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Report on the thesis entitled:
**"The Effect of Spread-Spectrum Modulated EMI on the Power Line Communication Systems"**
Submitted by mr. Waseem Elsayeda,
Doctoral candidate at the University of Zielona Gora

***To whom it may concern***

The thesis goal was to research the reliability of Power Line Communication (PLC) data transmission, such as the ones used in smart metering systems, against the modulation and control strategies of power electronic converters operating nearby. Two approaches have been employed to evaluate the performance of the PLC channels, while a buck-type power converter operates with both, conventional (fixed frequency) pulse-width modulation (PWM) and random spread-spectrum (SS) modulations, by: calculating the Frame Error Rate (FER) in percentage; and, calculating the channel capacity in kbit/sec using the Shannon Hartely equation. The purpose is to formulate a relationship between the communication system parameters and the power converter modulation parameters, thus this knowledge will enable that the PLC communication system can be improved by controlling the modulation parameters of the used power converters around it.

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 technical 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); a reference list of 85 for the whole document; two appendices (Chapter 7); an Acknowledgement part; a Biography and list of publications.

In **Chapter 1** the author describe the motivation of the thesis highlighting the importance of robust PLC communications in smart metering systems where power electronic converters operated nearby.

**Chapter 2** discusses various spread-spectrum modulation (SSM) techniques aimed at reducing electromagnetic interference (EMI) from power converters. Four main types of SSM are highlighted: RCFMFD, RCFMVD, RPWM, and RPPM. Each technique randomizes specific parameters within the PWM signal, such as switching frequency, duty cycle, or phase shift, thereby reducing signal power according to modulation settings to meet standards. RCFMFD was favored for implementation due to its widespread use. It enables control over the converter's spectrum shape by adjusting switching frequency and sampling time while maintaining a constant duty cycle. The EMI receiver settings was discussed as it significantly impact output measurements, with the spectrum shape influenced by receiver resolution bandwidth (RBW) and SSM bandwidth (Carson's band) selection.

**Chapter 3** delves into the operation of PLC systems amidst EMI presence, highlighting their essential components: transmitter, channel, and receiver. OFDM modulation is prevalent in smart grid PLC systems for enhanced robustness. However, interference from residential loads and power converters can distort PLC signals transmitted through power cables. The study explore the impact of nonlinear loads and power converter modulation on PLC performance. EMI mitigation solutions, divided into hardware and software approaches, are proposed to enhance communication. Moreover, the influence of converter modulation varies across different communication protocols used in PLC systems, with PRIME and G3 PLC being the most common in smart metering applications, thus meriting detailed discussion in this chapter.

**Chapter 4** simulates the impact of SS modulated EMI on G3-PLC system performance under various conditions using Matlab/Simulink software. Two circuits were simulated: a DC buck converter generating EMI and a G3-PLC circuit as the victim. They were interconnected with parasitic capacitance to simulate real-world EMI coupling. RCFMFD SS modulation was employed. The simulation considered SS parameter settings, particularly the spreading factor controlling modulation bandwidth and the driving signal affecting switching frequency. Results indicated that increasing SS modulation bandwidth decreased communication channel performance despite EMI mitigation. Different driving signal profiles were also analyzed, with non-periodic signals showing better performance than periodic ones. Performance was evaluated through bit error rate (BER) calculations across various scenarios, with the Shannon Hartley equation confirming channel behavior in EMI presence.

**Chapter 5** introduces the practical implementation of the thesis, confirming the simulation results discussed in Chapter 4. It highlights that increased amplitude of circuit EMI poses challenges for PLC channels, particularly when the converter's main switching frequency aligns with the communication system's intermediate frequency. The study explores how three parameters affect G3-PLC performance: spreading factor of EMI noise, driving signal profile (periodical or non-periodical), and sampling rate of the driving signal. Statistical analysis using IBM SPSS software and the Shannon Hartley equation evaluate PLC communication system behavior in the presence of spread-spectrum modulated EMI. Findings reveal that non-periodic signals, like random PAM, result in higher FER compared to periodic signals. Moreover, linearity between FER results and driving signal frequency varies with spreading factor. Despite spread-spectrum technique limitations in EMI mitigation, it can offer acceptable performance when considering a trade-off between maximum allowable amplitude and channel FER. The study concludes with recommendations, advising choosing switching frequency and driving signal sampling frequency far from communication system frequencies for optimal performance. The thesis's theoretical analyses and experimental results affirm its conclusions

In **Chapter 6**, the conclusions of the thesis 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 seems to contain 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 computational simulation tools and experimental tests. To present the simulation and experimental data the author take use of several well planned, and properly sized graphs.

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 integration of spread-spectrum modulation in power electronics converters to enhance EMI filtering has become a prominent subject of research in both power electronics and EMC disciplines. The vulnerability of smart metering systems to electromagnetic noise is a significant societal concern due to the potential for substantial measurement errors, impacting both end-users and distribution system operators (DSOs). The EMC challenges faced by smart meters are widely acknowledged. This doctoral thesis identifies a research gap by addressing the intersection of these two areas, providing valuable insights that complement existing literature.

***Are the methods applied in the reported investigation original?***

In summary, the author utilized established modulation techniques in conventional power electronics converters and assessed their impact on PLC communication systems. The methods and data analytics employed to measure this influence, along with the proposed measurement setups, are appropriate and familiar concepts. However, the effectiveness of simulations and hardware implementations may vary depending on the user's expertise, leading to differing results from person to person.

***What are the scientific value of the results?***

The author of this doctoral thesis has made contributions to research on EMC compliance of power electronics converters within micro-/nano-grids, particularly in contexts where PLC communication systems, such as those in smart metering systems, are utilized. His approach to optimization and implementation, centered around the concept of SSM, has focused notably on addressing conductive EMI noise in the supra-harmonic frequency range.

In general, SSM can be utilized in power converters to achieve satisfactory EMI mitigation and maintain acceptable communication channel performance under specific conditions. These conditions include selecting a switching frequency that is distant from the intermediate frequency of the communication system and choosing a driving signal sampling frequency that is far from the subcarrier frequency of the communication system. These guidelines can be embedded in future EMC compliance standard for power electronics systems.

Furthermore, he has authored numerous scientific articles in his research domain, a few of which include:

- **Waseem El Sayed**, Hermes Loschi, Robert Smolenski, Piotr Lezynski, Choon Long Lok ,"Performance Evaluation of the Effect of Power Converters Modulation on Power line Communication",XIV Konferencja Naukowa Sterowanie w Energoelektronice i Napedzie Elektrycznym 2019.

- **W. E. Sayed**, H. Loschi, C. L. Lok, P. Lezynski and R. Smolenski, "Prospective Analysis of the effect of Silicon based and Silicon-Carbide based Converter on G3 Power Line Communication,", 2020 International Symposium on Electromagnetic Compatibility - EMC EUROPE, 2020, pp. 1-6.
- **W. E. Sayed**, H. Loschi, M. A. Wibisono, N. Moonerr, P. Lezynski and R. Smolenski, "The Influence of Spread-Spectrum Modulation on the G3-PLC Performance", 2021 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC), 2021, pp. 1-4.
- **Sayed, W.E.**; Lezynski, P.; Smolenski, R.; Moonen, N.; Crovetti, P.; Thomas, D.W.P. "The Effect of EMI Generated from Spread-Spectrum-Modulated SiC-Based Buck Converter on the G3-PLC Channel", Electronics 2021, 10, 1416.
- **Sayed,W.E.**; Lezynski, P.; Smolenski, R.; Madi, A.; Pazera, M.; Kempski, A. "Deterministic vs. Random Modulated Interference on G3 Power Line Communication", Energies 2021, 14, 3257.
- **W. El Sayed**, P. Crovetti, N. Moonen, P. Lezynski, R. Smolenski and F. Leferink, "Electromagnetic Interference of Spread-Spectrum Modulated Power Converters in G3-PLC Power Line Communication Systems," in IEEE Letters on Electromagnetic Compatibility Practice and Applications, vol. 3, no. 4, pp. 118-122, Dec. 2021.

***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 Mr. Waseem Elsayeda is an original work of good scientific and technical level, which fulfils all the formal requirements for the doctoral dissertation.

Therefore,

**I recommend awarding the doctoral degree to Mr. Waseem Elsayeda after successful oral defense of his thesis.**

Thiago Batista Soeiro

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Prof. dr. Thiago Batista Soeiro

**Addendum**

*Questions/Comments*

1. The thesis work contribution focus on the benefits of implementing EMC-friendly PWM technique based on the SSM concept for the PLC communication system. The frequency of interest falls into the supra-harmonics frequency band (2kHz – 150kHz). It would be beneficial to correlate the EMC standards for harmonic mitigation in the supra-harmonic band for the EU market. Add the standard limits to the frequency band of interest. Make sure to address if the finds of the thesis would be mitigated by the existing supra-harmonic standards required power electronics filtering systems, e.g., if the necessary common- and differential mode filters were added to your designed buck-converter would you still have any issue in the PLC tests carried out in the thesis?

2. How can the insights gained from this thesis be applied to formulate an appropriate EMC harmonic compliance standard for power electronics systems aimed at safeguarding PLC communication systems in smart metering systems? Utilizing the guideline suggested: "Selecting a switching frequency that is distant from the intermediate frequency of the communication system, and choosing a driving signal sampling frequency that is far from the subcarrier frequency of the communication system," how would this translate into a more rigorous standard?

3. Chapter 5 details the coupling circuits implemented for the tests. In Figure 5.7, how the DC Voltage Supply impacts the test circuit? Questions arise regarding whether this is a galvanically isolated power supply and how its EMC filtering would influence the proposed tests. The common-mode current flowing through the artificial EMI capacitive coupling should also pass through the DC source. Therefore, it is advisable to depict the current circulation path and, if you agree that the DC voltage supply affects the measurements, please provide guidance in the thesis on how to design an effective tester.