Overcoming Frequency Response Measurements of Voltage Transformers: An Approach Based on Quasi-Sinusoidal Volterra Models

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***Abstract*—The most recent IEC standards about voltage transformers warn about nonlinearity, which may have significantly impact on the harmonic measurement performance. However, there is a lack of scientific literature about this topic: usually their characterization consists of frequency response measurements, which are clearly not able to capture the nonlinear behavior.**

In this paper, an innovative approach based on simplified frequency domain polynomial models developed by the authors is proposed. The method is applied to two different medium voltage inductive transformers. Models are identified and validated with a large set of realistic primary waveforms injected by a proper setup. Experimental results confirm the remarkable accuracy of the proposed models especially for low-order harmonics, which are the most affected by nonlinearity.

***Index Terms*—Instrument transformers; Voltage measurement; Nonlinear systems; Frequency response; Power system harmonics; Power quality; Frequency-domain analysis; Nonlinear distortion; Harmonic distortion; Intermodulation distortion.**

I. Introduction

UNTIL recently, the main target of electrical measurements in ac power systems was to estimating the fundamental component (both in amplitude and phase) of voltage and current waveforms, either for metering or protection purposes. However, from the beginning of the Twenty-First Century, the progress of power electronics, the impressive increase of generation from renewable sources together with the development of the electricity market have, on the one hand increased the voltage harmonic pollution, and on the other one triggered the awareness about power quality (PQ) issues. International Standards about PQ monitoring are available for several years and, as for Low Voltage applications, detailed requirements and methodologies are reported in the various editions of IEC 61000-4-30 Standard [1]. In this respect, the measurement of harmonic voltages has paramount importance.

The demand for PQ measurements is strong also in Medium and High Voltage grids, where suitable voltage transducers have to be interposed between power network and measurement instrumentation. In most cases, such transducers are represented by inductive instrument transformers. Their working principle, based on the Faraday's law and relying on an iron core, is at the same time the cause for their strengths and weaknesses. While it allows galvanic separation between primary and secondary circuits as well as high performance stability over time, it also produces nonlinear phenomena that may affect the measurement result.

It should be noticed that knowledge about this issue is far from being consolidated. For example, the previous editions of IEC 61000-4-30 stated that the effect of transducers was "acknowledged but not addressed". Rated measurement performance of conventional inductive power transformers, summarized by their accuracy class, is guaranteed only at the nominal frequency [2]. Furthermore, in many works the frequency response function of instrument transformers is measured [3]-[7], thus neglecting nonlinearities.

One of the first documents that clearly pointed out the potential impact of nonlinearities is the Technical Report IEC TR 61869-103 [8], prepared by a Joint Ad-Hoc Working Group. In particular, it highlights that since superposition cannot be exploited, a meaningful characterization procedure should employ realistic primary waveforms, comprising a strong fundamental component and harmonics that are much smaller in amplitude.

Harmonic measurement performance has to be assessed for

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low-power instrument transformers. Accordingly to [8], the relevant IEC standard [9] recommends to employ test voltages containing the rated input signal at the rated frequency plus a percentage of it at each considered harmonic frequency. Since this requires an adequate experimental setup, including a proper source allowing to apply such complex waveforms, [9] also states that it is allowed to perform accuracy tests by applying only one single harmonic frequency.

When looking at the scientific literature, only few works dealing with the potential effects of nonlinearity on the accuracy of voltage instrument transformers can be found [10], [11]. Papers [12], [13] propose the employment of the Best Linear Approximation theory [14] for the metrological characterization of voltage instrument transformers devoted to harmonic measurements. Having considered a peculiar class of primary voltages, the best linear compensation of the transformer response is obtained. At the same time, it also allows quantifying the impact of noise and stochastic nonlinearity, that is modeled as a random noise depending on the particular excitation signals.

However, being based on a linear representation, this procedure does not allow obtaining an accurate model of the voltage transducer which is able to capture its complex behavior; a nonlinear model is mandatory in this case. Harmonic measurements depend on the steady-state response of the instrument transformer to a distorted, periodic primary voltage. Among the several models proposed in the literature, the frequency domain Volterra representation [15]-[17] appears to be an attractive choice, being based on the straightforward extension of the frequency response to the nonlinear case.

The main drawback of such Volterra models is that they are defined by a number of coefficients that rapidly grows with the number of input harmonics and with the selected nonlinear degree; this unavoidably results in a long a complex identification procedure. By exploiting the large ratio between fundamental and harmonics in typical voltage signals, simplified frequency domain Volterra models can be obtained [18], [19] thus allowing a dramatic reduction of the number of coefficients without significant impact on the accuracy. In this work, these models are employed to represent the behavior of medium voltage inductive transformers. Experimental identification and validation tests have been performed at the Italian National Metrological Institute (INRIM).

II. Frequency Domain Modeling of Nonlinear Power System Devices

The Taylor expansion is often employed to approximate nonlinear functions. Similarly, the Volterra series can be seen as the generalization of the Taylor expansion that makes it applicable also to dynamic functionals. For this reason, the Volterra approach is often employed as nonparametric representation of the input-output relationship that characterizes a nonlinear time invariant system. The Volterra model can be written either in the time or in the frequency domain; the latter is usually preferable if the steady-state response to a multitone input signal has to be predicted. In this case, when considering a single-input, single-output system, the output signal spectrum $Y(m)$ produced by a periodic input signal characterized by its two-sided spectrum $X(n)$ can be written as:

$$Y(m)=\sum_{i=1}^{I}\left(\sum_{\substack{-N\le n_1,\ldots,n_i\le N \\ \sum_{k=1}^{i} n_k=m}} H^i(n_1,\ldots,n_i)\prod_{k=1}^{i}X(n_k)\right) \quad (1)$$

Where m and n are integers corresponding to the output and input harmonic orders, respectively, while I represents the degree of the Volterra series expansion. The input signal spectrum is supposed to be band-limited up to the N-th order harmonic and the system is assumed to have zero output for a null input signal.

When looking at (1), the m-th output spectral component results from I contributions coming from different subsystems, each characterized its order i. In turn, the output of the i-th order subsystem is given by the product between i components of the input spectra (such that the sum of their harmonic orders is equal to m) weighed by H^i, that is often called i-th order Generalized Frequency Response Function (GFRF). A first-order expansion corresponds to a linear representation, and the first order GFRF is actually a Frequency Response Function (FRF).

Under these assumptions, the generic i-th order GFRF is a correspondence between a group of i harmonic orders and a coefficient. It is clear that the frequency domain Volterra system is defined by a set of independent coefficients, whose number rapidly increases with I and N [15]. For this reason, only very low-order (two or three) Volterra models are usually employed.

As pointed out in the introduction, the authors already presented in [18], [19] a simplification of frequency-domain Volterra models devoted to the behavioral representation of power system devices. In particular, the number of coefficients can be greatly reduced thanks to the peculiar spectral content of electrical quantities in AC power systems, consisting of a strong fundamental tone, and harmonics that are much smaller in amplitude. This suggests a simplification of (1): all the i-th order intermodulation products that do not contain at least i-1 times the fundamental term (or its conjugate) are significantly smaller than the others, therefore they can be neglected. The goodness of the approximation increases with the ratio between fundamental and harmonics. In this respect, (1) can be written in the following form:

$$Y(m)=\sum_{i=1}^{I}\left(\sum_{-N\le n\le N} H^i(i_p,i_m,n)X(1)^{i_p}\,X(-1)^{i_m}\,X(n)\right) \quad (2)$$

where i_p, i_n are nonnegative integers subject to the conditions:

$$\begin{aligned} i_p + i_m &= i - 1 \\ i_p - i_m + n &= m \end{aligned} \tag{3}$$

The input output relationship can be rearranged in vector form:

$$Y(m) = \mathbf{W}(m)\mathbf{H}(m) = \begin{bmatrix} \mathbf{W}^1(m) \\ \vdots \\ \mathbf{W}^I(m) \end{bmatrix}^T \begin{bmatrix} \mathbf{H}^1(m) \\ \vdots \\ \mathbf{H}^I(m) \end{bmatrix} \tag{4}$$

$\mathbf{W}^i(m)$ is the set of all the considered products between i input components that affect the m-th output harmonic; $\mathbf{H}^i(m)$ contains the values of the corresponding i-th order GFRF.

Identifying the model consists in evaluating $\mathbf{H}(m)$ for all the output harmonics of interest. Introducing L as the maximum length of $\mathbf{H}(m)$, (4) can be inverted in a least squares sense by measuring the system response to a proper set of $P \geq L$ linearly independent signals. Introducing:

$$\mathbf{W}_{id}(m) = \begin{bmatrix} \mathbf{W}_{id}^{[1]}(m) \\ \vdots \\ \mathbf{W}_{id}^{[P]}(m) \end{bmatrix}; \mathbf{Y}_{id}(m) = \begin{bmatrix} Y_{id}^{[1]}(m) \\ \vdots \\ Y_{id}^{[P]}(m) \end{bmatrix} \tag{5}$$

Where $\mathbf{W}_{id}^{[p]}(m)$ has the same meaning as $\mathbf{W}(m)$ for the p-th identification signal, while $Y_{id}^{[p]}(m)$ represents the corresponding output. Finally, assuming that $\mathbf{W}_{id}(m)$ has linearly independent columns, $\mathbf{H}(m)$ can be estimated by using the Moore-Penrose pseudoinverse $\mathbf{W}_{id}^{\dagger}(m)$:

$$\mathbf{H}_e(m) = \mathbf{W}_{id}^{\dagger}(m)\mathbf{Y}(m) \tag{6}$$

In [19] the authors have validated the proposed simplification that has been applied to the behavioral representation of several nonlinear power system devices by means of numerical simulations. In this paper, the approach has been experimentally tested to model the steady-state behavior of medium voltage (MV) instrument transformers, namely to predict their secondary voltage harmonics (system output) produced by a known primary voltage (system input).

III. Experimental Setup

The proposed approach has been applied to represent the input-output relationship of two voltage instrument transformers (VT) whose specifications are reported in TABLE I. Secondary winding has been left open.

TABLE I
MEDIUM VOLTAGE INSTRUMENT TRANSFORMERS SPECIFICATIONS

	Primary Voltage [kV]	Secondary Voltage [V]	Class
VT[1]	15/√3	100/√3	0.5
VT[2]	20/√3	100/√3	0.5

As explained in the previous section, model identification requires applying known, complex excitation signals to the primary side of the voltage transformers under test. The experimental setup shown in Fig. 1 has been employed for this purpose. A portable MV amplifier (TREK Model 30/20A) allows generating primary waveforms having peak voltages up to 30 kV; it features DC÷2.5 kHz large-signal bandwidth (with less than 2% harmonic distortion), DC÷30 kHz small-signal bandwidth and 20 mA peak output current capability. Primary voltage has been acquired by means of a 30 kV wideband (DC÷12 kHz) reference voltage divider (VD) custom-designed by INRIM [20]. Considering 100 Hz÷1250 Hz frequency range and 20/√3 kV maximum rms operating voltage, the expanded relative uncertainty of the VD scale factor is ±300 µV/V and ±300 µrad for ratio and phase error, respectively.

A National Instruments NI-USB 6356 board featuring simultaneous sampling and 16 bit resolution connected to a PC allows generating the excitation signals as well as acquiring the secondary voltage of the reference transducer and of the instrument transformer under test. In this case, a resistive voltage divider has been employed to adapt the secondary voltage to the ±10V range of the data acquisition board. It is characterized by a ratio of 21.014 with relative uncertainty below 10^{-4} up to 2 kHz. The input channels feature a low total harmonic distortion (below -80dB) so that their nonlinearity is negligible with respect to that of the transducer under test. Furthermore, the board allows synchronized sampling and generation by using a common timebase; in this way, spectral leakage effects can be neglected. A 100 kHz sampling rate has been employed, and the acquired data has been processed in Matlab.

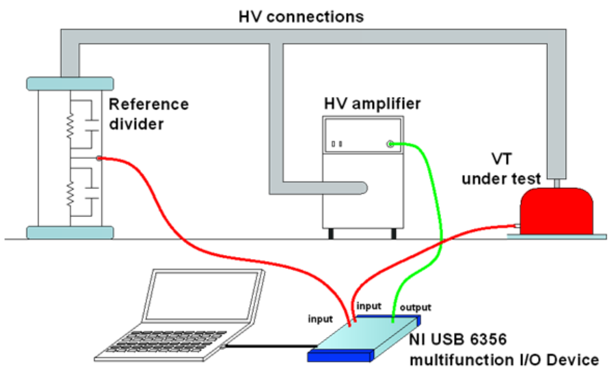

Fig. 1. Diagram of the experimental setup.

IV. Experimental Results

The experimental activity can be roughly divided in two steps. The first part is represented by the model identification. The GFRF coefficients are obtained by using (6) together with a proper set of identification signals. After that, model accuracy has been evaluated through statistical analysis using excitation signals that are similar to the voltage waveforms that can be found in typical distribution grids.

Both model identification and validation can be performed thanks to the experimental setup described in the previous section that allows applying arbitrary primary voltages. For a better accuracy, before each test the frequency response function of the generation system connected to the transformer under test has been measured with the Maximum Likelihood approach [14] by injecting a random phase multisine signal characterized by 50 Hz fundamental frequency and harmonics up to the 25th order. All the spectral components share the same amplitude, equal to 5% of the rated primary voltage. A two second time window (hence 100 fundamental periods) and 100 kHz sampling rate have been employed. The estimated FRF can be used to pre-filter the spectrum of the desired excitation signal, thus obtaining the signal v_g to be applied at the input of the power amplifier [21], [22].

A. *Model Identification*

The target is identifying simplified frequency-domain Volterra models of different degrees, in order to represent the relationship between primary and secondary voltage spectra ($V_p(n)$ and $V_s(m)$ respectively) for both the devices under test (DUT). It has been chosen to consider nonlinearity orders I ranging from one (linear model) up to eleven, thus highlighting the achieved accuracy improvement.

As from Section II the number P of identification signals has to be at least equal to L. In this case, P=30L has been selected in order to have a strongly overdetermined inverse problem for all the considered orders. Quasi-sinusoidal identification signals have been employed, consisting of a main 50 Hz component and harmonics up to the 25th order. The amplitude of the main component has been randomly extracted by using a uniform probability density function (pdf) between 80% and 120 % of the rated primary voltage, which is the range suggested by [23] for testing the accuracy of voltage instrument transformers. Harmonic amplitudes have been obtained from a uniform distribution between 2% and 3% of the fundamental component, while harmonic phases have been randomly extracted from a uniform pdf in the interval [-π, π].

The identification procedure requires applying the P random identification signals and measuring the primary and secondary voltages of the DUT. 100 fundamental periods of every signal have been acquired with 100 kHz sampling rate. For each realization, average input and output spectra have been computed in order to reduce the impact of measurement noise. Using the measurement data, considering the generic m-th order output harmonic, $\mathbf{Y}_{id}(m)$ and $\mathbf{W}_{id}(m)$ can be obtained, while (6) allows estimating the model coefficients. The procedure has been applied to both the instrument transformers VT[1] and VT[2] listed in TABLE I.

In order to evaluate the accuracy achieved by the models, other 100 random signals belonging to the same class of those employed for the identification have been synthesized and applied to the instrument transformers. Their responses have been acquired and processed. Considering the p-th input test signal spectrum $V_p^{[p]}(m)$, the corresponding vector $\mathbf{W}^{[p]}(m)$ can be obtained. Using (4) and the estimated coefficients $\mathbf{H}_e(m)$, the secondary output voltage spectrum $V_{s,e}^{[p]}(m)$ results:

$$V_{s,e}^{[p]}(m) = \left(\mathbf{W}^{[p]}\ (m)\right)^T \mathbf{H}_e(m) \tag{7}$$

The accuracy of instrument transformers is conventionally expressed by magnitude and phase errors [9]. Therefore, these indexes have been computed for each considered model, m-th harmonic order and p-th test signal. Introducing the measured secondary spectra $V_s^{[p]}(m)$ corresponding to the primary spectra $V_p^{[p]}(m)$, magnitude error is defined as:

$$e_{abs}^{[p]}(m) = \frac{\left|V_{s,e}^{[p]}(m)\right| - \left|V_s^{[p]}(m)\right|}{\left|V_s^{[p]}(m)\right|} \tag{8}$$

while the phase error:

$$e_{ph}^{[p]}(m) = \angle V_{s,e}^{[p]}(m) - \angle V_s^{[p]}(m) \tag{9}$$

Considering the instrument transformer VT[1], for each i-th degree model and m-th harmonic order, the 95th percentiles of the magnitude and phase errors absolute values have been computed, thus obtaining e_{abs}^{95} and e_{ph}^{95}; results are summarized in Fig. 2 and Fig. 3. The fundamental component is not shown since the linear model already reaches a very good accuracy; hence, increasing the model complexity is not so meaningful.

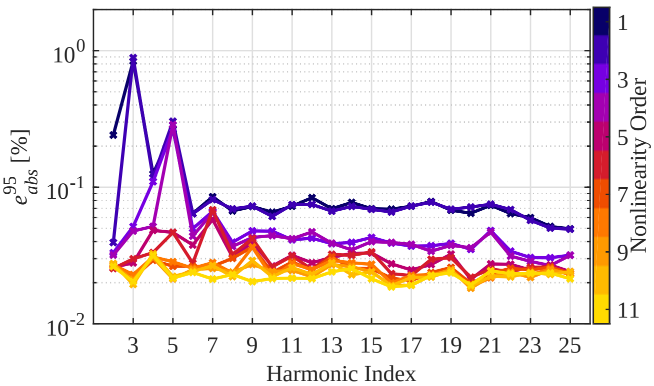

Fig. 2. Instrument transformer VT[1]: e_{abs}^{95} for each harmonic component, primary voltages belong to the class of identification signals.

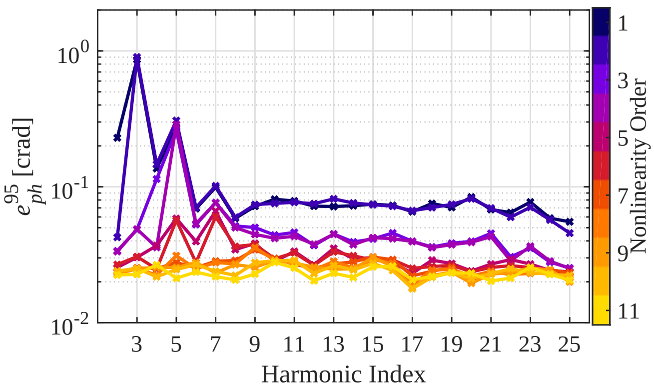

Fig. 3. Instrument transformer VT[1]: e_{ph}^{95} for each harmonic component, primary voltages belong to the class of identification signals.

As expected, the output spectrum of the instrument transformer under test is significantly affected by harmonic distortion and intermodulation; this is confirmed by the trend of the errors that diminish when the order of the nonlinear models is increased. Moreover, experimental results show that nonlinearity affects particularly the second and even more, low-order, odd harmonics. The major source of nonlinearity is the magnetic core of the VT, which typically introduces odd nonlinearity. Slight impact can be attributed to hysteresis (residual flux) resulting in a complex nonlinearity (non-fading memory) that cannot modeled with the Volterra approach.

It should be noticed that magnitude and phase error versus frequency plots exhibit basically the same behavior; moreover, when phase errors are expressed in centiradians, their values are also extremely similar. Therefore, since in this case magnitude and phase error plots carries almost the same information, a performance index able to jointly consider both the contributions could be employed. The Total Vector Error (TVE) is introduced for the purpose. For each test signal, it represents the distance on the complex plane between the m-th order harmonic phasors of the estimated and measured secondary voltage ($V_{s,e}^{[p]}(m)$ and $V_{s}^{[p]}(m)$ respectively) with respect to the amplitude of the second one:

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

As synthetic performance index, the 95th percentile value of $\mathrm{TVE}^{[p]}(m)$ has been obtained for each model order and output harmonic. In Fig. 4 the TVE^{95} values achieved by the proposed models in representing the behavior of VT^1 have been reported.

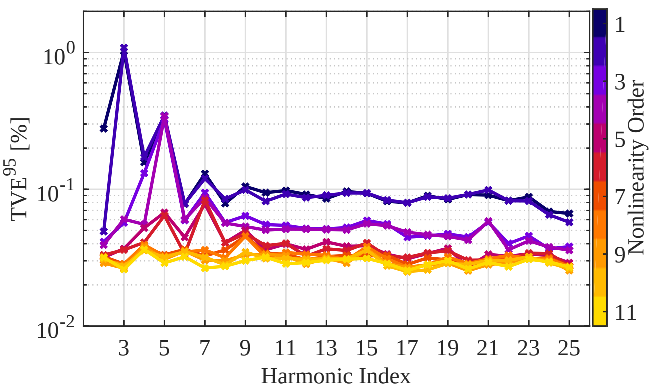

Fig. 4. Instrument transformer VT^1: TVE^{95} for each harmonic component, primary voltages belong to the class of identification signals.

As expected, TVE^{95} shows the same behavior of e_{abs}^{95} and e_{ph}^{95} reported in Fig. 2 and Fig. 3. Accordingly, for sake of brevity, model accuracy will be evaluated only in terms of TVE^{95} in the following. Hence, TVE^{95} values achieved in modeling the behavior of VT^2 are shown Fig. 5.

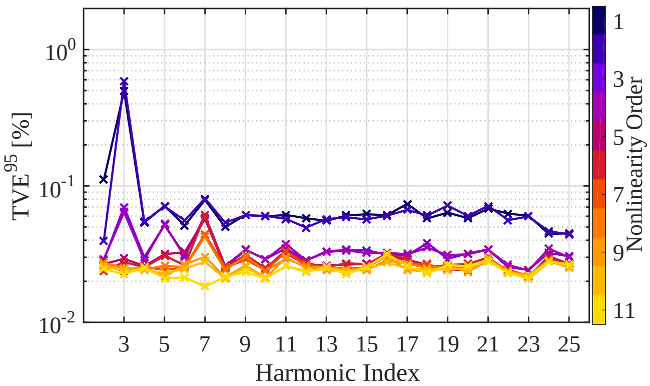

Fig. 5. Instrument transformer VT^2: TVE^{95} for each harmonic component, primary voltages belong to the class of identification signals.

The 3rd harmonic is the most affected by nonlinear contributions, since the TVE^{95} reaches its maximum value, as clearly shown in Fig. 4 and Fig. 5. For VT^1 and VT^2, the TVE^{95} achieved by the linear model is 1.08% and 0.6%; it decreases to 0.026% and 0.024% when the 11th order simplified model is considered. Nonlinearity has remarkable impact also on the 5th and the 7th order harmonic components: considering VT^1 (Fig. 4) the TVE^{95} drop from 0.34% and 0.13% of the linear model to 0.029% and 0.026% of the 11th simplified Volterra model. VT^2 shows slightly weaker nonlinearity (Fig. 5): for the 5th order harmonic TVE^{95} decreases from 0.07% to 0.021% while for the 7th order one the corresponding values are 0.081% and 0.018%.

It can be noticed that up to the 7th harmonic the highest error reduction is achieved when the model order I equals the harmonic order m. For example considering the 3rd harmonic of VT^1, TVE^{95} decreases from 1.08% to 0.06% when passing from a 2nd to 3rd order model. The same behavior is observed for the 5th harmonic: TVE^{95} drops from 0.34% to 0.067% when I is increased from 4 to 5. From (2) and (3) I=m is the lowest order that allows considering a direct impact of the fundamental tone on the m-th order harmonic. This means that up to the 7th harmonic, the major nonlinear contribution is represented by the harmonic distortion only due to the fundamental.

It should be noticed that in most cases (especially for high-order harmonics) increasing the model order above seven results in slight accuracy improvement. The impact of nonlinearity appears to be similar for all harmonics above the ninth, except of the highest two (namely the 24th and 25th). Unlike the others, these components are not affected by nonlinear contributions due to higher-order harmonics, which in this case have negligible magnitude.

The overall behaviors of the tested VTs are similar, but some differences can be pointed out. In particular, VT^1 is more affected by nonlinearity, especially for the fifth harmonic. This is probably due to the different magnetic core design and material.

For both VT^1 and VT^2 accuracies achieved by the proposed nonlinear models are remarkable, since TVE^{95} has order of magnitude of 0.01% over the whole considered frequency range.

As previously discussed, for both the tested voltage transformers a linear model allows reaching excellent accuracy at the fundamental component. For the sake of completeness, some results for both VT^1 and VT^2 are summarized in TABLE II.

TABLE II
TVE^{95} FOR THE FUNDAMENTAL COMPONENT: PRIMARY VOLTAGES BELONG TO THE CLASS OF IDENTIFICATION SIGNALS

TVE^{95}[%]	1^{st}	3^{rd}	11^{th}
VT^1	0.0036	0.0024	0.0011
VT^2	0.0015	0.0012	0.0011

B. Model Validation

In order to assess the robustness of simplified Volterra models and to test their accuracy under realistic conditions, a further validation activity has been performed. For this purpose, a new set of test voltages has to be defined.

EN 50160 Standard [24] defines the limits for harmonic voltages (up to the 25^{th} order) for public MV distribution networks. It states that considering a one week observation period, the 10 minute root mean square value of each harmonic should be below the corresponding limit for 95% of the time; these values are reported and compared in Fig. 6. Moreover, it states that the 10 minute root mean square voltage should be within 90% and the 110% of the rated value for 95% of the time.

The previous limits can be exploited to define a class of voltage waveforms similar to those that can be typically found in distribution networks. In particular, the harmonic amplitudes of the spectral components in the excitation signal have been considered as random variables whose 95^{th} percentile values are represented by the corresponding limits; Rayleigh pdfs have been considered. As for the fundamental amplitude, it is supposed to be normally distributed, having average equal to the rated voltage and standard deviation so that it falls between ±10% of the rated value with 95% probability. All the phases are considered as independent and identically distributed random variables having uniform distribution in the interval [-π, π].

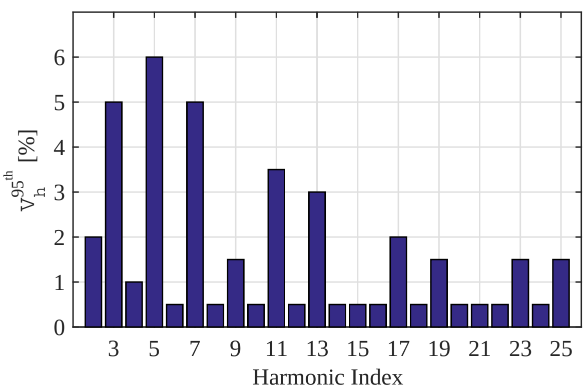

Fig. 6. EN50160 harmonic limits.

Having defined the pdfs, P=200 signals have been extracted, applied to the two instrument transformers and their response have been measured by following the same procedure explained in Section IV.A.

For each primary test signal, the corresponding secondary voltage spectrum predicted by the model can be used as in (7). Considering a spectral component, the TVE has been evaluated for all the test signals, and its 95^{th} percentile has been computed. Results for the fundamental term have been reported in TABLE III. Even in this case, nonlinear effects at the fundamental appear to be negligible.

TABLE III
TVE^{95} FOR THE FUNDAMENTAL COMPONENT: PRIMARY VOLTAGES BELONG TO THE CLASS OF THE VALIDATION SIGNALS:

TVE^{95}[%]	1^{st}	3^{rd}	11^{th}
VT^1	0.012	0.011	0.011
VT^2	0.0037	0.0035	0.0035

TVE95 for the harmonics component achieved by the nonlinear models have been reported in Fig. 7 and Fig. 8 for VT1 and VT2 respectively. A linear model (I=1, blue line) is not able to take into account nonlinear contributions, thus resulting in relatively high TVE95, especially for low-order odd harmonics. Errors at the third harmonic are significantly higher with respect to those achieved during model identification.

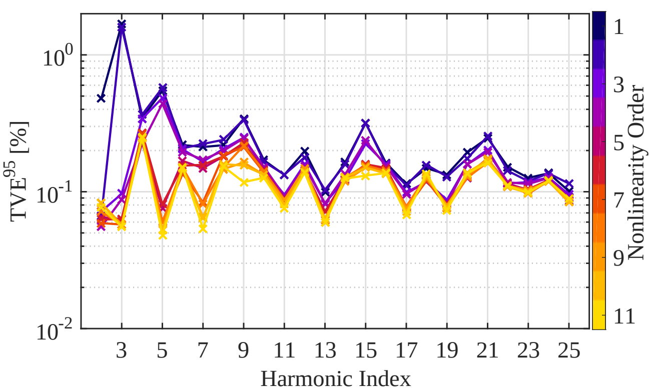

Fig. 7. . Instrument transformer VT^1: TVE^{95} for each harmonic component, primary voltages belong to the class of validation signals.

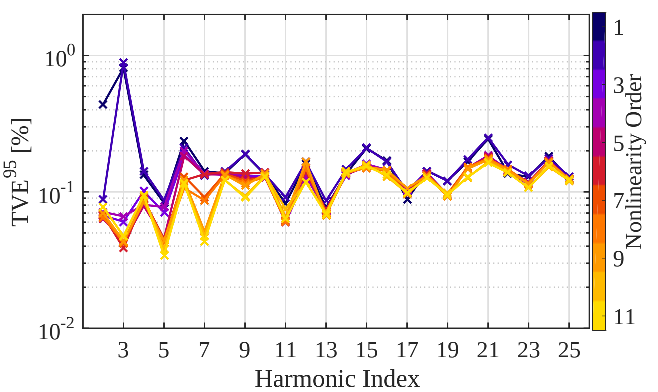

Fig. 8. Instrument transformer VT^2: TVE^{95} for each harmonic component, primary voltages belong to the class of validation signals.

It should be noticed that some harmonics seems to be more affected by nonlinearity. The reason is partly due to the transducer, partly to the spectral content of the excitation signals. As explained before, nonlinearity is mostly odd; hence low-order odd harmonics are supposed to be the most heavily affected by nonlinearity. However, being TVE^{95} a relative quantity, it is boosted for harmonics having lower expected amplitude. In particular, since practical power systems are weakly unbalanced, harmonics whose orders are multiples of three are expected to be extremely small, as it can be noticed from Fig. 6. For this reason, impact of nonlinearity is higher for odd harmonics whose order is multiple of three. Such components generally show the highest accuracy improvement when a nonlinear model is employed.

The third harmonic is the most affected by nonlinearity the TVE^{95} for VT^1 and VT^2 decrease respectively from 1.7% and 0.88% for I=1, to 0.060% and 0.047% for I=11. When considering VT^1, the fifth output harmonic is significantly jeopardized by nonlinearity, being TVE^{95} equal to 0.57% for the linear model; it drops to 0.048% when the eleventh order model is considered.

As for the 9th harmonic, results show that even in this case nonlinear phenomena are not negligible. TVE^{95} for VT^1 and VT^2 decrease respectively from 0.34% and 0.19% for I=1, to 0.11% and 0.043% for I=11.

V. Conclusion

Conventional characterization procedures of voltage transformers devoted to harmonic measurements are based on a linear model, hence on the estimation of frequency response functions. In this paper, the employment of a frequency-domain nonlinear model is proposed for the first time. The adopted approach is based on a simplified Volterra model that allows a consistent reduction in the number of coefficients, thus resulting in a faster identification procedure and less demanding computational burden.

The proposed method has been applied to represent the input-output functional of two different medium voltage inductive transformers. Models have been identified with a proper experimental setup that allows generating distorted excitation waveforms, and validated by with a large set of realistic primary voltages. Experimental results highlight the large accuracy improvement with respect to that achieved by a linear model. This is particularly evident when looking at the low-order, odd harmonics, which are the most affected by nonlinearity produced by the iron core.

When the proposed models are employed to predict output harmonics due to primary voltages belonging to the same class of those employed for the identification, the resulting relative errors are extremely low. Considering a different set of realistic waveforms, the proposed models achieve similar results for the low-order harmonics, but considerably higher errors when looking at the right part of the spectrum. The main reason is related with the small expected amplitude of these components.

It is worth noticing that the proposed approach, which is able to consider the combined effect of bandwidth limitations and static nonlinearity, can be applied for identifying any kind of voltage transformer. Other than for representing the behavior of the transducer, it can be a helpful tool for many other purposes, such as studying the impact of drift and aging and developing innovative calibration methods.

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