis for investigating how the reverse recovery phenomenon in diodes affects the conducted disturbances. The results show that a more accurate description of the diode reverse recovery process helps to predict the interference levels for a converter. The complex mechanisms (parasitic couplings within the PCB and electro-magnetic coupling between the components in the input filter) that affect the absolute interference levels are very difficult to calculate and quantify, but to some extent they may be calculated using the software Ansoft Maxwell and Ansoft Q3D (according to milestone 1). If these elements are included, a model of the conducted noise in the test step-down converter can be made valid for frequencies up to 10MHz. Overall, the report highlights the need for more detailed simulation models that take into account e.g. coupling between components and better dynamic events.

In addition to the three milestones described above, several smaller studies have also been performed. One of these investigations was initiated by SJ and consisted of an analysis of disturbances in machine drive system in the X2000 train set. The results showed that there is a difference in the components' performance due to its temperature, but no concrete conclusions could be drawn whether these differences gave rise to operational problems as it is practically impossible to measure the actual interference levels in the machine drive system within the train set during operation. The work resulted in an internal report for SJ.

5.1 Deliveries to FFI-goals

The project has contributed to the FFI objectives by fulfilling the following points.

- In order to design competitive hybrid vehicles in Sweden, *qualified* knowledge of the detailed design *is required in the* Swedish automotive industry. This project has highlighted several essential aspects of detailed design *that is* required for communication with e.g. subcontractors. Thus, the project has also strengthened the development of skills in the automotive industry through the participation of parties who have been involved in reference groups and provided relevant information.
- By achieving understanding of where electromagnetic interference is generated within a switching converter, the possibility of knowledge-based production has been strengthened significantly. Modern electric and hybrid vehicles require completely new knowledge in how state of the art electronic converters can be integrated in a vehicle. This project has helped to develop the Swedish automotive industry by a shortening the time to systemize and verify a hybrid vehicle with respect to electromagnetic interference levels.
- The cooperation between the Swedish automotive industry, Department of Electrical Engineering at Chalmers University in Gothenburg and other western Swedish companies with power electronic orientation has with this project has strengthened. Examples of this is e.g. comparative system analysis work between Volvo Cars AB and Ericsson AB, continued contact within the reference group, and future submissions of collaborative projects as a part of the FFI programs.
- Cooperation between the different companies within the reference group has contributed to an action plan to ensure a future supply of expertise in skilled engineers with power electronic knowledge from the university. Furthermore has the project been unique in its design, both in Sweden and internationally which have made it in focus at many presentations. The results have therefore contributed to the establishment of excellence with international competitiveness in the western Swedish power electronics industry.

The results derived from the project have reached the Swedish power electronics industry directly by several paths. The knowledge that has been acquired has not only been spread within the project but also to other parties through presentations and shorter working packages and projects with other companies and stakeholders.

6. Dissemination and publications

6.1 Knowledge and Results Dissemination

The project and its results have been presented several times for visitors to Chalmers who came both from industry and other universities and government agencies. Furthermore, knowledge transfer occurred when the project staff visited the industries, government agencies and other universities. The project has attracted considerable interest in these presentations because it has been unique in its design. The expertise that emerged from the project and the research about electromagnetic compatibility and switching converters is considered to benefit the Swedish power electronics industry to a large extent.

The former graduate student in the project now works with teaching of power electronics at the master's program in Electrical Power Engineering at Chalmers University of Technology. Project results and above all the contacts that were associated with the project will greatly benefit the students by enhanced and concretized teaching. Students have gained greater insight into what's going on in the area of power electronics and electromagnetic interference. Furthermore, the project has resulted in many new thesis works both at the department of electric power Engineering and at the industry partners, which further increased interest among students for the current theme on EMI, inverters and power electronic design. Continued and enhanced cooperation between the project partners and the Department of Electrical Engineering also allows for further improvements to be made in modern teaching and future investments to be made in power electronic design at Chalmers university of Technology.

The software and working methods that have been developed within this project have also been useful in other projects in the department. The methods have not only been found applicable within projects that deal with hybrid electric vehicles, but also in projects that deals with many broad subjects such as wind power and electric drives for pump and fan applications. The software from Ansys that originally was purchased for the project has become a standard development tool when advanced multi-physics problems are to be solved. Forthcoming PhD projects have therefore had a substantial lead as more advanced results can be obtained in significantly less time. Further work is underway to integrate use of the software in the standard education program. This could benefit many companies since the programs are widely used in industry and a basic knowledge of advanced multiphysics simulation tools can be a great advantage for a newly graduated engineer. At the time of this report's writing (March 2012), many western Swedish company that work with power electronics and drive systems have started using the software from Ansys. This vouches for a great synergy between Chalmers that can help with the dissemination of knowledge and the industry that can help to inspire for and start new research projects.

Finally it is worth mentioning that professor Torbjörn Thiringer assists Volvo Car Corporation on a part-time basis with hybrid vehicle development. This means that the knowledge generated within the project is directly beneficial to Volvo Cars AB.

6.2 Publications

A. Karvonen and T. Thiringer, "MOSFET Modeling Adapted for Switched Applications Using a State-Space Approach and Internal Capacitance Characterization " in *PEDS 2009 - The Eighth International Conference on Power Electronics and Drive Systems*, Taipei, Taiwan, R.O.C, 2009.

A. Karvonen, "MOSFET Modeling Aimed at Minimizing EMI in Switched DC/DC Converters Using Active Gate Control," Licentiate Thesis, Chalmers University of Technology, 2009, p. 165.

A. Karvonen, “On Dynamic Diode Characteristics and EMI Performance of an Inverter with Undeland Snubber” in *The 9th International Power and Energy Conference IPEC 2010*, Singapore, 2010.

H. Elofsson, "Design and study of the power grid influence of a single-phase 300W PFC rectifier," Master Thesis Work, Chalmers University of Technology, 2009.

M. Grenier, "Design of an on-board charger for plug-in hybrid electrical vehicle (PHEV)", Master Thesis Work, Chalmers University of Technology, 2009.

J. Andersson, M. Ramqvist, ”Circuit breakers, Melting fuses and Electronic fuses - Analysis and Design rules for use in Telecom power applications”, Master Thesis Work, Chalmers University of Technology, 2010.

F. Walderyd, “Hazard identification and safety goals on power electronics in hybrid vehicles”, Master Thesis Work, Chalmers University of Technology, 2010.

K. Berntsson, ”Four Phase Switch-Mode Inverter - Construction and Evaluation”, Master Thesis Work, Chalmers University of Technology, 2010.

J.Härsjö, “Parasitic Component Extraction and EMI Reduction Techniques in an Power Electric Drive System”, Master Thesis Work, Chalmers University of Technology, 2010.

M. Hedenskog, E. Hallgren, “Modeling and Validation of the EMI Performance of an Electric Drive System by Device Level Characterization”, Master Thesis Work, Chalmers University of Technology, 2010.

A. Karvonen, J. Åström, ”Simulating the EMI Characteristics of Step-Down DC/DC Converters”. VPPC'11- The 7th IEEE Vehicle Power and Propulsion Conference, Chicago, USA

A. Karvonen, T. Thiringer, “Simulating the EMI Characteristics of Flyback DC/DC Converters”. Intelec 2011 - The International Telecommunications Energy Conference 2011, Amsterdam, The Netherlands.

A. Karvonen, “EMI from Switched Converters – Simulation Methods and Reduction Techniques”. Gothenburg: Chalmers University of Technology. Dissertation.
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7. Conclusions and Future Research

At the time of this report's writing (March 2012), the resulting Ph.D. graduate within the project currently work with power electronic converter development in Swedish industry and within a research project at Chalmers University of Technology. The knowledge acquired during the project has thus been useful to Swedish industry directly and contributed to new ideas for future research projects.

8. Participating Parties and Contact Persons

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