XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

A TECHNIQUE FOR REAL-TIME BANDWIDTH ENHANCEMENT OF INSTRUMENT VOLTAGE TRANSFORMERS

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Abstract – The correct measurement, over a wide frequency spectrum, of the quality of power in electrical systems is becoming an essential aspect for the verification of the compatibility of power system with electrical equipment and the identification of unsafe situations. This work proposes a solution to improve the frequency response of instrument voltage transformers from some hertz up to tens of kilohertz. Mathematical formulation of the technique is presented. Then, the performance of the proposed method is verified with a simulated voltage transformer. Eventually, experimental results relevant to the compensation of a real voltage transformer are shown.

Keywords: instrument voltage transformer, optimization, power quality, power system measurement, field programmable gate array (FPGA)

1. INTRODUCTION

The amount of noise and distortion in the electricity grid is progressively increasing due to the wide diffusion of power electronic converters ([1]-[6]). In addition, the improvement of the performance of power converters on the one hand and the growing demand for "clean energy" on the other hand have encouraged the diffusion of renewable sources in the electricity system. Due to the necessary conversion between different types of energy (AC to AC, or DC to AC) and its variability in time, the connection to the electrical network of such sources must be accurately monitored. This lets perceive that the correct measurement of conducted disturbances in power systems is becoming an essential aspect for the verification of their compatibility with electrical equipment and identification of unsafe situations.

A reliable power quality measurement then requires analysis and evaluations over a wide frequency spectrum ([7]-[9]). Since measuring transducers are the first and essential part of a medium or high voltage power quality measurement chain, their frequency response heavily influences the accuracy of the obtained results. Voltage and current transformers (VTs and CTs) are the most common transducers in the electrical systems: typically they are designed and built to accurately measure the applied voltage/currents at industrial frequencies (50 or 60 Hz), so the the manufacturer does not provide any information about the error introduced at frequencies above the fundamental one. Obviously, their replacement with a more accurate transducer involves a significant economic burden, therefore the adoption of an additional device that is able to improve the measurement characteristics of the transformer would be an advantageous solution.

Methods for the corrections of the frequency response for both transducers [11], [12] and acquisition systems [13] – [16] have been developed and implemented. Some techniques only work at power frequency, some other utilize FIR (Finite Impulse Response) filters, which introduce a finite delay in the frequency response.

This work discusses a solution to improve the frequency response of the transformer in a wide frequency range from a few hertz up to tens of kilohertz. The technique discussed here was already presented in previous papers ([17]-[20]), where it was applied to the compensation of the response of transducers with different frequency behaviors, like current instrument transformer and Hall-effect voltage and current transducers, obtaining considerable performance improvements. In this paper, we refine and apply the method to measurement VTs. As shown in Fig. 1, the proposed technique is performed in two steps. The first step is done *off-line*, since it consists in: a) the characterization of the frequency response of the VT, by using an appropriate measurement system; b) the identification of an Infinite Impulse Response (IIR) digital filter, whose frequency response approximates the inverse fr response of the VT under test. The second steps is, instead, performed in *real-time*, as it entails the implementation of the filter using a field programmable gate array (FPGA) board, equipped with analog-to-digital converter (ADC), which acquires the VT output and executes the compensating filter. Depending on the specific application, f.i. when there is the necessity to provide the compensated transducer with an analog output, the FPGA can have a digital-to-analog converter (DAC). Section 2 deals with the theoretical background of the proposed technique while Section 3 presents its mathematical formulation. In Section 4 the method is tested with a simulated VT; finally, Section 5 shows the experimental results of the application to a real VT.

The research leading to the results here described is part of the European Metrology Research Program (EMRP), ENG52 Smart Grid II project. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

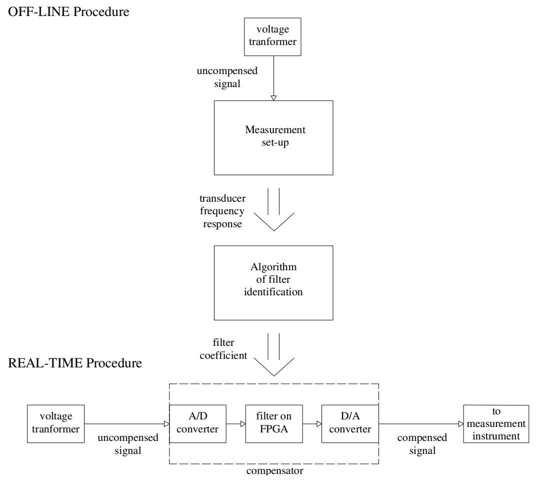

Fig. 1. Block diagram of the proposed compensation technique

2. COMPENSATION THEORETICAL BACKGROUND

A generic physical system, if linear, can be described by a transfer function which defines the algebraic relationship between the Laplace transform of the input and output.

From the transfer function of the system, the harmonic response can be determined by replacing the complex variable s with its imaginary part $j\omega$; in this way the relationship between the Fourier transform of input and output is obtained. A transducer such as a measurement transformer inevitably presents some nonlinearities in its behavior. due to the saturation of the magnetic core. In accordance with international standards [21] the class of accuracy of VTs must be maintained from 80% to 120% of rated voltage. If the primary voltage is inside this range, a VT with a reduced linearity error can be viewed as a linear system in amplitude. Therefore, its frequency response can be expressed as follows:

$$Y(f) = \frac{1}{R(f)e^{-j\varphi(f)}}X(f) \qquad (1)$$

where Y and X are respectively the spectra of the transducer output and input signals, that is their Fourier transforms

Under the assumption of a unitary rated transformation ratio of the device, $R(f)$ and $\varphi(f)$ are the systematic alterations introduced by the transducer, respectively in terms of magnitude and phase, to the output signal, as a function of the frequency of the input harmonic signal. In reference to the form presented in *(1)* we have that:

$$G(f) = \frac{1}{R(f)e^{-j\varphi(f)}} \qquad (2)$$

Once known the $G(f)$ of the transducer, which is given by a characterization in frequency of the device, it is possible to obtain its inverse function, that is the function of the compensator or filter, terms used interchangeably in the discussion), with the following frequency response:

$$H_d(f) = R(f)e^{-j\varphi(f)} \qquad (3)$$

In this way, the series connection of the transducer and the filter leads to a response of the system that is ideal for any frequency value. Theoretically the filter function can be realized by both analog and digital system. The implementation of the analog filter is generally not feasible, and leads to acceptable results only on a very limited range of frequencies. In fact, the realization of analog compensation systems is difficult, due to problems of different nature, such as: 1) instability and not repeatability of the over time, because of the inherent variability of the physical components (resistors, inductors, and capacitors); 2) rigidity of the compensator that is not reconfigurable except by replacement of hardware components, preventing the possibility of real-time changes (non-adaptive filters); 3) difficulty to provide a monitoring system and diagnostics. These problems are avoided by using a digital compensation system, although new drawbacks have to be faced. In particular: 1) sampling, that means time discretization of the input variables; 2) numerical quantization, that is amplitude discretization of the input variables; 3) delay of execution, since the execution of the implemented function necessarily lags behind the acquisition of the input. Anyway, a digital compensator is the most innovative and efficient choice ([17]).

3. IDENTIFICATION OF THE DIGITAL FILTER

The target is to find a filter expression that best reproduces the inverse frequency response of the transducer. Therefore, it is necessary to know the frequency response of the transducer, which is experimentally obtained, for a limited number of frequency values (points) N_f .

The filter function H(z) can be worked out through a mathematical formulation of an inverse problem (i.e. the reconstruction of the model of a physical system from its response), which is solved using probabilistic optimization techniques. So an optimization algorithm is realized that aims to reproduce the inverse transfer function of the transducer by minimizing a precise objective function.

3.1. Objective function

It can be numerically shown ([22]) that the sensitivity of the frequency response of the filter $H(z)$ to the variation of its coefficients can be minimized by using factorization:

$$H(z) = K\prod_{k=1}^{N}\frac{1 + b_{1,k}z^{-1} + b_{2,k}z^{-2}}{1 + a_{1,k}z^{-1} + a_{2,k}z^{-2}} \qquad (4)$$

where expression of the filter is decomposed into second-order factors SOSs (Second Order Sections). The number N (SOS number) of the factors can be chosen in an appropriate way depending on the frequency behavior to be characterized. Each SOS introduces four unknown coefficients in addition to the coefficient K. Therefore, the number of unknowns $\boldsymbol{c}$ is $4N + 1$. Consequently, an objective function is formulated that quantifies the difference between the reference response (i.e. the inverse of the transducer response) $H_d(f_i)$ and that of the considered filter $H(f_i)$, computed in the chosen N_f frequency points:

$$F(\boldsymbol{P}) = \sum_{k=1}^{N_f} w(f_k)\cdot\left[log_{10}\frac{H(f_k,\boldsymbol{P})}{H_d(f_k)}\right]^2\cdot\left[log_{10}\frac{f_{k+1}}{f_{k-1}}\right] \qquad (5)$$

where $\boldsymbol{P}$ is the vector of $4N + 1$ filter coefficients. $H(f_k,\boldsymbol{P})$ is the filter function calculated for the $\boldsymbol{P}$ values of the coefficients, in f_k points of interest, $H_d(f_k)$ is the inverse function of the transducer calculated in f_k points of interest, $w(f_k)$ is the vector of weights.

The accuracy of the compensation method depends primarily on the performance of the optimization algorithm to identify the most suitable filter coefficients.

3.2. Optimization algorithm

The optimization problem under analysis has a non-linear objective function with 4N + 1 independent variables. This means that the search space of the solutions is of dimension $\mathcal{R}^{4N+1}$ with $\mathcal{R}$ set of real numbers.

Due to its characteristics, the numerical problem is solved using a method based on a stochastic mechanisms, in particular a genetic algorithm is implemented.

The large solution space can be reduced by introducing constraints in the solutions, with an obvious computational advantage. In our case, there is a constraint on the solutions found (i.e. on the coefficients of the filter): the poles of the digital filter must have a radius of less than unity, that is proved to be a necessary condition for the stability of the filter.

For the case at hand, a hybrid scheme, based on the combination of a stochastic algorithm (genetic algorithm) and a deterministic algorithm (Sequential Quadratic Programming, SQP) was used ([23], [24]).

The optimization procedure consists of two nested loops: the outer varies the number of the filter SOS, while the inner repeats a fixed number of times the optimization algorithm in order to get as close as possible to the global minimum of the objective function.

To carry out the evaluation of the most suitable number of Second Order Section, we introduce two indices (I_R and I_φ), which quantify the improvement in the response, in terms of modulus and phase, provided by the filter.

For such a purpose, first we define $\Delta R(f_k)$ e $\Delta\varphi(f_k)$ as the values of ratio error and phase displacement related to the generic frequency f_k:

$$\Delta R(f_k) = \frac{1}{|H_d(f_k)|} - 1 \quad (6)$$

$$\Delta\varphi(f_k) = \arg(H_d(f_k)) \quad (7)$$

We define also $\Delta R_c(f_k)$ e $\Delta\varphi_c(f_k)$ as the values of ratio error and phase displacement of the compensated system related to the generic frequency f_k:

$$\Delta R_c(f_k) = \frac{|H(f_k)|}{|H_d(f_k)|} - 1 \quad (8)$$

$$\Delta\varphi_c(f_k) = \arg(H(f_k) - H_d(f_k)) \quad (9)$$

The indexes I_R and I_φ (improvement in terms of ratio error and phase displacement) are then defined as the ratio between the average quadratic error of magnitude and phase for each frequency of the transducer f_k compared to that of the compensated system:

$$I_R = \frac{\overline{\Delta R^2}}{\overline{\Delta R_C{}^2}} = \frac{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta R(f_k)]^2}}{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta R_C(f_k)]^2}} \quad (10)$$

$$I_\varphi = \frac{\overline{\Delta\varphi^2}}{\overline{\Delta\varphi_c{}^2}} = \frac{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta\varphi(f_k)]^2}}{\sqrt{\frac{1}{N_f}\sum_{k=1}^{N_f}[\Delta\varphi_c(f_k)]^2}} \quad (11)$$

The evaluation of the SOS optimum is achieved by comparison of indices I_R and I_φ for different values of SOS.

4. ANALYSIS OF THE ALGORITHM PERFORMANCE

In order to verify the capabilities of the proposed algorithm, a test case is implemented by considering the circuit model of a measurement VT for Medium Voltage (MV) networks.

4.1. Measurement voltage transformer under test

The proposed circuit model is presented in [25] and is depicted in Fig. 2.

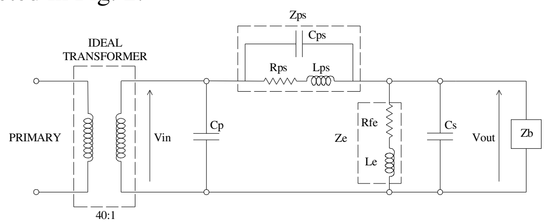

Fig. 2. Equivalent circuit diagram of the VT

VT ratings are: 4800 V primary, 40:1 turns ratio, ANSI accuracy class 0.3 with burden Y; 1.2 with burden Z at rated voltage, 120 V secondary output rated frequency 60 Hz.

Basing on VT ratings, the circuit parameters assume the following values: $C_P = 160$ nF, $R_{ps} = 1\,\Omega$, $L_{ps} = 1.7$ mH, $C_{ps} = 30$ nF, $R_{fe} = 35\sqrt{f}\,\Omega$, $L_e = \frac{5.6}{\sqrt{f}}$ mH, $C_s = 1$ nF, Zb = 1 MΩ.

It must be noted that the equivalent circuit includes the terms R_{fe} and L_e that are frequency dependent, taking into account that the circuit must also be valid at frequencies of tens of kilohertz. Fig. 3 shows the magnitude and phase of the VT inverse frequency response, from 10 Hz to 50 kHz. with a first resonance around 20 kHz.

4.2. Optimization results

With the aim of finding the optimal weights for the objective function (5), several runs of the procedure were performed; here we report only the main results for sake of brevity. In order to have better performance around power frequency and to ensure good convergence of the algorithm, the following weight vector is chosen:

- for frequencies up to 100 Hz the value of 5000 is chosen;
- from 100 Hz to 2500 Hz the value of 2000 is chosen;
- a value of 1000 is associated to the remaining elements.

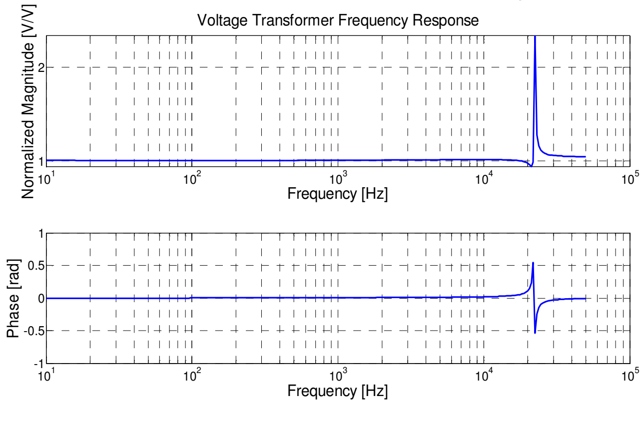

Fig. 3. Magnitude and phase inverse frequency response of the voltage transformer

Fig.4 shows the trend of the best I_R e I_φ on 5 extractions for each value of SOS. The indexes I_R and I_φ can reach values of 76 for I_R and 56 for I_φ when N is set to 5. Fig.5 shows the ratio error and phase displacement of the uncompensated and of the compensated VT from 10 Hz to 50 kHz. Fig.6 shows the ratio error and the phase displacement of the compensated VT: it can be seen that the maximum absolute value of the ratio error is lower than 0.2 % and the maximum absolute value of the phase displacement is lower than 5 mrad over the considered frequency range.

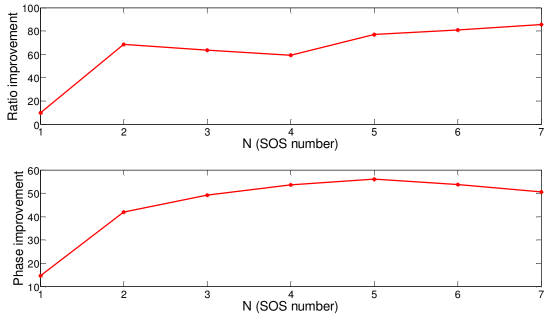

Fig. 4. Improvement on ratio error and phase displacement as a function of the number of SOSs

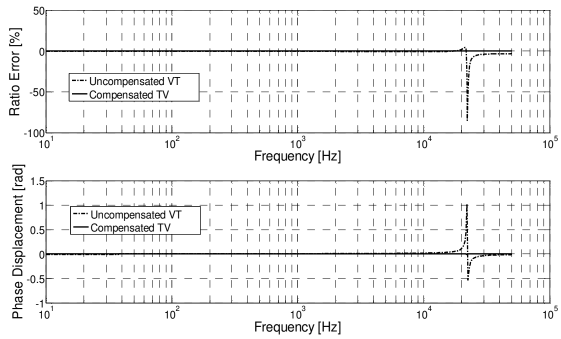

Fig. 5. Ratio errors and phase displacements of the compensated and uncompensated VT from 10 Hz to 50 kHz

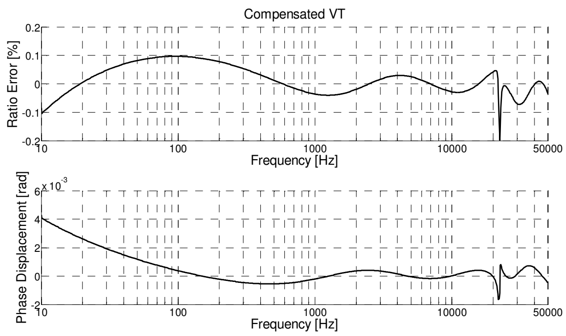

Fig. 6. Ratio error and Phase displacement of the compensated VT

5. EXPERIMENTAL RESULTS

To verify the results of the analysis carried out so far, a real VT was considered. The analyzed transformer is from *Epro Gallspach GmbH* and has primary voltage of 1 kV, turns ratio of 10:1, secondary voltage of 100 V, rated frequency of 50 Hz, rated burden of 1 VA, accuracy of 0.005 %.

5.1 VT characterization

An automated generation and measurement system was built up in order to characterize the VT ([26]-[28]). As a voltage signal generator to supply the VT the Fluke 5500a calibrator ([29]) is used. and the input and output of the VT are directly digitized by a data acquisition board, with 4 synchronous inputs at 16 bit, range of ± 10 V, maximum sampling rate of 1 MHz. The VT under test is supplied with sinusoidal signals from 3 Hz to 250 kHz: the chosen amplitudes are 7 V up to 100 kHz and 3 V above 100 kHz. The measurement software is written in Python and runs on a Personal Computer (PC), which supervises the instrumentation. Figs. 7a and 7b show the experimental setup. The measured magnitude and phase displacement inverse frequency responses of the VT are shown in Figs. 8 and 9 respectively. Both amplitude and phase displacement response are quite flat until 10 kHz, with first resonance at frequencies of some tens of hertz.

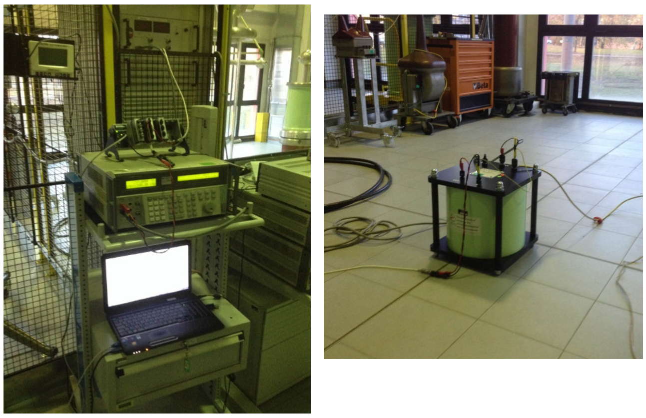

Fig. 7. a) The PC, the Fluke 5500 Calibrator and the data acquisition system employed in the experimental tests; b) The VT employed in the experimental tests

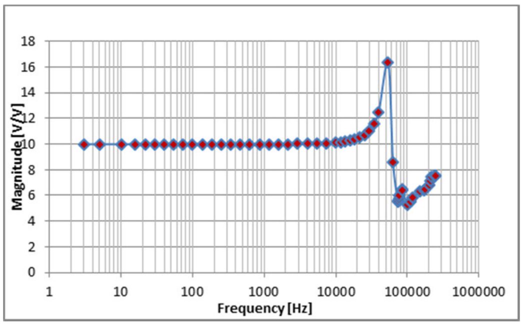

Fig. 8. Magnitude inverse frequency response of VT

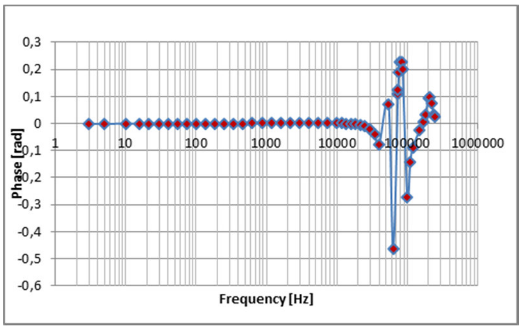

Fig. 9. Phase inverse frequency response of VT

5.2 Optimization results

To choose the optimal weight vector, the numerical considerations developed in the case of the simulated VT (Section 3) are made. In order to have better performance around power frequency and to ensure good convergence of the algorithm, the following weight vector is chosen:

- For the first 19 elements (i.e. up to 100 Hz) of w the value 5000 is assigned;
- the value 2000 is associated with the following 3 elements (up to 2500 Hz);
- a value of 1000 is associated with the remaining elements.

As in the previous case, the procedure uses 5 extractions and for each of them the I_R and I_φ values are evaluated. From Fig. 10 we can argue that, as expected, due to the presence of resonances in VT frequency response, we obtain better improvements, both in ratio error as well as in phase displacement, with higher SOS numbers. An SOS number equal to 5 was chosen and in Fig. 11 and Fig. 12 magnitude and phase frequency responses of the obtained filter and VT inverse ones are shown.

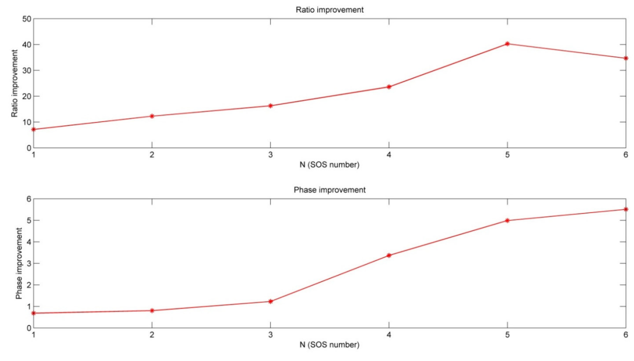

Fig. 10. Improvement on ratio error and phase displacement as function of the number of SOSs

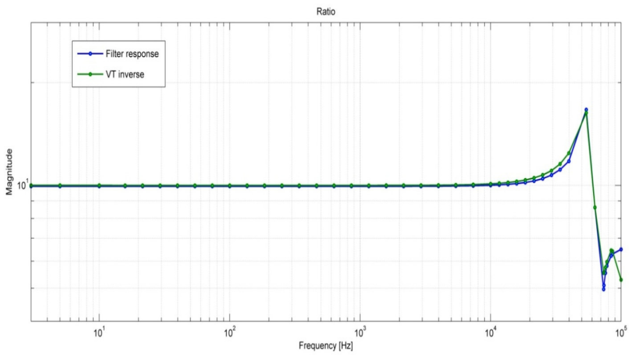

Fig. 11. Magnitude frequency response of the obtained filter and VT inverse one

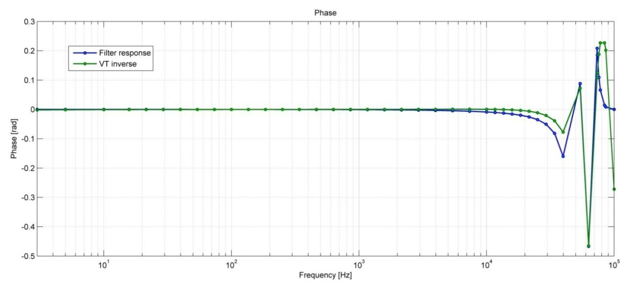

Fig. 12. Phase frequency response of the obtained filter and VT inverse one

5.3 Implementation on FPGA board

As shown in the block diagram in Fig.1, the digital filter identified in the first stage (off-line procedure) is then implemented using an FPGA board, equipped with analog-to-digital converter (ADC), and executed in real-time. For the case at hand the utilized FPGA is contained in a CompactRIO from National Instruments ([30]). CompactRIO is a reconfigurable embedded control and acquisition system based on two-processor architecture: an embedded controller and an FPGA which supervises the I/O, made through exchangeable I/O modules in a chassis. CompactRIO is programmed in LabVIEW environment. A module for data acquisition is used: it has 4 synchronous inputs at 16 bit, range of ± 10 V and maximum sampling rate of 1 MHz. For this application we did not use the DAC, since we were supposing to use the CompactRIO as both transducer compensating device as well as measuring instrument (f.i. a power meter or power quality instrument). The same tests described in Section 4.1 were performed: the VT was supplied by a Fluke 5500a Calibrator with sinusoidal signals from 3 Hz to 100 kHz. The output of the VT was acquired by CompactRIO and filtered. Fig. 13 and Fig. 14 show the simulated and actual magnitude and phase frequency responses of the filter. Considering the magnitude response, curves are practically overlapped. However, the phase response is affected by a time delay that changes the effective response of the filter, by adding to its phase frequency response a term that linearly increases with frequency.

6. CONCLUSIONS

A technique for real-time bandwidth enhancement of instrument voltage transformers has been presented. It is based on the implementation by an FPGA board of a digital IIR filter, whose frequency response approximates the inverse response of the VT to be compensated. The procedure performance was first tested with the frequency response of a simulated MV VT and then applied to a real 1 kV/100 V VT, by implementing the identified best compensation filter on the FPGA board. Taking into account the characteristic of the used hardware with respect to the complexity of filter function, obtained results show that the procedure can improve the frequency performances of the VT up to a factor of 40 when resonance frequencies are within a few ten of kilohertz.

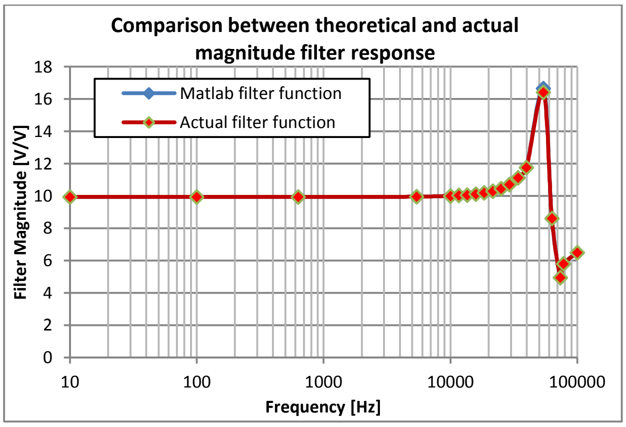

Fig. 13. Simulated and actual magnitude frequency response of the filter

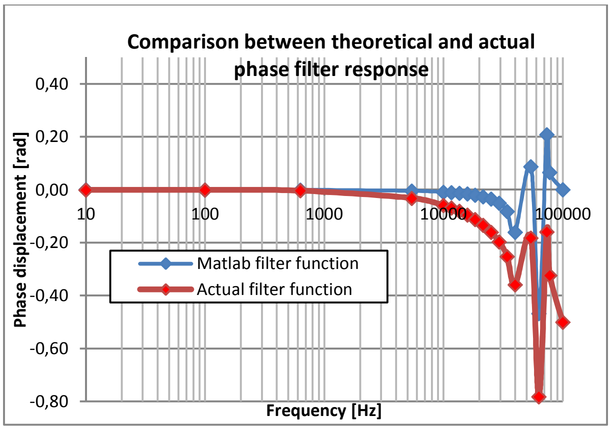

Fig. 14. Simulated and actual phase displacement frequency response of the filter

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