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Electromagnetic Interference of Spread-Spectrum Modulated Power Converters in G3-PLC Power Line Communication Systems

Waseem El Sayed, Paolo Crovetti, Niek Moonen, Piotr Lezynski, Robert Smolenski and Frank Leferink

***Abstract*— The impact of spread-spectrum techniques used to mitigate EMI from power converters on Power Line Communication (PLC) systems is studied in this paper. A buck converter, utilizing a Random Carrier Frequency Modulation with Fixed Duty cycle (RCFMFD) based control is considered as a source of conducted EMI and a narrowband G3-PLC as the victim. It is shown that, although considered to be an EMI mitigating technique, the spread spectrum technique has a detrimental effect on the communication channel, which can be explained in the framework of Shannon's information theory. Conventional emission evaluation methods are therefore incompatible with modern day's technology.**

Keywords—Power Line Communication (PLC) - Electromagnetic Compatibility (EMC) - Random Carrier Frequency Modulation Fixed Duty (RCFMFD)

I. Introduction

Nowadays, reliable communication between the smart grid elements is a very important issue for the system's operation. However, the communication network may be susceptible to Electromagnetic Interference (EMI) generated in the complex smart grid environment due to the increased utilization of power converters. Consequently, a higher number of converters will increase the total EMI level and thus the probability of the accumulated noise exceeding levels that devices can withstand is increasing. The presence of the power semiconductor devices in loads such as lamps, chargers, and any other nonlinear devices are the leading cause of the increase in conducted emissions [1]. On the other hand, the increased complexity of the system requires an increase in communication between smart grid elements to assure reliable system operation. Consequently, the communication network may be affected due to parasitic coupling with an EMI source[2], [3].

The Power Line Communication (PLC) is a very important communication network in smart grid systems, especially in smart meter home applications, as it uses the existing infrastructure for data transmission and it can be affected by conducted EMI generated in the system [4][5]. Most of the smart meters in the smart grid operate in the narrowband range of CISPR A standard (from 9 kHz to 150 kHz).

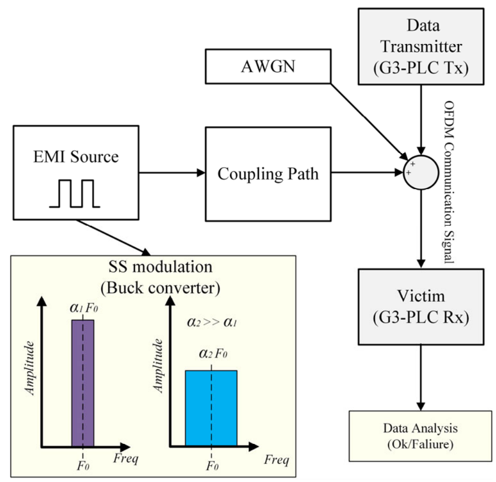

Fig. 1. Block diagram represents the SS moulation EMI with the PLC

Typical sources of EMI are power converters that utilize a fundamental switching frequency laying in the same frequency range of CISPR A. Their impact on the PLC can be quantified via the reduction in throughput, thus the transmission error rate occurring will give an in-situ performance assessment.

Spread spectrum techniques are used to mitigate EMI generated by the power converters at low cost and without requiring additional hardware [6], [7]. Randomized Pulse Width Modulation (PWM) techniques generate the wanted output voltage from the converters with variable switching frequency, as opposed to using a single one. This provides a decreased EMI power spectrum measured according to standard electromagnetic emission test procedures (e.g. CISPR 14-1).

Take-Home Messages:

- A buck converter interfering with a G3-PLC system is considered
- When Spread-Spectrum modulations are applied in the power converter, the measured frame error rate in the PLC system is found to be worse than without modulations.
- The results are consistent with the EMI-induced capacity loss expected from theory.
- While effective to comply with EMC standards, spread-spectrum modulations are not always a good way to mitigate EMI.

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Three recent papers, and one from 2016, in which four of the authors of this paper participated addressed the effects of the randomized techniques in the communication systems,[2], [8]–[10]. In this paper, the effect of the Random Carrier Frequency Modulation Fixed Duty (RCFMFD) based control is studied. It is applied to a buck converter while assessing its effect on the G3-PLC performance under different operating scenarios.

The theoretical background of the traditional EMI evaluation is introduced in Section II. Section III describes the proposed experimental setup and the results are introduced in Section IV. The results will be then discussed in the framework of Shannon's information theory and compared with the channel capacity loss which is brought by spread-spectrum EMI in digital communication channels, as discussed in [3]-[4], [16] is presented in Section V. Finally, the conclusion of the work is given in Section VI.

II. Traditional EMI Evaluation

In general, the EMI is evaluated based on the EMC standards measuring the amplitude spectrum in the applicable frequency range. The allocated narrowband PLC bandwidth is in the range between 3 to 150 kHz, following the CENELEC European standard, EN 50065-1. However, there is an overlap between the EN50065 standard designed for the transmitters of the PLC equipment and other standards such as CISPR 15 (EN55015) and CISPR 11 (EN 55011) [11] [12]. Moreover, the limits of these standards exceed the maximum limits of the non-intention EMI stated on the EN 50065-1 standard.

The most commonly used protocols in the narrowband PLC are the G3-PLC and the PRIME [13], [14]. Like any type of communication technology, the PLC system consists of three main parts: the transmitter, the channel, and the receiver. The transmitter combines Differential Phase Shift Keying (DPSK) and Orthogonal Frequency Division Multiplexing (OFDM) to transmit the data [15]. In this research we consider using the G3-PLC technology, the G3-PLC technology work with the Physical Layer (PHY) specifications defined in [13]. It has been shown in [16] and [17] that data transmission errors occur most likely at the center of the PLC band, which is where the impedance is the lowest.

During transmission, the data can be affected by several types of noises, e.g. additive white gaussian background noise (AWGN) and periodical impulsive noise [18]. The periodic impulsive noise could be due to the high switching frequency of spread spectrum modulation, especially in the CISPR A standard range which could overlap with CENELEC one.

The basic concept of spread-spectrum techniques is to distribute the power of a signal over a frequency band instead of concentrating it in a specific fixed frequency as shown in Fig.2 This can be accomplished by applying a uniform random distribution source on the PWM signal parameters. Based on [7], spread-Spectrum modulation techniques can be divided into three main types: Random Pulse Width Modulation (RPWM), Random Carrier Frequency Modulation Fixed Duty (RCFMFD), and Random Carrier Frequency Modulation Variable Duty (RCFMVD). In this paper, we focus on using the RCFMFD as a randomized technique for our test setup, at which the frequency changes around the main switching

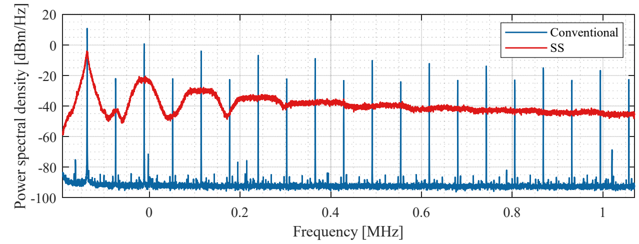

Fig. 2. PWM representation in the frequency domain.

frequency rapidly by a definite rate with time. The RCFMFD follows those equations

$$f_{PWM} = f_0 + \Delta f \times \delta \quad (1)$$

$$\Delta f = f_0 \times \alpha,\ \alpha: 0.05 \text{ to } 0.5 \quad (2)$$

where f_0 is the central frequency of the spread modulation signal, f_{PWM} is the output frequency of the spread signal, α represents the spreading factor of the signal and δ is a random variable with uniform probability density function in the [-0.5, +0.5] interval.

III. The Proposed Experimental Setup

In this section, the experimental testbed is presented. The experimental setup consists of two main circuits: the communication circuit and the power circuit. Both circuits are coupled together by means of mutual coupling between the communication cable and the power cable as shown in Fig. 3.

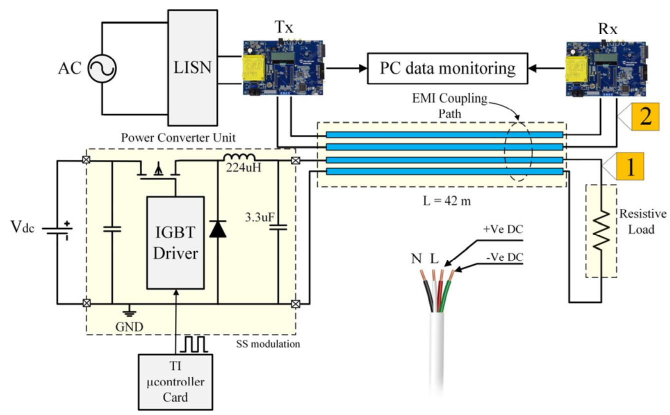

Fig. 2. PLC system connection diagram

A. PLC Circuit

Two PL360 PLC modems from Microchip are used to perform the point-to-point communication. The modems are programmed to operate using the G3-PLC standard. Between the mains connection and PLC system, the Line Stabilization Impedance Network (LISN) is used to provide a well-defined termination impedance to the cable and also to suppress additional EMI from the power grid. An overview of the PLC test parameters is given in Table. I.

TABLE I. PLC Test Assumptions

Type of PLC communication standard	G3-PLC
Data size	65 bytes
Physical layer	OFDM
Modulation	DBPSK
The nominal bitrate	0 to 33.4 kbit/Sec

Total sent packets	2000
The time between each packet	500 ms
The medium	Single-phase cable of length 42 m

B. Power Converter Circuit

The power converter considered in the experiment consists of a single transistor was utilized to perform the buck converter operation with a maximum operational power of 1800 W and with a maximum input voltage of 450V. Moreover, a lowpass LC filter was implemented with a cut-off frequency of 5.8 kHz to enhance the output voltage and current. A Texas Instruments TMS320f28335 DSP card is used to apply the RCFMFD modulation. The duty cycle is fixed to 50 % and the switching frequency is spread around a central frequency of 63 kHz, which coincides with the intermediate frequency of the PLC bandwidth. The used supply voltage is 150 V and a sliding resistor is adjusted so the maximum current drawn is 1.25 A. The positive output cable is placed close (in a bundle cable) to the PLC circuit to ensure coupling between the systems.

IV. PLC Experimental Results

All the results were taken using Gauss Instrument EMI receiver, the average detector (AV) was used in the frequency spectrum measurement with Intermediate Band Width (IFBW) of 200Hz, following the CISPRA standard. The RCFMFD equations are implemented in the MATLAB Simulink using a uniform random number generator and several additions and multiplications. The uniform random numbers are generated between -0.5 to 0.5 with a sampling time of 25 µs, the spreading factor (α) is a factor that controls the spreading of the generated signal, it can be between 5 % and 27 %.

Fig. 4. shows the 3D spectrogram of the PLC signal measured at point 2 in Fig. 2, near to the receiving modem. The G3-PLC standard operates between 35 kHz and 91 kHz, the amplitude of the PLC signal in the intermediate frequency of the signal (at 63kHz) is 76 dBuV.

Due to the coupling path between both circuits, the effect of the converter appears in the PLC circuit. The measured spectra for different values of α are shown in Fig. 5. These were measured at the PLC side, i.e. at point 2 in Fig. 3. It can be seen that with increasing values of α gives lower peak amplitudes and an increased spreading effect for the signal power.

The tests are performed by changing the value of α, i.e. varying the spreading in the RCFMFD modulation. The Frame Error Rate (FER) is a good indicator for the PLC performance in the presence of the EMI source [19], it is defined as the ratio between the broken frames data to the reference sent data, it is represented in percentage as

$$\mathrm{FER}(\%) = \frac{\text{Broken Frames}}{\text{Reference Frames}} \times 100 \qquad (3)$$

Fig. 6 shows the impact of the converter modulation on the PLC signal and it reveals that the FER percentage increase with increasing α.

The highest probability of erroneous data transmission appears in the case of α = 27 %. This effect is contradictory to the conventional assumption: "when applying spread spectrum techniques EMI is being mitigated". In the following section, the channel capacity is investigated to explain this contradicting phenomenon.

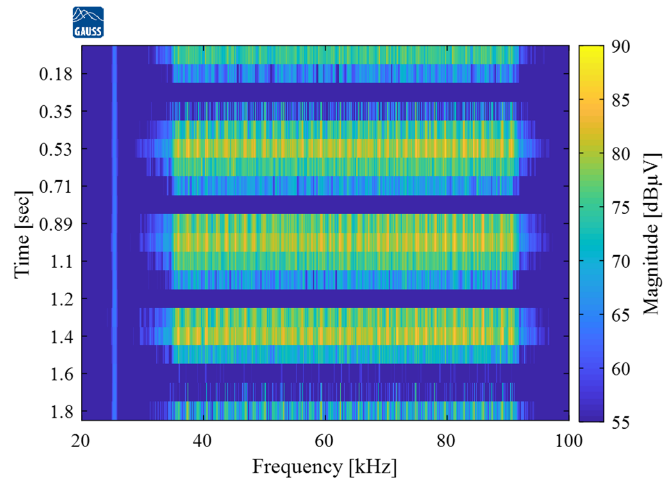

Fig. 3. Spectrogram of the G3-PLC signal

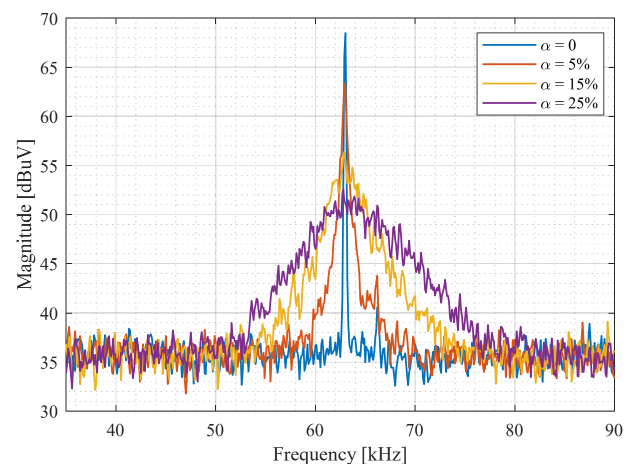

Fig. 4. The spectrum of the measured voltage at the PLC circuit side in case of different spreading factor α values and no PLC signal.

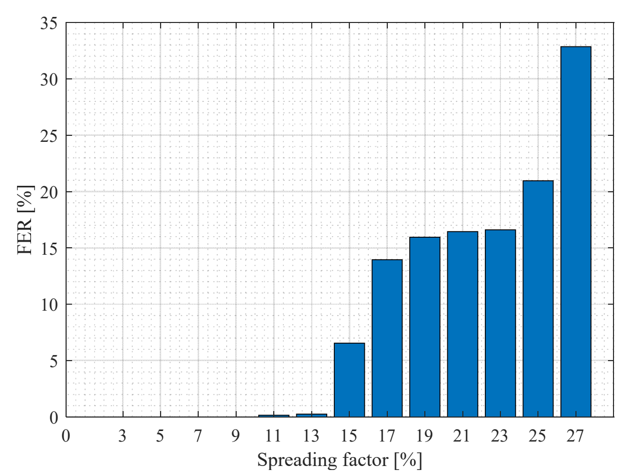

Fig. 5. FER vs Spreading factor.

V. Results Evaluation

Based on the results, the Shannon-Hartley [20] equation is used to evaluate the PLC channel capacity, which corresponds to the maximum rate of data that can be transmitted over a communications channel in the presence of noise and which can be approached in communication systems featuring advanced channel coding like forward error correction (FEC) codes adopted in G3-PLC and PRIME. Following the procedure presented in [20], the data in the G3-PLC channel is used in conjunction with the spread EMI for different values of the spreading factor. The capacity of the PLC channel can be expressed as

$$C_{PLC} = \int_{B_{min}}^{B_{max}} \log_2\left(1 + \frac{S(f)}{N(f)}\right) df \tag{4}$$

where B_{min} and B_{max} represent the minimum and the maximum frequencies of the PLC bandwidth channel, S(f) is the power spectral density of the PLC signal and N(f) is the total noise power spectral density. In the case of a noise-free PLC channel, the N represents the Additive White Gaussian Background Noise (AWGN) with spectral power density equal to N_0, however, in the case of an additional EMI source, N can be considered to be:

$$N(f) = S_{EMI}(f) \tag{5}$$

where S_{EMI} is the power spectral density of the spread conducted noise with the AWGN. Fig. 7 shows the capacity of the PLC channel after applying equation (5) for the measured power spectral density of each spreading factor ranging from 0 % to 27 %, the results show that the channel capacity value decreases with increasing α in the randomized signal. The channel data loss percentage can be calculated as:

$$C_{Loss}(\%) = \frac{C_0 - C_{PLC}}{C_0} \times 100\ \% \tag{6}$$

where C_0 is the calculated capacity of the PLC channel in noise-free case, i.e. only including the AWGN. Fig. 7 shows the channel capacity loss calculated from equation (6).

Even if the channel capacity (in the 600 kbps range) is just an upper bound of the achievable bit rate and the actual G3-PLC and PRIME rate is significantly lower (in the order of 100kbs), thus revealing a clear correlation between theoretical capacity loss and empirical error rate related to the adoption of Spread Spectrum modulation.

VI. Conclusion

This paper analyzes the impact of spread spectrum electromagnetic conducted emissions on the G3-PLC performance, the experimental setup is implemented to emulate a real situation in case of inductive coupling between the power circuit cables and PLC cables. The results show that despite the decrease in the spectrum amplitude provided by the randomized PWM techniques, they deliver more problems to the PLC performance. Furthermore, the increase in the spreading factor α in the used technique is followed by an increase in the percentage of the frame error rate of the sent data. Finally, the Shannon-Hartley channel capacity equation is used to confirm the behavior of the spread spectrum techniques, the capacity of the channel decreases with the increase of the spreading factor α. Based on the experimental results, spread spectrum techniques offer a spectrum peak reduction which helps to cope with EMC standards, but may provide more problems to the communication systems in the smart grid networks. The results can be used in the future as a guideline for the EMC standards, considering the suitable parameters setting of a randomized PWM technique utilized for the power converters in the smart grid environment.

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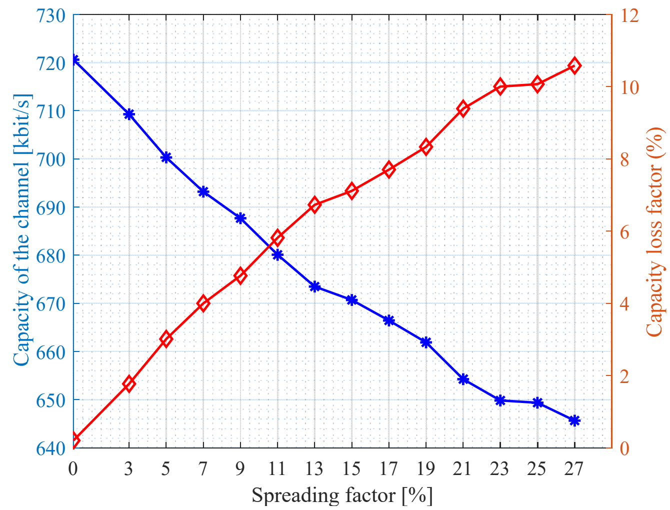

Fig. 6. The capacity of the channel and capacity loss percentage

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