The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Faculty of Engineering

The University of Nottingham
University Park
Nottingham
NG7 2RD

www.nottingham.ac.uk/engineering

Prof Ana Vukovic
George Green Institute for Electromagnetics research
Faculty of Engineering
University of Nottingham
Nottingham University Park
NG7 2RD

Nottingham, 23rd February 2024

Report on the Ph.D. Thesis titled:

"The Effect of Spread Spectrum Modulated EMI on the Power Line Communication Systems",

submitted by Waseem Elsayed, at Uniwersytet Zielenógorski, Poland.

Currently there exists a growing trend towards modernizing electrical grids and incorporating smart grid technologies for both metering and energy supply. Current advances in the Internet of Things (IoT) technology also result in its integration in the smart grid infrastructure. Developers and suppliers tend to use existing infrastructure for communication whenever possible as a way of minimizing costs. An example is the smart meter where existing power lines are used as communication channels. Power line communication is developed by G3-PLC regulation spanning the range 3-150kHz. At the same time most power converters use switching frequencies in the range 9-150kHz which falls into G3-PLC communication band and present themselves as Electromagnetic Interference (EMI) to the communication line. This EMI couples to the PLC line via parasitic coupling paths that exist between converter and the PLC.

It has been shown that Spread Spectrum Modulation (SSM) technique used on power converters can reduce the overall amplitude of EMI signal at converter switching frequencies albeit by spreading it over a wider range of frequencies. The thesis explores how the use of converter Pulse Width Modulation (both conventional and Spread Spectrum Modulation) affects the communication channel in PLC and whether SSM can be used to minimize the EMI impact on PLC. The thesis considers a buck converter both with Si and SiC based transistors as a source of EMI and PLC as the victim circuit.

In order to answer this question, the candidate has undertaken an interesting study in a topical area that is clearly a challenge to the community. A significant volume of work has been undertaken and includes both simulation and practical measurements and a number of results are presented.

The thesis is structured as follows:

- The introduction chapter briefly sets the scene for the motivation for this work and summarises types of conducted interference that can exist between devices. The chapter summarises the objective of the thesis and states the measurable quantities that would be used to assess the impact of PWM on communication channel in PLC, namely Frame Error Rate and Channel Capacity.
- The Chapter 2 introduces the main parameters of the Pulse Width Modulation (PWM) with a mathematical formulation. Spread of spectrum is achieved by randomising the modulation carrier or by randomising the duty cycle or the phase shift of modulation. Types of driving signals that are used to change the switching frequency are defined, namely pseudo random Pulse Amplitude Modulated (PAM) signal, sawtooth signal and sinusoidal signal. Throughout the chapter a number of figures showing impact of randomised parameters on the PWD time waveform are used to aid understanding of the main concepts. The impact of driving signal choice on the SSM spectrum is also shown. The strategy that is to follow is clearly summarised and aims to analyse SSM parameters (frequency deviation, driving signal) in order to achieve flat SSM spectrum.
- Chapter 3 starts by overviewing the previous research on the effects that different loads have on PLC communication namely LED and Flourescent lamps and number and type of power converters. Reported ways of minimising EMI using hardware and software solutions are also overviewed. PLC standards and regulations are introduced and the main parameters of the PLC communications system are summarised: at the side of transmiter (signal modulation, OFDM frame format and up-conversion), the main channel (channel noise and capacity) and the receiver (down-conversion, demodulation and synchronisation).
- Chapter 4 presents the MATLAB SIMULINK simulation model of the whole system that included the buck converter and PLC communication line. All parameters are clearly defined and MATLAB model for each part of the system is presented. The signal spectrum of the PLC line (30-90kHz) and the buck converter output voltage frequency spectrum (57-67kHz) is presented. A number of simulation results are presented: the system main parameters are analysed as a function of spreading factor, driving signal and driving signal frequency. The main parameters such as magnitude of the differential voltage, the capacity of the channel, buck converter spectrum and Bit Error Rate (BER) are observed. Particularly interesting results are presented in Fig 4.22 and 4.23 where BER is evaluated for different driving signals and for different spreading factors as a factor of sampling frequency and its subsequent impact on channel capacity. Whilst results are all clearly presented, the comments on results should be

more thorough – for example distinguishing between spreading factors and comparing between driving signals. Fig. 4.21 is not very clear – according to text modulation index is calculated as the ratio of the bandwidth (9450Hz) and modulating signal frequency (say maximum of 1000Hz). How then in Fig.4.21 the modulation index takes values greater than 10? This will be probed at viva. There is a link between the spreading factor and the modulation index and it is also not clear how modulation index affects the spectrum of the buck converter signal and that will be probed at the viva.

- Chapter 5 presents practical implementation of the buck converter-PLC setup and defines all practical parameters and parasitic capacitive and mutual coupling scenarios between PLC and the buck converter. Two types of buck transistors are considered: Silicon (Si) and Silicon Carbide (SiC), supply voltage and switching frequency. Text states that Fig.5.15 is showing that SiC based buch converter has 4dB lower magnitude spectrum – that is not obvious to the reader - perhaps a zoom-in picture at around 60Hz should be added to the graph. Measured results show that SiC and Si based buck converter have similar effects on the Frame Error Rate (FER) on PLC line. The chapter proceeds with investigating how the spreading factor, the driving signal profile and driving signal frequency affects the frequency spectrum of the buck converter, Frame Error Rate (FER) and capacity of the line. There are few typos and inconsistencies in the presenting data: Fig.5.43 should be a heat map and not a 3D surf plot and spreading factor is sometimes given in percentage and sometimes not. Overall results give same qualitative behaviour as those presented using MATLAB SIMULINK model. No direct comparison was given with simulation results. When the experimental and simulation results are directly compared there are significant differences in actual values for example, simulation results predict capacity loss of ~70% and experimental results predict a maximum of 30%. Similarly EMI peak magnitude reduction is greater in experimental measurements than in simulation. It would be beneficial to the reader for these results to be compared and comments included on possible sources of difference.

  Results presented in the table 5.5 and 5.6 are difficult to interpret and this will be probed at the viva.
- The Chapter 6 presents the main conclusion for each chapter and discusses further work.

The thesis is written very clearly, outlining all the parameters of relevance and the structure of the thesis is easy to follow. My only issue of concern is the level of commenting on results and making a stronger overall conclusion. In particular:

- Comparing experimental and simulation results and commenting on sources of difference.
- The thesis shows that SSM can reduce the amplitude of the EMI interference arising from the buck converter in the PLC line albeit at a loss of channel capacity. Experimental results show that

that loss is much lower compared to the simulation results. The main question now is if this loss is acceptable in practical scenarios.

- Above point is directly connected with actual engineering of the whole system i.e. correct switching frequency, sampling frequency, drive signal and factor. A much stronger conclusion could be drawn based on reported results as to what are the optimal parameters that minimise EMI amplitude and also loss of channel capacity.

Overall, the candidate has demonstrated that he can make a comprehensive and detailed analysis of the impact SSM has on the PLC communication line. The publication of a number of journal and conference papers also demonstrates the value of this work. The thesis is very well presented and structured. Overall, comments I consider that the proposed work meets the formal requirements for the doctoral degree and I propose that the thesis is admitted to a public defence.

Ana Vukovic

Ana Vukovic, Dipl.Ing, MPhil, Ph.D., MIEEE, MIET
Professor of Electromagnetic Applications
Head of George Green Institute for Electromagnetics Research
Director of Lightning Technology Research Centre

A: A31a Coates Building, Dept. of Electrical and Electronic Engineering
University Park, University of Nottingham, Nottingham NG7
2RD, UK.
T: +44(0)115 951 5593/ +44 (0) 7969571976

https://www.nottingham.ac.uk/research/groups/ggiemr/index.aspx
https://www.nottingham.ac.uk/research/groups/lightning-technology/index.aspx