Compensation of Time-Domain Waveforms by Applying the Complex Transfer Function of a Current Probe in the kHz-MHz Range

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***Abstract*—The advance in power converters is demanding a higher set of measurement tests, in large bandwidths and with waveform monitoring in the time domain. Current probes contain many advantages for such measurements, but the direct use in the time domain is not straightforward due to the non-constant transfer impedance, which can cause critical distortion on the probe output. This work demonstrates through laboratory measurements an FFT-based technique for compensation of signals measured in the time domain. By applying the current probe's transfer function together with the signal spectra of its measured current, the applied voltage can be recovered and the supply current can be estimated. Also, the calibration steps for measurement of the probe's complex transfer function are detailed, comparing three different approaches. The results have shown excellent accuracy with the measurements for the compensation of a simple triangular signal in the kHz range.**

***Index Terms*—calibration jig, current probe, time domain measurements, time-frequency compensation, transfer impedance.**

I. INTRODUCTION

The current probe is often used by EMC and power engineers for current monitoring without making direct contact with the conductive source, as the probe can clamp on around the conductor. The probe is exposed to a magnetic field produced by the current in the conductor passing through the aperture of the probe and the probe's output voltage is measured with an oscilloscope or spectrum analyser when properly calibrated. The current transformer type is the focus of this paper, as it is very common in power conversion applications and distribution networks. A detailed description of the operation principle can be found in [1] and a more comprehensive review of current sensing techniques for electronic-based converters is described in [2].

For the employment of current probes in time domain measurements, the user should be attentive to the fact of its non-constant transfer impedance and the possibility of highly distorted outputs that do not correspond to the real waveform measured. There are some suggestive solutions for that, for example, the application of a simple frequency response compensation method of ESD currents using current probes [3], including a derivation of an equivalent circuit of the probe's transfer impedance.

In [4], deconvolution is used for the accurate estimation of power losses and EMI in power converters. In [5], a common-mode (CM) current measurement with current probes was investigated, with improvements in the coupling minimization. The CM current along cables can be a good indicator of radiated emission in power converters. In [6], an alternative technique using a current clamp was used for CM current prediction in three-phase systems.

This work investigates the current compensation by using a time-frequency compensation method and the probe's complex transfer impedance. This methodology uses convolution via a Fast Fourier Transform (FFT) of the measured signal, calculations in the frequency domain with the probe's transfer function. Then, the waveform is reconstructed back to the time domain. Also, an investigation of the transfer impedance measurement is performed, including the calibration steps of the vector network analyser (VNA) from different guidelines.

II. METHODOLOGY

A. Measurement of the transfer function

The concept of the transfer function is very functional in the analysis of systems where output functions can be related to a set of inputs and can be described by linear differential equations [7] and represented in the Fourier domain (1).

$$H(\mathrm{j}\omega) = \frac{G(\mathrm{j}\omega)}{F(\mathrm{j}\omega)} \tag{1}$$

where G is the output and F is the input complex functions.

The transfer function of a current probe can be described as the ratio of the measured voltage output by the current flow through its aperture, describing the probe's dynamics. Their measurement is usually in compliance with methods provided by international standards, such as CISPR 16-1-2 [8] and ISO 11452-4 [9]. However, those standards have unspecified parameters that reduce the reproducibility in different measurement scenarios [10].

The test arrangement has two steps and involves a network analyser, and coaxial cables. This arrangement contains 50Ω terminations on all ports. The first step is to calibrate the VNA with its respective calibration kit, so any effect of the measurement chain that is not the device under test itself is properly compensated. Then, the transfer function can be

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 812753.

measured. The transfer function is obtained according with the description found in three sources: the standards ISO 11452-4 / CISPR 16-1-2, the manufacturer's guidelines [11], and cases in the literature [10]. One difference among those methods, is that the description given in ISO 11452-4 does not specify the VNA calibration method, even though the chosen parameters can change the results.

For the three methods, a thru-open-short-match (TOSM) calibration was performed in the two ports, as it provides a general higher accuracy, and after the calibration is applied from 20 to 100 000 kHz, the test composition to obtain the transfer impedance (Z_t) of the current probe was prepared.

The VNA will measure the ratio of the voltage appearing at the output of the current probe (V_P) by the current applied to the calibration fixture (I_IN) and terminated with 50 Ω, represented by the forward transmission coefficient (S_{21}). In complex form, the transfer impedance relates to S_{21} as in (2).

$$Z_{\mathrm{t}[\Omega]} = \frac{V_\mathrm{P}}{I_\mathrm{IN}} = 50_{[\Omega]} \cdot S_{21} \tag{2}$$

The calibration technique of a current probe manufacturer (FCC, Inc.) complies with ISO 11452-4, except for the thru response calibration [10] and the current probe is inserted in the calibration fixture and terminated at 50 Ω, so any reflection caused by the coupling impedance between the probe and the inner conductor of the test jig is considered. The transfer impedance is as the same as in (2).

For the approach found in the literature, the reflection behaviour due to the influence between the probe, cabling and the calibration fixture is to be removed [10]. The forward transmission coefficient $S_{21(\mathrm{jig})}$ of the calibration system and the probe's forward coefficient S_{21} are recorded. Then, the probe's transfer impedance can be obtained (3).

$$Z_{\mathrm{t}[\Omega]} = \frac{V_\mathrm{P}}{I_\mathrm{IN}} = 50 \cdot \frac{S_{21}}{S_{21(\mathrm{jig})}} \tag{3}$$

Note the differences in each approach become evident in the high-frequency portion of the transfer impedance, as shown in Fig. 1. This transfer characteristic is used for the compensation technique.

B. The time-frequency compensation technique

The Fourier analysis is fundamentally a method for expressing a function as a sum of periodic components and for recovering the function from those components. The FFT is an algorithm for computing the finite DFT, eliminating most of the repetition with better accuracy and fast computation of spectral components.

The general methodology is summarized in Fig 2. Using similar principles as in [12], the authors expanded that approach with laboratory measurements and employed the FFT instead of the Laplace transform. Moreover, an interpolation is performed up to the FFT limit frequency, not only for frequency matching but also for extrapolation of low-frequency points not acquired by the VNA (from 0 to 20 kHz), accompanied by a zero-phase, low-pass filter.

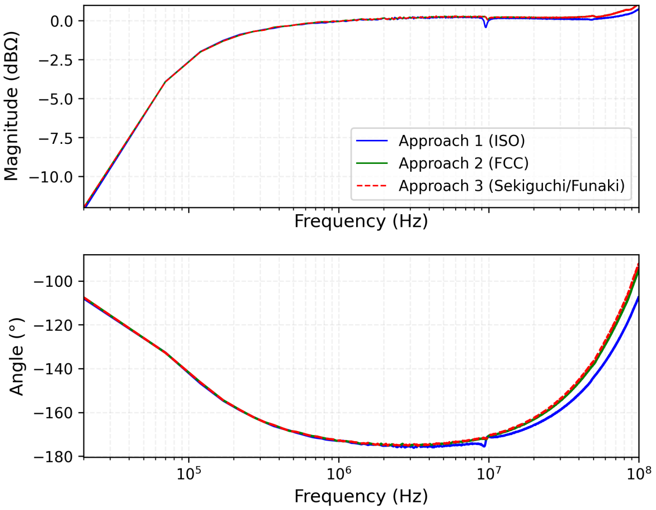

Fig. 1. Complex transfer impedance

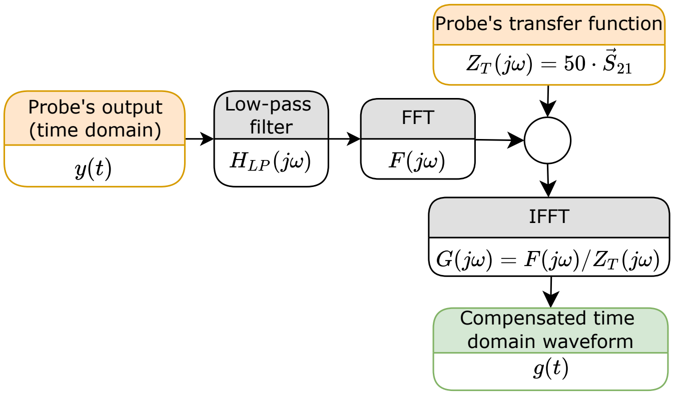

Fig. 2. Flowchart of the process for current compensation using the complex transfer impedance and Fast Fourier Transforms.

III. TEST CASE AND FINDINGS

The input signal generated is a 50 kHz, triangular waveform without DC offset and connected through a coaxial cable to one terminal of the calibration fixture; an oscilloscope port at 50 Ω is connected to the other terminal. The output signal is from the current probe's terminal, which is also connected to an oscilloscope port at 50 Ω and the probe is clamped to the fixture.

If the probe is placed over the coaxial cable or shielding conduit, only the current flowing on the external surface of the screen is measured. Although this can be useful for the evaluation of the shielding effectiveness, this is not the objective here. Thus, the calibration fixture is needed to separate the current flowing in the inner conductor from the shield.

Time-domain signals were captured with the oscilloscope and two-periods are shown in Fig. 3. Note that the current clamp output (blue curve) is distorted when compared with the input voltage (black curve), which is an unexpected behaviour for a matching resistive configuration.

Following the procedure in the flowchart along with the transfer function, the probe output can be compensated and the applied input voltage can be recovered, i.e., the current measured times the impedance of $50\ \Omega$. The deconvoluted time-domain voltage signal is shown in Fig. 4. As the voltages were directly measured with matching impedance, this comparison is valid. The current is expected to have a similar shape to the voltage and a peak current of $20\,\mathrm{mA}$, so this method can be also used for prediction of the current waveform.

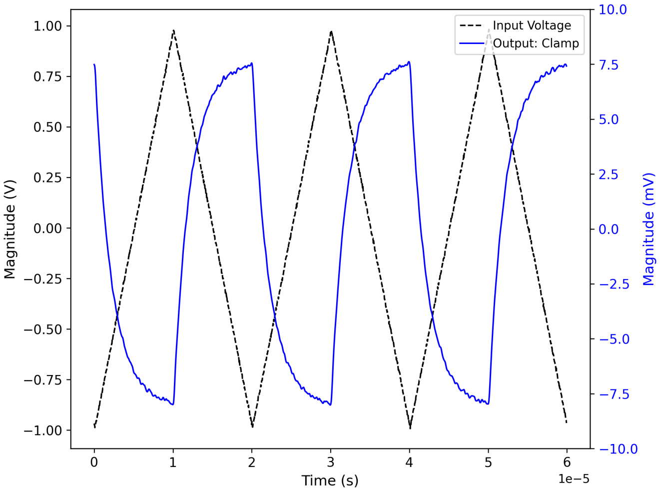

Fig. 3. Time-domain measurements

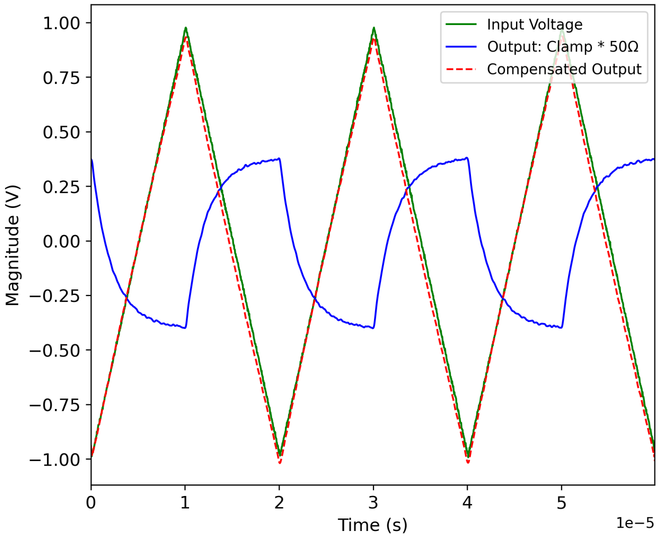

Fig. 4. Original and compensated voltage waveforms

It can be observed that the compensated output is alike the measured input voltage, except that it does not exactly match the peaks. This is probably due to a DC offset resulting from the FFT or the filtering processing. Also, an inverse FFT containing the transfer function outcomes in a complex time-domain waveform due to its unsymmetrical configuration, but only the real part of the compensated waveform is used and displayed in Fig. 4.

IV. CONCLUSIONS

This work presented the preliminary results of a time-frequency FFT compensation technique applied to a waveform measured in the time-domain with a current probe and applying the probe's transfer impedance, which demonstrated excellent performance, with an small DC offset arising in the compensated output. Additionally, the processes for measuring the transfer impedance of a current probe among three methods are compared.

This FFT technique can be used for compensation and prediction of typical signals measured in the time domain with a current probe, but only with suitable consideration about its complex transfer characteristic.

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