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***Abstract*—The paper introduces a simplified method for the frequency characterization of instrument transformers for transmission and distribution grids. The proposed method makes extremely easy and affordable the MV instrument transformers frequency characterization. It involves, in the first step, an evaluation and a compensation of the non-linearity introduced by the voltage transformer when it is supplied with a 50 Hz sinusoidal input at rated value. Then, the voltage transformer is characterized with a low voltage sinusoidal signal from the second harmonic frequency up to the first resonance frequency. In this way, its approximated frequency behavior is obtained by compensating the non-linearity errors at the lower harmonics and using a piecewise curve at the higher frequencies. The proposed approach is applied to the evaluation of the ratio errors of a commercial voltage transformer up to the first resonance. Significant improvement of the VT performance is obtained, compared to the use of a frequency dependent ratio obtained from the low voltage characterization.**

Keywords*— *Power system measurement, Instrument Transformer, Voltage Measurement, Harmonics, Power Quality

I. INTRODUCTION

Modern transmission and distribution grids are experiencing an increase of the harmonic distortion levels, due to the presence of high frequency power converters and electronic non-linear loads, as well as of the large scale integration of renewable energy sources, which introduce harmonics due to power electronics devices as well as inverter operation. Quantifying the harmonic levels is a matter of growing importance both for the assessment of the grid power quality, the identification of disturbance sources, the power line communication, the communications in railway systems and for accurate metering and effective protection [1]-[14]. Accuracy of the harmonic level measurements in medium voltage (MV) and high voltage (HV) grids clearly depends on the performances of the whole measurement chain, which must include, besides the harmonic/PQ measuring instrument, a voltage sensor, which in many situation is an already installed measurement or protection voltage instrument transformer.

The metrological performances of these sensors in presence of harmonic distortion significantly depend on their operating principles [15]-[22]. In the particular case of the frequently used inductive instrument transformers, not negligible ratio and phase errors can be introduced both at low and high frequency harmonics [23]-[24]. In the majority of cases, the ratio and phase errors of the instrument transformers (ITs) are evaluated by carrying out a frequency sweep at low voltage under sinusoidal supply, not considering the non-linearity of the device, which can lead to additional errors of the order of the percent. Alternative approaches have been proposed, where the instrument transformer response is measured under a more realistic situation, by applying a bi-tone or a multi-tone signal (fundamental at rated voltage plus superimposed harmonic) [25], [26]. The experimental set-up is in this case quite complex and expensive, requiring in particular the capability of generating complex waveforms at high voltage values and a reference wideband measurement chain [27].

A procedure allowing the compensation of the IT non-linearity errors, which affect the measurement at the first harmonics where the ratio and phase errors strongly depend on the harmonic phase value, has been presented by the authors in [27]. However, non-linearity effects are significant in a limited harmonic frequency range (e.g. up to the 10^{th}-15^{th} harmonic order). With the increase of the frequency, depending on the characteristics and rated primary voltage of the VT, the frequency behavior of the VT is more linear and it is dominated by the winding stray capacitances. If a linear behavior can be assumed at higher frequencies, then its frequency behavior can be measured by carrying out a frequency sweep at low voltage under sinusoidal supply, simplifying, in this way, the requirements of the characterization setup.

Therefore, in this paper a method for the construction of an approximated frequency response of a VT is presented. It starts from the previously proposed approach, i.e. SINDICOMP (SINusoidal characterization for DIstortion COMPensation) [27], which is integrated and extended. The VT is characterized with a two-step procedure. In the first step, SINDICOMP is applied, that is the VT is characterized with the fundamental rated voltage and the harmonic phasors introduced at the output are measured: these harmonic phasors are used to reduce in a strong way the VT non –linearity by accounting them when a distorted waveform is measured by the VT. In the second step, a low voltage frequency sweep, starting from the second harmonic frequency, is carried out. The approximated VT frequency response is constructed by combining the behavior measured in the two steps, as it is better explained in the paper. It is worth to highlight two important aspects: 1) even if a VT is a non-linear device and, in principle, the concept of frequency response is defined for a linear system, with the proposed approach (SINDICOMP is used to strongly reduce the non-linearity) the VT can be assumed linear; 2) the proposed approach involves the generation of the rated voltage just at power frequency and then low voltage sinusoidal signals, thus generation and measuring instruments already available in practically all the ITs calibration laboratories.

The paper is organized as follows: Section II explains how to construct the approximated VT frequency response, in Section III the proposed measurement procedure and the measurement setup are presented. Finally, preliminary results are shown in Section IV.

II. Approximated VT Frequency Response

The approximated VT frequency response is constructed starting from three different curves: 1) the response measured at 50 Hz, 2) the low voltage response and 3) the tangent at the low voltage response. Three different frequency regions are defined and in each region a different curve is used to approximate the actual VT response.

The situation is depicted in Fig. 1, where the ratio errors versus frequency are shown.

In the first region, that is from 50 Hz up to the frequency f_{lim}, a flat frequency response can be assumed basing on the consideration that the frequency response of a VT, after the compensation of non-linearity error, is quite flat up to some hundreds of hertz [27]. Therefore, the ratio error is assumed constant, and equal to that measured at 50 Hz $\varepsilon_{50\,Hz}$, up to the limit frequency f_{lim}, as it specified in (1).

$$\varepsilon(f) = \varepsilon_{50\,Hz}\,, \qquad 50\,Hz < f < f_{lim} \tag{1}$$

The frequency $f = f_{lim}$ is defined as the intersection between the line $\varepsilon(f) = \varepsilon_{50\,Hz}$ and a straight line $\tau(f)$ with negative slope D_{lim}, which is tangent in f_{Dlim} to the ratio error curve $\varepsilon_{LV}(f)$, measured at low voltage. Therefore, the second region is identified from the frequencies f_{lim} and f_{Dlim} and the ratio error is assumed equal to $\tau(f)$, as specified in (2):

$$\begin{gathered} \varepsilon(f) = \tau(f), \qquad f_{lim} < f < f_{Dlim} \\ \tau(f) = D_{lim} \cdot (f - f_{Dlim}) + \varepsilon_{Dlim} \\ D_{lim} = \left.\frac{d\varepsilon_{LV}}{df}\right|_{f=f_{Dlim}} \end{gathered} \tag{2}$$

Since f_{lim} is the frequency where $\tau(f)$ is equal to $\varepsilon_{50\,Hz}$, it results the (3):

$$f_{lim} = f_{Dlim} + \frac{\varepsilon_{50\,Hz} - \varepsilon_{Dlim}}{D_{lim}} \tag{3}$$

The analysis of the frequency behavior of the derivative of the ratio error, *D*, allows to discriminate the frequency range where linear effects on the VT error frequency dependence are predominant on the non-linear ones. In details, the downhill of *D* (see Fig. 2) can be associated to the increasing weight of the stray capacitances among windings and ground (linear effects) on the frequency dependence of VT errors. According to this, for frequencies higher than f_{Dlim} the predominance of the linear effects allows to state that the VT error obtained at rated primary voltage and at low voltage are overlapped. According to experience gained in the experimental tests, the right value for D_{lim} can range between - 0.10 [0.01/Hz] and - 0.2 [0.01/Hz]. More information on the selection of the optimum D_{lim} and thus the frequency limit f_{Dlim} are provided in section IV.

The third region is defined for frequencies higher than f_{Dlim} and the ratio error $\varepsilon(f)$ is assumed equal to the ratio error $\varepsilon_{LV}(f)$ measured at low voltage, as in (4):

$$\varepsilon(f) = \varepsilon_{LV}(f)\,, \qquad f > f_{Dlim} \tag{4}$$

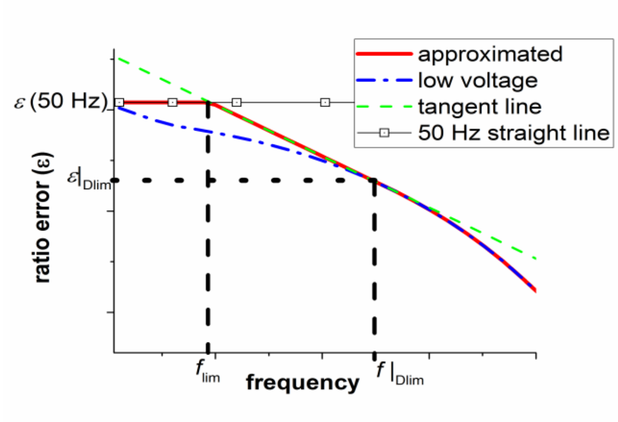


Fig. 1. Graphical description of the asymptotic fitting procedure for the identification of the VT frequency response

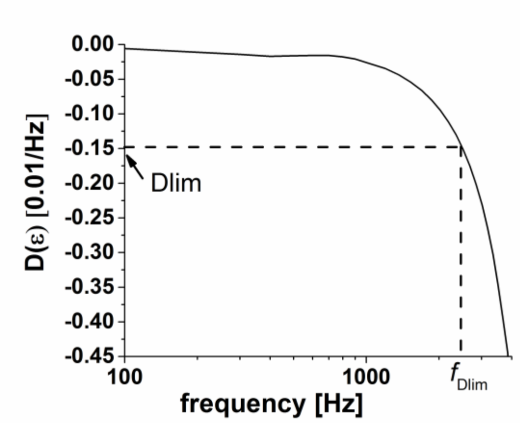


Fig. 2. Behavior of the frequency derivative of the VT ratio error. The point [f_{dlim}, D_{lim}] that identifies the limit beyond which the linear effects affecting the ratio error are predominand on the non-linear ones is provided.

It is worth to underline that the last equation applies up to the first resonance of the VT: in fact, the behavior of a VT in correspondence of a resonance and over, where very high slopes can be found, does not allow accurate measurements.

III. Characterization of VT

A. *Proposed measurement procedure*

From the Section II, it follows that for the construction of the approximated VT frequency response, the ratio error at power frequency and the ratio error at low voltage, from the second harmonics up to the first resonance, have to be measured. Therefore, here, a two-step measurement procedure is proposed for the characterization of the VT. Both are based on the use of a single tone signal for the primary voltage.

The first step is analogous to the approach presented in [27] and consists of a sinusoidal test performed at power frequency with the voltage amplitudes indicated by the standards [28]-[29], i.e. at various values from 80 % to 120 % of the rated voltage of the VT under test. The measurement is performed at zero and rated burden. In this test, the ratio and phase errors at power frequency, but also the first N_h harmonic phasors introduced by the VT at its output, because of its non-linear behaviour, are measured.

According to [27], a primary voltage phasor at each harmonic *h* can be expressed as:

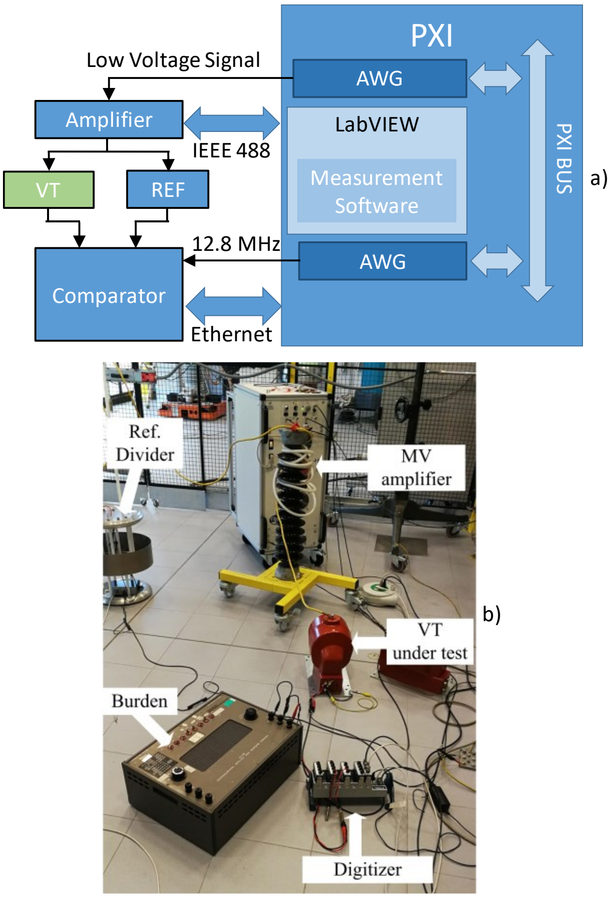


Fig. 3. Setup for the VT characterization: a) Block diagram, b) Experimental test bench at INRIM.

$$\bar{V}_{p,h}^{d} = \bar{V}_{s,h}^{d} + \dot{Z}^{*} \cdot \bar{I}_{m,h} = \bar{V}_{s,h}^{d} - \bar{V}_{s,h}^{sin} \quad (5)$$

where:

- the subscripts "p" and "s" stand for primary and secondary side respectively;
- $\dot{Z}^{*}$ and $\bar{I}_{m,h}$ are respectively the VT leakage series impedance and the *h*-harmonic component of the VT magnetization current;
- the superscript "*d*" and "*sin*" refer to tests performed under distorted and sinusoidal conditions.

The VT rated transformation ratio does not appear explicitly in (5) since all the secondary quantities are referred to the primary side. The secondary voltage harmonic components ($\bar{V}_{s,h}^{sin}$ amplitude and phase), measured under power frequency sinusoidal conditions, can then be used as a correction for the harmonic component ratio and phase error due to VT non-linearity when the VT operates under distorted conditions. By applying the compensation illustrated in (5), the non-linearity errors are strongly reduced and, therefore, the VT behavior can be considered linear.

Non-linearity effects are significant in a limited harmonic frequency range (e.g. up to the 10^{th}-15^{th} harmonic order). With the increase of the frequency, depending on the characteristics and rated primary voltage of the VT, the frequency behavior of the VT is dominated by the winding stray capacitances. The second step of the procedure then consists of a frequency sweep performed using a low voltage supply signal V_{low} (from some volt up to a few hundreds volt). For each test frequency, ratio and phase errors are evaluated according to:

$$\varepsilon_{h_{\%}} = \frac{k_r V_{s,h} - V_{p,h}}{V_{p,h}} \cdot 100 \quad (6)$$
$$\varphi_h = \varphi_{s,h} - \varphi_{p,h}$$

where:

- $k_r = {}^{V_{p,r}}/_{V_{s,r}}$ is the rated transformation ratio ($V_{p,r}$ and $V_{s,r}$ are the rated primary and secondary voltages);
- $V_{p,h}$ and $V_{s,h}$ are the root mean square (rms) values of the primary and secondary *h*-order harmonic voltage;
- $\varphi_{p,h}$ and $\varphi_{s,h}$ are phase angles of the primary and secondary *h*-order harmonic voltage.

B. Measurement setup

The setup used for VT characterization is shown Fig. 3: Fig. 3a shows the block diagram, whereas Fig. 3b shows a picture. The signal generation is obtained by means of an Arbitrary Waveform Generator (AWG), the NI PXI 5421, with 16 bit, variable output gain, ± 12 V output range, 200 MHz maximum sampling rate, 256 MB onboard memory. It is inserted in a PXI chassis, and the 10 MHz PXI clock is used as reference clock for its high resolution Phase Locked Loop circuitry. The generation frequency of the AWG is therefore chosen to be an integer multiple of the generated fundamental frequency. Another AWG is used to generate a 12.8 MHz clock, which is used as time base clock for the comparator. The voltage waveform generated by the AWG is amplified by a Trek high-voltage power amplifier (30 kVpeak, 20 mApeak) with wide bandwidth (from DC to 2.5 kHz at full voltage and 30 kHz at reduced voltages), high slew rate (<550 V/µs) and low noise. Applied voltage reference values are obtained by means of a 30 kV wideband reference divider designed, built and characterized at INRIM.

The acquisition system is obtained through NI cDAQ chassis with four different acquisition modules: NI 9225 (± 425 V, 24 bit, 50 kHz), NI 9227 (± 14 A, 24 bit, 50 kHz), NI 9239 (± 425 V, 24 bit, 50 kHz), NI 9238 (± 500 mV, 24 bit, 50 kHz). The sampling clock of the comparator is derived from the 12.8 MHz time base clock. In this way, generation and acquisition are precisely synchronized.

The VT primary and secondary voltage are acquired with a sampling frequency f_s=50 kHz, the time window chosen is 1 s and ten repetitions are executed for each test. The Discrete Fourier Transform (DFT) is performed on the acquired samples and the phasors of the voltages are measured.

IV. Results and Validation

As a first example of application, the described procedure is used to the estimate the frequency behavior of a VT for industrial application. The results obtained are validated by measurement performed on the same VT up to the first resonance frequencies by applying and measuring the response to distorted MV voltages ($FH1_{ref}$ procedure).

A. Device under test

The VT considered for this analysis is a commercial resin insulated VT for MV phase-to-ground measurement application. The VT main features are:

1) rated primary voltage 20/√3 kV,

2) rated secondary voltage 100/√3 V,

3) rated frequency 50 Hz,

4) rated burden 50 VA,

5) accuracy class 0.5.

B. Estimate of the VT frequency response

The measurement procedure step 1 is performed by applying the 80%, 100% and 120% of the rated primary voltage at power frequency. Ratio and phase error at 50Hz are evaluated and the harmonic phasors at the VT output are detected. The frequency behavior of the phasor magnitudes is provided in Fig 4. For step 2, two different low voltage values are experimented: 7 V and 40 V. A single tone frequency sweep is performed up to 10 kHz and, for each frequency involved in the test, the ratio error is evaluated. The results are shown in Fig. 5. The first resonance peak is found at about 6 kHz. The comparison between the behavior at the two supply voltage highlights a good superimposition at high frequency while, as can be seen in the inset zoom, a deviation of about 1 % is reached at 100 Hz. In particular, the ratio error for the 40 V curve tends to reach the value of the ratio error found at 50 Hz (i.e. 3.56 mV/V) with a rated sinusoidal voltage supply; the 7 V curve shows a lower value of about 1% also at 50 Hz. This behavior can be explained by the very low excitation of the iron-core reached with a supply of only 7 V.

C. FH1 test result (reference test)

The frequency response of the VT at MV is measured by comparison with the INRIM reference measurement system above described. The applied waveform is composed of a fundamental and a harmonic component. In particular, the fundamental tone has frequency of 50 Hz and amplitude of 80%, 100% and 120 % of the rated value. The harmonic tone has fixed amplitude of 1 % of fundamental tone, variable order, from 2nd to 200th, and variable phase angle, from -π to π rad. The measurements were performed with zero burden. The ratio error frequency behavior obtained by following this procedure is presented in Fig. 6a. The error bars represent the ratio error variability due to the harmonic phase angle variability. In detail, this relation is shown in Fig. 6b where the behavior of the ratio error associated with the applied third harmonic, as a function of its phase deviation with respect to the fundamental tone, is provided.

D. Composed ratio error frequency behavior

Assuming the ratio error frequency behavior of the VT that one obtained by applying a single tone frequency sweep at 40 V, the systematic error made is summarized in Table I.

TABLE I. RATIO ERROR DEVIATION BETWEEN LOW VOLTAGE AND FH1 TEST

Frequency (Hz)	Ratio error difference [%]
350	0.671
1000	0.964
2500	0.666
6000	-0.941
10000	-2.36

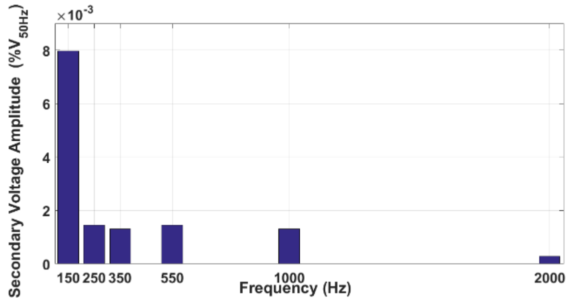


Fig. 4. Frequency behavior of the phasor magnitude detected at the output of the VT when a pure sinusoidal waveform of 120% of the rated voltage is applied to the input

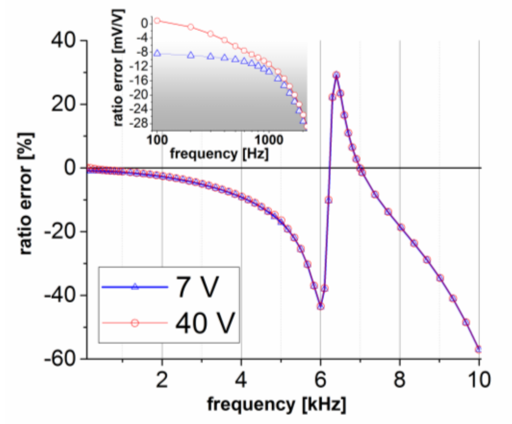
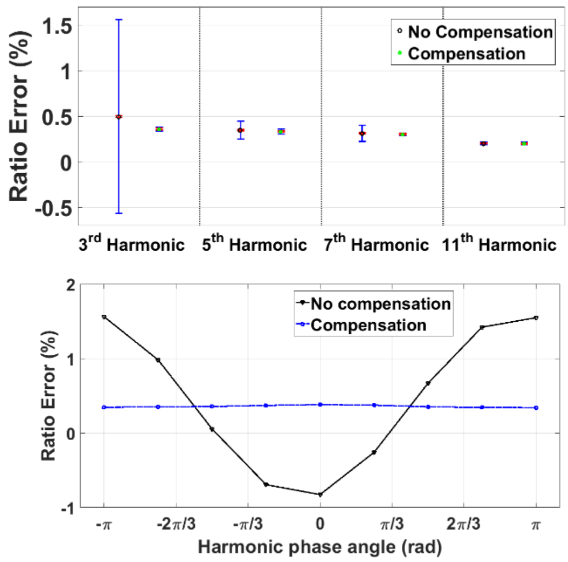


Fig. 5. Comparison between the single tone frequency sweeps obtained applying 7V and 40 V to the input of the DUT



a)

b)

Fig. 6. a). Ratio error frequency behavior obtained with the FH1 test without and with the compensation method SINDICOMP. b) Ratio error associated with the applied third harmonic versus its phase displacement.

To reduce these errors, the approximated ratio error behavior related to a VT working under likely distorted conditions is the result of the proposed fit strategy. In detail, at low frequency, since the actual frequency behavior obtained by the FH1 test, at 120 % of the rated voltage, is quite flat up to hundreds of hertz (see Fig. 7), the approximated ratio error is assumed constant and equal to 0.36 % up to 900 Hz. This value is obtained by the simple test

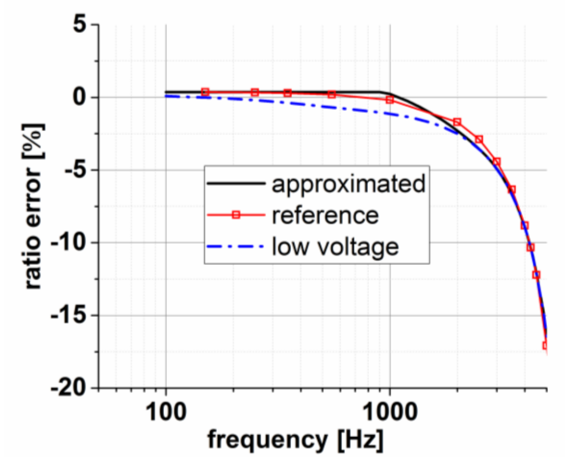


Fig. 7. Comparison among the single tone frequency sweep at 40 V, the VT behavior under the FH1 test (reference test) and the proposed asymptotic behavior

at 50 Hz. In this range, the behavior recorded with the 40 V frequency sweep diverges from the reference behavior. For frequencies higher than 900 Hz and lower than 2524 Hz, the ratio error follows the connecting straight line as described in (3). For frequencies higher than 2524 Hz, the VT ratio error coincides with that measured at 40 V.

The proposed approach then reduces the systematic errors. At 1 kHz, the difference between the approximated ratio error estimation and the reference value reduces from about 1 % (obtained with the 40 V test) to 0.4 %.

V. Conclusions

A simplified "low cost" procedure for the evaluation of the frequency response of VTs has been introduced. According to the adopted method, the non-linear effect due to the VT magnetic core is estimated by applying a 50 Hz sinusoidal signal at the rated voltage. In this way, the non-negligible errors, up to some percent for the third harmonic, which can occur as a function of the harmonic phase value, can be compensated. The VT frequency behavior is then obtained by compensating the non-linearity errors at the lower harmonics and using a suitable piecewise curve at the higher frequencies. The experimental tests can be easily carried out by making use of generation and measurement setups already available in industrial laboratories equipped with VT calibration facilities at power frequency. Moreover, such an approach can be in principle applied to the characterization of both MV and HV VTs.

A comparison between the approximated frequency curve and the one obtained by reference methods provides a maximum deviation of 0.4% at 1 kHz. This accurate and detailed characterization can represent the first step in the implementation of an electronic device that upgrades the performance of the traditional voltage instrument transformers, making them suitable for the measuring and monitoring of the frequency distortion of power voltage in distribution and trasmission grids. In order to make easy the proposed characterization technique utilization, future works will involve the study of the proposed method to different sizes of VTs for MV applications, in order to associate to each VT size the best D_{lim} value. Further studies about the accuracy of the presented method, as function of the fundamental amplitude and the harmonic distortion are still in progress.

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References

[1] F. C. De La Rosa "Harmonics, Power Systems, and Smart Grids" CRC Press, Taylor & Francis Group, 2015.

[2] S. Elphick, V. Gosbell, V. Smith, S. Perera, P. Ciufo, G. Drury, "Methods for Harmonic Analysis and Reporting in Future Grid Applications", (2017) IEEE Trans. Power Del., 32 (2), pp. 989-995.

[3] A. Kalair, N. Abas, A. R. Kalair, Z. Saleem, N. Khan, "Review of harmonic analysis, modeling and mitigation techniques", Renewable and Sustainable Energy Reviews, vol. 78, pp. 1152-1187, Oct. 2017.

[4] Dolce, S., Fiorucci, E., Bucci, G., D'Innocenzo, F., Ciancetta, F., Di Pasquale, A., "Test instrument for the automatic compliance check of cast resin insulated windings for power transformers", (2017) Measurement: Journal of the International Measurement Confederation, 100, pp. 50-61.

[5] Fiorucci, E., The measurement of actual apparent power and actual reactive power from the instantaneous power signals in single-phase and three-phase systems (2015) Electric Power Systems Research, 121, pp. 227-242.

[6] G. Artale *et al.*, "PQ Metrics Implementation on Low Cost Smart Metering Platforms. A Case Study Analysis," *2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS)*, Bologna, 2018, pp. 1-6.

[7] G. Artale, A. Cataliotti, V. C. S. Nuccio, D. Di Cara, G. Tinè and G. Privitera, "A set of indicators for arc faults detection based on low frequency harmonic analysis," 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, Taipei, 2016, pp. 1-6.

[8] A. Cataliotti, V. Cosentino, S. Guaiana, D. Di Cara, N. Panzavecchia and G. Tinè, "Experimental investigation on PLC signal crossing of power transformers," *2014 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) Proceedings*, Montevideo, 2014, pp. 1235-1239.

[9] G. Crotti et al., "Pantograph-to-OHL Arc: Conducted Effects in DC Railway Supply System," 2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS), Bologna, 2018, pp. 1-6. doi: 10.1109/AMPS.2018.8494897

[10] G. Artale, A. Cataliotti, V. Cosentino, D. Di Cara, R. Fiorelli, S. Guaiana, N. Panzavecchia, G. Tinè, "A new PLC-based smart metering architecture for medium/low voltage grids: Feasibility and experimental characterization", Measurement: Journal of the International Measurement Confederation, vol. 129, 2018, pp. 479-488.

[11] S. Rinaldi *et al.*, "Characterization of IP-Based Communication for Smart Grid Using Software-Defined Networking," in *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 10, pp. 2410-2419, Oct. 2018.

[12] Del Prete, S., Delle Femine, A., Gallo, D., Landi, C., Luiso, M., "Implementation of a distributed Stand Alone Merging Unit", (2018) Journal of Physics: Conference Series, 1065 (5), DOI: 10.1088/1742-6596/1065/5/052042

[13] G. Artale *et al.*, "A new low cost power line communication solution for smart grid monitoring and management," in *IEEE Instrumentation & Measurement Magazine*, vol. 21, no. 2, pp. 29-33, April 2018.

[14] Delle Femine, A., Gallo, D., Giordano, D., Landi, C., Luiso, M., Signorino, D., "Synchronized Measurement System for Railway Application", (2018) Journal of Physics: Conference Series, 1065 (5), DOI: 10.1088/1742-6596/1065/5/052040

[15] A. Cataliotti, D. Di Cara, A. E. Emanuel, S. Nuccio, "Improvement of Hall Effect Current Transducer Metrological Performances in the Presence of Harmonic Distortion," IEEE Trans. on Instrumentation and Measurement, vol. 59, no. 5, May 2010, pp. 1091-97.

[16] E. Mohns, G. Roeissle, S. Fricke and F. Pauling, "An AC Current Transformer Standard Measuring System for Power Frequencies," in

IEEE Transactions on Instrumentation and Measurement, vol. 66, no. 6, pp. 1433-1440, June 2017.

[17] R. Stiegler, J. Meyer, J. Kilter and S. Konzelmann, "Assessment of voltage instrument transformers accuracy for harmonic measurements in transmission systems," 2016 17th International Conference on Harmonics and Quality of Power (ICHQP), Belo Horizonte, 2016, pp. 152-157.

[18] A. Cataliotti, V. Cosentino, D. Di Cara, S. Nuccio, G. Tinè, "Rogowski coil current transducer compensation method for harmonic active power error", Measurement, vol. 63, Mar. 2015, pp. 240-251.

[19] G. Crotti, D. Giordano, A. Delle Femine, D. Gallo, C. Landi and M. Luiso, "A Testbed for Static and Dynamic Characterization of DC Voltage and Current Transducers," 2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS), Bologna, 2018, pp. 1-6. doi: 10.1109/AMPS.2018.8494873

[20] G. Crotti, A. D. Femine, D. Gallo, D. Giordano, C. Landi and M. Luiso, "Measurement of the Absolute Phase Error of Digitizers," in IEEE Transactions on Instrumentation and Measurement. doi: 10.1109/TIM.2018.2888919

[21] A. J. Collin, A. Delle Femine, D. Gallo, R. Langella and M. Luiso, "Compensation of Current Transformers' Non-Linearities by Means of Frequency Coupling Matrices," 2018 IEEE 9th International Workshop on Applied Measurements for Power Systems (AMPS), Bologna, 2018, pp. 1-6. doi: 10.1109/AMPS.2018.8494893

[22] Crotti, G., Delle Femine, A., Gallo, D., Giordano, D., Landi, C., Letizia, P.S., Luiso, M., "Calibration of Current Transformers in distorted conditions", (2018) Journal of Physics: Conference Series, 1065 (5), DOI: 10.1088/1742-6596/1065/5/052033

[23] G. Crotti, D. Gallo, D. Giordano, C. Landi, M. Luiso and M. Modarres, "Frequency Response of MV Voltage Transformer Under Actual Waveforms," in IEEE Transactions on Instrumentation and Measurement, vol. 66, no. 6, pp. 1146-1154, June 2017

[24] G. Crotti; D. Gallo; D. Giordano; C. Landi; M. Luiso; M. Modarres; M. Zucca, "Frequency Compliance of MV Voltage Sensors for Smart Grid Application," IEEE Sensors Journal, vol. 17, no. 23, pp. 7621-7629, Dec.1, 1 2017

[25] M. Faifer, C. Laurano, R. Ottoboni, S. Toscani, M. Zanoni, "Characterization of Voltage Instrument Transformers Under Nonsinusoidal Conditions Based on the Best Linear Approximation", in IEEE Transactions on Instrumentation and Measurement. doi: 10.1109/TIM.2018.2806949.

[26] M. Faifer; R. Ottoboni; S. Toscani, C. Cherbaucich; P. Mazza "Metrological Characterization of a Signal Generator for the Testing of Medium-Voltage Measurement Transducers", IEEE Trans. Instrum. Measur., Vol. 64, no: 7, July 2015, pp. 1837-1846

[27] A. Cataliotti et al., "Compensation of Nonlinearity of Voltage and Current Instrument Transformers," in IEEE Transactions on Instrumentation and Measurement.

[28] Instrument transformers - Part 2: Additional requirements for current transformers. IEC 61869-2 (2013)

[29] Instrument transformers - Part 2: Additional Requirements for Inductive Voltage Transformers. IEC 61869-3 (2012)