The Effect of the Current Pulse Width from LEDs on Narrowband Power Line Communication and its Analysis in Time and Frequency Domain

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Abstract—This paper presents the time and frequency domain analysis of the current pulse width from a non-linear load and its interference on the Power Line Communication (PLC). This investigation arises from the time-domain characteristics of the current from modern non-linear loads such as Light-Emitting Diode (LED) which show that the current generated by such loads have impulsive characteristics with a certain amplitude and pulse width. Communication test with PLC modem have been performed and the effects are simulated using LTSpice by creating an artificial non-linear load which can produce current pulses with an adjustable pulse width without changing the amplitude. The current pulse from the artificial load is analyzed in the time and frequency domain with MATLAB to observe the emission levels between 2-150 kHz using Fast Fourier Transform (FFT) and Short-Time Fourier Transform (STFFT).

Keywords—Pulse width, non-linear load, interference, time and frequency domain, FFT, STFFT.

I. INTRODUCTION

Interference cases between electrical equipment are growing rapidly in the frequency band between 2-150 kHz, while only a few emission standards in this band are available [1], [2]. The interferences are mainly caused by modern non-linear loads that produce periodic impulsive currents. These impulsive currents can disrupt electrical equipment such as smart meters [3] and also Power Line Communication (PLC) modems which work in the CENELEC-A band between 9-95 kHz. They are for instance used as Mains Communicating Systems (MCS) for Smart Grids. Only PLC below 150 kHz is considered in this paper, as PLC performed at higher frequencies can result in EMI in several wireless communication systems [4].

Cases of malfunctioning PLC due to modern electrical equipment have been reported in several countries [5]. The influence of Switched-Mode Power Supplies (SMPS) on PLC is investigated using the average detector from an EMI receiver [6]. Other research has shown that the performance of PLC can be disrupted by energy-efficient lamps such as LEDs. However, it was assumed that the interference from the LEDs does not affect the Narrowband PLC (NB-PLC) in the CENELEC-A band because its interference level is well-below the PLC signal level [7]. Nevertheless, when the current load is increased linearly with the number of LEDs it does affect the performance of the NB-PLC modem, where the performance is quantified by the Frame Error Rate (FER) [8]. However, the pulse width of the current from LEDs also

slightly increases with the number of LEDs, which also increases the duration of the interference. Therefore, the pulse width of the current pulses will be analyzed to estimate its effect on the spectral content of the interference in the frequency band of the NB-PLC. The analysis needs to be performed in the frequency and time-domain because the non-linear loads have time-varying characteristics which cannot be analyzed by only using a frequency domain analysis [9], [10]. The objective of this work is to provide a better understanding of the effect of the current pulse width from the non-linear loads on the interference between 2-150 kHz. This is performed to implement smarter EMC standards for the interference measurement and to enable the communication inside the grid using NB-PLC.

The time and frequency domain analysis of the effect of the current pulse width can be performed by using a Short-Time Fast Fourier Transform (STFFT) [11], [12] to show that the spectral content of the current pulse also changes in the time domain because of the time-varying characteristic of the load. A spectrogram resulting from the STFFT can show that there are low interference areas between the current pulses which can be utilized for communication purpose with NB-PLC [13], [14]. However, the pulse width of the current from the non-linear loads also affects the duration of the low interference areas or the so-called “green zones” in the time domain.

In this paper, a measurement of the interference from LEDs on NB-PLC is performed, and the EMI from LEDs current pulse widening is analyzed in the time and frequency domain separately, but also simultaneously using a spectrogram. An artificial non-linear load is simulated using LTSpice. The artificial load consists of a Pulse Width Modulation (PWM) generator, a switch and a resistor to produce currents with adjustable pulse width and a constant amplitude. The impulsive current from the load is simulated and analyzed in the time and frequency domain using FFT and STFFT to observe the emission level in the frequency band between 2-150 kHz.

The paper is structured as follows: Section II describes the interference from LEDs on Narrowband PLC, Section III describes the time and frequency domain analysis of the current pulse width, followed by the simulation results and analysis in Section IV, discussions in Section V, and conclusions in Section VI.

II. INTERFERENCE FROM LEDs ON NARROWBAND PLC

A. Experimental Setup

A measurement is performed to observe the interference from LEDs on NB-PLC as shown in Fig. 1. The

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communication test is performed using two ATPL360-EK PLC modems from Microchip which work in the frequency range between 35-95 kHz. Up to 32 LEDs are used as possible interference sources. A Line Impedance Stabilization Network (LISN) is used for isolating the test setup from the interference of the mains. A breakout box is used in combination with a multichannel digitizer to measure voltages and currents simultaneously [15], [16]. The differential mode current is measured using a TA189 current clamp from Pico Technology [17] and a Picoscope 4824 as the multichannel digitizer.

Fig. 1. Measurement setup.

B. Measurement of the Current Pulse and the PLC signal

The time-domain plot of the voltage and current of 32 LEDs is shown in Fig. 2. The period of the current pulses from the LEDs is 20 ms. The amplitude of the current pulses is 3.2 A, which is the highest value of the peak amplitudes and thus the worst interference case as shown in TABLE I. The pulse width of the current pulses is 2 ms, which is defined by the duration when the current is above 0 A to show that the current pulse represents the interference duration.

Fig. 2. The time-domain plot of the voltage (blue) and current (red) of 32 LEDs.

The time-domain plot of the PLC signal is shown in Fig. 3. The period and duration of the PLC signal is 40 ms and 17.9 ms, respectively. From the time diversity concept, the PLC signal length is still less than the available low interference duration, which means that the PLC signal should not have interfered. The current amplitude of the PLC signal is 0.4 A. The amplitude of the PLC signal is already below the value of the current from 4 LEDs in TABLE I. However, the power and the energy of the current pulse is distributed over a certain range of frequencies. Therefore, the current pulse will also be analyzed in the frequency domain.

By processing the measurement data, the spectrum can be obtained as shown in Fig. 4. It can clearly be seen that the noise produced by the LEDs is well below the signal levels of the PLC (approximately 40 dB) in the frequency band

between 35-95 kHz. Hence, from the frequency domain analysis, it was not expected that the communication would be disturbed, however as the next subsection will show communication is disturbed when using more than 15 LEDs.

Fig. 3. The time-domain plot of the PLC signal.

Fig. 4. FFT plot of the current from the PLC modem and 32 LEDs

C. Communication Test Result

A communication test was performed to observe the impact of the current pulses from the LEDs to the performance of the PLC modem which is measured in FER. 10000 frames are sent during the test, each frame containing 10 bytes of data that requires 17.9 ms of transmission, while the period of the PLC frames is 40 ms. Correct and broken data frames have been counted and used to calculate the FER using (1)

$$FER = \frac{\text{Broken Frames}}{\text{Received Frames}} \times 100\% \quad (1)$$

In TABLE I. the effect of the number of LEDs is summarized. Obviously, increasing the number of lamps linearly increases the peak amplitude.

TABLE I. IMPACT OF LEDs ON PLC

# LEDs	Peak current (A)	Pulse width (ms)	Broken Frames	Total Received Frames	FER
0	0	0	0	9996	0%
4	0.45	1.7	0	9997	0%
8	0.89	1.8	0	9777	0%
12	1.31	1.89	0	9950	0%
16	1.75	1.82	19	9983	0.19%
20	2.11	1.93	509	9997	5.1%
24	2.5	1.9	437	9997	4.4%
28	2.91	1.96	916	9959	9.2%
32	3.2	2.03	1330	9992	13.3%

The communication test result shows that the frame errors are starting to occur with 16 LEDs which produces currents with an amplitude of 1.75 A and a width of 1.82 ms. 32 LEDs produce a FER of 13.3%, which is significantly high for data communication. The experiments show that the PLC has increasingly interfered with more LEDs. The current pulse width also increases, which increases the probability of PLC data frames and the LED current pulses coinciding. The effect of the current pulse width will be further analyzed in the next section.

III. TIME AND FREQUENCY DOMAIN ANALYSIS OF THE CURRENT PULSE WIDTH

A. Time Domain Parameters of the Current Pulses

In order to analyze the effect of the current pulse width, a trapezoidal signal is used as a simple model for the current pulse. The trapezoidal pulse in the time domain has several parameters which represent the current pulses from LEDs, e.g. pulse width (τ), rise time (t_r), and fall time (t_f) as shown in Fig. 5a. Based on the time-diversity concept proposed in [13], the duration where there is no current or only DC is the area where there is very low or almost no interference. Hence it can be used for communication purposes using the NB-PLC.

B. Spectral Analysis

Based on the signal spectra of a trapezoidal pulse, the important parameters which determine the spectral content of the current pulse is the pulse width (τ) and rise time (t_r). τ determines the first breakpoint frequency from the 0 dB/dec. to -20 dB/dec. slope, while t_r determines the second breakpoint frequency from the -20 dB/dec. to -40 dB/dec.

slope as shown in Fig. 5b. From this figure, it can be seen that narrower pulse width will have a higher breakpoint frequency and thus strong spectral components up until a higher frequency as compared to the wider pulse width [18].

C. Short-Time Fast Fourier Transform (STFFT)

The frequency-domain analysis with FFT in Fig. 4 shows that the current pulses from LEDs are around 40 dB below the PLC signal level in the frequency band between 35-95 kHz. Hence, the frequency domain analysis also does not show that the PLC signal is being interfered with. However, TABLE I. shows that frame errors are starting to occur with 16 LEDs and also increases with the number of LEDs.

To more accurately predict the interference from the LEDs on the PLC signal, STFFT is performed to analyze the interference simultaneously in time and frequency domain. STFFT is performed by dividing the signal into smaller windows in the time domain to be transformed into the frequency domain. The spectrums from each window in the time domain are combined to show the change of the spectrum over time in a spectrogram [11]. Fig. 5c shows the spectrogram from the STFFT of the trapezoidal signal in Fig. 5a. It can be seen that the wide spectral contents from the trapezoidal pulse occur only during the rise and fall time of the signal. Hence, the pulse width of the trapezoidal pulse does not affect the duration of the interference. The peak emission during the rise and fall time of the trapezoidal pulse is shown in Fig. 5d. The spectrogram also shows that there are low interference areas (shown in dark blue color) when there is no current and during the constant (DC) current.

Fig. 5. (a) The trapezoidal pulse, (b) its spectral content, (c) its spectrogram, and (d) the peak emission during the rise and fall time

In order to model the current pulses from the LEDs, LTSpice is used to simulate the effect of the wider pulse due to the higher number of LEDs without changing the amplitude of the current pulse. An artificial load that generates an adjustable pulse width and constant peak amplitude is shown in Fig. 6. The circuit consists of the mains voltage V_1 , a voltage divider (R_2 and R_3), a comparator with reference voltage V_2 , a voltage-controlled switch SW, and a fixed 100 Ω resistor R_1 .

Fig. 6. Schematics of the artificial load in LTSpice

The pulse width of the current is adjusted by the LT1017 voltage comparator which produces a PWM signal based on the comparison between the mains voltage divided by 1000 and the reference voltage V_2 . Larger pulse width is obtained by lowering the reference voltage. The correlation between the reference voltage V_2 and the pulse width τ (in ms) can be written in (2), where V_1 is the mains voltage amplitude which is 325 V and ω is the angular frequency of the mains, while R_2 and R_3 are the voltage divider resistors which are 50 k Ω and 50 Ω , respectively.

$$V_2 = V_1 \frac{R_3}{R_2 + R_3} \cos\left(\frac{\omega\tau}{2}\right) \quad (2)$$

In this case, the pulse width values which will be analyzed are 1 ms, 2 ms, 4 ms, and 8 ms. The 1 ms and 2 ms pulse width are based on the measurement results with LEDs, while the 4 ms and 8 ms pulse width are aimed at other types of interferers. Therefore, based on (2), the values of V_2 for each pulse width are 0.321 V, 0.309 V, 0.263 V, and 0.100 V, respectively. The voltage comparator will produce the PWM control signal which drives a switch (SW) to draw the current with constant amplitude from the mains voltage via the fixed 100 Ω resistor. The next section will begin with the analysis of the PWM signal from the comparator.

IV. SIMULATION RESULTS AND ANALYSIS

A. Time Domain Waveform of the PWM control signal

The time-domain waveforms of the 5 V PWM control signal from the voltage comparator are plotted in Fig. 7. The PWM control signals have 1 ms, 2 ms, 4 ms, and 8 ms pulse width with 5 V amplitude and 20 ms period. Fig. 8 shows that the PWM control signals have around 7.5 μ s of a rise time between low and high state of the comparator output voltage, defined by the 10% to 90% value from the 5 V amplitude.

Fig. 7. The waveform of the mains voltage and PWM control signal from the comparator

Fig. 8. Switching time and the change of the PWM control signal for the current pulse width of (a) 1 ms (b) 2 ms (c) 4 ms, and (d) 8 ms

B. Spectral Analysis of the PWM control signal

The spectral analysis of the PWM control signal is carried out by performing FFT from the PWM voltage waveform in MATLAB. The spectrum of the current pulses is plotted for certain values of the current pulse width, which are 1 ms, 2 ms, 4 ms, and 8 ms.

Fig. 9. The spectral content of the PWM control signal

The spectrum of the PWM control signals from Fig. 7 is shown in Fig. 9. It can be seen that the 8 ms pulse width has the highest spectral content in the 50 Hz frequency due to the lowest first breakpoint frequency (39.8 Hz). The spectral

content of the PWM control signal has the same values for all pulse width at the frequencies above 1 kHz due to the same rise time for all pulse width values. Hence, the pulse width of the trapezoidal signal does not affect the spectral content at the frequency above 1 kHz.

C. Time Domain Waveform of the Current Pulses

In order to obtain a more accurate representation of the current pulse from LEDs, the current over R_1 will also be analyzed in the time and frequency domain. The waveform of the mains voltage V_1 and the current over R_1 is shown in Fig. 10. It can be seen that the current pulses have the same amplitude, which is equal to the amplitude of V_1 divided by R_1 or 3.2 A, which also represents the highest current amplitude from TABLE I. Fig. 11 shows that the current pulses have 4 μ s switching time, which is defined by the duration of the transition of the switch from the “off” to “on” state. The current pulses also have a 20 ms period due to the positive reference voltage of the comparator.

Fig. 10. The waveform of the mains voltage and the current over R_1

Fig. 11. Switching time between “off” and “on” state of the switch and the change of the current with a pulse width of (a) 1 ms (b) 2 ms (c) 4 ms, and (d) 8 ms

D. Spectral Analysis of the Current Pulses

Fig. 12 shows the spectral content of the current pulses by using FFT. The spectrum shows that the 8 ms current pulse width has higher spectral content in the 50 Hz frequency since the current pulse has a 20 ms period. The 2 ms current pulse width also has the closest correlation with continuous 50 Hz sine wave signal and it has the lowest first breakpoint frequency.

The difference of the spectral level between the 1 ms, 2 ms, and 4 ms pulse width is less than 5 dB at the frequencies above 1 kHz due to the slight difference in the

change of the current during the switching time as shown in Fig. 11, while the 8 ms current pulse has around 10 dB lower emission level compared to the 4 ms current pulse due to the lowest change of current during the switching time.

Fig. 12. The spectral content of the current pulses

E. Time and Frequency Domain analysis with STFFT

Fig. 14a to Fig. 14d shows the spectrograms for the 1 ms, 2 ms, 4 ms, and 8 ms current pulse, respectively. It can be seen that a larger pulse width has more interference duration, and the low interference areas or the “green zones” are reduced. Peak emissions are observed at the edge of the current pulses due to the high change of current during 4 μ s switching time.

Fig. 13. The spectral content of the peak emission of the 1, 2, 4, and 8 ms current pulse width

Fig. 13 shows the spectral content of the peak emission of the 1 ms, 2 ms, 4 ms, and 8 ms current pulse, respectively. It can be seen that the 1 ms, 2 ms, and 4 ms current pulses are not significantly different in the spectral content (less than 2 dB). However, the 8 ms current pulse gives around 10 dB lower spectral content compared to the 4 ms current pulse. This is due to the significantly lower change of current during the 4 μ s switching time. The peak emission of the 1 ms pulse width is between -50 dB and -60 dB in the PLC frequency band between 35 kHz and 95 kHz, which is around 10 dB higher than the emission from the same current pulse value at the same frequency band in Fig. 12.

Fig. 14. Spectrogram of the current pulses over R_1 for (a) 1 ms (b) 2 ms (c) 4 ms, and (d) 8 ms of current pulse width

V. DISCUSSIONS

The time and frequency domain analysis of the current pulse from the artificial non-linear load shows that the spectral content of the emission at the frequencies above 2 kHz can be reduced by increasing the pulse width. The spectral content of the peak emission above 2 kHz was also reduced by increasing the pulse width due to the lower change of current during the 4 μ s switching time. However, the STFFT and spectrogram show that increasing the pulse width gives longer interference duration. This means that there is a tradeoff between the pulse width and the interference duration. The rise and fall time of the current pulse also can be analyzed to determine its impact on the performance of the NB-PLC as the victim of the interference in the frequency band between 2-150 kHz.

VI. CONCLUSIONS

The analysis of the interference current pulse from the artificial non-linear load in the time and frequency domain has been presented. The frequency-domain analysis with FFT shows that wider pulse width gives lower spectral content in the frequency band between 2-150 kHz. The simultaneous time and frequency domain analysis with STFFT and spectrogram shows that wider current pulse width gives longer interference duration, which can be devastating for the NB-PLC signal. The STFFT also shows that the current pulses from the artificial load produce peak emissions during the switching time, which is higher than the emission level shown with FFT. This means that STFFT and spectrogram are better for predicting and analyzing the interference from LEDs on the NB-PLC. Further analysis and measurements can be performed to determine the impact of the current pulse width on the performance of the NB-PLC modem.

REFERENCES

- [1] B. J. A. M. Van Leersum, R. B. Timens, F. J. K. Buesink, and F. B. J. Leferink, "Time-domain methods for the analysis of conducted interference on the power supply network of complex installations," *IEEE Int. Symp. Electromagn. Compat.*, pp. 605–610, 2014.
- [2] F. Leferink, "Conducted Interference, Challenges and Interference Cases," *IEEE Electromagn. Compat. Mag.*, vol. 4, no. Q1, pp. 78–85, 2015.
- [3] B. Have, T. Hartman, N. Moonen, and F. Leferink, "Misreadings of Static Energy Meters due to Conducted EMI due to Fast Changing Current," *Jt. Int. Symp. Electromagn. Compat. Asia-Pacific Int. Symp. Electromagn. Compat.*, pp. 445–448, 2019.
- [4] CENELEC SC 205A, Study Report on Electromagnetic Interference between Electrical Equipment/Systems in the Frequency Range Below 150kHz, October 2015.
- [5] CENELEC TR 50627, Study Report on Electromagnetic Interference between Electrical Equipment/Systems in the Frequency Range Below 150kHz, November 2015.
- [6] W. El Sayed, H. Loschi, R. Smolenski, P. Lezynski, and C. L. Lok, "Performance Evaluation of the Effect of Power Converters Modulation on Power line Communication," *Sterowanie w Energoelektronice i Napędzie Elektrycznym (SENE)*, Łódź, 2019.
- [7] A. S. De Beer, A. Emleh, H. C. Ferreira, and A. J. H. Vinck, "Effects of LED lamps on the power-line communications channel," *ISPLC 2013 - 2013 IEEE 17th Int. Symp. Power Line Commun. Its Appl. Proc.*, pp. 209–213, 2013.
- [8] M. A. Wibisono, N. Moonen, and F. Leferink, "Interference of LED Lamps on Narrowband Power Line Communication," *IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity (IEEE EMC + SIPI)*, 2020, to be published.
- [9] B. Ten Have, T. Hartman, N. Moonen, and F. Leferink, "Why Frequency Domain Tests Like IEC 61000-4-19 Are Not Valid; A Call for Time Domain Testing," *EMC Eur. 2019 - 2019 Int. Symp. Electromagn. Compat.*, pp. 124–128, 2019.
- [10] T. Hartman, N. Moonen, B. Ten Have, and F. Leferink, "Fast Magnetic Emission Tests for Continuous Measurements Around an Equipment Under Test," *Proc. 2019 ESA Work. Aerosp. EMC, Aerosp. EMC 2019*, no. 1, pp. 1–5, 2019.
- [11] S. K. Rönnerberg *et al.*, "On waveform distortion in the frequency range of 2 kHz–150 kHz—Review and research challenges," *Electric Power Systems Research*, 2017.
- [12] S. K. Rönnerberg, S. Member, M. H. J. Bollen, and M. Wahlberg, "Interaction Between Narrowband Power-Line Communication and End-User Equipment," *IEEE Trans. Power Deliv.*, vol. 26, no. 3, pp. 2034–2039, 2011.
- [13] I. Setiawan, C. Keyer, F. Buesink, and F. Leferink, "Time-frequency diversity for solving e deadlock in defining interference levels in power lines," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2016-Novem, pp. 364–369, 2016.
- [14] I. Setiawan and F. Leferink, "Time-frequency diversity measurements in power systems," *2017 XXXIIInd General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS)*, pp. 1–3, 2017.
- [15] C. Keyer, F. Buesink, and F. Leferink, "Mains power synchronous conducted noise measurement in the 2 to 150 kHz band," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2016-Novem, pp. 865–869, 2016.
- [16] T. Hartman, N. Moonen, and F. Leferink, "Evaluation of Multichannel Synchronous Conducted TDEMI Measurements for High Voltage Power Electronics," *IEEE Int. Symp. Electromagn. Compat.*, vol. 2018-Augus, pp. 839–843, 2018.
- [17] M. Appelman, M. A. Wibisono, W. Shalannanda, N. Moonen, and F. Leferink, "Comparison of Time-domain Measurement Techniques for Interference Analysis in Power Line Communication," *2019 IEEE 5th Int. Conf. Wirel. Telemat.*, pp. 1–5, 2019.
- [18] C. R. Paul, *Introduction to Electromagnetic Compatibility {Wiley Series in Microwave and Optical Engineering; 2nd Ed.}*, 2006.