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Published in:
IEEE International Symposium on Electromagnetic Compatibility - EMC Europe

DOI (link to publication from Publisher):
10.1109/EMCEurope61644.2025.11176235

Publication date:
2025

Document Version
Accepted author manuscript, peer reviewed version

Power Electronics Converters Impedance Characterization Device for Low Frequency EMI Analysis

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Abstract — **Knowing the impedance of power converters is crucial for designing effective electromagnetic interference filters and predicting electromagnetic interference behaviour in system-level investigations. This paper introduces a novel impedance characterization device for power converters, designed to operate while the converter is in its active state. The device employs transformer-based injection of predefined arbitrary waveforms to capture real-time impedance measurements of the converter. A key innovation of the device is the development of a compact and cost-efficient digital amplifier, which enhances the overall efficiency of the characterization process. The device has been thoroughly tested and shown to provide accurate measurements, with performance extending up to 150 kHz, limited by the specific characteristics of the injection transformer. It has been successfully utilized to characterize both the artificial main network impedance and the differential-mode impedance of a single-phase converter, achieving precise and reliable results.**

Keywords — **electromagnetic compatibility, electromagnetic interference, impedance, power converter, supraharmonics.**

I. Introduction

Accurate impedance characterization of power converters is crucial for designing effective electromagnetic interference (EMI) filters, especially in the 2-150 kHz supra-harmonic frequency range. Power converters with switching frequencies in this range can interfere with sensitive devices, including ICT equipment and power line communication systems in smart grids [1-3]. As such, precise impedance characterization is vital for minimizing EMI and ensuring the proper functioning of power electronics converters [4],[5].

Current methods often use impedance analyzers or vector network analyzers (VNAs) to measure impedance in off-condition states. While useful, these measurements fail to capture the real-time, dynamic impedance behavior of converters during active operation, leading to incomplete EMI predictions [6]. More advanced techniques pair VNAs with bulk injection probes to inject signals and measure impedance in real-time either using capacitive or inductive coupling. However, these systems are costly and often have limited accuracy at lower frequencies, particularly below 150 kHz [7-10].

A recent study [11] attempted to characterize the impedance of DC-DC converters using time-domain multitone signals within the 30 Hz to 100 kHz range. However, in addition to the limited frequency coverage, the proposed setup is expensive and occupies significant space. More recently, online characterization of power converters has been explored in [12], [13], but these methods still rely on bulky signal generators and amplifiers, leading to similar cost and size limitations.

To overcome these limitations, this paper introduces a novel impedance characterization device that operates during the converter's active state, providing real-time, dynamic impedance measurements essential for accurate EMI prediction. The device injects predefined arbitrary waveforms using an injection transformer and integrates a GaN-based digital amplifier. GaN amplifiers offer higher efficiency, smaller size, and better power handling compared to traditional linear amplifiers, making the system more compact and cost-effective.

The device also utilizes a PicoScope for both waveform generation and real-time capture of voltage and current signals. This integration minimizes the size and cost of the equipment while simplifying operation compared to the methods presented in [11-13], where, in addition to a bulky linear amplifier, separate signal generators and oscilloscopes are required, increasing both cost and complexity. The captured signals are then post-processed to calculate real-time impedance, providing a thorough analysis of the converter's impedance characteristics during operation. The schematic of the proposed impedance characterization device is shown in Fig. 1.

The proposed device has been rigorously tested, providing precise impedance measurements up to 150 kHz, constrained by the injection transformer's characteristics. It has been successfully used to measure both Artificial Mains Network (AMN) and differential-mode (DM) impedance of a single-phase converter, delivering reliable results. By enabling real-time active-state impedance characterization, this device addresses the limitations of traditional methods and offers a more efficient, cost-effective solution for EMI prediction and filter design. Its compact size, affordability, and ability to measure a wide frequency range make it valuable for both research and industrial applications.

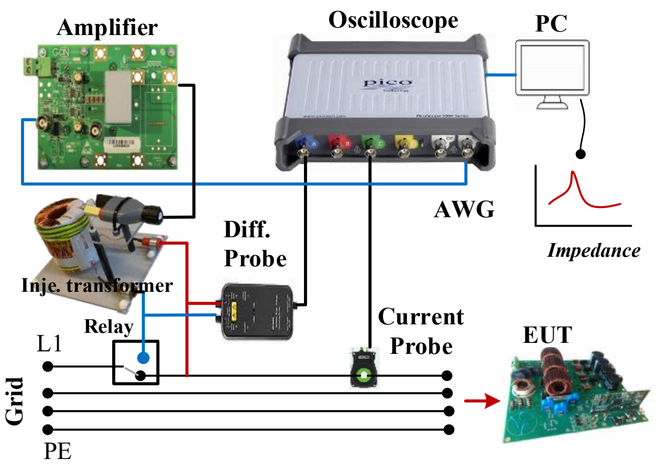


Fig. 1. Schematic of the proposed power converter impedance characterization device

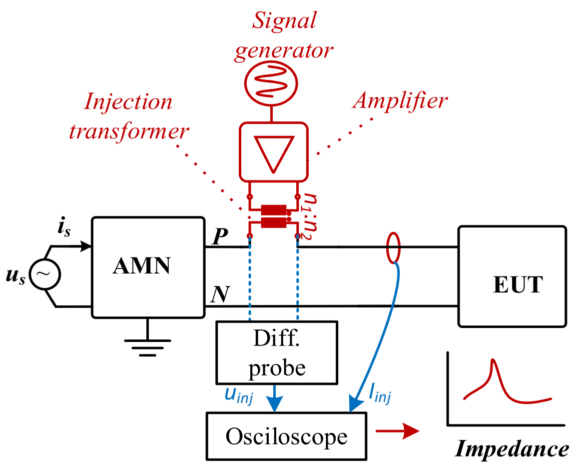


Fig. 2. Illustration of main principle behind the proposed impedance characterization method.

The rest of the paper is structured as follows: Section II explains the working principle of the characterization device, Section III presents the impedance measurements obtained using the proposed device, and Section IV provides the conclusions.

II. Working Principle of the Impedance Characterization Device

The impedance characterization device consists of three main units designed to measure the impedance of a power converter during normal operation. The first unit is the Arbitrary Waveform Generator (AWG), which generates a series of frequency points necessary to stimulate the converter. Since the output power of the AWG is often not sufficient for driving the converter, the second unit, the Power Amplifier, amplifies the signal to the required power level. The amplified signal is then injected into the converter, typically through an injection transformer, ensuring proper impedance matching and isolation. The third unit involves voltage and current measurement: differential voltage probes measure the voltage across the converter, while current probes capture the current flowing through it. The impedance is calculated using the voltage and current data and results in a detailed impedance profile. These three units work together seamlessly to provide accurate and reliable impedance characterization of the power converter under typical operating conditions.

Since the grid-side impedance is often unknown, variable, and can change over time or depending on the location, a known reference impedance is necessary for accurate impedance characterization. In this case, an AMN is used to provide a stable and controlled reference impedance. The AMN ensures that the test setup receives a known and consistent impedance, isolating the equipment under test (EUT) from any variations or disturbances on the grid side. This helps maintain measurement accuracy by minimizing the impact of grid noise, harmonics, or other fluctuations that could distort the results.

By using an AMN, the impedance characterization process becomes more reliable, as the reference impedance remains consistent regardless of external grid-side changes, allowing for precise analysis of the EUT's performance. Fig. 2 illustrates the schematics of the impedance measurement.

A multi-tone signal with 170 injection frequency points, excluding integer multiples of the 50 Hz mains, is created using (1) and injected using injection transformer.

$$S_{multi-tone}(t) = \sqrt{\frac{2}{N}} \sum_{k=1}^{N} \sin\left(2\pi k f t + \Theta_k\right) \tag{1}$$

$$\text{Where, } \Theta_k = \frac{\pi(k-1)^2}{N} \tag{2}$$

and N is number of frequency points.

The frequency 'f' is set to 53 Hz to prevent interaction with the converter controller. In fact, the 5444D PicoScope, featuring four channels, a 200 MHz sampling frequency, and an AWG capability, is utilized to both generate the arbitrary waveform and capture the injected voltage and current. This integration streamlines the characterization device, making it highly compact and eliminating the need for separate AWG and oscilloscope units.

For signal amplification, a cost-effective and compact solution is proposed using half-bridge GaN evaluation boards, as shown in Fig. 4. In this setup, the arbitrary waveform is first digitized and sent to the gate drivers, where a 180° phase shift and delay time are applied to control the upper and lower leg MOSFETs. The MOSFETs then amplify the digitized waveform, with the amplification determined by the DC supply voltage (Vs). The resulting output voltage (Vo) is an amplified version of the waveform, which is injected into the mains via an injection transformer. A small series resistor (Zs) is included to prevent short circuits caused by the low impedance seen from the transformer's primary side.

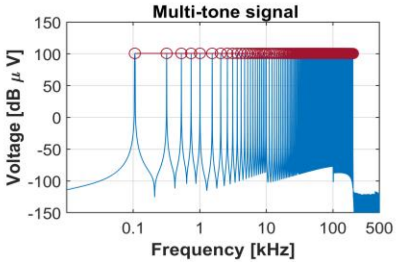
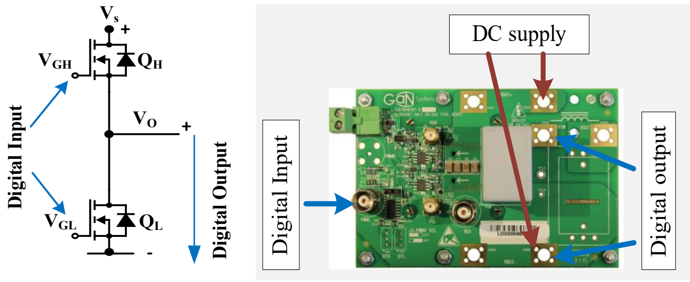
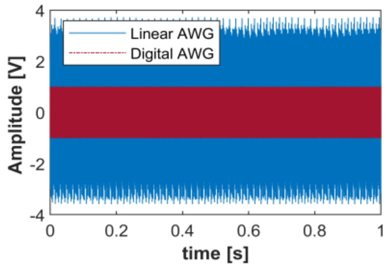


Fig. 3. Multi-tone signal with 170 injection frequency points.

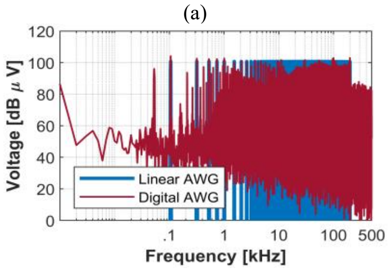


(a) (b)

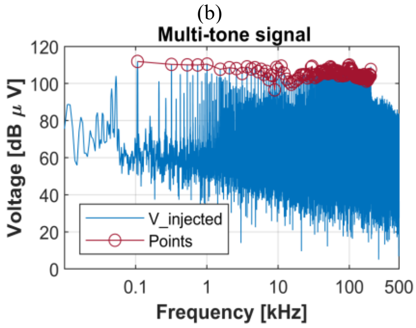
Fig. 4. Proposed GaN based Digital amplifier (a), schematics; and (b) GS66508T half-bridge evaluation board.



(a)



(b)



(c)

Fig. 5. Comparison of analogue based arbitrary wave (old method as in [12]) with digital amplifier based arbitrary wave both in time and frequency domain.

The GS66508T half-bridge evaluation board from GaN Systems was selected for this application. A 24V DC supply

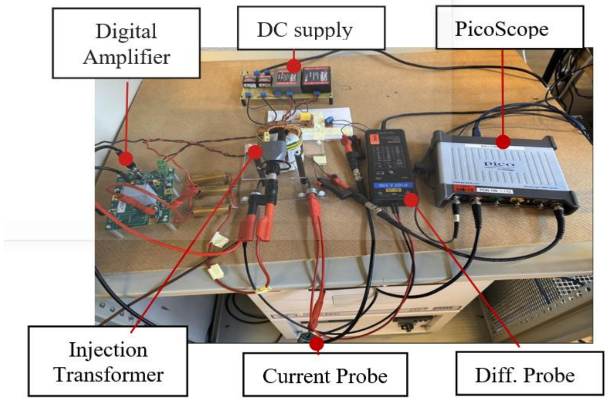


Fig. 6. Experimental test bench to characterize the impedance.

voltage is chosen to ensure that the transformer's secondary side reaches the required voltage level (2V), given the 100:10 turn ratio. The evaluation board also includes an internal controller with sufficient dead time. As noted earlier, a 10 Ω series resistor is placed between the digital amplifier and the transformer to prevent short circuits.

Fig. 5 (a) compares the original arbitrary waveform used in the old setup (Fig. 5, created using (2)) with the digital arb itrary waveform (zeros and ones) in the time domain.

Fig. 5 (b) shows the FFT of these signals, indicating that the energy of the original waveform is nearly preserved in the digital arbitrary waveform.

Fig. 5 (c) illustrates the arbitrary waveform after the digital amplifier was applied (with 24V Vs), where all intended frequency points are present with sufficient amplitude. Additionally, the signal level can be increased by raising the DC supply voltage, Vs.

In addition, a DC power supply is designed to supply the necessary voltages for the gate driver, comparator, and the DC supply voltage (Vs). For this purpose, a simple AC to DC converter from Tracom Power is selected, which is capable of converting 230V AC to 24V DC, 12V DC, and 3.3V DC. Finally, the AWG output from the PicoScope is digitized using a comparator to ensure the voltage level is sufficient to turn on the GaN module. The experimental test bench is shown in Fig. 6.

III. Measurement Result and Discussion

The proposed impedance characterization device was thoroughly tested by measuring the impedance of both the AMN and a single-phase power converter. The following section presents a detailed summary of the results obtained from these tests.

A. AMN Impedance Characterization

The proposed digital amplifier was evaluated by measuring the Line-to-PE impedance of the CISPR 16-1-2 AMN, implemented as a two-stage network with 250 µH and 50 µH inductors. The impedance was successfully measured,

Table 1. CISPR 16 AMN impedance comparison based on digital and linear amplifier.

Frequency (kHz)	2	10	50	150
Measured Impedance (dB) using digital amplifier	16.68	16.01	23.2	30.3
Reference CISPR 16 AMN Impedance (dB) measured using linear amplifier	16.57	15.63	22.93	30.22

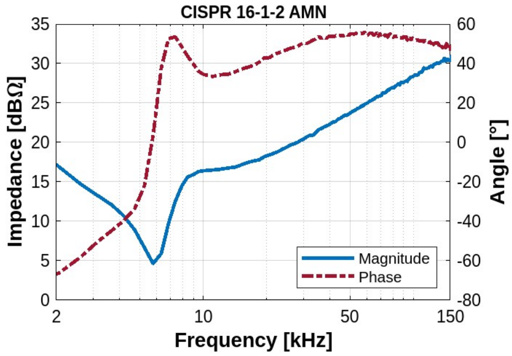


Fig. 7. Measured impedance of the CISPR 16-1-2 AMN with the digital amplifier.

as shown in Fig. 7. These results are compared with reference measurements obtained using the setup proposed in [12], which is based on a linear amplifier. As listed under "Reference CISPR 16 AMN" in Table 1, the deviation between the proposed method and the reference is less than 0.5 dB.

B. Single-Phase Converter DM Impedance Characterization

The DM impedance of a single-phase converter (as detailed in Table 2) is characterized in this case. The setup used for measuring the DM impedance of the converter is shown in Fig. 2. The AMN stabilizes the grid impedance, ensuring that the impedance measurement is independent of grid conditions. In this process, a CISPR 16-1-2 AMN is employed. A multi-tone signal generator produces signals at selected frequency points, which are then injected into the phase conductor through a coupling transformer. The PE conductor remains unconnected.

As a result, the ratio of voltage to current at the transformer's secondary represents the sum of the DM impedances of the AMN (Z_{AMN}) and the DM impedance of the converter (Z_{dm}), as expressed in the following equation:

$$\frac{U_{inj}}{I_{inj}} = Z_{AMN} + Z_{dm} \tag{3}$$

The resulting DM impedance of the converter is displayed in Fig. 8 (a), showing resonances due to the EMI filter type used. Additionally, Fig. 8 (b) highlights that the DM impedance varies significantly between the converter's on and off states, especially above 80 kHz. This variation underscores the importance of measuring DM impedance while the converter is in the on state. The DM impedance of the converter measured with the digital amplifier were also compared with the measurement carried out in [10], showing a

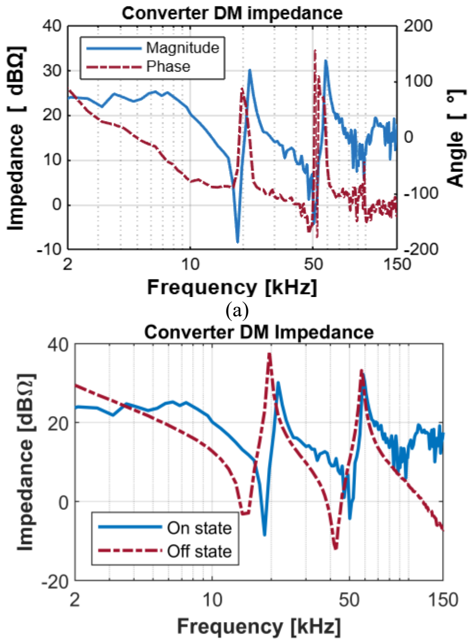


Fig. 8. Measured DM impedance of the single-phase converter: (a) characterized while the converter is in on state; and (b) comparison of on and off state impedances.

very close agreement. In fact, the digital amplifier-based measurement not only reduced both complexity and cost but also produced better results.

Table 2. Summary of the single-phase converter considered for this activity

Input (AC)	Output (DC)	Load (kW)	Switching Frequency (kHz)
230 V	400 V	2.5	100

IV. Conclusion

In this paper, a novel power converter impedance characterization device is introduced. The device characterizes the impedance of the converter while it is in its operating state, allowing for the capture of real-time conditions. The characterization is achieved by injecting predefined arbitrary waves through transformer-based injections. The device characterized the impedance of CISPR 16-1-2 AMN and a single-phase PFC converter, of course it can be used to characterize three phase converters as well. The paper also proposed a GaN based digital amplifier that is smaller in size and more cost-effective than traditional amplifiers, which are typically used to amplify arbitrary waveforms. The proposed device has been tested and demonstrates high accuracy. It functions effectively up to 150 kHz, with limitations primarily due to the specific injection transformer employed. Future work will focus on extending the frequency range by designing a new transformer and further characterizing the impedance.

Acknowledgment

This work was supported by the Supra-EMC (Supra-EMC: Supraharmonics ElectroMagnetic Compatibility strategies in power electronic based power grid) project funded by Innovation Fund Denmark.

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