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Şcoala Doctorală de Studii Inginereşti

METHODS FOR ENHANCING POWER LINE COMMUNICATION OVER LOW VOLTAGE NETWORKS (ORIGINAL TITLE)
TEHNICI DE ÎMBUNĂTĂȚIRE A PERFORMANȚELOR COMUNICAȚIEI PRIN LINIILE DE ALIMENTARE CU ENERGIE ELECTRICĂ DE JOASĂ TENSIUNE (Traducere)

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1 Introduction

The two main directions approached in this PhD thesis are the avoidance and filtering conducted emissions (CE) present in the electricity grid. Both techniques have the scope to increase performance, efficiency, and effectiveness of power line communication (PLC) on low voltage power lines.

The noise avoidance and filtering techniques researched in this thesis are intended to increase the reliability, decrease the error rate, decrease latency, and increase data rate.

1.1 Thesis structure

The thesis is structured in the following manner:

Chapter 1 presents the motivation for choosing enhancement methods of narrow band power line communication (NB-PLC) as subject of the thesis together with the list of articles, in which I served as first author, all pertaining to the topic of my doctoral research and produced during that period. The scope and objectives together with the assumptions and limitations of the thesis are presented in this chapter.

Chapter 2 provides an introduction into PLC thus covering the following aspects: PLC working principle, communication channel characteristics, PLC applications in the electricity distribution grid, standardization together with standardization gaps, PLC protocols and frequency spectrum allocation, PLC signal coupling techniques.

Chapter 3 presents an innovative method for detecting devices connected to the power line that generate CE in the frequency band of PLC. The approach involves utilizing smart meters (SM) to establish a link between energy measurements of the load and the communication quality reports obtained from the PLC-G3 modem. By observing practical results, a clear relationship between energy measurements and the noise generated by specific loads becomes evident thus allowing the creation of a transmission schedule for PLC.

Chapter 4 introduces a novel approach for designing and simulating power line filters (PLF) using S-parameters. Although S-parameters have been applied in other high frequency designs in the past, this work is the first to employ this particular strategy for designing PLFs for filtering applications in NB-PLC frequency band. A 13^{th} order passive PLF was created to show the viability of the proposed design framework. Based on the outcomes, it is possible to develop PLFs that perform better compared to the ones available on the market, in terms of NB-PLC frequency band insertion loss, quiescent power, and input/ output impedance.

Chapter 5 marks the concluding segment of my thesis. It commences with overarching conclusions drawn from the research conducted over the past years. The theoretical contributions that this thesis makes to the field of PLC research are then presented, together with the newly developed practical contributions. The conclusion is followed by outlining prospective future routes in this particular field of study that may be of interest to researchers and experts.

1.2 Scope and Objectives

To establish clarity, this section will outline the scope and objectives of the thesis. It will define the specific aspects of PLC that will be addressed. Additionally, the intended outcomes and goals of the research will be stated.

This thesis provides extensive answers for these questions:

1. How and why is PLC integrated in the electricity grid?
2. What are the challenges that PLC face in the power distribution grid?
3. Is there a way to address these challenges without any modification in the electricity grid? How to implement this non-invasive improvement technique?
4. What modifications could be needed in the power grid? How to implement these modifications?

1.3 Assumptions and Limitations

Acknowledging the assumptions made within the thesis is essential to maintain transparency and establish the boundaries of the research. This section will discuss the limitations of the research, such as specific environments or scenarios that are not considered.

The concepts researched and presented in this thesis have been developed for CENELEC A, B, C, and D bands and validated in laboratory environment using measurement setups that are derived or identical to international standards, which are suitable for AC European power grid. Extension of the usage towards FCC (9- 490kHZ) [1] and ARIB (10-450kHZ) [2] PLC bands as well as different power grid standards (i.e. North American electricity grid) is possible but it will require redesign due to different topologies, frequency bands and standards.

1.4 Introduction

The following topics are covered in the introduction: the working principle of PLC, characteristics of communication channels used in PLC, applications of PLC in the power distribution grid, standardization along with existing gaps, PLC protocols, and frequency spectrum allocation, as well as PLC signal coupling techniques.

PLC is using the existing power lines as transmission medium on which a relatively high frequency signal of low amplitude is superimposed on the low frequency high amplitude mains voltage [3]. Figure 1.1 presents the PLC signal basic principle while Figure 1.2 presents two PLC devices communicating between them.

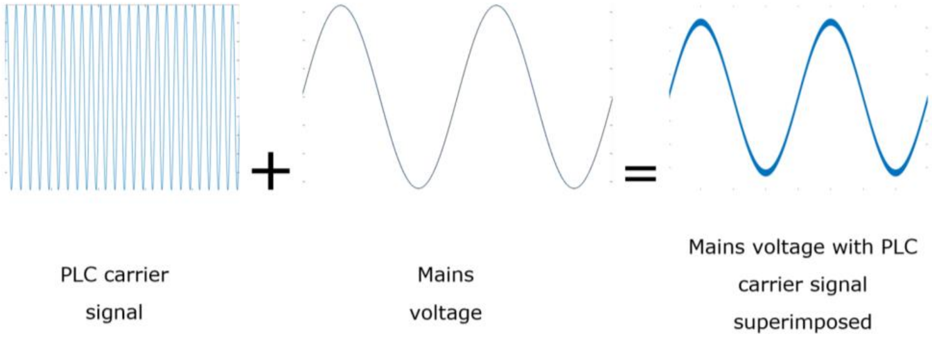

Figure 1.1 PLC signal basic principle

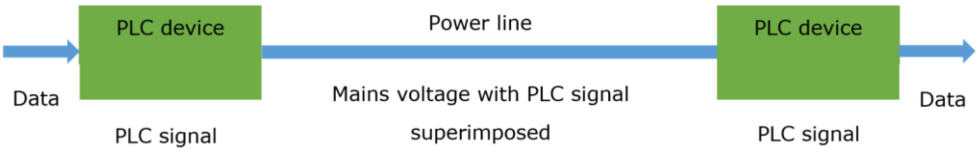

Figure 1.2 Two PLC devices communicating

PLC uses the existing power lines, which poses numerous challenges such as uncontrollable network topology, noise, attenuation and low impedances. Figure 1.3 provides the simplified model of the PLC channel.

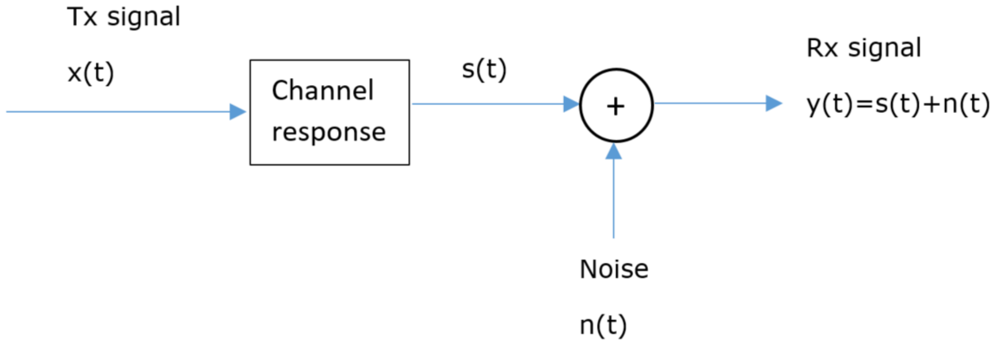

Figure 1.3 PLC channel simplified model

2 Conducted noise source detection and avoidance technique

In this chapter, I put forth a novel approach to identify loads that generate noise within the frequency band of PLC. The method involves leveraging SMs to establish a correlation between energy measurements of the load and the quality reports obtained from the PLC-G3 modem channel. By examining practical results, clear connection between energy measurements and CE originating from specific loads can be observed. To further validate the findings, spectrum measurements using PLC-G3 on power lines with both low and high impedance were performed, allowing for a comprehensive comparison with the noise spectrum. This correlation allows the creation of a transmission schedule based on when the loads generating noise are operated.

An effective method for reducing noise is the utilization of a PLF positioned between the smart meter (SM). This filter serves the purpose of eliminating noise within the PLC band, but it comes at a cost and introduces losses at mains frequency. This option of improving PLC is presented in chapter 3 of the thesis.

To prevent noise altogether, one can opt for PLC frequency bands that operate above 150 kHz, which are covered by standardized CE regulations. The available PLC frequency bands include FCC and ARIB, although in Europe, only the CENELEC-A band is allocated specifically for PLC communication.

2.1 Concept

By harnessing the capabilities of SMs, the loads connected on the customer side that introduce CE in the PLC frequency band can be effectively identified. This is achieved by utilizing channel quality reports obtained from the PLC modem and energy measurements acquired from the metrology ADC. Figure 2.1 is the block diagram of a SM with PLC [4]–[9] that is capable of creating a correlation between load power consumption and the noise generated by the load.

Beyond the SM concept discussed from Figure 2.1, I have designed a metering system that utilizes the same PLC-G3 modems from Texas Instruments™. However, this system incorporates a cutting-edge metrology analog front end (AFE) from Analog Devices™ capable of self-calibrating and monitor the metrology parameters, and features a power supply design comprising a non-isolated flyback converter followed by a buck converter.

The primary motivation behind the development of the new SM concept was to investigate the potential interference between the mSure™ technology utilized in the metering AFE and PLC. This is due to the fact that mSure™ superimposes a proprietary AC signal onto the mains AC waveform which passes through the metrology shunt for the purpose of self-calibration and sensor supervision. Wi-Fi connectivity was introduced to provide a backup option for connectivity in situations where PLC communication might be unreliable, and a reliable Wi-Fi connection is accessible.

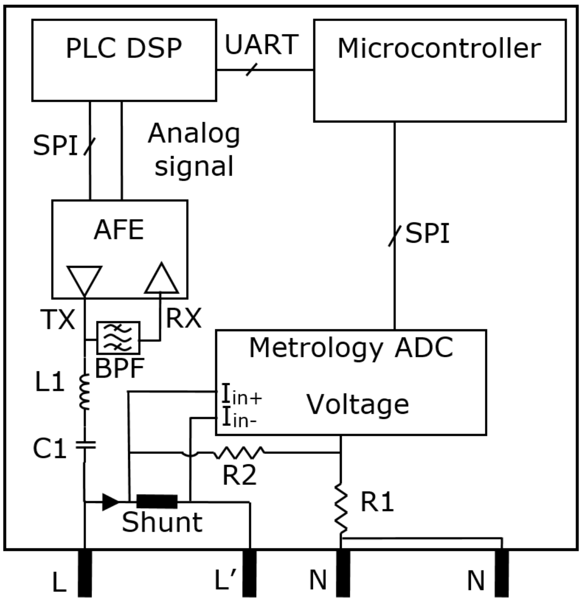

Figure 2.1 Architecture of a single-phase SM with PLC

SNR, RSSI, BER and power measurements have been performed using the measurement setup and test methods presented in Figure 2.2.

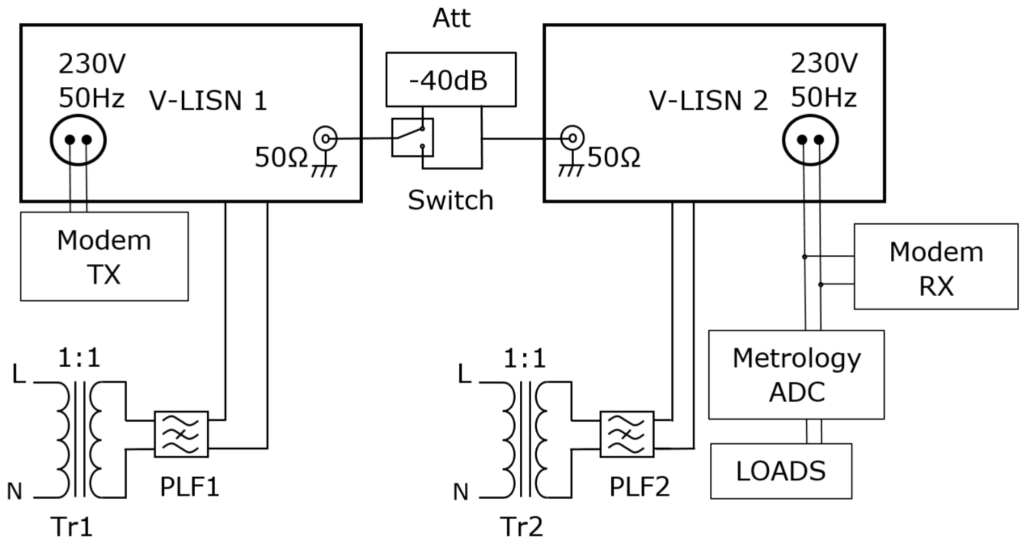

Figure 2.2 PLC SNR and RSSI measurement setup

Figure 2.3 together with Figure 2.4 presents PLC-G3 channel quality measurements; one modem is in TX mode and the other in RX mode. SNR and RSSI measurements were carried out in the presence of six standard loads. These measurements were conducted both with and without the presence of -40dB attenuation introduced between the two modems. This attenuation serves the purpose of emulating the characteristics of a power line segment, generating test conditions closer to the real-world.

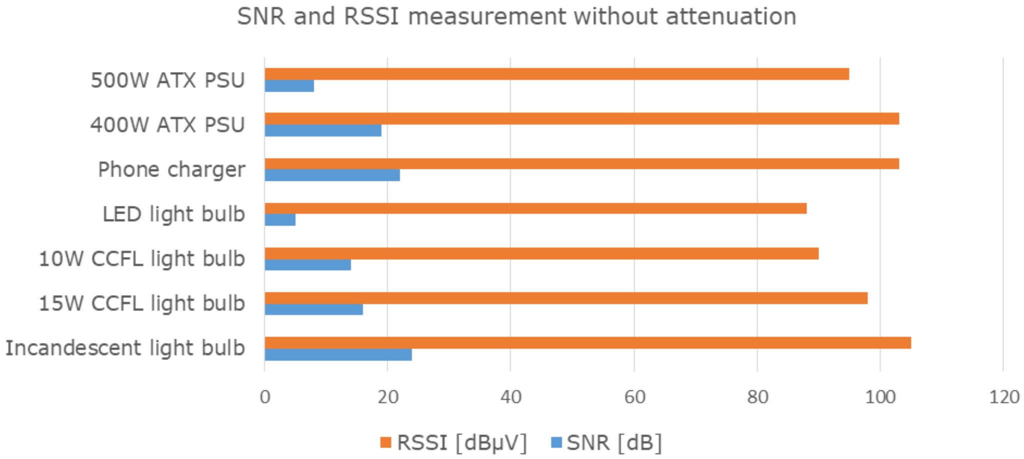

Figure 2.3 PLC-G3 SNR and RSSI measurements without channel attenuation

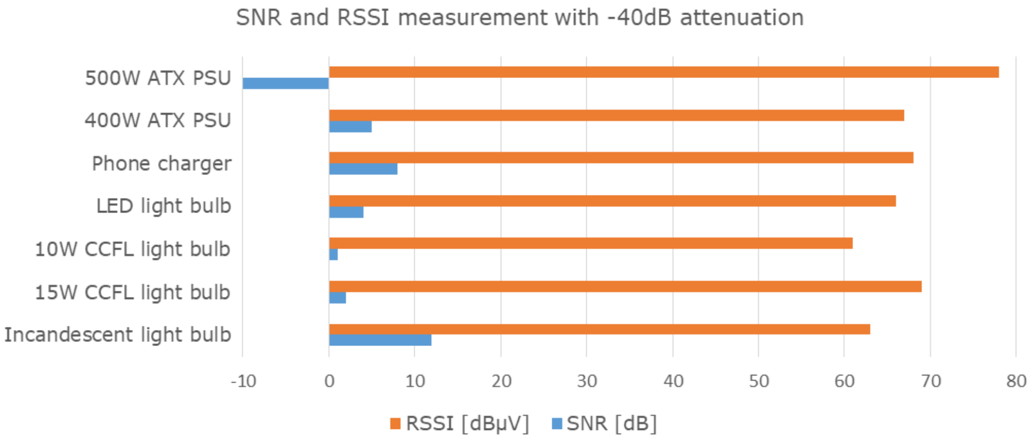

Figure 2.4 PLC-G3 SNR and RSSI measurements with -40 dB channel attenuation

Figure 2.5 presents the power measurements of the loads for which their influence in channel quality was assessed and is presented in Figure 2.3 and Figure 2.4. A reference meter having the error e<0.05% [10] was used to validate that the measurements reported by the metering ADC are accurate. The metering ADC measures current and voltage as well as the phase shift between them and computes P, Q, S and PF. The total power consumption of the loads was found to be P= 246 W, Q= 134 VAR, S= 280 VA while PF= 0.88.

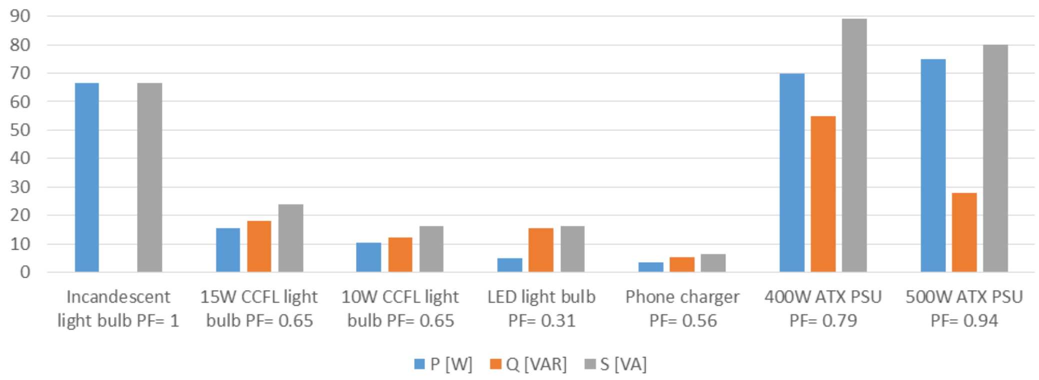

Figure 2.5 Power measurements of the six common loads

3 Conducted noise filtering using PLFs

Passive PLFs are employed to address CE in the power grid [11]–[13] or to isolate various PLC network segments [14]. By tackling a few novel problems, I contribute to this field of knowledge. First and foremost, this research serves as a complete informational resource for developing and evaluating PLFs for NB-PLC filtering applications. It offers an in-depth understanding of the development, integration, and testing aspects related to PLFs built for NB-PLC filtering applications by a thorough examination of the literature.

The study discussed in this chapter also suggests a novel method for designing and simulating PLFs by using S-parameters. Although S-parameters have been used in design and simulation methodologies before [15], [16], this study is the first to employ this particular strategy to design PLFs for NB-PLC applications.

I have created a 13th order PLF utilizing specially built inductors to show the effectiveness of the suggested design techniques. At frequencies below 150 kHz, the intended PLF demonstrates significant insertion loss, achieving an attenuation of over -130 dB at 50 kHz with input and output impedances of 3.36 Ω while consuming only 597 mW of quiescent power.

These findings underscore the advantages and opportunities inherent in employing these methods to create PLFs capable of enhanced performance with regard to insertion loss, attenuation, power efficiency, and impedance characteristics.

3.1 PLF integration, topology and impact in the electricity grid

Typically, PLFs for PLC applications are used in the SG in the following cases:

- Located on the consumer side ideally between the SM and the fuse box to filter the conducted noise produced by devices on consumer side [17]. Installing the PLF after the main fuse is not problematic if it does not need a ground connection or if the main fuse is not a RCD. However, if the main fuse is differential or the PLF does need a ground connection, putting the PLF after the main fuse may result in the fuse tripping. In Figure 3.1, this filter use case is designated as PLF Type 1.
- For the purpose of splitting SMs in two PLC areas whilst still connected to the same electrical grid branch. The separation into two sections makes sure that each SM using NB-PLC connects to the appropriate PLC-DC. When many SMs are linked to a branch and an additional DC is installed to increase the throughput, this form of PLF installation is necessary [14]. Figure 3.1 designates this filter use case as PLF Type 2.

The two typical PLF usage scenarios in the low voltage SG are shown in Figure 3.1 [18], [19]. Only single-phase devices are presented for simplicity.

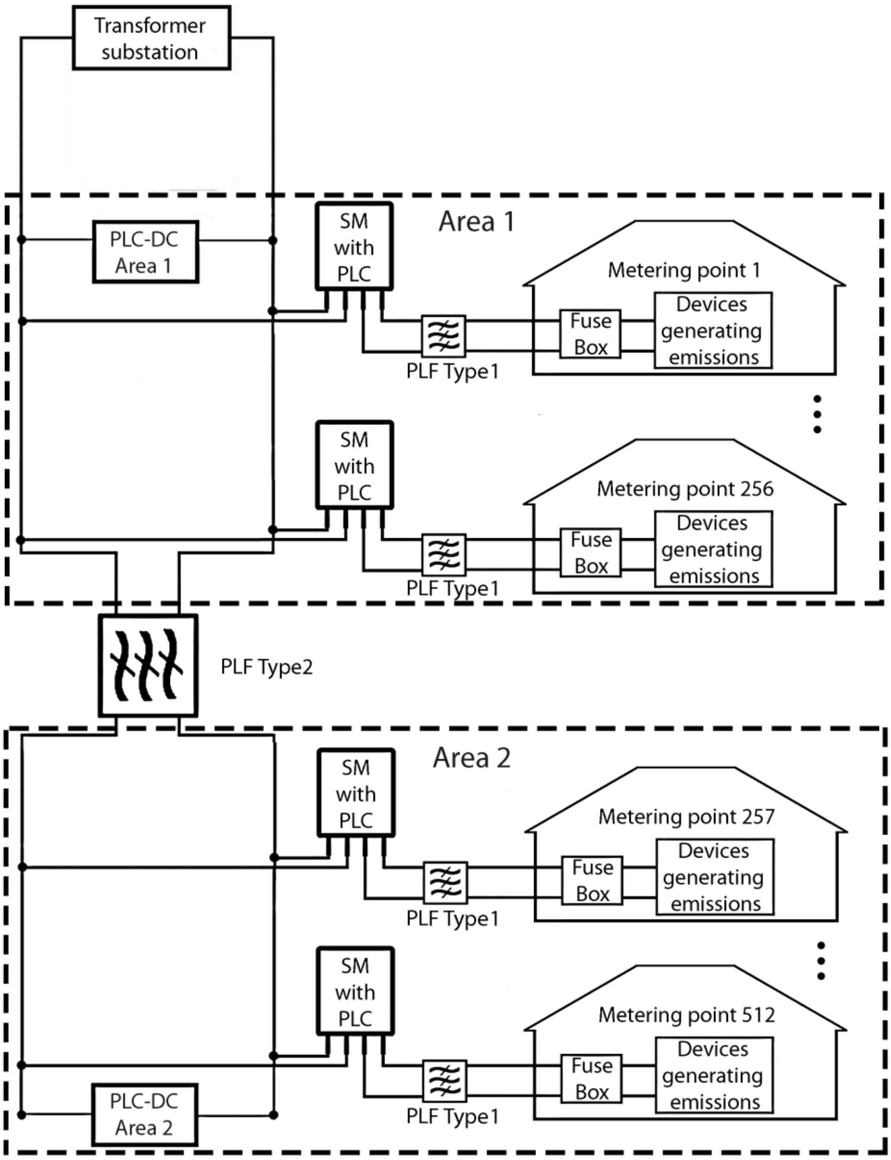

Figure 3.1 PLFs use cases in the SG [18]

3.2 PLF design

The design of the PLF was guided by the following requirements:

- Achieve a minimum attenuation of -120 dB at 50 kHz to effectively block the PLC signal, considering the maximum PLC signal level of 120 dBμV [20].
- Optimize mains quiescent power consumption.
- Ensure a rated current of at least 30 A to enable installation as type 2 PLF between the SM and the building's electrical system (e.g., main fuse).
- Does not interfere with desired communication; keep the input/output impedance high in the NB-PLC frequency band. The impedance should be more than 2 Ω as a minimum requirement because PLC modems are built and verified to transmit on this low impedance [20].
- The PLF design and its component selection should be done in a way that makes it easy to comply with the tests listed in Section **Error! Reference source not found.** of the thesis.

Following the earlier specified requirements, the 13th order PLF shown in Figure 3.2 was created.

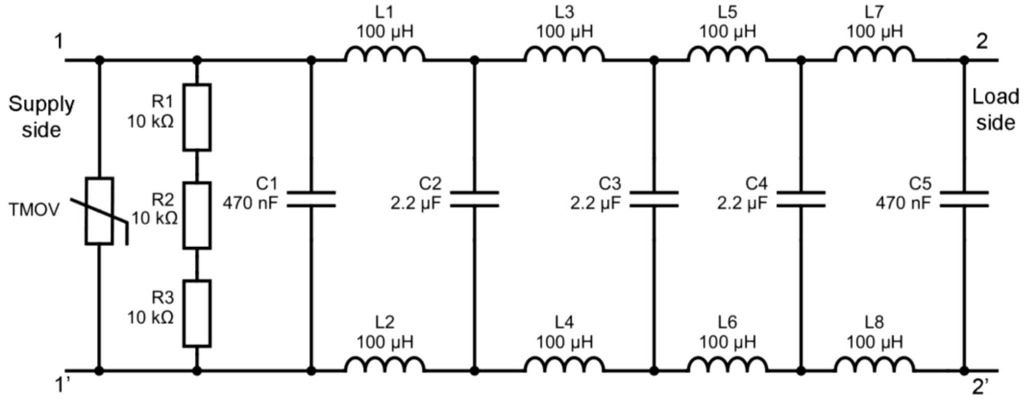

Figure 3.2 Designed PLF

With the best insertion loss across the NB-PLC frequency range, a threefold increase in attenuation at 50 kHz (more than -130 dB) compared to the best commercially available PLF (-40 dB), and a power consumption of 597 mW, which is comparable to the other commercial PLFs, the designed PLF exhibits exceptional qualities. Additionally, in the frequency range between 36 kHz and 90.6 kHz, the proposed PLF achieves the second-best input and output impedance of 3.36 Ω.

The designed PLF, is appropriate as a type 1 PLF but unsuitable as a type 2 PLF for separating two portions of the electrical grid because of its maximum rated current of 30 A.

4 Conclusions, contributions and future work

In this concluding chapter, I bring together the various aspects of my research journey, presenting a comprehensive synthesis of the methods for enhancing PLC over Low Voltage Networks. I will begin by addressing the initial questions, which guided my activity, providing concise and answers that shed light on the core objectives of my study. Subsequently, the discussion will delve into the theoretical and practical contributions resulting from this research, emphasizing the novel perspectives and valuable knowledge added to the academic and practical realms. Furthermore, potential paths for future work and research will be outlined, facilitating continued exploration and advancement in the field. This chapter marks the culmination of my research endeavors, providing a comprehensive understanding of the study's significance and its impact on both theory and practice.

Overall, my research activity during the PhD studies significantly contributes to the advancement of PLC technologies, offering valuable methods for noise identification, avoidance and suppression as well as the design and evaluation of PLFs. The outcomes of this thesis can potentially enhance the reliability and efficiency of PLC systems, paving the way for broader applications in various industrial and residential settings.

4.1 Conclusions

The significance and widespread adoption of NB-PLC in SG applications have been demonstrated. However, it is clear that there are existing gaps in standardization and the coexistence of grid-connected devices operating at frequencies below 150 kHz as well as insufficient practical ways to address NB-PLC communication issues arising from the fact that the power distribution network was not intended for communication. These factors highlight the need to resolve these issues, ensuring seamless communication among Smart Grid devices. With the increasing demand for Smart Grid technologies, it becomes necessary to bridge these disparities and improve the dependability and effectiveness of NB-PLC in Smart Grid applications. The first approach introduces a method for identifying noise-generating loads within the PLC frequency band. By correlating SM power measurements of the load with channel quality reports obtained from the PLC-G3 modem, a clear connection between power measurements and noise originating from specific loads was established. This connection enabled the creation of a PLC transmission schedule based on the operation of noise-generating loads. The practical results showcased the efficacy of this method, emphasizing its potential for real-world implementation and enhancing PLC system performance.

The second approach focused on the development and evaluation of PLFs, particularly targeting the CENELEC A, B, C, and D communication bands. The design of a PLF was achieved using simulation methods and passive components. Detailed information on component selection and PLF design was presented. The simulated values were validated through practical measurements, confirming the accuracy of the designed PLF. Comparative benchmarking against commercial PLFs revealed that the designed PLF outperformed other PLFs, exhibiting exceptional characteristics, including superior insertion loss, significant attenuation at 50 kHz, and low power consumption. The proposed PLF, though suitable as a type 1 PLF, serves as a basis for future work exploring the design of a type 2 PLF using the methodologies presented in this thesis.

At the end of my research activities, I was able to answer the questions that I raised at the beginning in section 0:

1. **How and why is PLC integrated in the electricity grid?**

I have shown in sections **Error! Reference source not found.**, **Error! Reference source not found.** and **Error! Reference source not found.** of the thesis how and why is PLC used as communication protocol in the power line. The electricity grid already has an extensive network of power lines which allow integrating PLC into the grid by utilizing this existing infrastructure for communication purposes without the need to lay additional dedicated communication cables or deploy costly wireless systems. PLC is mostly used in the electricity grid as last mile communication protocol between SM and data concentrator.

2. **What are the challenges that PLC faces in the power distribution grid?**

There are many challenges that PLC must overcome in order to ensure proper communication: in-band conducted noise, signal attenuation and low power line impedance.

The power grid is a noisy environment, and PLC is affected by various sources of CE from other electrical devices, radio frequency interference from radio broadcasts and impulse noise from power equipment. CE affects PLC signal quality and affects communication reliability. The types of noise present in the electricity distribution grid are presented in section **Error! Reference source not found.** and section **Error! Reference source not found.** of the PhD thesis and article {Citation} This section outlines the theoretical contributions introduced to this specialized field of study throughout the research activities in the doctoral program. .

Signal Attenuation: As PLC signals travel through power lines, they experience attenuation due to line losses and impedance mismatches. This limits the range and coverage of PLC communication, especially over long distances or in areas with poor power line conditions. This is presented in section **Error! Reference source not found.** of the PhD thesis.

Power line impedance is much lower compared to what standard equipment used in the design process can be achieved. A survey of these extremely low values as well as adaptations of the design methods are presented in sections **Error! Reference source not found.** and **Error! Reference source not found.** of the PhD thesis.

3. **Is there a way to address these challenges without any modification in the electricity grid? How to implement this non-invasive improvement technique?**

A novel approach for identifying noise-generating loads within the PLC frequency band is presented in chapter 2 and article [4]. By leveraging SMs to correlate energy measurements of the load with PLC-G3 modem channel quality indicators, a clear connection between energy measurements and noise originating from specific loads has been established. This correlation enables the creation of a transmission schedule based on the operation of loads generating noise, enhancing the efficiency of PLC communication.

4. **What modifications could be needed in the power grid? How to implement these modifications?**

Filtering out conducted noise in a PLC system is commonly approached through the use of a low pass filter. However, this straightforward method presents challenges due to the relatively low frequencies (below 150 kHz) utilized for NB-PLC communication. Additionally, the power grid contains various services, and its impedance differs significantly from commercially available PLF designs.

Section 3.1 of the thesis delves into the integration of PLFs in the electricity grid, exploring the PLF topology and its impact on grid operations. Addressing these complexities, a novel methodology for designing PLFs specifically for NB-PLC using S-parameters is proposed in section **Error! Reference source not found.**. This innovative approach aims to tackle the unique requirements posed by the power grid's characteristics and the specific frequency range used for NB-PLC communication.

4.2 Theoretical contributions

This section outlines the theoretical contributions introduced to this specialized field of study through research activities

1. **Challenges of NB-PLC communication in the context of SGs.**

The importance of mitigating or filtering Common-Mode Interference (CE) affecting NB-PLC communication has been acknowledged, including the identification of sources, types, and features of CE within the CENELEC A, B, C, and D frequency bands. Standardization gaps concerning CE, which impact NB-PLC, have also been recognized. This analysis was performed using an extensive literature review and it is summarized in section **Error! Reference source not found.** . This was presented also in two of my articles [4], [18] .

2. **Identification of SM architecture in the context of communication protocols and services present in the power grid.**

In Figure 3.1 I present an SM architecture suitable for implementing noise avoidance techniques, which was developed incrementally with commercially available electronic components while adhering to international standards, as supported by my previous [4], [7], [8], [19].

3. **CE in NB-PLC frequency bandwidth identification techniques.**

Section 2.1 of the thesis summary presents the innovative method I’ve created for identifying loads that operate and introduce noise within the PLC frequency band. This approach utilizes components and functionalities that exist in SM to establish a correlation between energy measurements of the load and the channel quality reports obtained from the PLC-G3 modem thus enabling identification of the load generating CE or create a transmission schedule when the load does not operate. This innovative approach is detailed in [4].

4. **CE filtering techniques and overview of the integration of PLFs into the electricity grid, highlighting the services and features present in the grid as well as main types of PLFs.**

In case the loads generating CE cannot be avoided than filtering techniques should be employed. To comprehend the criteria for low-voltage PLFs, I conducted an extensive literature review. This review revealed two methods of connecting PLFs: between the SM and the fuse box and between two segments of the power line. Additionally, it highlighted the importance of ensuring that services in the power grid remain unaffected by PLFs, namely residual current protective devices, RCSs, and remote control of the disconnect unit. The results of this literature review are presented in section 3.1 and partially presented in my previous published articles [18], [19].

5. **Performance, safety and immunity tests that ought to be conducted as part of PLF benchmarking.**

In sections **Error! Reference source not found.** and **Error! Reference source not found.** of the thesis I propose filter benchmarking methods and insertion loss measurement techniques, PLC signal attenuation and PLF impedance measurements which have been optimized in order to obtain results as close as possible to the real power line. The main improvement was the implementation of 2Ω LISN, which is a good practical approximation of the real power line impedance. The proposed benchmarking methods are present in the article [18].

6. **Design and simulation methods for PLFs in NB-PLC frequency.**

In sections 3.2 and **Error! Reference source not found.** of the PhD thesis, I propose the design of PLFs using S-parameters and RFSim99. While the design methods themselves are not novel, they have not been previously applied to low-frequency applications like PLF design for PLC. This became feasible due to the advancement of measuring equipment capable of providing S-parameters measurements in the kHz range. The design and simulation methodologies are comprehensively detailed in the article [18].

4.3 Practical contributions

For validating the theoretical contributions brought to this field of research, I conducted a series of experiments in a laboratory setting that closely replicated real-world conditions. This section enumerates the practical advancements I have achieved in this specialized field through the research undertaken during my doctoral studies:

1. **CENELEC A, B, C and D frequency bands CE measurements of common types of loads.**

The conducted measurements from **Error! Reference source not found.** of the thesis underscore and quantify the effect of CE generated by typical loads on the PLC signal. The results of the measurements have shown that CE identification & avoidance and/ or filtering techniques are a valid research subject. The results have been included in the previous article [4].

2. **Impact of loads generating conducted noise on PLC communication.**

Figure 2.3 together with Figure 2.4 displays the outcomes of the measurements conducted to illustrate the influence of typical loads connected to the low voltage power grid on the PLC signal. The results outline that the loads connected in its proximity and in the same electrical circuit influence the PLC channel quality reports RSSI and SNR. The results were also published in the article [4].

3. **Practical trials for validating the concept of identifying loads generating CE in the frequency band used by PLC by correlating PLC channel quality data and power measurements for the identification of loads generating noise and determination of optimum time schedule for communication.**

Sections **Error! Reference source not found.** and **Error! Reference source not found.** of the thesis present the validation activities conducted for establishing the feasibility of correlating PLC channel quality information with load power measurements for PLC noisy load detection and its implementation in the SM architecture as a proof of concept. This results of this activity was published in my previous article [4].

4. **Implementation of an enhanced SM architecture capable of detecting loads generating CE in the NB-PLC frequency band**

In section **Error! Reference source not found.** of the thesis an enhanced SM concept is presented which comes as an improvement to the one from section 2.1 of this summary. Compared to the architecture presented in section 2.1 it uses the same PLC-G3 modems from Texas Instruments™ but the metrology AFE is capable of self-calibrating together with sensor monitoring and features a power supply design comprising of a non-isolated flyback converter followed by a buck converter. The primary motivation behind the development of the enhanced SM concept was to investigate the potential interference between the mSure™ technology utilized in the metering AFE and PLC. The enhanced SM architecture was presented in my previous article [19] which is an evolution of the architectures presented in my articles [4], [9], [21].

5. **Implementation and evaluation of a passive PLF for NB-PLC frequency band**

The 13th order passive PLF has been designed with carefully selected components so that it offers enough attenuation in order to block CE and PLC signal while it presents a sufficiently high impedance at both ends thus not disturbing the intended PLC communication. The designed PLF is extensively presented in sections 3.2 and **Error! Reference source not found.** of the thesis as well as in my article [18].

6. **Comparing the designed PLF to the ones that are currently on the market.**

The designed PLF exhibits exceptional qualities, including the lowest insertion loss across the NB-PLC frequency range, a threefold increase in attenuation at 50 kHz (more than -130 dB) compared to the best commercially available PLF (-40 dB). Additionally it has a power consumption of only 597 mW, which is comparable to the other commercial PLFs. Additionally; the suggested PLF achieves the second-best input and output impedance of 3.36 Ω in the frequency range between 36 kHz and 90.6 kHz. The benchmarking process and results are shown in chapter **Error! Reference source not found.** of the thesis and validated by my article [18].

4.4 Future work

In the context of continuing my research activities, I intend to build upon the activities laid out in this thesis and my published articles by pursuing the following objectives:

- Develop the enhanced SM concept presented in section **Error! Reference source not found.** into a standard SM [22] by adding the following peripherals: display, optical communication port, buttons, relays for load management and consumer disconnection, and a real-time clock.
- The designed PLF is appropriate for use as a type 1 PLF but inadequate for serving as a type 2 PLF (for isolating two sections of the power grid) because it has

maximum rated current of 30 A as shown in section **Error! Reference source not found.** of the thesis. It is of interest to implement a type 2 PLF using the techniques covered in the research activities.

- I intend to assess more PLFs using the testing procedures detailed in section **Error! Reference source not found.**. Furthermore, it is of interest to explore the design and evaluation of a hybrid PLF that combines resonant and nth order types of PLFs, aiming to decrease the filter order while still ensuring attenuation and impedance suitable for type 1 and type 2 PLF.
- Conducting field trials to validate the methodologies for improving PLC over low voltage networks should be performed as the ultimate validation step for the solutions investigated during my doctoral research.

5 References

[1] "FCC ONLINE TABLE OF FREQUENCY ALLOCATIONS." FEDERAL COMMUNICATIONS COMMISSION OFFICE OF ENGINEERING AND TECHNOLOGY POLICY AND RULES DIVISION, Aug. 23, 2022. Accessed: Jul. 01, 2023. [Online]. Available: https://www.fcc.gov/file/21474/download

[2] "Power Line Communication Equipment (10kHz-450kHz)." Nov. 27, 2002. Accessed: Jul. 01, 2023. [Online]. Available: https://www.arib.or.jp/english/std_tr/telecommunications/desc/std-t84.html

[3] A. Majumder and J. Caffery, "Power line communication: An overview," *Potentials IEEE*, vol. 23, pp. 4–8, Nov. 2004, doi: 10.1109/MP.2004.1343222.

[4] S. Avram, "Power line communication channel noise source detection using art meters," in *2016 12th IEEE International Symposium on Electronics and Telecommunications (ISETC)*, Oct. 2016, p. 106. doi: 10.1109/ISETC.2016.7781067.

[5] P. Guyard, R. Fiorelli, and J. Houee, "STCOMET smart meter and power line communication system-on-chip development kit." 2017. Accessed: Aug. 01, 2023. [Online]. Available: https://www.st.com/resource/en/application_note/an4732-stcomet-smart-meter-and-power-line-communication-systemonchip-development-kit-stmicroelectronics.pdf

[6] P. Sausen, A. Sausen, M. Campos, L. F. Sauthier, A. Oliveira, and R. Emmel, "Power Line Communication Applied in a Typical Brazilian Urban Power Network," *IEEE Access*, vol. PP, pp. 1–1, May 2021, doi: 10.1109/ACCESS.2021.3078697.

[7] S. Avram, V. Plotenco, and L.-N. Paven, "Design and development of an electricity Meter Test Equipment," in *2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP)*, May 2017, pp. 96–101. doi: 10.1109/OPTIM.2017.7974954.

[8] S. Avram, A.-M. Safta, C. Daniel Căleanu, and R. Vasiu, "Hardware and software implementation of an embedded metering webserver," in *2017 40th International Conference on Telecommunications and Signal Processing (TSP)*, Jul. 2017, pp. 43–46. doi: 10.1109/TSP.2017.8075933.

[9] S. Avram, C. D. Căleanu, R. Vasiu, A.-M. Safta, and H. G. Belei, "Hardware and Software Integration of an Electrophoretic display on a smart meter," *ITM Web Conf.*, vol. 29, p. 03003, 2019, doi: 10.1051/itmconf/20192903003.

[10] "Calmet TE30 Datasheet." Jul. 2022. Accessed: Aug. 01, 2023. [Online]. Available: https://www.calmet.com.pl/images/pdf/TE30-Three-Phase-Working-Standard-Data-Sheet-EN.pdf

[11] V. Tarateeraseth, "EMI filter design: Part III: Selection of filter topology for optimal performance," *IEEE Electromagn. Compat. Mag.*, vol. 1, no. 2, pp. 60–73, Second 2012, doi: 10.1109/MEMC.2012.6244975.

[12] D. Varajão, R. Esteves Araújo, L. M. Miranda, and J. A. Peças Lopes, "EMI Filter Design for a Single-stage Bidirectional and Isolated AC–DC Matrix Converter," *Electronics*, vol. 7, no. 11, p. 318, Nov. 2018, doi: 10.3390/electronics7110318.

[13] K. Bernacki, D. Wybrańczyk, M. Zygmanowski, A. Latko, J. Michalak, and Z. Rymarski, "Disturbance and Signal Filter for Power Line Communication," *Electronics*, vol. 8, no. 4, p. 378, Apr. 2019, doi: 10.3390/electronics8040378.

[14] A. Vukicevic, M. Bittner, A. Rubinstein, M. Rubinstein, and F. Rachidi, "A concept to enhance system data rate for PLC access networks," in *2008 IEEE International Symposium on*

Power Line Communications and Its Applications, Jeju City, Jeju Island, South Korea: IEEE, Apr. 2008, pp. 105–110. doi: 10.1109/ISPLC.2008.4510407.
[15] S. Liu, Y. Zhang, and D. Yu, "Research and design of EMI digital filters using scattering parameters," in *2009 International Conference on Wireless Communications Signal Processing*, Nov. 2009, pp. 1–5. doi: 10.1109/WCSP.2009.5371392.
[16] P. C. Sekhar, Y. Gopal, and T. rao, "DESIGN OF S PARAMETERS FOR VARIOUS FILTERS," 2013. Accessed: Aug. 09, 2023. [Online]. Available: http://www.tjprc.org/publishpapers/--1366185303-11.-Design%20of%20s%20parameters.full.pdf
[17] "Blocking Filter - Grupo Premo." https://www.grupopremo.com/content/102-blocking-filter (accessed Aug. 01, 2023).
[18] S. Avram and R. Vasiu, "Passive Power Line Communication Filter Design and Benchmarking Using Scattering Parameters," *Appl. Sci. 2023*, vol. 13, no. 11, doi: https://doi.org/10.3390/app13116821.
[19] S. Avram, R. Vasiu, D. Chiciudean, L.-N. Paven, and M. L. Crauciuc, "Hardware and Software Implementation of a Self-Calibrating Smart Meter with Tamper Detection," in *2021 10th International Conference on ENERGY and ENVIRONMENT (CIEM)*, Oct. 2021, pp. 1–5. doi: 10.1109/CIEM52821.2021.9614900.
[20] "EN 50065-1:2011 - Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz. General requirements, frequency bands and electromagnetic disturbances." Accessed: May 07, 2019. [Online]. Available: https://shop.bsigroup.com/ProductDetail/?pid=000000000030235497
[21] S. Avram, A.-M. Safta, C. Căleanu, and R. Vasiu, "Hardware and software implementation of an embedded metering webserver," Jul. 2017, p. 46. doi: 10.1109/TSP.2017.8075933.
[22] "EN 50470-1:2006+A1:2018 Electricity metering equipment (a.c.). General requirements, tests and test conditions. Metering equipment (class indexes A, B and C)." Accessed: May 28, 2019. [Online]. Available: https://shop.bsigroup.com/ProductDetail?pid=000000000030361398