Fault detection and increased reliability of a 3.3 kW on-board battery charger for PHEVs

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Summary

Reliability is an important performance index of a modern power electronics converter. The failure modes and effect analysis (FMEA) is one the mostly used techniques to evaluate or possibly improve the reliability of a power electronic system. This is one of the key challenges in electronics converters for vehicle industry. The project aim is to increase the reliability of a 3.3 kW on-board vehicle battery charger. However, the techniques can be utilized in other electronic converters like traction inverters and DC/DC converters.

For a 3.3 kW vehicle battery charger an FMEA is provided to evaluate and quantify the reliability for important fault scenarios. In addition, the cause of failures and recommended actions are provided also. After the fault detection, appropriate changes in software are provided to be able to continue the charger operation but probably with a reduced functionality. For example reduced charging power to a pre-determined level is necessary in many fault cases.

In addition to the fault detection and changes in operation, some design changes in electronic hardware are suggested to increase the reliability. For example providing a bypass current flow path by adding an extra diode to the charger circuit is suggested. Computer simulations have been performed to verify the theoretical analysis, fault detection algorithms and provided solutions for increased reliability. Hardware development to verify the analytical and simulation results is in process.

The project is performed within Electric Power Engineering Division in Chalmers University of Technology in January 2015 till June 2015 with a budget of 700 ksek by Saeid Haghbin as the main researcher and Torbjörn Thiringer as the scientific advisor.

The project was in collaboration with ePower (Kongsberg Automotive) as one of the leading on-board charger producers. The idea was to use the project results to enhance the products performance.

Around 70% of the project funding is allocated to the staffing and 30% is dedicated to the equipment purchasing including the software and hardware.

Background

On-board battery chargers are the favourable option by automotive industry because of ease of usage and security of supply by drivers. The chargers with an input voltage level of 230 Vac and an input current of 16 A can provide slightly more than 3.3 kW charging power. These devices are one of the widely used chargers for plug-in vehicles and subject of this project.

The design of a power converter like a vehicle on-board battery charger is a multi-objective optimization problem with an interdisciplinary engineering task including the electrical, mechanical, thermal and packaging design. The trend of power electronic advancement is toward a higher efficiency, a lower volume/mass, and more reliability while meeting the requirements from standard regulations with a competitive price.

The reliability is defined as the probability of performing a component, a device or a system its intended function over a time period under a set of pre-known conditions. A power electronics device, in specific an on-board vehicle charger, can fail due to one or several reasons as electrical stress, mechanical stress, over temperature, aging, fire, contamination and so on. Theoretically there are infinite combinations of faults or failures that one can't investigate all of them. There are several tools to identify, prioritize and evaluate the risk of the converter known as FMEA. Basically, it is intended to analyse fault/failure cases as much as possible. There might be different actions as the results of this analysis such as using hardware/software full redundancy, isolation of the faulty area, reconfigure hardware and/or software for a reduced functionality, and calling for a maintenance. The chosen strategy has direct impact on the cost. It is a common engineering case that the converter design will be modified from the planning to application. Depending on when the design is changing, the cost of this change is different.

The main aim of the project is to provide a systematic methodology to enhance the reliability of an on-board charger subjected to important electrical faults. Fault selection, detection, analysis, mitigation and hardware/software design changes are the main parts of the project to achieve the goal that is a more reliable power electronic converter. The developed methodology can be used in other converters like inverters or DC/DC converters.

The required background in project is mainly basic knowledge in power electronics. Electronic components functionality like a power Mosfet and circuit analysis like Boost converter are the main required background to touch the project results in detail. However there are some parts which a general knowledge in quality control like FMEA will be helpful.

General project description

Usually there are two converter stages in the charger circuit: a front-end AC/CD converter as the power factor corrector (PFC) and an isolated DC/DC stage. There are different topologies and variations for each stage. For the first stage, an interleaved Boost AC/DC converter is selected and for the second stage a transformer isolated Full-bridge converter with a Phase-shifted control and zero voltage switching is assumed. The complexity of the charger design considering intended specifications and regulation for a healthy converter is a very challenging task that hinders one to fully investigate the reliability of the device.

Important fault cases are selected and divided into three main categories: semiconductor faults, power capacitor faults, and sensor network faults. Each fault case is investigated in detail and is quantified based on the cause of failure, the failure probability provided by the related standards like US military standard MIL-STD-1629A and SAE-J1739.

For each fault three steps have been considered: fault detection, changing in control strategy after the fault, and providing some design recommendations in each case or some of them to enhance the device reliability. The result of this part is reported as an FMEA table according to SAE-J1739 formatting guidelines. The next step is utilizing the developed FMEA in the circuit level for analytical analysis, computer simulation and a possible practical verification.

For the interleaved Boost AC/DC converter a dynamical simulation model has been developed based on the designed converter. For the control strategy, average current mode control method is selected which provides some enhanced features such as more noise immunity. Conventional protection schemes are added to the developed simulation model to achieve a more realistic set up compared to the available controllers in the market. Different fault cases are analysed from the circuit point of view by using the relevant equivalent circuit and control strategy. In addition, extensive simulations have been performed to verify analytical results. The idea is to continue the work to develop a hardware setup for a practical verification.

For the DC/DC stage, a transformer isolated phase-shifted Full-bridge converter is considered. Different fault cases are investigated in steady state. Dynamical simulations are still in development process. For this stage a peak current mode control scheme is considered including conventional protection schemes like over voltage, under voltage and over current.

The aim of this work is firstly to develop the FMEA of the charger considering the important failures in semiconductors, dc bus capacitors and sensor networks. More than 20 faults are investigated in which for some of them it is possible to enhance the after-fault functionality by the developed appropriate detection or mitigation algorithms. The

FMEA table is updated according to the developed methods to show the reliability improvement of the charger.

After fault detection, a proper control action is proposed to be able to continue charging, but maybe with a reduced functionality. In addition, some circuit design changes are provided to enhance the reliability with a reasonable added price. There are some faults that have large risks like explosion, in which hardware modifications are suggested to reduce those risk. During the project extensive dynamical simulations are developed and performed to verify the theoretical analysis. The final aim of the project is to verify some cases in a practical setup that is under progress.

Achieved results

The achieved results of the project that is reliability improvement of a 3.3 kW on-board battery charger can be listed as:

1. Selection and evaluation of important electrical faults
2. Analysis and investigation of each fault
3. Providing post-fault control strategies to reduce the impact of faults as much as possible, for instance with a reduced functionality
4. Providing some hardware changes to increase the charger reliability, especially for the faults with a high risk number

The fault selection cases are according to experience, suggestions by the relevant standards and exploring technical literature. More than 20 faults are considered in this project that each of them are quantified by a risk number to prioritize them. Analysis and simulation of each fault is the next result. For each fault case, a post-fault control strategy is suggested to reduce the impact of the fault, even with a reduced functionality such as a lower charging power. Finally, some hardware changes are suggested, especially for the faults with a high risk number to increase the system reliability. The results are summarized on the developed FMEA and computer simulation files.

A 3.3 kW battery charger is designed based on one of the most popular circuit configurations. The healthy charger is analysed and simulated by using the Ansoft/Simplorer package. A FMEA is developed to cover the most important fault cases according to the recommendation provided by SAE and US military standards. Fault cases are theoretically analysed and dynamically simulated. Proper actions are provided to continue the device operation after a specific fault. In addition, some electronic circuit level design recommendations are provided to enhance the charger reliability.

Contribution to hybrid vehicle technology

The main contribution of the project is to improve the battery charger reliability and functionality subject to different electrical faults. In addition, a systematic methodology is developed to translate the before/after fault specifications/conditions to the circuit component level to enhance the device reliability. In general, reliability is one of the key area for further developments of a more electric transportation system. Cost, efficiency, volume, and weight are other key area that are always subject of further improvements. The selected on-board charger is a company product and the project results can directly be used to improve the product reliability and functionality.

Uniqueness and news value

The developed fault detection algorithms and provided recommendations to enhance the circuit performance is developed within this project and authors couldn’t find similar results, specially the connection of the FMEA with circuit level components. Some post-fault control schemes are unique to this project. However, the practical verification can increase the value of the work. The selected charger is one of the state of the art products that needs further investigations towards the reliability direction.

Timing and finance

The project main activities and timing is provided in Table I. The total granted funding to the project is 700 ksek. The initial funding was 500 ksek which increased to 700 ksek to be able to purchase components, equipment, and software to develop a practical setup. The project is fully financed by SHC.

Table I: Fault detection project main activities and timing

Item	Activity	Timing
1	Literature study	January 2015
2	Topology selection	February 2015
3	Analysis of the healthy charger	February 2015
4	Reference group meeting	February 2015
5	FMEA analysis	March 2015
6	Fault Analysis an Simulation according to FMEA	May 2015
7	Providing reliability improvement suggestions and design improvement suggestions	June 2015
8	Reporting	June 2015

Executors and collaboration

The project is carried out in collaboration by the researchers, reference group and the industrial partner and SHC as is specified at the following:

- Main researcher: Saeid Haghbin from Chalmers
- Scientific advisor: Tobjörn Thiringer from Chalmers
- Industrial partner: ePower
- Reference group: Sonja Lundmark (Chalmers), Elna Homberg (SHC), Christer Lundh (ePower) and Mahmoud Afshari Rad (Volvo Truck)

Dissemination of Results

The project is presented in SHC conference event in 2nd of March 2015 in Hallsberg. The hardware development is in process and the results will be published in an IEEE transaction and a conference after the practical verification.

Papers and publications

Saeid Haghbin and Torbjörn Thiringer, 'Electrical Failure Mode Electrical Failure Mode and Effect Analysis of a 3.3 kW Onboard Vehicle Battery Charger,' submitted to IEEE European Conference on Power Electronics and Applications (EPE) 2016 in Germany.

Saeid Haghbin and Torbjörn Thiringer, 'Reliability Improvement of a 3.3 kW Onboard Vehicle Battery Charger by Development of Appropriate Fault Detection Algorithms,' in review in IEEE transactions in Vehicular Technology.

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