Improving Harmonic Measurements with Instrument Transformers: a Comparison Among Two Techniques

non-sinusoidal signals. On the contrary, the behavior of VTs and CTs in the presence of harmonics should be studied by applying distorted waveforms, resembling those typically found in power systems. Moreover, it was shown in [13]-[18] that both VTs and CTs can introduce errors up to some percent when they are used to measure harmonics without taking into account their complex behavior.

Considering the importance of harmonic measurements and the widespread diffusion of conventional ITs, several digital signal processing techniques aimed at mitigating their nonlinear behavior have been proposed in the literature [15]-[18], thus improving their accuracy. In this respect, the target of the present paper is deeply analyzing the performance of two of them: SINDICOMP [15] and the compensation of Harmonic Distortion (HD) through polynomial modeling in the frequency domain [18], recently proposed by some of the authors. Both techniques assume that the harmonic distortion produced by the fundamental component is the most significant nonlinear effect and they are characterized by their ease of implementation. In fact, just simple algebraic operations are needed to reconstruct the phasors of the harmonics at the primary side, starting from the phasors of the harmonics at the secondary side, thus removing a significant part of the nonlinear effects. Comparison has been carried out by means of numerical simulations using a model of the VT that accurately represents the nonlinear hysteretic behavior of the core. In this way, results are not affected by the unavoidable measurement uncertainty: therefore, the performance of the methods can be better studied.

The paper is organized as follows. Section II gives a brief review of SINDICOMP and polynomial HD compensation methods. Section III describes the employed model of the VT and the performed numerical simulations. Section IV discusses the results and compares the accuracies in harmonic measurement that can be achieved thanks to the proposed approaches. Finally, Section V draws the conclusions.

II. Nonlinearity Compensation Techniques

A. SINDICOMP

The SINDICOMP technique [15] starts from two assumptions: 1) the distorted waveforms measured by the VT are *quasi sinusoidal*, i.e. composed by the superposition between a large-signal contribution at the fundamental frequency f_0 and a small-signal contribution at the harmonics; 2) the transformer nonlinearity is rather weak. If these two hypotheses are verified, it can be stated that each generic *h*th order harmonic of the magnetization current $I_m(h)$ mostly depends on the primary side fundamental component, thus on $V_1(1)$. Considering the series impedance of the primary winding referred to the secondary side:

$$Z_1''(h) = R_1'' + j2\pi f h L_1'' \tag{1}$$

this results in a distorted voltage at the secondary side even when the primary side voltage is purely sinusoidal:

$$V_2^{sin}(h) = -Z_1''(h) I_m(h) \tag{2}$$

the superscript *sin* indicates a phasor obtained by applying a sinusoidal primary voltage. Conversely, when applying a distorted primary voltage whose harmonics are $V_1(h)$ with the same fundamental, the secondary voltage results:

$$V_2(h) = V_1''(h) - Z_1''(h) I_m(h) \tag{3}$$

where $V_1''(h)$ is the *h*th order harmonic of the primary side voltage referred to the secondary side according to the turn ratio. If equation (3) is inverted, it can be written:

$$V_1''(h) = V_2(h) + Z_1''(h) I_m(h) = V_2(h) - V_2^{sin}(h) \tag{4}$$

Therefore, $V_1''(h)$ can be obtained by measuring the correspondent secondary harmonic phasor and compensating it by subtracting the secondary harmonic phasor measured when only the fundamental is applied. Knowing the transformer ratio and the phase error, the primary side harmonic phasors can be reconstructed. The necessary steps to apply SINDICOMP are:

a) Step 1: characterization of the VT by applying sinusoidal primary voltages at fundamental frequency whose amplitudes cover the measurement range of the VT while measuring the secondary harmonic phasors introduced by nonlinearity. They are the entries of a lookup table. Ratio and phase error at the fundamental have also to be determined.

b) Step 2: when generic distorted multitone waveforms are applied, measure the fundamental component, find the corresponding $V_2^{sin}(h)$ from the lookup table and using (4) to reconstruct the primary side harmonics.

The advantages of SINDICOMP are: 1) the laboratory characterization is performed with sinusoidal signals, so involving measuring instrumentation typically available in every calibration laboratory; 2) very easy implementation.

B. Polynomial compensation of Harmonic Distortion 2

The HD compensation technique proposed by [18] assumes that the VT can be considered as a (weakly) nonlinear time-invariant device. The generic *h*th order harmonic $V_2(h)$ (with $h \geq 2$) appearing in the secondary voltage can be decomposed into the sum of two different contributions:

$$V_2(h) = V_{2,L}(h) + V_{2,NL}(h) \tag{5}$$

The first term $V_{2,L}(h)=V_1(h)H_L(h)$ represents the linear contribution to the transformer output, and hence proportional to the primary voltage harmonic having the same frequency. $H_L(h)$ is the Frequency Response Function (FRF) characterizing the underlying linear part of the VT. The second term, $V_{2,NL}(h)$, is produced by the nonlinear behavior of the VT; in general, it is a function of all the primary side spectral components.

As already stated in Section II.A, since voltage waveforms in ac power systems are *quasi sinusoidal*, the strongest VT nonlinear effect is represented by the HD due the fundamental primary voltage. Under this assumption, it is possible to consider $V_{2,NL}(h)$ as dependent on the fundamental primary voltage only. Since nonlinearity has small impact on the fundamental term, $V_{2,NL}(h)$ is proportional to the fundamental secondary voltage. Hence, it is possible to obtain an expression of the primary voltage harmonics:

$$V_1(h) = K_L(h)V_2(h) + V_{1,HD}(h) \tag{6}$$

$V_{1,HD}(h)$ is a function of the fundamental secondary voltage only, while $K_L(h)$ is the inverse of $H_L(h)$. By adopting a frequency-domain polynomial approach to model $V_{1,HD}(h)$:

$$V_1(h) = K_L(h)V_2(h) + \sum_{i=0}^{\left\lfloor \frac{I-h}{2} \right\rfloor} K^i(h)\left|V_2(1)\right|^i e^{jh\varphi} \tag{7}$$

where $\varphi=\angle V_2(1)$, $I\geq 2$ is the maximum degree of the employed polynomial model and $\lfloor \cdot \rfloor$ denotes the floor function. Adopting vector notation, (7) can written as:

$$V_1(h) = \square^T(h)\square(h) \tag{8}$$

where:

$$\square(h) = \begin{bmatrix} V_2(h) \\ \left|V_2(1)\right|^h e^{jh\varphi} \\ \ldots \\ \left|V_2(1)\right|^{2\left\lfloor \frac{I-h}{2} \right\rfloor + h} e^{jh\varphi} \end{bmatrix} \quad \square(h) = \begin{bmatrix} K_L(h) \\ K^m(h) \\ \ldots \\ K^{2\left\lfloor \frac{I-h}{2} \right\rfloor + h}(h) \end{bmatrix} \tag{9}$$

(8) allows reconstructing the primary side harmonics from the secondary side. However, this requires identifying the vector of coefficients $\square(h)$. It can be performed by applying a proper set of P realistic primary voltages to the VT under test while observing the corresponding secondary output. Since for each signal and harmonic an equation in the form (8) is defined, a matrix relationship can be written:

$$\square_{1,id}(h) = \square_{id}(h)\square(h) \tag{10}$$

Assuming that P is greater than the maximum length of $\square(h)$ and that the applied signals results in a full-column rank matrix $\square_{id}(h)$, estimating $\square(h)$ is an overdetermined problem which can be solved in the least squares sense.

The main advantages of the approach are essentially two: 1) reconstructing voltage harmonics just requires measuring the secondary side spectrum while computing (8); 2) robustness with respect to the identification signals: there are no particular requirements except being *quasi sinusoidal* periodic multisines.

III. Numerical Simulations

The previously described techniques for mitigating the nonlinearities introduced by VTs have been implemented in Matlab and their performance have been compared by means of numerical simulations. For the purpose, the usual circuit model of the transformer reported in Fig. 1 has been considered. It allows an accurate representation of a VT for distribution grids up to few kilohertz, when capacitive phenomena can be neglected.

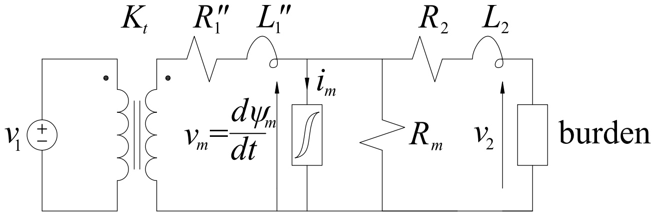

Fig. 1. Equivalent circuit of the VT.

All the parameters are referred to the secondary side; their values, reported in Table I, resemble those of a class 0.5 VT having 15kV/√3:100V/√3 ratio, 30 VA rated burden and 50 Hz nominal frequency.

TABLE I. Equivalent Circuit Parameters.

R ”Ω[	**L** ” [mH	**R** [Ω	**L**	K_t
0.282	0.398	0.338	0.398	149.6

For a significant comparison, it is mandatory that the model is capable of accurately considering the nonlinear effects occurring in a VT. Therefore, the nonlinear, hysteretic relationship between the magnetization flux linkage ψ_m and the magnetizing current i_m under quasi-static conditions have been represented by the Tellinen model [19]. Eddy current loss is considered thanks to the resistor R_m. Simulation have been performed with the rated burden and with 20 % of the rated burden; 0.8 power factor has been assumed.

Both the identification and the verification of the compared techniques requires applying periodic multisine voltages having rated fundamental frequency while observing the corresponding secondary waveforms under steady state conditions. The Discrete Fourier Transform (DFT) has been used to evaluate the spectra and data have been saved with 100 kHz sampling rate, which is multiple of the fundamental frequency to avoid spectral leakage and high enough so that aliasing has negligible impact.

The parameters required by SINDICOMP have been evaluated by applying three sinusoidal voltages having amplitude of 0.8 p.u., 1 p.u. and 1.2 p.u. Spline interpolation between these large-signal operating points have been used during verification. The procedure has been repeated for the two different burdens.

In order to identify the parameters of the HD compensation method, a class E_1 of primary voltage multisines have been defined. They are characterized by random fundamental amplitude, with uniform distribution between 0.8 p.u. and 1.2 p.u., and harmonic amplitudes equal to 1 % of the fundamental. Harmonics up to the 25th order have been injected and phase angles are independent and uniformly distributed between $-\pi$ and π. Parameter identification have been performed by applying P=100 of these waveforms to the VT model and solving the problem (10). Degrees ranging from 1 to 11 have been considered in the comparison. It should be noticed that considering I=1 it corresponds to the Best Linear Approximation, namely the FRF that allows the best reconstruction of primary side harmonics from the secondary side in the least squares sense for the class E_1 of signals. The identification procedure has been performed with both of the considered burdens.

IV. Simulation Results

A. *Primary voltages belonging to class E_1*

Firstly, the proposed compensation techniques have been applied considering 20 % of rated burden and a set of P=500 randomly extracted primary voltages belonging to the previously defined class E_1. Considering the pth excitation and hth order harmonic, the achieved performance has been quantified in terms of harmonic Total Vector Error (TVE), defined as:

$$\mathrm{TVE}_h^{[p]}(h) = \left| \frac{V_{1,e}^{[p]}(h) - V_1^{[p]}(h)}{V_1^{[p]}(h)} \right| \qquad (11)$$

where $V_1^{[p]}(h)$ is the actual hth order harmonic of the pth voltage waveform while $V_{1,e}^{[p]}(h)$ represents its estimate provided by one of the considered techniques. In order to obtain an overall performance indicator, TVE_h^{95} has been computed as the 95th percentile value of $\mathrm{TVE}_h^{[p]}$ over the P excitation waveforms. The obtained results are reported in Fig. 2; since the methods are addressed at compensating nonlinearities occurring at low-order harmonics (that are also by far the most affected), harmonic orders up to 11 are considered.

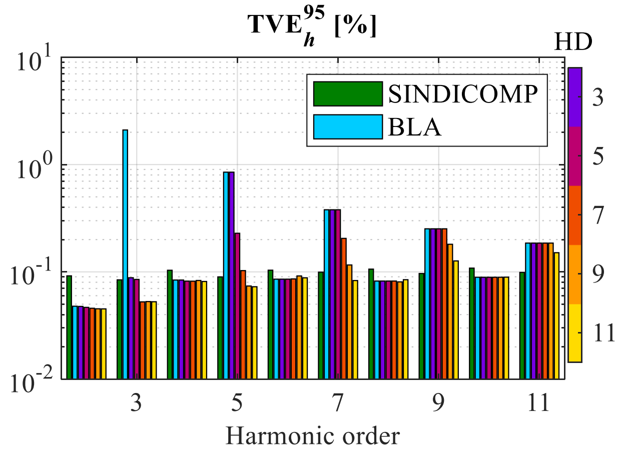

Fig. 2. TVE_h^{95} achieved by the proposed compensation methods, class E_1 of primary voltages, 20 % of rated burden.

The capability of the proposed techniques to improve dramatically measurement accuracy at low-order harmonics is evident. When the degree of HD compensation is increased, TVE_h^{95} values are progressively reduced. It is worth noting that none of the methods is capable of improving accuracy at even order harmonics. In fact, since the used VT model has perfectly symmetric magnetization characteristics, they are not affected by HD, but only by intermodulation, which is not addressed by both the considered techniques. For the same reason, only the results obtained by odd-order polynomial HD compensation are reported.

Since the model does not introduce even order nonlinearity, increasing the compensation degree from an odd value to the next even does not improve accuracy.

As typically happens, the 3rd order harmonic is the most heavily affected by nonlinearity. In that case, the BLA results in a TVE_h^{95} of 2.1 %, lowered to 0.084 % by SINDICOMP or to 0.052 % thanks to the 11th degree polynomial HD compensation. As for the 5th order harmonic, the optimal FRF results in 0.85 % TVE_h^{95}, while SINDICOMP achieves 0.090 % and the 11th degree HD compensation 0.073 %. While at the very low order harmonics the polynomial HD compensation results in slightly better accuracy, the situation is the opposite as far as the 9th and 11th order harmonics. The reason is that for these two harmonics HD is modeled by just two and one coefficient, respectively.

While the TVE is capable of providing an overall performance figure at each harmonic, metrological performance of a VT is typically quantified in terms of ratio and phase error (e_{abs} and $e_{\angle}$, respectively). For each pth primary voltage and hth order harmonic, they are defined as:

$$\begin{aligned} e_{abs}^{[p]}(h) &= \frac{\left|V_{1,e}^{[p]}(h)\right| - \left|V_{1}^{[p]}(h)\right|}{\left|V_{1}^{[p]}(h)\right|} \\ e_{\angle}^{[p]}(h) &= \angle V_{1,e}^{[p]}(h) - \angle V_{1}^{[p]}(h) \end{aligned} \tag{12}$$

The average values and the 95th percentile band over the P different waveforms have been computed for each harmonic order and compensation method. Results are reported in Fig. 3 and Fig. 4; dash dot lines represent the average values, while error bars denote the 95th percentile bounds. For the sake of clarity, only the results achieved by the 11th degree polynomial HD compensation are reported.

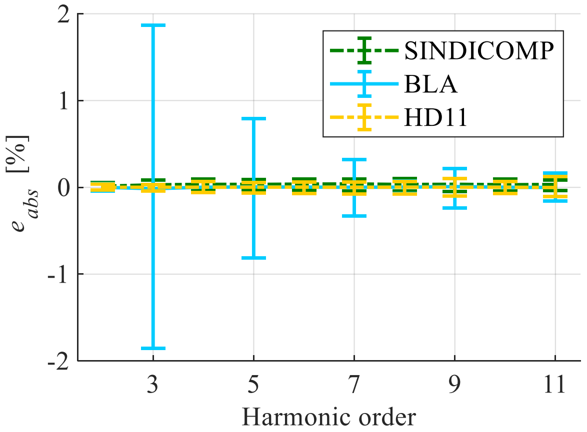

Fig. 3. Ratio error achieved by the proposed compensation methods, class E_1 of primary voltages, 20 % of rated burden.

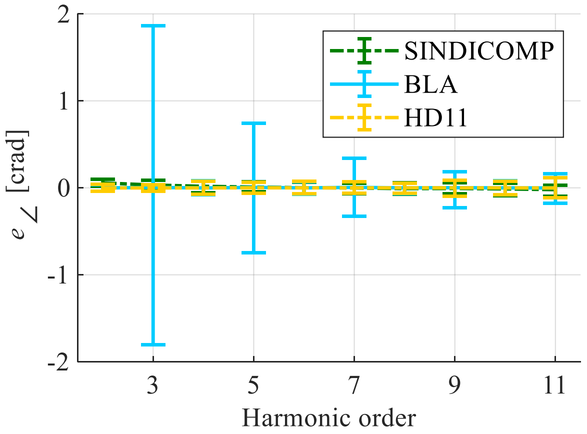

Fig. 4. Phase error achieved by the proposed compensation methods, class E_1 of primary voltages, 20 % of rated burden.

Magnitude estimates are virtually unbiased in all the cases, while phase measurements performed with SINDICOMP show a weak bias: the reason is that it is not capable of including the filtering behavior of the VT. The 95th percentile bounds of ratio error and phase error are strongly correlated and exhibit almost the same values when the first is expressed as percentage and the second in crad. The widths of the error bars reflect the trend of TVE_h^{95}, but here the accuracy enhancement provided by the considered techniques is even more evident thanks to the linear scale. It is confirmed that at very low order harmonics the polynomial HD compensation achieves slightly lower errors, while SINDICOMP is marginally more effective at the 9th and 11th order harmonics.

After that, the same P=500 random signals have been applied to the model of the VT now feeding the rated burden. The obtained values of 95th percentile harmonic TVE for the different harmonic orders and compensation methods are shown in Fig. 5. The accuracy obtained with polynomial HD compensation and with the BLA are virtually identical to those achieved considering 20 % of the rated burden. However, the TVE_h^{95} values reached by SINDICOMP are considerably higher in this case. At the 3rd order harmonic, it increases to 0.23 %; similar values are obtained also at the other components. In order to understand the issue, it is worth analyzing the average and the 95th percentile bands of ratio error and phase error, reported in Fig. 6 and Fig. 7.

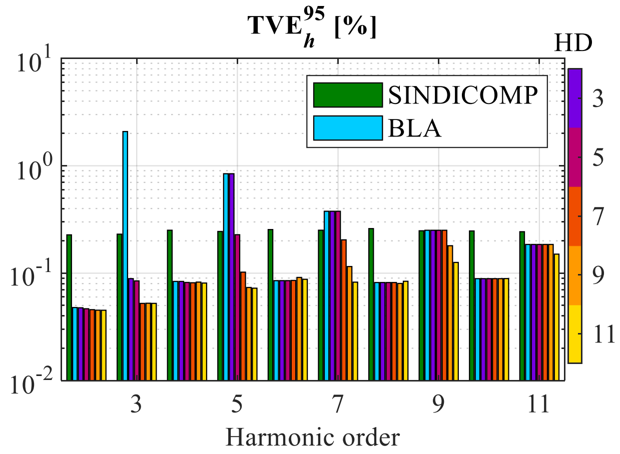

Fig. 5. TVE_h^{95} achieved by the proposed compensation methods, class E_1 of primary voltages, rated burden.

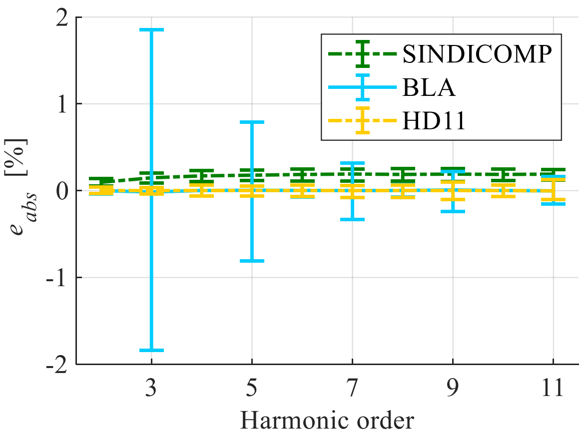

Fig. 6. Ratio error achieved by the proposed compensation methods, class E_1 of primary voltages, rated burden.

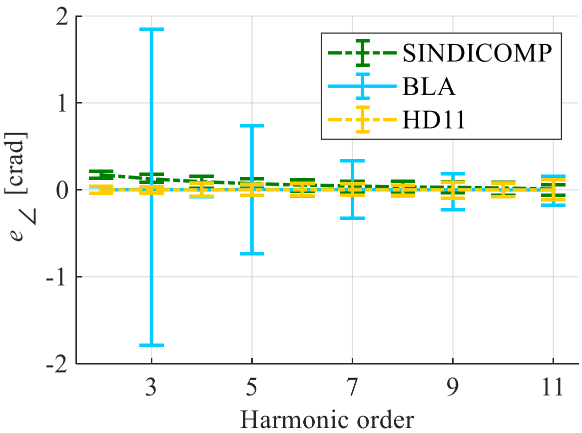

Fig. 7. Phase error achieved by the proposed compensation methods, class E_1 of primary voltages, rated burden.

It is not surprising that the behavior of the polynomial HD compensation and of the BLA is very close to that observed in Fig. 3 and Fig. 4. However, a significant difference arises when considering SINDICOMP. While the 95th percentile bands are quite similar to those observed with 20 % burden, the errors now exhibit a noticeable bias. Specifically, the bias of the ratio error is stronger in the rightmost part of the plot, while the average phase error is higher at the lowest order harmonics. The reason for these biases is that SINDICOMP is not able to compensate for the filtering behavior of the VT, which becomes stronger with higher burden.

B. Realistic primary voltages

The previously defined class E_1 of excitation signals has been employed to highlight some peculiarities of the compensation methods, but it is extremely important to quantify their perrformance in the presence of realistic primary voltage waveforms. For this purpose, a new class E_2 of excitation signals has been introduced, starting from the standard EN 50160 [20] ruling the voltage characteristics in public distribution grids. In particular, it reports the limits for the 10 minute mean root mean square (rms) values of harmonic amplitudes (up to the 25th order) that should not be exceeded for more than 95 % of the time over a one-week interval. These limits have been employed as 95th percentile values for harmonic amplitudes. The fundamental component is assumed to be within 90 % and 110 % of its rated value for 95 % of the time. The standard does not provide information about the probability distributions or about phases. A Gaussian probability density function (pdf) with mean value equal to the rated voltage has been considered for the fundamental term. Relative harmonic amplitudes are supposed to follow Rayleigh distributions, while phases are considered as uniformly distributed between -π and π. P=500 primary voltage waveforms have been obtained by sampling the previously introduced pdfs and applied to the VT model, firstly considering 20 % of the rated burden. Results in terms of TVE_h^{95} are summarized in Fig. 8.

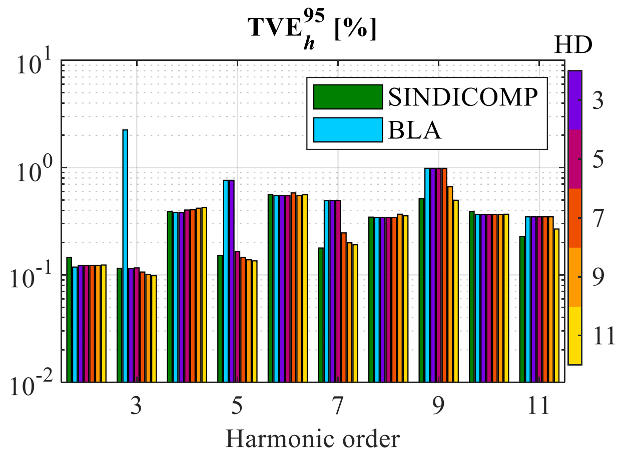

Fig. 8. TVE_{exp}^{95} achieved by the proposed compensation methods, class E_2 of primary voltages, 20 % of rated burden.

In general, TVE values are higher with respect to those measured by applying the class E_1 of primary voltage waveforms. In particular, the TVE_h^{95} value at the generic hth order harmonic is heavily affected by the random realizations having the smallest harmonic amplitudes. Furthermore, TVE_h^{95} is generally higher for those harmonics having smaller expected amplitude, such as the even order ones and the 9th order. Anyway, at the 3rd order harmonic and using the BLA results in a TVE_h^{95} of over 2.2 %, reduced to 0.12 % with SINDICOMP and to 0.098 % adopting the 11th degree polynomial HD compensation. Also in this case, at the 11th order harmonic, SINDICOMP performs slightly better than the polynomial HD compensation (TVE_h^{95} equal to 0.23 % with respect to 0.27 %), which in this case uses just a term to represent nonlinearity.

Finally, the same P=500 signals belonging to the class E_2 of primary voltage waveforms have been applied to the model of the VT, now loaded with the rated burden. The obtained values for the 95th percentile values of the harmonic TVE are shown in Fig. 9. When compared to Fig. 8, the higher burden does not affect the performance achieved with the BLA or with the polynomial HD compensation, as happened as long as the class E_1 of primary voltage signals was considered. Conversely, the higher burden results in higher errors when adopting the SINDICOMP technique. Considering the 3rd order harmonic, TVE_h^{95} increases to 0.25 %, while it becomes equal to 0.34 % at the 11th order harmonic. Anyway, the performance degradation is not so high and, in particular, it is considerably smaller with respect to that observed when primary voltage waveforms belonging to the class E_1 were applied. The reason is strictly related with the random harmonic amplitudes characterizing the class E_2.

In general, when estimating a harmonic, two sources contributes to the value of the TVE. The first one is due to the nonlinearity, and thus mostly on HD; hence, it depends only on the fundamental. Therefore, in relative terms it has higher impact as long as the harmonic to be evaluated is small. The second contribution depends on the filtering behavior of the VT; in absolute value, it is proportional to the harmonic to be evaluated. When applying voltages belonging to the class $E_{2,}$ thus having random harmonic amplitudes, the TVE_h^{95} strongly depends on the accuracy achieved when the harmonic to be evaluated is small (below 1 %). In this case, the impact due to the filtering behavior of the VT, which cannot be addressed by SINDICOMP, has a smaller impact.

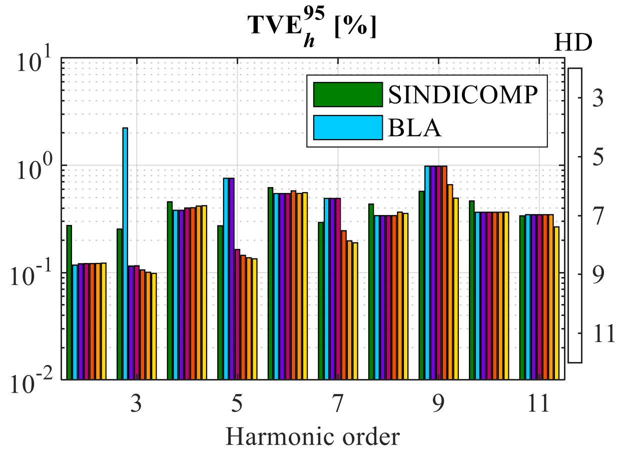

Fig. 9. TVE_{exp}^{95} achieved by the proposed compensation methods, class E_2 of primary voltages, rated burden.

CONCLUSIONS

This paper has presented a comparison among two techniques for the improvement of harmonic measurements performed by using a VT. Both of them, SINDICOMP and polynomial HD compensation, have been recently presented by some authors. They work in the frequency domain and, through proper algorithms, they allow reconstructing the harmonic phasors at the primary side from those measured at the primary side, while taking into account the nonlinear effects. The performances of the techniques have been studied by means of numerical simulations, feeding a VT model with voltages that are representative of the typical waveforms in power systems. They show that the performances of the two techniques are equivalent when the VT works with a low burden (lower than 20 %) or with harmonics having quite low amplitudes (1 % or lower). Instead, when the VT works at rated burden, or when the harmonics have higher amplitudes (higher than 1 %), SINDICOMP performs worse than the polynomial HD compensation, since it does not account for the filtering effect of the VT.

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