Passive Analog Blocking Filter for Narrowband PLC Systems

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***Abstract*—This paper delves into the design of passive analog blocking filters to mitigate conductive emissions and address impedance mismatches, which significantly impair the performance of narrowband power line communication systems. These systems have emerged as pivotal data communication technologies for Internet of Things applications, especially within the electricity sector. Experimental analyses centered on scattering parameters and power spectral density demonstrate that the designed passive analog blocking filter is not only straightforward and cost-effective but also performs satisfactorily when compared to another passive analog blocking filter.**

***Index Terms*—power line communication, analog blocking filter, internet of things, low bit rate.**

I. Introduction

The growing integration of non-linear loads into electric power grids intensifies conductive emission-related problems, complicating compliance with electromagnetic compatibility (EMC) regulations [1], [2]. A well-established approach to address this issue is the deployment of analog EMC filters. Typically positioned at the inputs of loads, these filters are designed to prevent emissions from infiltrating the electric power grid. In essence, a passive analog EMC filter is instrumental in protecting electronic equipment from the adverse effects of high-power conductive emissions originating from specific devices connected to the electric power grid. Such emissions can inflict damage, diminish immunity, and degrade the performance of other devices in the same electric circuit, such as narrowband (NB) power line communication (PLC) systems [3], [4]. These systems, which are enabling technologies for Internet of Things (IoT) applications [5]–[7], can witness performance deterioration due to these emissions.

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For NB PLC systems operating at frequencies up to 500 kHz, it is recognized that existing loads in electric power systems can significantly attenuate and distort PLC signals. The former, severe attenuation, results from impedance mismatching between the loads and electric power grids, while the latter, signal distortion, arises due to high-power conductive emissions generated by the loads. Given these challenges, there's a pressing need to develop advanced analog blocking filters[1]. In light of these findings, the studies mentioned in [8] and [9] put forth a proposal for a directional PLC signal blocking filter. Subsequently, they derive comprehensive transfer functions tailored for PLC systems with different filtration strategies. These filters should prioritize impedance matching mitigation and conductive emissions reduction, all the while maintaining simplicity and cost-effectiveness.

This paper focuses on the design of a passive analog blocking filter for NB PLC systems, which are connected to low-voltage electric power grids (i.e., 127 V_{rms} and 220 V_{rms}), when the frequency band of 9-500 kHz is considered. Initially, it outlines the constraints that analog blocking filters must adhere to for success, expressed in terms of scattering parameters. Subsequently, the paper introduces a passive analog blocking filter that balances performance and simplicity. Through an analysis of the power spectral density (PSD) of the voltage waveform and the scattering parameters, a comparison is drawn between the newly designed filter and an existing model. The PSD assessment underscores the designed filter's efficacy in countering conductive emissions, while the scattering parameter analysis highlights advancements in impedance mismatch management. Field experiment evaluations further attest to the superior performance of the designed filter compared to the existing analog blocking filter.

[1]Within the PLC community, the term "blocking filter" refers to EMC filters that fully reflect signals at their input and output ports.

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II. PROBLEM STATEMENT

A measurement campaign was conducted to illustrate the severity of high-power impulsive noise, with the analysis of raw data depicted in Fig. 1. Specifically, Fig. 1(a) displays the measurement setup constructed to capture the additive noise produced by a load connected to the power grid. This setup consists of three outlets interconnected through power cables, each with a length of l = 18 m. The system is also linked to a mono-phase R&S ENV216 line impedance stabilization network (LISN), which supplies a mains voltage signal of 127 V_{rms} at 60 Hz. In addition, two of the outlets are attached to PLC coupling devices [10] that operate within the frequency band of 9-500 kHz. This PLC coupling devices enable the measurement of scattering parameters and the capture of the electrical signal waveform. Impedance measurements were obtained using the reflection in port one of the R&S FSH8 vector network analyser (VNA), set to an impedance of $Z_0 = 50\ \Omega$, in the frequency range of 100-500 kHz. Voltage waveforms were recorded using the R&S RTH1002 oscilloscope. Moreover, the high-power impulse source employed for this measurement was an electric drill, known to significantly impair the performance of NB PLC systems because of the introduction of high-power impulsive noise.

Having built the measurement setup, scattering parameters and waveform of the voltage signal were measured when the electric drill was off and on. Fig. 1(b) shows the measured waveform of the voltage signal without (wo/) and with (w/) additive noise generated by the electric drill in the off and on states, respectively. As we can see, the electric drill introduces a high-power impulsive noise that might severely degrade the performance of any NB PLC systems operating in the frequency band of the PLC coupling circuit. As the measured waveform of the voltage signal is considered an additive noise modeled as a random process, Fig. 1(c) shows an estimate of its PSD with one sample function. This plot shows that the presence of an electric drill in an electric power grid increases the PSD of the additive up to 28 dB in several frequency sub-bands. Fig. 1(d) shows the magnitude of the measured impedance when the electric drill is off and on. Note that the presence of the electric drill introduces selectivity in the magnitude of the measured impedance, making impedance matching a difficult task to accomplish. Based on the measured data, we verify that electric equipment, such as a drill, is a relevant source of interference that can compromise the immunity of other equipment and degrade the performance of NB PLC systems.

To avoid the degradation introduced by sources of high-power additive noise, as illustrated in Fig. 1, the EMC best practice suggests several strategies to introduce an attenuation on the amplitude of voltage waveform. As the purpose is to improve the performance of NB PLC systems, the following strategies are considered to mitigate high-power conductivity interference of equipment like electric drills:

- **Strategy #1**. It refers to the redesign of the electric equipment to integrate a passive analog blocking filter into it or the electric circuit redesign to reduce interference emissions. It can remarkably reduce interference emissions, and consequently, it is most effective. On the other hand, it is complex because it might demand the redesign of electric circuits of equipment to accommodate a proper capacity to avoid the emission of conductive interference.
- **Strategy #2**. It uses a passive analog blocking filter between the load and the outlet. It reduces the interference emissions caused by loads (e.g., electric drills) connected to the outlet; however, it may be less effective because it must be a general-purpose analog blocking filter. Lastly, it can be easily designed and attached to the outlets without redesigning the electric equipment

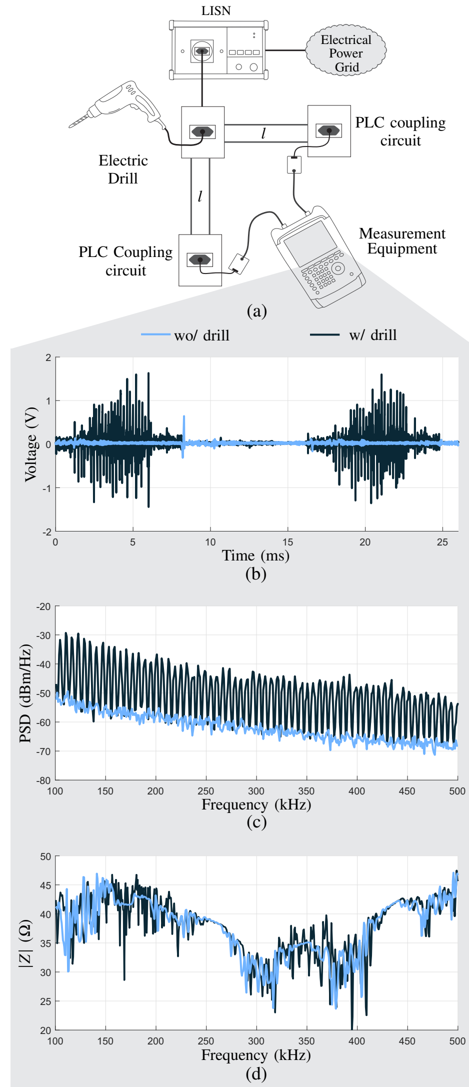


Fig. 1: Measurement Campaign. (a) Measurement setup, (b) voltage waveform of the additive noise, (c) PSD of the additive noise, and (d) measured impedance at one outlet.

Relying on **Strategy #2**, Section III design a passive analog blocking filter for NB PLC systems.

III. Passive and Analog Blocking filter

For designing a passive analog blocking filter, it is pertinent to consider the following issues:

- Specifications. A passive analog blocking filter should be able to mitigate the spectral content of conductive emissions at the operational frequency of NB PLC systems while concurrently permitting the passage of the main voltage component.
- Current handling. Given the application of a serial configuration to integrate the analog blocking filter between the power source and the load, the analog blocking filter design must sufficiently accommodate the current requirement of a load connected to the outlet.
- Installation simplicity. It is crucial that the design of a passive analog blocking filter allows for connection to a single-phase electrical outlet, regardless of the phase and return identification. Therefore, it is necessary to ensure the existence of the symmetry property in the analog blocking filter.
- Complexity. A balance between circuit complexity and associated cost should be deliberated upon in a cost-efficiency analysis. The design of the analog blocking filter should aim for minimal use of small-sized passive components. This is a significant consideration as the current handling capability directly influences the size of passive components.

Based on these issues, Subsections III-A and III-B detail the design and prototypes of the proposed passive analog blocking filter.

A. Design

The aim is to design a passive analog blocking filter that allows the mains signals to be transmitted through with minimal attenuation and provide maximal attenuation in the spectrum content of a signal in the operating frequency of PLC systems. In other words, the analog blocking filter behaves like a low-pass passive analog filter in which the scattering parameters must be under certain constraints. In this sense, let us assume that the analog blocking filter is a passive circuit, Ω_p is the 3-dB cut-off frequency at the edge of the passband, Ω_s is the frequency at the edge of the stopband, and $\Delta\Omega = \Omega_s - \Omega_p > 0$. The effective design of a passive blocking filter must fulfill the following specifications:

- The scattering parameters $S_{ii}, i = 1, 2$, must comply with the following constraint:

$$|S_{11}| = |S_{22}| = \begin{cases} 1 - \epsilon_p, & |\Omega| \leq \Omega_p \\ \delta_s, & |\Omega| \geq \Omega_s \end{cases} \tag{1}$$

  in which $0 \leq \epsilon_p \ll 1$ and $0 \leq \delta_s \ll 1$. It means that the reflection parameters must be close to one at the passband and close to zero at the stopband.
- The scattering parameters S_{12} and S_{21} must comply with the following constraint:

$$|S_{12}| = |S_{21}| = \begin{cases} \delta_p, & |\Omega| \leq \Omega_p \\ 1 - \epsilon_s, & |\Omega| \geq \Omega_s \end{cases} \tag{2}$$

  in which $0 \leq \delta_p \ll 1$ and $0 \leq \epsilon_s \ll 1$.
- The components must be chosen to support a maximum voltage (i.e., $V_{\max}$) at its terminals and to ensure the maximum current (i.e., $I_{\max}$) flowing through it.

Note that the design of a blocking filter has to ensure an attenuation higher than 40 dB in the stopband to meet the requirements for conducted emissions, such as the one in the standard MIL-STD-461G [11]. Furthermore, note that such attenuation must be ensured by correctly choosing parameters δ_s and ϵ_s.

There are several filter topologies for satisfying these specifications. However, we focus on the symmetric 3rd-order Butterworth low-pass analog filter because it is simple and cost-effective and provide suitable improvements. The magnitude-squared response function of the 3rd-order Butterworth low-pass analog filter is

$$|H(j\Omega)|^2 = \frac{1}{(1 + \frac{\Omega}{\Omega_c})^6}, \tag{3}$$

where Ω_c is the cutoff angular frequency. A few justifications underpin the selection of this particular analog filter. Firstly, its insertion loss maintains a low and flat profile (i.e., maximally flat magnitude response) within the passband, thereby minimizing the attenuation of the mains voltage component. Secondly, it can fulfill (1)-(2) under certain circumstances. Thirdly, it demands a few components that are easy to calculate and offers a quasi-linear phase function in the frequency band near $f = 0$, which includes the mains frequency (i.e., 50 or 60 Hz).

Fig. 2 shows the schematic of the proposed passive analog blocking filter. It is constituted by gas discharge tube metal-oxide varistor (GMOV) components at input and output (i.e., $U1$ and $U2$) for ensuring electric protection. In between both GMOV components, we have the symmetric 3rd-order Butterworth low-pass analog filter. This analog filter comprises four inductors of inductance equal to $L/2$ in series and one shunt capacitor of capacitance equal to C. The distribution of inductors in the two branches provides equal attenuation in the line and neutral conductors, reducing the risk of electric shock when the blocking filter is connected to a single-phase low voltage (LV) electric power grid. It is important to emphasize that the inductors must be able to deliver the mains current demanded by the load with irrelevant attenuation. Moreover, the shunt capacitor provides a low-impedance path for the high-frequency content of electric signals.

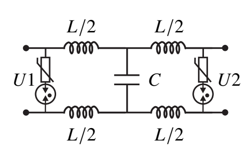
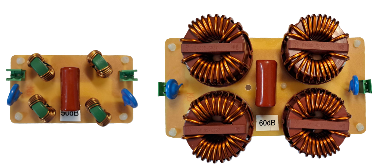


Fig. 2: The proposed passive analog blocking filter.

B. Prototype

The design of the proposed passive analog blocking fundamentally depends on the values of the inductive components and the current they support. Accordingly, two prototypes were constructed. The first prototype, referred to as **prototype** bf#1 and depicted in Fig. 3(a), has a cutoff frequency (f_c) of 1500 Hz and can support a maximum current ($I_{\max}$) of 10A. In contrast, the second prototype, named **prototype** bf#2 and illustrated in Fig. 3(b), has a cutoff frequency (f_c) of 610 Hz and can sustain a maximum current ($I_{\max}$) of 25 A. The variation in the f_c values between the two prototypes arises from using distinct inductors, each accommodating different maximum currents. Table I lists the components used in both prototypes. Note that the electric protection provided by the GMOV is consistent with LV electric power grids.



(a) **prototype #1** (b) **prototype #2**

Fig. 3: (a) The front views of **prototype #1** (dimension 90×50 mm) and (b) **prototype #2** (dimension 155×75 mm).

TABLE I: Prototypes: Details of components

Prototype #1

Label	Description	Value
$L/2$	PDMCAT18107-202ML	2 mH/10 A
C	Polyester	4.7 μF/400 V
$U1$ and $U2$	GMOV-14D151K	150 Vrms

Prototype #2

Label	Description	Value
$L/2$	T60405-R6123-X227	12 mH/25 A
C	Polyester	6.8 μF/400 V
$U1$ and $U2$	GMOV-14D151K	150 Vrms

IV. Performance Analysis

This section evaluates the performance of the designed passive analog blocking filter in terms of the analyses of the PSD of the voltage waveform and scattering parameters. Furthermore, it conducts a comparative analysis against an existing passive analog blocking filter[12], henceforth referred to as the “Mattron”. A comparison with the “Mattron’ devices aims to show the relative advantages of the designed blocking filter with respect to an existing device. The performance comparison covers the frequency band of 100-500 kHz because it is the operating frequency of the Mattron device.

A. Scattering Parameters Analysis

Fig. 4 shows the measured $|S_{11}|$ and $|S_{21}|$ scattering parameters because the circuit is symmetric. The measurement was done with the R&S FSH8 VNA. The plots compare the prototypes of the proposed passive analog blocking filter and the Mattron device. Analyzing $|S_{21}|$, we see all of them provide insertion loss higher than 45 dB, having the prototype presenting a flat insertion loss.

Regarding $|S_{11}|$, we can see that the prototypes attain reflection loss lower than 2.2 dB while the Mattron device attains an insertion loss higher than 4.5 dB. Overall, the proposals provide a better fulfillment to (1)-(2) than the Mattron device. It will be evident in the field test analysis discussion in Subsection IV-B.

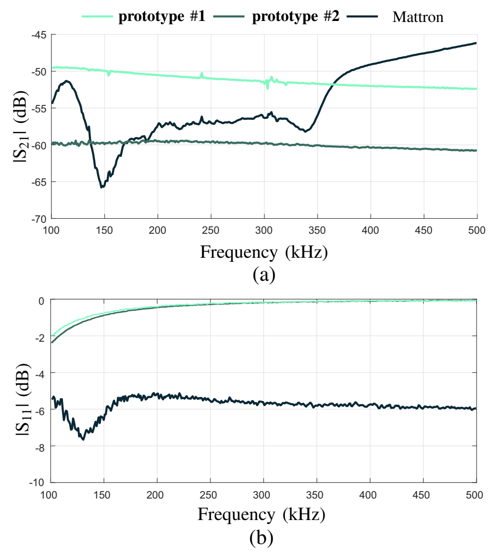


Fig. 4: Magnitude of the scattering parameters for **prototype #1**, **prototype #2**, and Mattron. (a) Transmission parameter and (b) Reflection parameter.

B. Field Experiment Analysis

To perform this analysis, the measurement setup in Fig. 1 and the corresponding measurement procedures were considered with the following modification: a passive analog blocking filter is inserted between the electric drill and the outlet, and two copper wires of diameter and length equal to 2.5 mm and l = 18 m, respectively, are used to connect two consecutive outlets.

Fig. 5 shows a comparison of the measured results obtained without a blocking filter (wo/ blocking filter) and with a blocking filter - prototypes (**#1** and **#2**) and the Mattron device. First, Fig. 5(a) shows the voltage waveform measured in an outlet without the presence of the electric drill. Note that **prototype #1** and **#2** and Mattron device provide, in this order, the highest to lowest performance. The PSDs of voltage waveform shown in Fig. 5(b) confirm that the “Mattron" device cannot effectively mitigate conducted emissions, mainly in the lower frequencies. Moreover, Fig. 5(c) shows that the impedance magnitude attained with the Mattron device is completely different from what should be expected, meaning that the Mattron device can seriously compromise the performance of NB PLC systems.

Now, the purpose is to analyze the behavior of the electric circuit between the two outlets when a blocking filter is

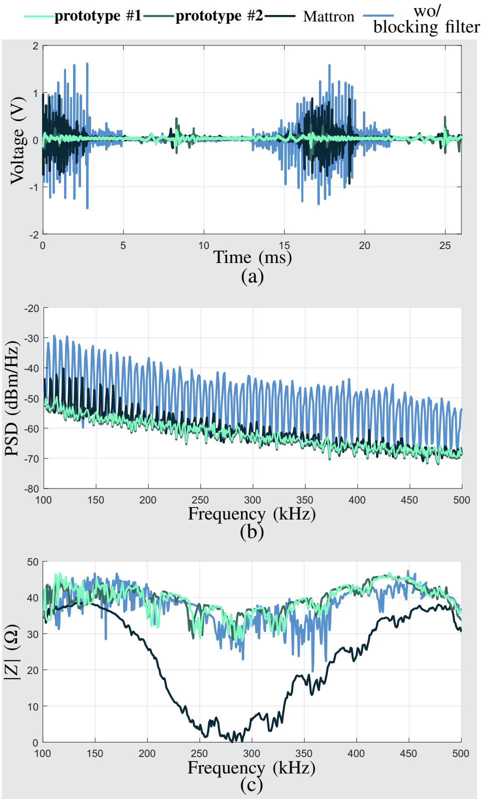


Fig. 5: Measurement Campaign. (a) voltage waveform of the additive noise, (b) PSD of the additive noise, and (c) measured impedance at one outlet.

inserted between the electric drill and the electric power grid. In this sense, Fig. 6 displays the measured scattering parameters $|S_{21}|$ and $|S_{11}|$ for the electric circuit between the two outlets. The $|S_{21}|$ curves demonstrate that prototypes **#1** and #**2** effectively counteract the high-power noise introduced by the electric drill and ensure a minimal insertion loss in the electric circuit between the two outlets. Conversely, the "Mattron" device results in significantly low values of $|S_{21}|$, which ultimately undermines the performance of a NB PLC system used for data transmission between the outlets. Additionally, the $|S_{11}|$ curves indicate that prototypes bf#1 and bf#2 attain a low value of reflection parameter, meaning less power is lost in the connection between the PLC devices and the electric power grid and, consequently, better performance of NB PLC system operating between the two outlets is attained. In contrast, the "Mattron" device yields a higher $|S_{11}|$, contributing to the poor performance of a NB PLC system operating between the two outlets.

V. Conclusion

This paper introduced a passive analog blocking filter designed to mitigate conducted emissions and ensure an essential level of impedance mismatch between loads (disturbance sources) and the electric power grid. These problems can compromise the performance of NB PLC systems, which are enabling data communication technology for IoT applications.

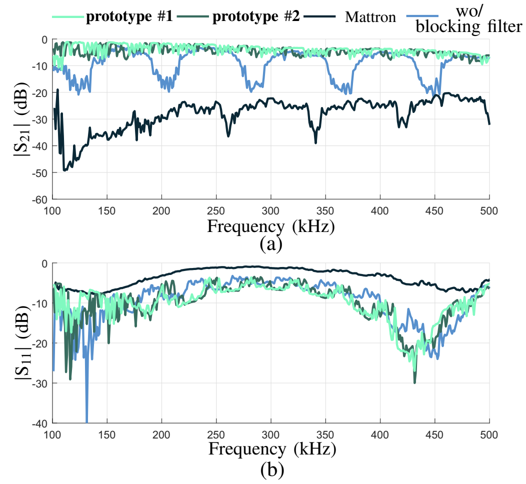


Fig. 6: Magnitude of scattering parameters for the electric circuit between the two outlets. (a) $|S_{21}|$ and (b) $|S_{11}|$.

Numerical results showed that the designed passive analog blocking filter provides improvements in terms of the PSD of the voltage waveform and scattering parameters. Furthermore, field experiments underscored the enhancements provided by our designed filter compared to an existing one.

References

[1] M. Girotto and A. M. Tonello, “EMC regulations and spectral constraints for multicarrier modulation in PLC,” *IEEE Access*, vol. 5, pp. 4954–4966, March 2017.

[2] C. Cano, A. Pittolo, D. Malone, L. Lampe, A. M. Tonello, and A. G. Dabak, “State of the art in power line communications: From the applications to the medium,” *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 7, pp. 1935–1952, July 2016.

[3] S. Galli and T. Lys, “Next generation narrowband (under 500 kHz) power line communications (PLC) standards,” *China Communications*, vol. 12, no. 3, pp. 1–8, March 2015.

[4] T. F. Moreira, A. Camponogara, S. Baig, and M. V. Ribeiro, “Performance analysis of orthogonal multiplexing techniques for PLC systems with low cyclic prefix length and symbol timing offset,” *Sensors*, vol. 23, no. 9, April 2023.

[5] C. Chauvenet, G. Etheve, M. Sedjai, and M. Sharma, “G3-PLC based IoT sensor networks for smartgrid,” in *IEEE International Symposium on Power Line Communications and its Applications*, 2017, pp. 1–6.

[6] L. d. M. B. A. Dib, V. Fernandes, M. de L. Filomeno, and M. V. Ribeiro, “Hybrid PLC/wireless communication for smart grids and internet of things applications,” *IEEE Internet of Things Journal*, vol. 5, no. 2, pp. 655–667, April 2018.

[7] S. Barker, D. Irwin, and P. Shenoy, “Pervasive energy monitoring and control through low-bandwidth power line communication,” *IEEE Internet of Things Journal*, vol. 4, no. 5, pp. 1349–1359, Oct. 2017.

[8] K. Bernacki, D. WybraÅczyk, M. Zygmanowski, A. Latko, J. Michalak, and Z. Rymarski, “Disturbance and signal filter for power line communication,” *Electronics*, vol. 8, no. 4, pp. 1–17, March 2019.

[9] S. Avram and R. Vasiu, “Passive power line communication filter design and benchmarking using scattering parameters,” *Applied Sciences*, vol. 13, no. 11, pp. 1–21, Jun. 2023.

[10] L. G. S. da Costa, A. A. M. Picorone, A. C. M. de Queiroz, V. L. R. da Costa, and M. V. Ribeiro, “Projeto e caracterização de acopladores para power line communications,” in *Proc. XXXIII Brazilian Symposium on Telecommunications and Signal Processing*, Sep. 2015, pp. 1–5.

[11] United States Department of Defense, “Electromagnetic Compatibility Requirements for Systems,” United States Department of Defense, Military Standard MIL-STD-461G, Dec. 2015.

[12] Mattron, “Blocking Filter, 100 kHz - 450 kHz,” http://www.mattron.kr/eng/prod4.php, March 2023.