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Report on the thesis entitled:
"Modulation Algorithms of Power Electronic Converters for Shaping of Conducted Interference"
Submitted by mr. Hermes José Loschi,
Doctoral candidate at the University of Zielona Gora

To whom it may concern

The thesis goal was to research and develop new dedicated power converter's control algorithms that allow shaping the spectrum of the inherently generated conductive electromagnetic interference (EMI) to meet standardization or application technical requirements. A methodology is proposed to control the switching rate of change of DC-DC converters (but not limited to) using pseudo-random modulation, which can achieve a suitable EMI measurement. For validation of the study a National Instruments (NI) controller with programmable FPGA hardware is used as a cyber-physical platform for fast prototyping. This engineering tool enables the necessary EMI investigations for the proposed pseudo-random modulated converters. A case study for a DC-DC converter is used for showing the flexible implementation and validation of developed concepts.

The doctoral work was supported by the SCENT (Smart Cities EMC Network for Training) project. SCENT was a consortium of three universities and has received funding from the European Union's Horizon 2020 Research and Innovation Program under the Marie-Skłodowska-Curie grant agreement No 812391.

The content of the thesis is distributed within four main chapters, complemented by: an introduction (Chapter 1); a conclusions and directions for further research (Chapter 6); an Acknowledgement part (Chapter 7); a Biography and list of publications (Chapter 8); a references list of 152 for the whole document; and three appendices.

In **Chapter 1** the author highlights the EMI concerns due to the proliferation of power electronics circuits, and introduces the state of art works on control and modulation strategies of power converters using the approaches of deterministic modulation (DetM) and pseudo-random modulation (RanM). Both methods affect the generation of EMI noise differently, and particularly the latter is well-suited for EMI noise spreading. Therefore, the work and main scientifical contributions of this thesis are focused on RanM techniques and implementation. An important point to note is that for benchmarking purposes the average switching frequency for DetM and RanM are kept similar, so that, there are no substantial changes in the power converter's efficiency and the losses in the system are approximately the same. This is very relevant so the benchmark results are mainly focused on the merits of electromagnetic compatibility (EMC). Herein, the main research questions addressed in the thesis are given, and the outline of the work is presented.

Chapter 2 present the behavior of the typical DC-DC converters' generated rectangular pulse trains. It highlights the possibility of defining different values of duty cycle (D) and switching rate of change for DC-DC converters connected in parallel or series. It covers the expected behavior model of rectangular pulse trains based on RanM and DetM.

Chapter 3 complements Chapter 2 with the analysis of rectangular pulse trains through the conducted EMI measurement standards. The considered EMC-test bench system are based on the standards IEC 61000-2-2 and CISPR 16-2-1. This chapter highlights the influence of the super-heterodyne frequency band stepping EMI test receivers in the EMI evaluation. It also provides an overview about the settings of the dwell time when assessing DetM and RanM in DC-DC converters.

In **Chapter 4** the utilized NI PXIe-8135 FPGA-based control platform is presented. This development tool is selected because it is well-suited for the implementation of different PWM techniques, while providing high customization and flexibility. Furthermore, probability density functions (PDF) are used to analyze and improve the RanM algorithms Implementations. The author proposes four methods of distribution the PDF in FPGA without arithmetic division and using fixed-point operations. Also, the PWM algorithms are presented and discussed in terms of expected EMI noise shape.

Chapter 5 presents the main results achieved of the developed LabVIEW-based PWM algorithms (from Chapter 4) when applied to a DC-DC converter with the experimental results carried out in accordance with technical EMI standards.

In **Chapter 6**, the conclusions on the PWM control algorithms, hardware and software details, and conducted EMI measurements are given. The suggested directions for further research are also presented in this chapter.

All in all, the doctorate thesis is well-written and structured in a logical way. The literature review and listed references contains the most relevant state-of-art work in the subject discussed in the thesis. The theory of the proposed research topics are complemented well with step-by-step mathematical modeling, and these are verified with scientific methods by means of computational tools and experimental tests. To present the simulation and experimental data the author take use of several well planned, good-looking and properly sized graphs. This is highly appreciate by other researchers which would be able to replicate and to continue the developments from this thesis work.

Nevertheless the key points from this thesis review are listed in the followings:

How much is the topics of the thesis relevant and up to date?

The implementation of RanM in power electronics converters for improvement of EMI filtering is a hot topic in both power electronics and EMC research fields. This modulation methodology has also been utilized as prior-art for the reduction of converter's power losses while achieving a target control dynamics or system power density or cost, and/or to achieve a flattening of power efficiency curves as function of processed power (for improvement of solar inverters' California

or European efficiency metrics, or consumer electronics energy star efficiency metric, etc), and to improve control dynamics in transient operations. Particularly from the EMI filtering challenges point of view, which is also the focus of this thesis, the key research effort is typically given on shaping the harmonic spectrum of the converter's generated EMI noise, and design guidelines of easy to implement RanM techniques are the most sought research questions. This doctoral thesis complements well other developments found in the literature.

Are the methods applied in the reported investigation original?

All in all, the author investigated and proposed RanM control algorithms with a random stream based on different methods. The detail FPGA implementation and benchmarking of each studied methods are given. Although RanM methods exist previously to this thesis work, the main novelty of the proposed developments lie on the identification and selection of the most suited random stream method for the problem at hand, and its necessary modification for implementation in a fixed-point processor. It is the opinion of the reviewer that this constitute an original and relevant work, particularly the contributions toward the combination of the proposed RanM methods and FPGA implementation, and the detail EMI-test bench development and presented experimental measurements.

What are the scientific value of the results?

The author of this doctoral thesis has undoubtedly contributed to the research of control of power electronics converters with his optimization and implementation approach based on the concept of RanM, particularly focused on conductive EMI noise attenuation. He has produced several scientific articles in his research field, to name a few:

- **H. Loschi**, R. Smolenski, P. Lezynski, W. El Sayed and D. Nascimento, "Reduction of Conducted Emissions in DC/DC Converters with FPGA-based Random Modulation," 2020 International Symposium on Electromagnetic Compatibility - EMC EUROPE, Rome, Italy, 2020, pp. 1-6
- **Loschi, H.**, Smolenski, R., Lezynski, P., Nascimento, D., & Demidova, G. (2020). Aggregated Conducted Electromagnetic Interference Generated by DC/DC Converters with Deterministic and Random Modulation. Energies
- **Loschi, H.**, Lezynski, P., Smolenski, R., Nascimento, D., & Sleszynski, W. (2020). FPGA-Based System for Electromagnetic Interference Evaluation in Random Modulated DC/DC Converters. Energies
- Hamid, A., L. Wan, **H. Loschi**, D. Nascimento, F. Grassi, R. Smolenski, G. Spadacini, Giordano, and S. Pignari, "PSpice-Simulink Co-Simulation of the Conducted Emissions of a DC-DC Converter with Random Modulation," 2020 6th Global Electromagnetic Compatibility Conference (GEMCCON), 2020, pp. 1-4,
- Lezynski, P., Smolenski, R., **Loschi, H.**, Thomas, D., & Moonen, N. (2020). A novel method for EMI evaluation in random modulated power electronic converters. Measurement, 151, 107098.
- **Hermes Loschi**, Douglas Nascimento, Robert Smolenski, Waseem El-Sayed, and Piotr Lezynski. "Shaping of Converter Interference for Error Rate Reduction in PLC Based Smart Metering Systems " Measurements.
- Angel Pena-Quintal, **Hermes Loschi**, Robert Smolenski, Mark Sumner, Dave Thomas, Steve Green, Piotr Lezynski and Frank Leferink. "Impact of Pseudo- Random Modulation on Measured Conducted EMI." IEEE EMC Magazine.

The knowledge derived can be explored in other converter design metrics, e.g., to optimize converter power density, efficiency, dynamic performance among others.

Has the goal of the thesis been achieved?

Based on the research carried out and presented in this thesis, which were confirmed by computational tools and experimental results carried out in accordance with technical EMI standards, it becomes clear that the main goal of the thesis has been successfully achieved.

In conclusion, I state that the thesis manuscript by Hermes José Loschi is an original work of high scientific and technical level, which fulfils all the formal requirements for the doctoral dissertation.

Therefore,

I recommend awarding the doctoral degree to Mr. Hermes José Loschi after successful oral defense of his thesis.

12.04.2023
Enschede, the Netherlands

Addendum

Questions/Comments

1. The thesis work contribution aim on EMC-friendly PWM technique based on the RanM concept. How the research of the best proposed RanM technique would differentiate if the main goal of the proposed PWM technique would focus on other performance metrics gain instead of EMI attenuation, e.g., different scenarios can be used as benchmarking, such as How the cost of a converter design could be optimized while using a minimal power efficiency target, among others?

2. The author mentioned that harmonic spreading methods is considered by some scholars as "fraudulent way to comply with EMC standards". Is it a problem with the standard that needs to be updated? How the standardized EMC test receiver or measurement techniques/data analytics should be adapted to have a fair way for identifying better EMC problems?

3. DC-DC converter are typically design with multi-stage passive filtering which are necessary for compliances with EMC standards. PWM implementation with variable frequency can cause problems for the feedback control loop stability because filter resonances may be trigged during operation. Passive damping techniques could be used to solve this issue, but at a cost of power efficiency, therefore it should be avoided. Active damping could be used, but depending on the resonance frequency high accuracy sensors, high speed analog-to-digital converters, etc would need to be devised to avoid undesirable delays in the measurement. Therefore, how should the variable frequency band be designed to avoid control stability problems?