Compensating Nonlinearities in Voltage Transformers for Enhanced Harmonic Measurements: the Simplified Volterra Approach

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***Abstract*—The number of nonlinear devices in distribution grids has rapidly grown in the last years, and this trend is likely to increase in a near future. In this scenario, power quality monitoring and identification of disturbance sources are critical aspects. Inductive transformers are often employed for this purpose, although their metrological performances are guaranteed only near rated frequency. Secondary voltage harmonics are affected by the filtering behavior of the transformer, but also by nonlinearities due to the iron core that may have remarkable impact. In this work a novel post-processing technique allowing to dramatically reduce the detrimental effects of nonlinearities is proposed and discussed. After explaining the methodology, it has been applied to enhance the harmonic measurement accuracy that can be obtained by using an inductive medium voltage instrument transformer. Experimental tests carried out in laboratory show the significant performance improvement achieved thanks to the proposed approach.**

***Index Terms*—Power system harmonics, Power quality, Error compensation, Instrument transformers, Voltage transformers, Voltage measurement, Nonlinear systems, Frequency response, Uncertainty.**

I. Introduction

MODERN distribution grids (DGs) are characterized by a continuously growing penetration of power electronics. The reasons are multifold: on the one hand the decreasing cost together with the performance improvement of semiconductor devices have dramatically boosted the diffusion of variable speed drives and switch-mode power supplies. On the other hand, we have experienced an impressive increase of distributed energy generation from renewable sources, often requiring power electronic interfaces [1]. The number of power electronics converters is expected to increase in the future also because many electric vehicle chargers are going to be installed in the next years [2]-[5].

This widespread use of power electronics brought severe power quality (PQ) issues due to their nonlinear, time-varying behavior [1]-[6]. Among them, harmonic pollution is probably the most serious one [7], since it may trigger resonances other than causing increased thermal stresses, lower efficiency, etc. [8]. Harmonic pollution can be tackled thanks to extensive PQ monitoring, which includes harmonic state estimation [9]-[12] and location of disturbing sources [13]-[17]. Accurate measurements over a wide frequency band are required to these purposes [18]; therefore a lot of efforts have been addressed at developing techniques to extract spectral components from voltage waveforms [19], [20]. However, results are deeply related to the metrological characteristics of the employed instrument transformers (ITs).

Usually the harmonic measurement performance of an IT is assumed to be fully represented by its frequency response function (FRF) [21]-[24], thus supposing a linear time invariant behavior. However, even weak nonlinearities may have significant impact on accuracy: their effect is heavily magnified by the peculiar spectral characteristics of waveforms in ac power systems, consisting of a strong fundamental component which is superimposed to harmonics having considerably smaller amplitudes. Technical Report IEC TR 61869-103 [25] was one of the first documents that warned about the impact of nonlinearities on harmonic measurements. For this very reason, it states that a significant metrological characterization of ITs should employ test waveforms having realistic spectral contents.

As far as medium voltage (MV) DGs are concerned, the inductive transformer is by far the most common voltage transducer, and it is likely to remain such for several years to come. Its metrological characteristics, expressed in terms of ratio error and phase displacement, refer only to the fundamental component [26]. Several works show that even if it could be employed to measure harmonics up to 1-2 kHz with a high impedance burden [25], accuracy is considerably degraded; nonlinearities due to their core play a non-negligible role, especially for low-order components [27]-[29]. Nonlinearities can be reduced through an oversized design, but this results in severe drawbacks in terms of size, weight and cost, which are key factors when an IT has to be chosen. Furthermore, it should be noticed that small nonlinearities appear also if the core operates well below the knee point.

Papers dealing with different methods that allow improving

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the performances of existing inductive voltage transformers (VTs) without changing their design can be found in the literature. Most of them are aimed at extending their bandwidths through linear post-filtering [30], [31]; harmonic measurement errors are well above those expressed by the accuracy class [28]. Nonlinearities in VTs have been addressed only recently, and methods for their partial compensation have been proposed. When considering low-order harmonics, the main nonlinear effect is represented by the harmonic distortion: it is the direct impact of the strong primary fundamental term on the secondary voltage harmonics. As a result, secondary voltage is distorted even when the VT is fed with a purely sinusoidal waveform. [32], [33] propose an innovative technique based on a polynomial frequency-domain model enabling a considerable reduction of harmonic distortion. Similarly to [34], these methods are characterized by easy implementation, but they are not able to take into account intermodulation, namely the interaction between multiple components in the primary voltage spectrum. With respect to harmonic distortion, intermodulation has a noticeable impact on higher order components. Addressing and compensating for this effect is one of the main targets of the present work.

From a conceptual point of view, designing a post-compensation technique requires a model that provides an accurate description of the input-output relationship of the VT. Then, the model has to be inverted in order to reconstruct the primary voltage for a given secondary voltage spectrum. Performance depends on the adopted model, which should be able to represent the behavior of the device as accurately as possible. In this way, the model is able to embed many uncertainty contributions that are converted into systematic effects, so that they can be compensated.

Volterra models under quasi-sinusoidal conditions [35], [36] have proven to be effective in representing the steady-state response of power system devices excited by periodic inputs [37]. It has been shown that, when applied to inductive VTs, the accuracy of the predicted secondary voltage spectrum is extremely good [38]. In the present work the same approach is employed for the first time to obtain post-compensation filters capable of heavily mitigating the impact of both harmonic distortion and intermodulation introduced by the VT. The method is introduced and implemented in order to enhance the metrological characteristics of a MV inductive VT. Test results obtained in laboratory are reported and deeply discussed in order to quantify the achieved accuracy improvement.

II. Compensating Nonlinearities Using Simplified Volterra Models

A. Forward and Inverse Models

Black-box modeling approaches are employed when only limited *a priori* information about the insight of a system is available, or when a satisfactory, physically-based representation is too complex to be tackled. Their flexibility makes them widespread tools in multifold engineering applications. The most straightforward employment of black-box (also known as behavioral) models is predicting the output of a system S for a given, known input; in this case, a *forward* modeling problem has to be faced. In some applications the output of system S is available while the input has to be reconstructed. This represents an *inverse* modeling problem, since it requires obtaining an inverse representation of S; it is rather common in telecommunications and it is usually called *post-compensation*. However, it is also a typical situation that happens as long as measurements have to be performed: the measurand has to be obtained by compensating all the systematic effects which can be embedded into the model S of the measurement process. Selecting a proper model is a key task which heavily affects the accuracy (uncertainty) of the result.

In order to estimate the inverse of system S, two main approaches can be adopted [39]:

1. Identifying the model of system S and inverting the input-output representation.
2. Assuming a structure for the inverse of system S and directly perform the identification.

Of course, there is no *a priori* reason to prefer a method: the choice strictly depends on the application.

B. Voltage Transformer Modelling

Now, let us focus on harmonic voltage measurements; the VT can be considered as a nonlinear time invariant (NTI) system whose input and output are the primary and secondary voltage, respectively. The primary voltage waveform can be assumed to be periodic at the rated frequency; excluding complex nonlinearities (e.g. ferroresonance) the corresponding steady-state secondary voltage has the same fundamental frequency. Adopting a black-box approach, the relationship between primary and secondary voltage spectra can be represented by using a frequency-domain Volterra model [40], [41]. Let us consider the two-sided spectrum of the primary voltage, which is assumed to be bounded up to the Nth order harmonic: the generic primary spectral component is $V_1(n)$, with $-N \le n \le N$. The mth order secondary voltage harmonic $V_2(m)$ results from the sum of contributions coming from an infinite number of nonlinear homogeneous subsystems:

$$V_2(m) = \sum_{i=1}^{\infty} V_2^i(m) = \\ = \sum_{i=1}^{\infty} \left(\sum_{\substack{\sum_{h=1}^{i} n_h = m \\ -N \le n_1,\ldots,n_i \le N}} H^i(n_1,\ldots,n_i) \prod_{k=1}^{i} V_1(n_k) \right) \quad (1)$$

Each homogeneous subsystem is characterized by a degree i. Its contribution $V_2^i(m)$ to the mth order secondary voltage harmonic is due to all the sets of i input components (with repetitions) whose sum of the harmonic orders $n_1,\ldots,n_i$ is equal to m. For each set, the product between input harmonics is computed and weighted by a coefficient $H^i(n_1,\ldots,n_i)$. It is worth noticing that the first degree homogeneous subsystem is linear (hence known as underlying linear system) and its coefficients $H^1(n_1)$ represent a FRF. Extending this concept, the set of coefficients of the ith degree homogeneous

subsystem characterizes the *i*th degree generalized FRF.

For practical applications, the maximum degree of the subsystems is upper bounded to *I*, which is the degree of the truncated Volterra (or polynomial) system. Increasing *I* yields a more detailed representation of the nonlinear behaviour, just as a higher order Taylor expansion ensures better approximation of a nonlinear function. The main problem is that the number of coefficients $H^i(n_1,\ldots,n_i)$ defining the model behaviour rapidly increases with *N* and *I* [42], thus resulting in computational issues and troublesome identification. Therefore low values of *I* (typically 2 or 3) are employed in most applications, but this severely limits the capability to accurately represent nonlinearities.

In order to overcome this problem, a simplification of the conventional frequency domain Volterra model has been developed; in particular, the peculiarity of voltage waveforms in ac power systems has been exploited [35], [36]. In this case, it should be noticed that the fundamental component $V_1(1)$ and its image $V_1(-1)$ are considerably larger than all other harmonics. Therefore the contributions in the summation (1) involving more than a spectral component different from $V_1(1)$ or $V_1(-1)$ are assumed to be negligible. The obtained representation, known as simplified Volterra model under quasi-sinusoidal conditions, takes into account both harmonic distortion due to the strong fundamental term and intermodulation between fundamental and each harmonic component in the primary voltage spectrum; on the contrary, interactions between harmonics are neglected. Under this assumption, the input-output relationship can be written as:

$$V_2(m)=\sum_{i=1}^{I}\sum_{\substack{i_p-i_m+n=m\\ -N\le n\le N}} H^i(i_p,i_m,n)V_1(1)^{i_p}V_1(-1)^{i_m}V_1(n) \quad (2)$$

which can be rearranged in a more compact form by adopting a vector notation:

$$V_2(m)=\mathbf{H}^T(m)\mathbf{W}_1(m) \quad (3)$$

$\mathbf{W}_1(m)$ is the vector which contains all the products between up to *I* primary voltage components affecting the *m*th order secondary voltage harmonic while meeting the aforementioned quasi-sinusoidal simplification. Vector $\mathbf{H}(m)$ contains the corresponding sensitivity coefficients and ^{T} denotes the transpose operator. In previous works it has been shown that, thanks to the typical spectral content of electric waveforms in ac power systems, the proposed simplification results in slight accuracy degradation [36] with respect to the conventional Volterra approach having the same degree. From another point of view, it allows more precise modelling for a given number of coefficients.

Up to now this innovative model has been employed to represent the behaviour of conventional, inductive VTs. A much more accurate characterization has been achieved with respect to the simple evaluation of their frequency responses. Results clearly show the detrimental impact of nonlinearities on metrological performance at low-order harmonics.

C. Compensation of Voltage Transformers

The above considerations suggest, as straightforward development, the employment of the simplified Volterra model to reconstruct primary voltage harmonics starting from the secondary side. This allows mitigating the uncertainty contributions due to the unmodeled nonlinearities.

As stated in Section II.A, a first possibility requires identifying the *forward* model and then obtaining its *post-inverse*. Let us suppose that (1) holds with very good accuracy, hence that an infinite degree Volterra system can be used as forward model. Under proper assumptions (met in most practical applications), it is possible to prove the existence of the *p*th order inverse [40], namely a system that, when tandem-connected, results in a Volterra system having an underlying linear subsystem characterized by perfectly flat FRF, and nonlinear contributions only due to the subsystems whose degrees are higher than *p*. The *p*th order inverse is a *p*th order Volterra system; a procedure to obtain its coefficients from the forward model can be found in the literature [43], but it is rather complex [44]. In practical implementations the knowledge about the forward model is affected by uncertainty due to the measurement process and to the employment of an approximated Volterra representation having a manageable number of coefficients. Unfortunately the impact of such uncertainty on the computed *p*th order inverse may be very significant.

The existence of the *p*th order inverse can be exploited in a completely different way. In fact, this property suggests a structure for the *post-inverse*, which is still a Volterra system. Therefore, the corresponding input-output representation is the same as (1) once having swapped the primary voltage with the secondary one and *vice versa*; of course truncation up to degree *I* is required for implementation. This allows one adopting the second approach mentioned in Section II. -A. It is worth noticing that also the secondary voltage of the VT features a large fundamental component and weaker harmonics. Since the *quasi sinusoidal* simplification is expected to hold with good accuracy, an accurate reconstruction of the primary voltage components from the secondary side spectrum can be obtained as:

$$V_1(m)=\sum_{i=1}^{I}\sum_{\substack{i_p-i_m+n=m\\ -N\le n\le N}} K^i(i_p,i_m,n)V_2(1)^{i_p}V_2(-1)^{i_m}V_2(n) \quad (4)$$

Alternatively, using vector notation:

$$V_1(m)=\mathbf{K}^T(m)\mathbf{W}_2(m) \quad (5)$$

where $\mathbf{W}_2(m)$ is defined as $\mathbf{W}_1(m)$ but now involving the secondary voltage spectral components.

Identifying the post compensation filter means, for each *m*-th order secondary harmonic, computing the elements of vector $\mathbf{K}(m)$. A possibility is feeding the VT with a proper set of *P* known, realistic primary voltages (meeting the quasi sinusoidal assumption) while measuring the corresponding secondary voltage spectra. Considering the generic *m*th order harmonic, it leads to the following system of equations:

$$\mathbf{V}_{1,\mathrm{id}}(m)=\mathbf{W}_{2,\mathrm{id}}(m)\mathbf{K}(m)$$
$$\mathbf{V}_{1,\mathrm{id}}(m)=\begin{bmatrix}V_{1,\mathrm{id}}^{[1]}(m)\\ \vdots \\ V_{1,\mathrm{id}}^{[P]}(m)\end{bmatrix}\quad \mathbf{W}_{2,\mathrm{id}}(m)=\begin{bmatrix}\left(\mathbf{W}_{2,\mathrm{id}}^{[1]}(m)\right)^{T}\\ \vdots \\ \left(\mathbf{W}_{2,\mathrm{id}}^{[P]}(m)\right)^{T}\end{bmatrix} \tag{6}$$

$V_{1,\mathrm{id}}^{[p]}(m)$ represents the mth order harmonic of the pth primary voltage excitation signal; $\mathbf{W}_{2,\mathrm{id}}^{[p]}(m)$ is the vector of the L products between secondary voltage components corresponding to the pth excitation signal which affect the mth order primary voltage harmonic. Let us suppose having applied a number P of excitation signals which is greater than the maximum length L of the vector $\mathbf{K}(m)$. Assuming that the employed identification signals result in a matrix $\mathbf{W}_{2,\mathrm{id}}(m)$ having full column rank, (6) represents an overdetermined system of equations. In this case coefficients can be obtained by minimizing the root mean square error of the predicted primary voltage harmonics for the set of identification signals. The left pseudoinverse of $\mathbf{W}_{2,\mathrm{id}}(m)$ has to be computed, while the vector $\mathbf{K}_e(m)$ of the estimated coefficients is computed as:

$$\mathbf{K}_e(m)=\mathbf{W}_{2,\mathrm{id}}^{\dagger}(m)\mathbf{V}_{1,\mathrm{id}}(m)$$
$$\mathbf{W}_{2,\mathrm{id}}^{\dagger}=\left(\mathbf{W}_{2,\mathrm{id}}^{T}\mathbf{W}_{2,\mathrm{id}}\right)^{-1}\mathbf{W}_{2,\mathrm{id}}^{T} \tag{7}$$

Having obtained the compensation filter coefficients, the primary voltage harmonics can be reconstructed from the secondary spectrum by computing the vectors $\mathbf{W}_2(m)$ and applying (5).

III. Experimental Setup

The proposed approach has been applied to enhance the harmonic measurement capability of a commercial MV VT whose specifications are listed in TABLE I. Its metrological behavior strongly depends on the burden connected to the secondary winding [45]; however, an unique operating condition has to be selected in order to perform the tests. Among them, high-impedance burden ensures the largest bandwidth, hence it is the most favorable condition for a VT devoted to harmonic measurements [25]. Furthermore, voltage drop across series parameters is minimized because of the negligible secondary current: core flux is slightly higher in this case, and arguably also nonlinearities. Therefore, tests have been performed without burden connected to the secondary winding.

TABLE I. Voltage Transformer Specifications

Primary voltage	Secondary voltage	Frequency	Class	Burden
15/√3 kV	100/√3 V	50/60 Hz	0.5	30 VA

Computing the coefficients of the compensation filters and testing the achieved performance require applying proper multisine voltage waveforms to the primary winding of the VT under test, thus characterized by complex spectral content. For this purpose, a voltage waveform generator based on the architecture proposed in [46], [47] has been employed; the block diagram is reported in Fig. 1.

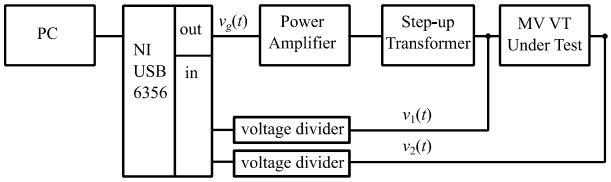


Fig. 1. Block diagram of the experimental setup.

The required voltage amplitudes can be reached thanks to an AETechron 7548 power amplifier (specifications are listed in TABLE II) feeding a 100 V/15 kV step-up transformer. In order to test the proposed method, it is extremely important that the measurement system used to acquire primary and secondary voltages introduces negligible nonlinearities with respect to those due to the VT under test. For this reason, the applied voltage v_1 has been monitored thanks to a high performance calibrated wideband compensated divider, resulting in a uncertainty of $5\cdot10^{-4}$ and $5\cdot10^{-4}$ rad up to 2 kHz for ratio and phase, respectively; the secondary voltage v_2 of the VT under test has been measured by using a calibrated resistive divider having ratio and phase uncertainty of 10^{-4} and 10^{-4} rad up to 2 kHz. A National Instrument USB-6356 board featuring 16 bit resolution and simultaneous sampling up to 1.25 MSa/s per channel has been employed to generate the periodic excitation signals and to acquire both the primary and secondary voltages of the VT. Input channels are characterized by an extremely low total harmonic distortion level (-80db) while synchronized generation and acquisition capability allows avoiding spectral leakage.

TABLE II. Power Amplifier Specifications

Maximum voltage	Gain	Bandwidth	SNR	THD
200 V	20	DC÷30 kHz (+0.1,-0.5 dB)	>120 dB	<0.1%

When adopting the setup shown in Fig. 1, the applied primary voltage v_1 is far from being a scaled up replica of the power amplifier input v_g. The reason is mainly related to the step-up transformer which is needed to reach the required voltage level. Most of the alterations have been canceled by measuring the FRF between v_g and v_1 and using it to pre-filter the reference voltage waveform to be generated [47]. Of course, nonlinearities introduced by the generation system cannot be compensated with this approach. On the other hand, they just produce small variations of the actual primary voltage spectrum with respect to its reference value: their impact is negligible since the primary voltage is acquired.

IV. Experimental Results

The experimental activity can be divided into two main steps. Firstly, the compensation filter coefficients have to be obtained by applying a proper set of proper identification signals to the VT under test while using (7). The second step is evaluating the accuracy that can be reached by using the previously designed compensation filters under real-world conditions. This requires feeding the VT under test with a set of realistic, multitone validation voltages (similar to those typically found in MV DGs) and comparing the reconstructed

primary voltage harmonics with those directly measured by the reference divider.

A. Synthesis of the Compensation Filters

The target is computing different simplified Volterra compensation filters for the MV VT considering nonlinearity degrees ranging from I=1 (linear) to I=11. As aforementioned, this requires applying a proper set of primary voltages in order to write an overdetermined problem to be inverted. Of course, these voltage waveforms must be periodic multisines meeting the quasi sinusoidal assumption, should cover the whole operating voltage range of the VT under test and should be reasonably similar with respect to those typically found during normal working conditions. To this purpose, a class of multisine identification signals have been defined; it is characterized by 50 Hz fundamental frequency (the rated frequency of the VT under test) and all the harmonics up to order N=25. Fundamental amplitude is assumed to be uniformly distributed between 80% and 120% of the rated primary voltage, thus fully covering the measuring range required by [26]. Harmonic amplitudes have uniform probability density functions (pdfs) between 2% and 3% of the fundamental one, while phases are uniformly distributed between $[-\pi, \pi]$.

For each nonlinearity degree a set of P=30L signals have been synthesized and applied to the VT under test. Primary and secondary voltages have been measured and acquired with 100 kSa/s rate and 2 s time window (100 fundamental periods). Average input and output spectra have been computed in order to reduce the impact of noise. Finally, the compensation filter coefficients can be estimated by applying (7). In order to verify the accuracy achieved by the compensation filters, a new set of 2000 primary voltage waveforms belonging to the class of the identification signals have been applied to the MV VT under test. For the generic pth test waveform, the primary voltage harmonics can be reconstructed from the secondary voltage spectrum using the compensation filters, thus obtaining $V_{1,e}^{[p]}(m)$. In order to take into account ratio error and phase displacement simultaneously, the Total Vector Error (TVE) is introduced. For each test signal and mth harmonic order, it represents the distance in the complex plane between $V_{1,e}^{[p]}(m)$ and $V_1^{[p]}(m)$, which is the primary voltage harmonic phasor measured with the reference transducer. It has been expressed as percentage of the magnitude of $V_1^{[p]}(m)$:

$$\mathrm{TVE}^{[p]}(m) = \frac{\left|V_{1,e}^{[p]}(m) - V_1^{[p]}(m)\right|}{\left|V_1^{[p]}(m)\right|} \tag{8}$$

In order to summarize the achieved performance for each harmonic order, the 95$^{\text{th}}$ percentile value of $\mathrm{TVE}^{[p]}(m)$ has been computed and denoted as $\mathrm{TVE}^{95}(m)$. Results obtained with compensation filters having different degrees are shown in Fig. 2.

The fundamental term is not reported, since conventional calibration is able to guarantee satisfactory performance. On the contrary, the other spectral components are affected by nonlinearities, in particular 3$^{\text{rd}}$ and 5$^{\text{th}}$ order harmonics. In fact, linear reconstruction provides 95$^{\text{th}}$ percentile TVE values of about 1% and 0.4%, respectively. Conversely, using the proposed compensation filters enables dramatic accuracy improvement in harmonic measurements. Focusing on the 3$^{\text{rd}}$ order harmonic, adopting a compensation filter having I=11 reduces TVE^{95} below 0.025%; a similar value of 0.026% is obtained for the 5$^{\text{th}}$ order harmonic. As far as the higher order harmonics, nonlinear compensation filters result in a flat TVE^{95} of about 0.026%. In this case, performance improvement is achieved thanks to the capability of the filter to take into account intermodulation. It should be noticed that increasing the degree of the compensation filter from an odd value to the next even does not result in improved accuracy. The reason is the almost purely odd nonlinearity of the VT under test which is due to the iron core.

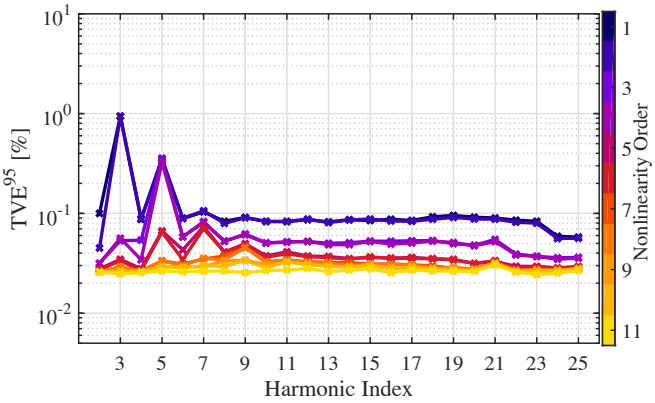


Fig. 2. TVE^{95} for each harmonic component and compensation filter degree - class of identification signals.

B. Performance Evaluation

It is extremely interesting to quantify the measurement performance which can be obtained as long as the VT under test is fed with realistic primary voltages, namely resembling those typically found in DGs; a new class of multisine validation signals has to be defined. In this respect, standard EN50160 [48] reports the limits for harmonic voltages in public MV DGs. It states that, considering a one-week observation period, the ten-minute root mean square value of each harmonic should be below the corresponding limit for 95% of the time; values for harmonic orders up to 25 are reported in TABLE III. [48] also states that the ten-minute root mean square value of the voltage should be within 90% and the 110% of its rated value for 95% of the time.

TABLE III
LIMITS FOR HARMONIC VOLTAGE AMPLITUDES
(PERCENTAGES OF THE FUNDAMENTAL COMPONENT)

Odd Harmonics				Even Harmonics	
k	V_k	k	V_k	k	V_k
3	5.0 %	15	0.5 %	2	2.0 %
5	6.0 %	17	2.5 %	4	1.0 %
7	5.0%	19	1.5 %	6	0.5 %
9	1.5 %	21	0.5 %	8	0.5 %
11	3.5 %	23	1.5 %	10	0.5 %
13	3.0 %	25	1.5 %	14÷24	0.5 %

These limits have been adopted as 95$^{\text{th}}$ percentiles values of the pdfs of the random fundamental and harmonic amplitudes characterizing the class of validation signals. It should be noted that the standard does not provide information about the shapes of these pdfs, nor about phases; reasonable hypotheses

have to be introduced. Fundamental amplitude is assumed to have Gaussian distribution centered around the rated voltage, while harmonic phasors are supposed to follow complex normal distributions. This corresponds to Rayleigh distributions for harmonic amplitudes and uniform distributions in the interval $[-\pi; \pi]$ for phases.

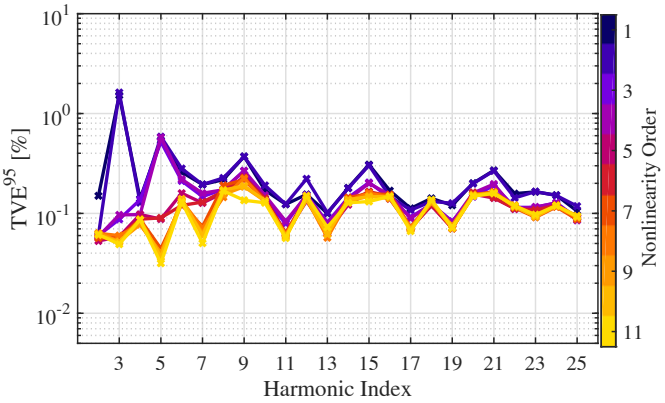


Fig. 3. TVE^{95} for each harmonic component and compensation filter degree - class of validation signals.

P=200 multisine signals with 50 Hz fundamental frequency have been obtained from the previously defined pdfs and applied to the VT under test. Primary and secondary voltages have been measured and processed according to the same procedure that has been adopted during identification. TVE values have been computed for each signal, harmonic and compensation filter; 95th percentile values over the *P* signals have been computed as synthetic performance indexes and reported in Fig. 3.

Results confirm the robustness of the method: the proposed family of compensation filters allows remarkable accuracy improvement even when a completely different class of validation signals is applied. However, significant discrepancies with respect to Fig. 2 are evident. TVE^{95} shows an uneven behavior over the considered frequency range: the reason is the spectral content of the validation set of signals, having different expected amplitudes for the different harmonics. When looking at TABLE III it can be noticed that harmonics whose orders are even or multiple of three have significantly lower limits, thus lower expected amplitudes; therefore nonlinearities have considerably higher impact in relative terms.

Focusing on the 3rd order harmonic, a linear reconstruction results in a fairly high TVE^{95} of about 1.6%. Increasing the nonlinearity degree of the compensation filter up to 11, error drops below 0.05%. The 5th order component is also significantly affected by nonlinear contributions, being TVE^{95} equal to 0.6% as long as a linear compensation filter is adopted. Moving to a 11th degree compensation filter, this value falls to 0.03%. The low expected amplitude of the 9th order harmonic has boosted the value of TVE^{95} with respect to the set of identification signals. Its value is about 0.33% for a linear compensation, while it is reduced below 0.09% using 11th degree compensation filter.

In order to perform a deeper analysis of the achieved performance improvement, the complex error $e_c(m)$ is introduced. It is defined as the difference between estimated and measured *m*th order primary voltage harmonic phasors referred to the amplitude of the measured one:

$$e_c^{[p]}(m) = \frac{V_{1,e}^{[p]}(m) - V_1^{[p]}(m)}{\left|V_1^{[p]}(m)\right|} \tag{9}$$

It is possible to compute the 95th percentile ellipsoids in the complex plane and their mean values. Results for the 3rd and 5th order harmonics are reported in Fig. 4 and Fig. 5 (crosses denote average complex errors) and confirm the good performance of the compensation filters considering the set of validation signals. Both mean values and ellipsoid axes dramatically decrease as long as higher degree compensation filters are employed. Using linear reconstruction, the 3rd order harmonic has real and imaginary average errors of 0.06% and -0.07%; values become negligible by using the 11th degree compensation filter ($2\cdot10^{-3}$% and $3\cdot10^{-3}$%, respectively). Similar considerations apply to the 5th order harmonic: real and imaginary average errors have been reduced from -0.015% and -0.024% to $-1\cdot10^{-3}$ % and $-5\cdot10^{-4}$ %.

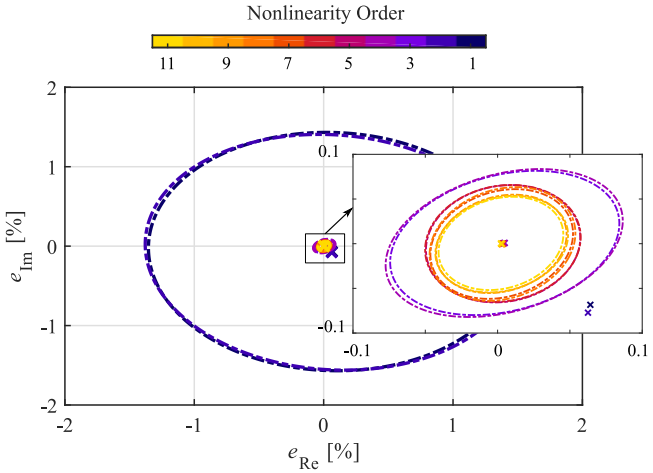


Fig. 4. Complex error for the 3rd order harmonic: 95th percentile ellipsoids and mean value for different compensation filters.

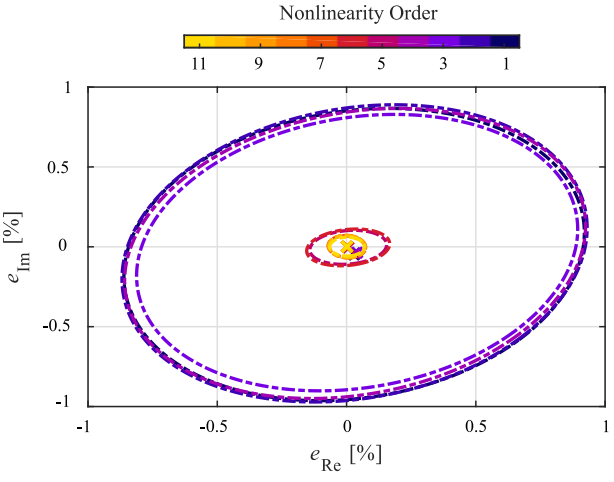


Fig. 5. Complex error for the 5th order harmonic: 95th percentile ellipsoids and mean value for different compensation filters.

The accuracy of ITs is typically expressed in terms of ratio error and phase displacement. Therefore, for each considered compensation filter, *m*th harmonic and *p*th test signal, the ratio

error is computed as:

$$\varepsilon^{[p]} = \frac{\left|V_{1,e}^{[p]}(m)\right| - \left|V_{1}^{[p]}(m)\right|}{\left|V_{1}^{[p]}(m)\right|} \tag{10}$$

while phase displacement is defined as:

$$\Delta\varphi^{[p]}(m) = \angle V_{1,e}^{[p]}(m) - \angle V_{1}^{[p]}(m) \tag{11}$$

For each compensation filter and harmonic order, the 95th percentiles of the ratio error and phase displacement absolute values (ε^{95} and $\Delta\varphi^{95}$) have been computed over the validation signals. Results are summarized in Fig. 6 and Fig. 7.

At first glance, it can be noticed that the ratio error and phase displacement versus frequency plots exhibit essentially the same behavior, which is similar to that of TVE_m^{95}. It becomes evident that the three figures carry almost the same information, and thus TVE_m^{95} represents a reliable performance indicator under these conditions. The enhancement that can be obtained through nonlinear compensation is evident; using the proposed 11th degree filter, the 95th percentile values of ratio error and phase displacement are below 0.15%. Accuracy is improved also at high order harmonics thanks to the capability of the proposed approach to compensate for intermodulation effects. The overall result is that the metrological performance reached by the VT under test now complies with its accuracy class also for harmonic components.

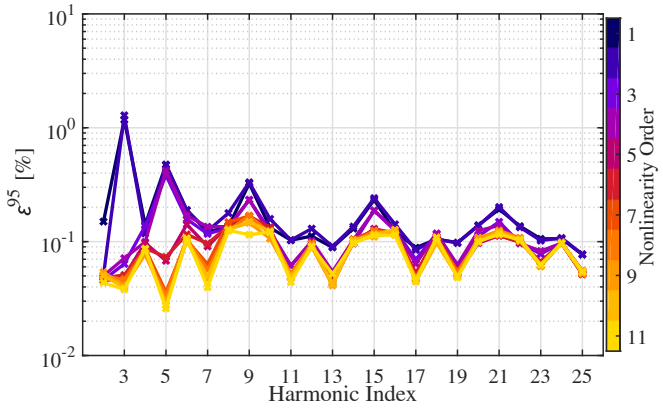


Fig. 6. ε^{95} for each harmonic component and compensation filter degree - class of validation signals.

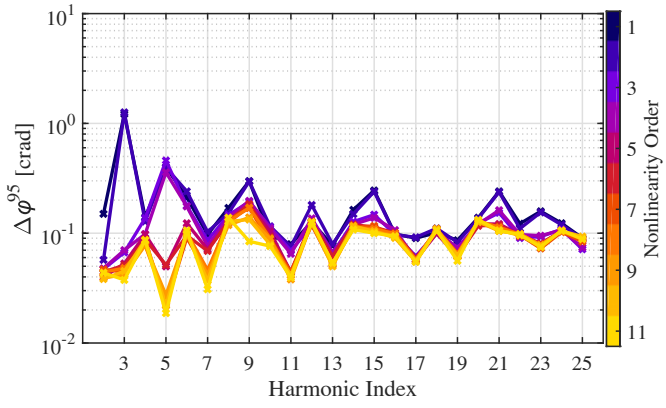


Fig. 7. $\Delta\varphi^{95}$ for each harmonic component and compensation filter degree - class of validation signals.

V. Conclusions

Several methods to improve the accuracy of inductive VTs in measuring harmonic components have been proposed in the past. Most of them are based on a linear representation of the VT and thus not capable to deal with nonlinearities which may have a significant impact on harmonic measurements.

In this paper, a compensation method based on simplified Volterra modeling has been proposed for the first time. Its advantage is that it allows embedding harmonic distortion and intermodulation effects occurring in VTs; a MV inductive VT has been considered as case study. Compensation filters of different complexities have been synthesized and the achieved performance has been evaluated by considering a large set of realistic primary voltage waveforms. Experimental results obtained in laboratory highlight the significant accuracy improvement which has been achieved in harmonic measurements. The proposed technique allows employing less accurate VTs to reach the same accuracy target, thus permitting to optimize overall cost-effectiveness. The approach is not physically based, hence in principle it can be applied to increase the performance of VTs regardless the specific design and rating, even including the so-called low power ITs. Of course, further tests are required in this case in order to evaluate the achievable performances. Finally, it is worth highlighting that this work represents a preliminary step towards the employment in a real-world scenario. In fact, other challenges have to be faced in the final applications: as an example the compensation filter has to be implemented on a processing unit, while the robustness of the method with respect to environmental conditions and noise should be assessed.

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