Fast Calibration Procedure for Low Power Voltage Transformers up to 2.5 kHz using Sinc response

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Abstract – **A The progressive deployment of Low Power Instrument Transformers in power network for measurement purposes requires studies on their characterization and on the effect of different quantities on their accuracy. In this paper, a fast calibration procedure is introduced. By using a sinc signal, a Low Power Voltage Transformer has been characterized in the power quality frequency range (50 Hz to 2.5 kHz) under the rated voltage conditions.**

Keywords – **LPVT, Power Network, Sinc Response, Impulse Response, characterization**

I. INTRODUCTION

Instrument Transformers (IT) are conventionally used for monitoring, measuring and protection purposes. To measure both voltage and current as state variables for power networks, Voltage Transformers (VT) and Current Transformers (CT) are deployed. To face the new requirements, due to development of the so-called Smart Grids, a new generation of ITs has been developed. These are referred to as Low Power Instrument Transformers (LPIT) or sensors. LPITs in both active and passive configurations are progressively deployed in power networks for their small size, high bandwidth (up to 20 MHz), and accurate operation for measuring purposes. For these reasons, studies on LPITs are becoming more and more popular in the current literature. For example, in [1,2] a test-bed has been developed for voltage and current LPITs; while their accuracy is tackled in [3-5]. Several applications adopting LPITs are discussed in [6-8]; whereas an interesting overview on their modelling is described in [9,10].

The characterization of LPITs is typically evaluated in terms of ratio error and phase displacement to be aligned with the Standard IEC 61869-6 [11].

To characterize any dynamic system in whatever range of frequencies, hence including the Power Quality (PQ) one, Impulse Response (IR) and Sweep Frequency Response (SFR) tests are well-known and tackled in literature. The IR test used for characterization at different ranges of frequency is presented in [12-17]. On the other hand, SFR test characterizes dynamic systems by testing each frequency separately. This process is time-consuming compared to a simple IR test. However, the limitations imposed by IR test, such as slew rate of impulse signal and impulse response signal detection techniques, make the SFR test more feasible even if it is time-consuming. As an example, SFR analysis performed on VTs are described in [18-20].

In literature, there are not many studies on the LPVTs characterization, but there are several on conventional VTs, like [21]. In [22] instead, a practical application of VTs frequency characterization under distorted conditions due to dip voltage in power network is presented. There are also other applications of IR and SFR tests for power transformers like [23], which compares IR and SFR test on power transformers for winding fault diagnostics. Moreover, [24] studies the IR test on distribution transformers for the dielectric design.

In this work, authors started from the IR idea to present a new test signal to test capacitive Low Power Voltage Transformers (LPVTs) in the PQ frequency range (50 Hz – 2.5 kHz). Such signal, briefly detailed in the paper because already adopted in [25], is a rectangular window in the frequency domain, which results in a sinc signal in the time domain. Therefore, the so called Sinc Response (SR) test is introduced as an improvement of IR test with specified limited range of frequency, and with a high resolution. Afterwards, the idea is to compare the SR characterization with the typical SFR test to prove the accuracy and applicability of what proposed when applied to LPVTs.

What follows is structured as: Section II describes the SR test and the sinc signal design. Sections III and IV describe the measurement setup and the experimental tests, respectively. In section V the experimental results are reported and commented. Finally, section VI briefly

summarizes the achievements and the conclusion of the work.

II.   SIGNAL DEVELOPMENT

A. Motivation

Characterization and modeling of dynamic systems with impulse response test is a well-known procedure. The IR test provides the dynamic system behavior for all the frequencies at the same time. This procedure is one-time test compared to the sweep frequency test which has to be repeated for all desired frequencies.

LPVTs design are based on capacitive, resistive, and capacitive-resistive voltage dividers. Considering a pure capacitive LPVT as the dynamic system to be characterized, the IR test is critical because of the LPVT frequency independency in ideal model. In this case, IR signal is equal to the secondary LPVT output scaled by the transformation ratio.

The purpose of this study is to characterize a non-ideal capacitive LPVT considering its slightly frequency dependency. Such a dependency is the critical aspects when modeling and characterizing an LPVT. The sources of non-idealities in capacitive LPVTs are the frequency dependency of the primary capacitor dielectric permittivity and the resistive leakage of the primary capacitor.

The main problem in LPVT characterization with IR test is the short pulse width of the impulse response and technical limitations for detecting such short width signal. This limitation is imposed by the limited sampling frequency of typical Analog to Digital Converters (ADC). Furthermore, the resolution of the measured IR signal should be high enough to accurately measure all frequency components (which is not possible due to frequency limitation mentioned before). However, this a must-have requirement to guarantee high standard of accuracy when evaluating the ratio error ε and phase displacement $\Delta\varphi$ of the device.

The solution adopted in this work, to overcome the abovementioned challenges, is to use a Sinc signal

$$sinc(x) = \begin{cases} 1 & x = 0 \\ \frac{\sin(x)}{x} & x \neq 0 \end{cases} \quad , \quad (1)$$

instead of an impulse signal. In (1) x is a generic input quantity of the sinc function. Such a function has a limited frequency range and a specific number of lobes. The design of the sinc, described in what follows, guarantees that conventional Data Acquisition Boards (DAQ) are capable of acquiring such a signal. In correlation with IR test, from now on the test using sinc function is called Sinc Response (SR) test.

B. Sinc signal design

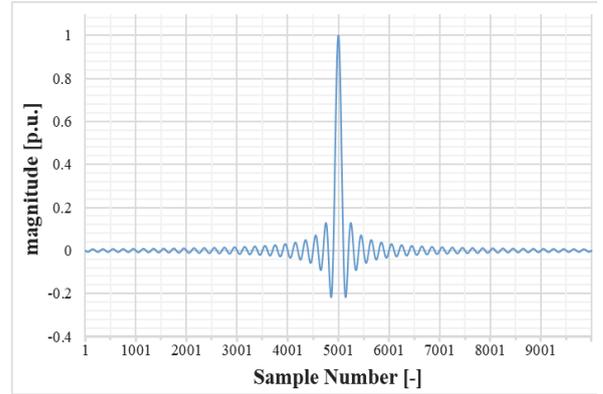The analog sinc function Fourier Transform (FT) is a

Fig. 1. Designed sinc function in time domain

rectangular window representing the amplitude of the frequency components. In contrast to the ideal impulse, such function has a limited range. In this work, the frequency range for the sinc function is fixed from 50 Hz to 2.5 kHz, which reflects the power quality frequency range in power networks.

The sinc signal is designed and sampled in software environment to be generated, amplified, and applied to the LPVT under test. The measured output analyzed in software environment is converted to digital signal. For this reason, the performed frequency domain analysis is the Discrete Fourier Transform (DFT) with Fast Fourier Transform (FFT) algorithm on the measured output signal with N number of samples. The test procedure and measurement setup are explained in section III and IV in details, respectively.

As for the sinc function design, it consists of time-domain series of samples from -50 to +50 passing through 100 integer numbers in which the zeroes of sinc function appear. According to (1), the sinc function has one main lobe at $x = 0$ and 50 side lobes (considering both maxima and minima) on each side of the main lobe. The number of samples is N=10000 which represents the magnitude of 0.01 for the Fourier Series coefficients. Finally, the period of the entire sinc signal is 20 ms.

In the frequency domain, the FFT of the designed sinc has a magnitude of 100 (for sinc signal with 10000 samples). The frequency imposed by the designed sinc, ranges from 50 Hz to 2.5 kHz with frequency steps of 50 Hz. Out of this frequency range, the FFT is zero. The obtained time-domain sinc function is shown in Fig. 1.

III.   MEASUREMENT SETUP

The test setup implemented to characterize the LPVT, depicted in Fig. 2, is composed of:
- Agilent 33250A 80 MHz Function/arbitrary waveform generator used to generate the designed sinc signal.
- Trek High Speed/High Voltage power amplifier Model 20/20C-HS to amplify the generated signal to the almost 16 kV rated voltage. Its main characteristics are listed in Table I.
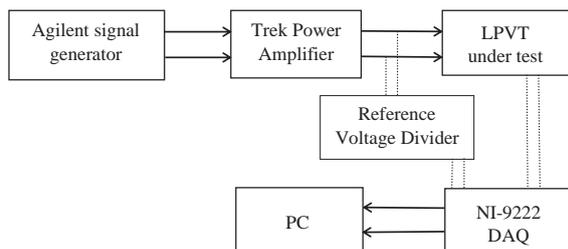
Fig. 2. Schematic representation of the test setup

Table I. Trek power amplifier features

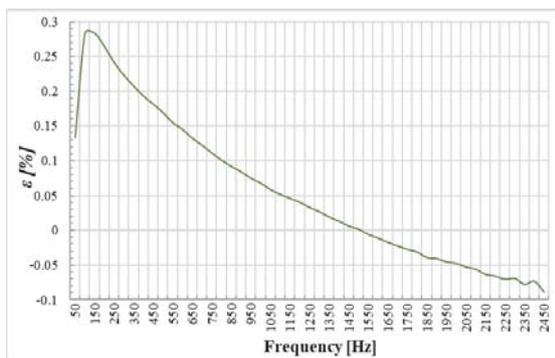| Output voltage range	0 to 20 kV DC or AC peak
Input voltage range	0 to 10 V DC or AC peak
DC voltage gain	20000 V/1V
DC voltage gain accuracy	>0.1 % of full scale
Slew rate	800 V/µs
Large signal bandwisth	DC to 5.2 kHz
Drift with time	Less than 50 ppm/hr
Drift with Temperature	Less than 100 ppm/°C

Fig. 3. Ratio Error v.s. frequency

- Passive capacitive LPVT under test with $20/\sqrt{3}$ /2.73/$\sqrt{3}$ kV rated voltage and 0.5 accuracy class.
- Resistive-capacitive reference voltage divider with $20/\sqrt{3}$ kV/3.34/$\sqrt{3}$ V rated voltage and 0.1 accuracy class to measure the primary signal and used as a reference.
- NI 9222 Data Acquisition Board that features: i) ±10 V range, ii) a sampling frequency of 500 kSa/s. and iii) ±0.02 % gain error and ±0.01 % offset error.

In brief, the required signals are generated and amplified before applying them on the LPVT under test. Then, the primary and secondary voltages are acquired to compute ε and $\Delta\varphi$ at each frequency of interest.

IV. TESTS DESCRITPION

Two different tests have been performed. One is the LPVT frequency characterization by exploiting the presented SR approach. The second is the well-known SFR test which has been used as a reference method to assess the SR test.

The peak voltage for both SFR test and SR test is 16 kV as the rated voltage for LPVT is $20/\sqrt{3}$ kV rms. This

implies the fact that the frequency characterization is performed under rated voltage (in other opinion the correct voltage level to adopt). With 16 kV peak voltage for the sinc signal, the Fourier Series coefficients for all frequency components are 162 V.

A. Sinc Response test

The purpose The purpose is to apply the amplified sinc function to the LPVT, to measure the output, and to compute ε and $\Delta\varphi$ for each frequency components ranging from 50 Hz to 2.5 kHz with frequency step of 50 Hz. As it is well-known, ε and $\Delta\varphi$ are defined as:

$$\varepsilon = \frac{kU_2 - U_1}{U_1} * 100\%, \tag{2}$$

$$\Delta\varphi = \widehat{U_2} - \widehat{U_1}, \tag{3}$$

where U_2 and U_1 represent the secondary and primary voltage rms values of each frequency component, respectively; while k is the rated transformation ratio of the LPVT under test. Finally, $\widehat{U_2}$ and $\widehat{U_1}$ represent the secondary and primary voltage phases, respectively, which will be computed for each frequency component.

To perform the test, the designed sinc function, is uploaded to an Agilent 33250A 80 MHz Function/arbitrary waveform generator. The arbitrary waveform generator output is amplified by a Trek high voltage power amplifier, and then applied to the LPVT. Then, ε and $\Delta\varphi$ at each frequency component have been computed in software environment after acquiring the primary and secondary LPVT signals with the NI 9222 DAQ.

B. SFR test

To perform the SFR test, single sine waves are applied during three separate tests at 50 Hz, 500 Hz and 1 kHz under the LPVT rated voltage. Afterwards, ε and $\Delta\varphi$ have been computed to be compared with those obtained in subsection A.

V. EXPERIMENTAL RESULTS

Fig. 3 and Fig. 4 show, for the considered range of frequencies, ε and $\Delta\varphi$ computed when applying the SR approach. Note that in Fig. 3 ε increases from first harmonic to third harmonic and then decreases as the frequency increases. In Fig. 4, instead, it can be appreciated that $\Delta\varphi$ computed for all harmonics and an extreme decrease can be seen from first harmonic to few harmonic orders.

The passive capacitive LPVT fabrication suffers from accurate design of primary capacitance in terms of fixed transformation ratio and phase displacement from one sensor to another. Normally this problem is solved with two solutions: one is to provide to the customer a correction factor for both ε and $\Delta\varphi$; another is to
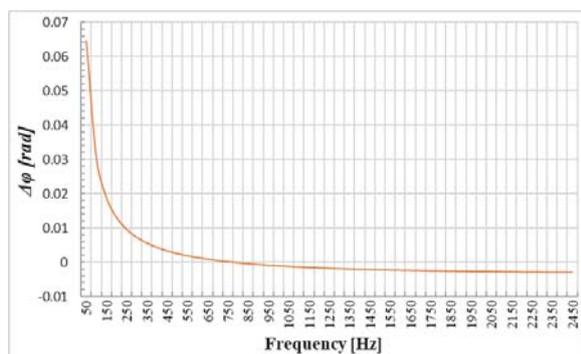
Fig. 4. Ratio Error v.s. frequency

compensate them by means of the internal electronic components (in case of active devices). The LPVTs with embedded electronic parts, form the so-called active LPVTs family. The LPVT used in this work is a passive sensor and this is the reason for high value for the phase error (about 64 milliradians) at 50 Hz.

To compare the SR test results with SFR ones Table II contains, for 3 different frequencies, ε, $\Delta\varphi$, and their absolute variation from one method to another. From the table it can be concluded that the SR approach provides very accurate results, which always differ less than 10 % with respect to the SFR ones [26]. This confirms i) the effectiveness of the SR test method and ii) that a one-time SR test leads to results as reliable as those of time-consuming series of single frequency characterization tests.

VI. CONCLUSION

In this work, a synthetized sinc signal is applied to a capacitive low-power voltage transformer to characterize it in the power quality frequency range under rated voltage. The obtained results assessed with those obtained with a typical sweep frequency test. From the comparison it is possible to confirm the applicability and accuracy of the developed characterization procedure. Therefore, the sinc response can be used to fast characterize the transformers and, thanks to the shortness of the test, it might be even used during in-field transformers testing.

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