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Towards a Novel Approach to the On-Line Diagnosis of the Instrument Transformer

Ting Lei, Marco Faifer, Roberto Ottoboni, Sergio Toscani

DEIB, Politecnico di Milano
Piazza Leonardo da Vinci 32 – 20133 Milano ITALY

Abstract — The conventional instrument transformers (CITs) are still widely used in the power network, thanks to their high reliability, insulation capability and low drift over time and temperature. Their traditional reliability is very often used as justification for skipping a periodical calibration, which requires putting off-line the CIT, thus implying a very complex and expensive procedure. For this reason, in the last years, a growing interest has been addressed towards the diagnostic/calibration methods based on on-line procedure. The typical approach is based on the frequency response analysis that permits, under sinusoidal conditions, to detect possible deterioration of the behavior of CIT. Anyway, the real interest is to check the CIT fleet already installed and operating on the grid without requiring the disconnection from the grid. As well known the actual voltage of the grid features a not negligible harmonic distortion that combined with the intrinsically non-linearity of the CTI reduces the feasibility of the on-line diagnostic methods based on the frequency response method. This paper proposed a novel approach to the on-line diagnosis of CIT based on a non-linear simplified Volterra model of the CIT. This opens the way to a different approach to the in-site characterization process of a CIT based on the actual voltage of the grid and thus not requiring the disconnection of the CIT from the grid.

Keywords—*voltage transformer, Volterra model, harmonic monitoring.*

I. INTRODUCTION

Nowadays, along with the concept of the sustainable development, many renewable power generators, such as solar panels and wind turbines, are connected to the power grid by means of electronic converters. The same kind of interface is used for connecting modern electrical loads. Since these generators and converters are usually nonlinear devices, the harmonic distortion is increasing on the grid. The presence of the harmonics may be responsible for the increase of energy losses, overheating in power transformers and malfunction of electronic switches. Consequently, the transducers used in the grid have to guarantee a proper measurement accuracy not only at the main frequency but also over a suitable bandwidth of frequencies in order to allow a proper monitoring of the phenomena.

Another mandatory prerequisite of the transducers is a high reliability and negligible drift over time of their measurement accuracy. Any replacement and/or off-line calibration of this kind of devices implies a probable interruption of the grid service and hence it has a great economic impact.

Despite the incoming availability of a new generation of non-conventional instrument transformers (NCITs), based on electronics and/or optical technologies, the CIT, based on the electromagnetic principle, is still the most widely used device for current and voltage measurement in the medium and high voltage systems. In terms of overall evaluation, their robustness, passive working principle and long-term stability are features very often preferred to wider bandwidth, higher linearity and smaller size of NCITs.

As a consequence, the CITs are also used for harmonic monitoring purpose. In order to guarantee proper performances, it is necessary to characterize their accuracy in the frequency band of interest. The classic approach is to evaluate the ratio and the phase error versus frequency, adopting the tradition method of the sinusoidal frequency sweeping. In the last years, many researches have been addressed to exploit the knowledge of CIT's frequency response for improving their performances. In particular, the target was to extend and improve the bandwidth of the device with real-time frequency compensation techniques [1],[2],[3],[4], and, more interesting, to support self-diagnosis techniques for detecting a drift in the accuracy characteristic of the device [5].

Despite of their conceptual interest, both cases have a clear limit in the practical application. In fact, they suppose that the CIT is a linear device so that it can be completely identified by a frequency response function. However, CIT is an intrinsically nonlinear device. Besides this, it usually does not operate with a pure sinusoidal input but rather with a polluted signal. In real working conditions, the intermodulation products between the harmonics have a relevant impact on the amplitude and phase of some harmonics [6]. Hence, it is clear that this kind of diagnostic methods cannot be operated without putting off-line the transformer and supplying its primary with a pure sinusoidal signal, thus heavily limiting their interest.

In this paper, a new approach to the on-line diagnosis of the CTI is proposed. The main idea is to check the drift of the CTI's characteristics not in terms of frequency response (FR) but as the variations with respect to a reference nonlinear model. In particular, it is possible to define preliminarily a non-linear model, based on the Volterra's series approach, which permits to take into account the nonlinearity of the transformer and hence to predict, with a good accuracy, its output voltage for a large class of input signals. In particular, this is always valid when the input signals are those present in the grid. Once defined the parameters of the model with a first calibration of the transformer, any variation between the real output signal and that predicted by the model is an index of the drift in the device characteristics.

As well-known, the main limit of the Volterra series approach is the huge number of coefficients required when the kernel order increases. Thanks to a previous research, the authors have developed a simplified Volterra series model [7]. The Volterra theory and the simplified model are described in section II and III. In section IV, the proposed model has been validated by experimental tests. A preliminary investigation of possible diagnostic application of this model for CTIs is presented in section V.

II. THE VOLTERRA MODEL

Volterra series is one of the most widely used methods for representing nonlinear systems. For a single-input, single-output (SISO), time-invariant and homogeneous system, the input/output representation based on the Volterra series is given by the equation (1) [8].

$$\begin{cases} y(t) = \sum_{i=1}^{\infty} y_i(t) \\ y_i(t) = \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} h_i(\tau_1, \tau_2, \ldots, \tau_i) \prod_{l=1}^{i} u(t-\tau_l) d\tau_1 \ldots d\tau_i \end{cases} \quad (1)$$

where $u(t)$ is the input signal, $y(t)$ the output, $y_i(t)$ the contribution to the output of the i-th order homogeneous subsystem characterized by its kernel h_i which is the generalization of the impulse response of a linear system.

Equation (1) cannot be employed in actual applications since it is continuous time, other having an infinite number of kernels and unlimited memory length. Therefore, from a practical point of view, a more significant representation of a nonlinear system is the truncated discrete Volterra series:

$$\begin{cases} y(n) = \sum_{i=1}^{I} y_i(n) \\ y_i(n) = \sum_{k_1=1}^{K-1} \cdots \sum_{k_i=1}^{K-1} h_i(k_1, \ldots, k_i) \prod_{l=1}^{i} u(n-k_l) \end{cases} \quad (2)$$

where I is the order and K is the memory length. It can be shown that the truncated Volterra model is characterized by a number of independent coefficients c_{ind} which rapidly grows with I and K [9]:

$$c_{ind} = \sum_{i=1}^{I} \frac{(K+i-1)!}{(K-1)!\,i!} \quad (3)$$

Now, let us suppose that the input signal is periodic, characterized by the fundamental angular frequency ω_0 and containing a set of harmonic components, being N the highest order. In this case the model can be noticeably simplified by moving into the frequency domain. Let us call $U(jm\omega_0)=U(m)$ and $Y(jm\omega_0)=Y(m)$ the spectra of the input and output respectively. The frequency domain expression of (2) becomes:

$$\begin{cases} Y(m) = \sum_{i=1}^{I} Y_i(m) \\ Y_i(m) = \sum_{-N \le m_1, \ldots, m_i \le N} H_i(m_1, \ldots, m_i) \prod_{l=1}^{i} U(m_l) \end{cases} \quad (4)$$

Where:

$$\sum_{l=1}^{i} m_l = m \quad (5)$$

(4) represents the relationship between the harmonic components of the input and output signals. The total number of independent coefficients now results:

$$c'_{ind} = \sum_{i=1}^{I} \frac{(M+i-1)!}{(M-1)!\,i!} \qquad (6)$$

Basically, it is the same as (3) where K is replaced by M=2N+1; since usually M is considerably lower than the memory length K, the frequency domain representation allows to considerably simplify the model. However, the number of coefficients still rapidly grows with I, therefore in most cases low nonlinearity orders are considered for practical applications.

III. THE SIMPLIFIED VOLTERRA MODEL

As previously discussed, in order to test the instrument transformers under the real working condition, the test voltage has to resemble those really present in the grid. In particular, the standard EN 50160 [10] defines the limits, in terms of harmonics amplitude and phase, of this signal, as indicated in Table 1.

Table 1: harmonics voltage limits according to EN 50160.

Odd harmonics				**Even harmonics**	
Not multiples of 3		***Multiples of 3***			
Order	***Relative amplitude***	***Order***	***Relative amplitude***	***Order***	***Relative Amplitude***
5	6.0%	3	5.0%	2	2.0%
7	5.0%	9	1.5%	4	1.0%
11	3.5%	15	0.5%	6…24	0.5%
13	3.0%	21	0.5%		
17	2.0%				
19	1.5%				
23	1.5%				
25	1.5%				

Now, let us investigate the application of the frequency-domain Volterra approach to instrument transformers. According to (4), the m-th harmonic component of the output is the contributions of I nonlinear homogeneous subsystems. For each order i, the subsystem contributions are calculated by combining all possible i-th order intermodulation products between the input harmonic components, weighted by the corresponding coefficient of the i-th order GFRF. If the test signal follows the restriction of Table 1, the amplitude of the largest harmonic component is only 6% of the fundamental frequency. For this reason, the contributions to the output of the intermodulation products which contain more than one harmonic component are quite small. In other words, for each order i the model can be considerably simplified by considering only the intermodulation products consisting of the fundament frequency component or at most one harmonic component, namely those which can be written in the form:

$$U(1)^{i_p}\, U(-1)^{i-i_p-1}\, U(n) \qquad (7)$$

This allows to obtain a simplified Volterra model, so that higher orders can be employed without having to estimate a huge number of coefficients during its identification. In fact, the maximum number of coefficients now reduces to:

$$c''_{max} = M\,\frac{I(I+1)}{2} = ML \qquad (8)$$

Furthermore, not all of them are independent: the number of coefficients to be identified is actually lower than c''_{max}. However, even neglecting this, it is clear that (8) is much smaller than (6), thus the hypothesis about the input signal allows a drastic simplification of the model. Comparing (8) with (7), it can be immediately concluded that, under well-defined assumptions, a drastic reduction in the number of coefficients can be achieved. The fifth order simplified model employed in this paper has been presented and deeply discussed in [7]; obviously only the independent coefficients have been considered in the model.

For each spectral component, the input-output relation of the simplified model can be written as:

$$Y(m) = \mathbf{U}^{red}(m)\mathbf{H}^{red}(m) \qquad (9)$$

$\mathbf{U}^{red}(m)$ and $\mathbf{H}^{red}(m)$ are vectors having no more than L elements. Now, the target is to identify the model: it corresponds to compute $\mathbf{H}^{red}(m)$ for the considered spectral components. This can be performed by applying a set of $R \geq L$ independent input signals to the system to be identified and measuring the responses. Then, it is possible to write:

$$\mathbf{U}_{id}^{red}(m) = \begin{bmatrix} \mathbf{U}_1^{red}(m) \\ \mathbf{U}_2^{red}(m) \\ \vdots \\ \mathbf{U}_R^{red}(m) \end{bmatrix} \qquad \mathbf{Y}_{id} = \begin{bmatrix} Y_1(m) \\ Y_2(m) \\ \vdots \\ Y_R(m) \end{bmatrix} \qquad (10)$$

Having employed a proper set of identification signals, the matrixes $\mathbf{U}_{id}{}^{red}(m)$ are full rank. The model coefficients can be estimated using the least squares approach.

IV. EXPERIMENTAL VALIDATION OF THE PROPOSED MODEL

The model discussed in the previous section has been validated by experimental tests. The setup is based on an arbitrary low voltage generator, similar to that described in [3], [11], able to generate the proper voltage signals required by the testing of the voltage transformer (VT) under test (TUT). The voltage signals of the primary and the secondary windings of the TUT are collected by two high-accuracy, wide bandwidth voltage transducers. The TUT is an voltage transformer having 0.5 accuracy class and its voltage ratio is 200V/100V. The basic structure of the experiment system is shown in Fig 1.

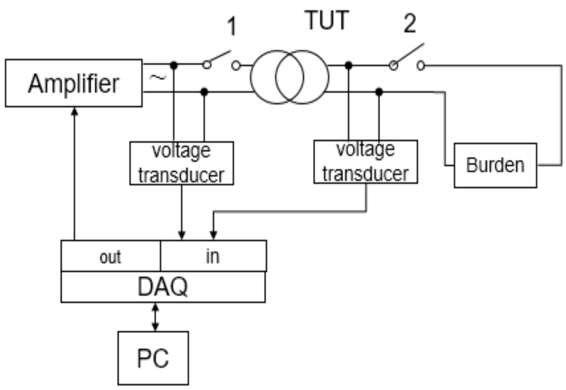

Fig. 1. *Experimental setup*

Estimated the coefficient of the model as described in the previous section, some tests have been carried out in order to verify the reliability of the model for different input signals. The validation process consisted of three different tests, each of them repeated 140 times, and based on the input signals described in Table 2. In Test 1, harmonics have the same amplitude but a different phase of those of the signal adopted in the identification process. In Test 2, the input signal is still composed of four harmonics, but their amplitudes are increased with respect to that of Test 1. Finally, in Test 3, an input signal having all the possible harmonic components provided by EN 50160 is used.

Table 2: Specifications of three tests.

	Input signal(2nd - 5th harmonic)		
	Amplitude (percentage of fundamental component)	Phase	Number of tests
Test 1	2nd:1%, 3rd:5%, 4th:1%, 5th:5%	Random	140
Test 2	2nd:2%, 3rd:7%, 4th:2%, 5th:8%	Random	140
Test 3	Random (under the limits of table 1)	Random	140

In order to evaluate the difference between the physical output of the VTI and that of the model, several indexes have been evaluated, namely the amplitude error (AE), the phase error (PE), and the total vector error (TVE).

$$
\begin{aligned}
AE &= \frac{\left|Y_{MO}(m)\right| - \left|Y_{AO}(m)\right|}{\left|Y_{AO}(m)\right|} \times 100 \\
PE &= \angle Y_{MO}(m) - \angle Y_{AO}(m) \\
TVE &= \left| \frac{Y_{MO}(m) - Y_{AO}(m)}{Y_{AO}(m)} \right| \times 100
\end{aligned}
\tag{12}
$$

where Y(m) represents the *m-th* component of the Fourier transform. The label *MO* and *AO* represent the model output and the actual output, respectively.

The results are reported in Table 3, 4 and 5, which show, for every index, both the mean value and the expanded uncertainty, U, evaluated with a level of confidence of 95%.

Table 3: Experiment result of Test 1.

TEST1	AE(%)		PE(°)		TVE(%)	
	Mean	U	Mean	U	Mean	U
50Hz	1×10^{-3}	1.5×10^{-2}	4×10^{-3}	2.1×10^{-2}	1×10^{-2}	1×10^{-2}
100Hz	1×10^{-2}	1.8×10^{-1}	6×10^{-3}	1.3×10^{-1}	6×10^{-2}	1.4×10^{-1}
150Hz	1.4×10^{-2}	7.2×10^{-2}	-1.4×10^{-3}	9.4×10^{-2}	8.2×10^{-2}	6.7×10^{-2}
200Hz	1.5×10^{-2}	6.6×10^{-2}	2×10^{-3}	1.8×10^{-1}	6.7×10^{-1}	1.9×10^{-1}
250Hz	4.3×10^{-2}	3.5×10^{-2}	2×10^{-3}	1.5×10^{-1}	1.3×10^{-2}	1.1×10^{-1}

Table 4: Experiment result of Test 2.

TEST2	AE(%)		PE(°)		TVE(%)	
	Mean	U	Mean	U	Mean	U
50Hz	1.6×10^{-2}	1.6×10^{-2}	-5.6×10^{-5}	5.8×10^{-3}	1.7×10^{-2}	1.5×10^{-2}
100Hz	9×10^{-3}	8.9×10^{-2}	-1.4×10^{-3}	5.2×10^{-2}	5.8×10^{-2}	5.4×10^{-2}
150Hz	1.8×10^{-2}	7.1×10^{-2}	-3.3×10^{-4}	4.7×10^{-2}	5.3×10^{-2}	4.3×10^{-2}
200Hz	1.6×10^{-2}	4.8×10^{-2}	2×10^{-3}	3.4×10^{-2}	3.5×10^{-2}	4.2×10^{-2}
250Hz	1.6×10^{-2}	2.8×10^{-2}	2×10^{-4}	3.4×10^{-2}	2.7×10^{-2}	4.9×10^{-2}

Table 5: Experiment result of Test 3.

TEST3	AE(%)		PE(°)		TVE(%)	
	Mean	U	Mean	U	Mean	U
50Hz	2.5×10^{-2}	1.2×10^{-2}	-1.1×10^{-5}	5.2×10^{-3}	2.5×10^{-2}	1.2×10^{-2}
100Hz	1.6×10^{-2}	2.4×10^{-1}	2.2×10^{-3}	1.2×10^{-1}	1.3×10^{-1}	1.8×10^{-1}
150Hz	2.1×10^{-2}	1.2×10^{-1}	-2×10^{-3}	6.1×10^{-2}	6.8×10^{-2}	8.8×10^{-2}
200Hz	2.3×10^{-2}	1.1×10^{-1}	2×10^{-4}	7.5×10^{-2}	7.5×10^{-2}	9.6×10^{-2}
250Hz	2.5×10^{-2}	3.7×10^{-2}	3×10^{-3}	2.8×10^{-2}	3.5×10^{-2}	4.0×10^{-2}

For all indexes, the measurement uncertainty is on the same order of magnitude or higher than the mean value. Anyway, these values are always well below the measurement error permitted by the accuracy class of the voltage transformer. These results demonstrate that the proposed model fits the transformer behavior very well. In particular, even in test 3, where the effect of the transformer nonlinearity is emphasized, the difference between model and physical device is still hold down. For the sake of completeness, based on the same data of test 3, the FR (namely, the linear model) has been used to estimate the transformer output. Table 6 reports the comparison between the results obtained in this case and those given by the proposed nonlinear model.

Table 6: comparison between the model and the FR.

TEST3	AE(%)		PE(°)		TVE(%)	
	Model	FR	Model	FR	Model	FR
50Hz	2.5×10^{-2}	2.5×10^{-2}	-1×10^{-5}	-3.4×10^{-4}	2.5×10^{-2}	2.5×10^{-2}
100Hz	1.6×10^{-2}	1.1×10^{-1}	2×10^{-3}	-1.2×10^{-1}	1.3E-01	1.2
150Hz	2×10^{-2}	6.80	-2.2×10^{-3}	1.74	6.8×10^{-2}	1.2×10^{-1}
200Hz	2.3×10^{-2}	2.0×10^{-2}	1.6×10^{-4}	-3.1×10^{-3}	7.6×10^{-2}	6.7×10^{-1}
250Hz	2.5×10^{-2}	9.2×10^{-2}	2.9×10^{-3}	1.7×10^{-2}	3.5×10^{-2}	9.8×10^{-1}

As clearly pointed out, the linear model heavily fails at 150 Hz, where the effects of the intermodulation products between the harmonics are not negligible. This effect is well represented by the proposed nonlinear model.

As a consequence, it is demonstrated that the implemented Volterra model can be assumed as a benchmark for possible in-situ diagnostic procedures. In fact, once the input signal is known, any significant difference between the output signal of the CIT and that given by the model is an index of a possible change in the device behavior.

V. FAULT DIAGNOSTIC APPLICATION

In this section, a preliminary investigation about the possibility of using the proposed model for the transformer fault diagnostic purpose has been discussed. The sketch in Fig.2 illustrates the transformer used for the tests, which has a resistor connected to two taps of the secondary winding. This permits to emulate an inter-turn fault, in which the isolation between turn to turn has reduced. In fact, by changing the value of the resistance, it is possible to change the fault severity [5].

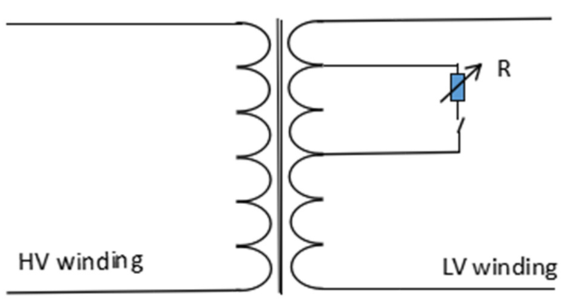

Fig. 2. *Schematic diagram of a transformer which has a variable resistor connected to its secondary.*

The primary of the transformer has been fed with the signal already used in Test 3 and two values of resistance *R* have been connected (1 Ω and 2 Ω).

In Table 7 the evaluation of the TVE by using the FR approach is reported.

Table 7: the TVE under different resistance conditions evaluated by the FR approach.

	NR		2 Ω		1 Ω	
	Mean	U	Mean	U	Mean	U
50 Hz	4.9×10^{-2}	2×10^{-3}	3.5×10^{-1}	3×10^{-2}	1.3×10^{-1}	4.1×10^{-3}
100 Hz	3.4	2.7	3.5	2.7	3.5	2.7
150 Hz	1.9	1.4	2.0	1.4	2.0	1.4
200 Hz	1.0	8.0×10^{-1}	1.1	8×10^{-1}	1.1	8×10^{-1}
250 Hz	5.0×10^{-1}	3.5×10^{-1}	6.5×10^{-1}	3.8×10^{-1}	5.9×10^{-1}	3.6×10^{-1}

Fig. 3 shows the TVE variations in each condition with respect to the no resistance (NR) condition. It can be noticed that it is possible to detect a variation of resistance just at the main frequency. In fact, the uncertainties of the TVE, reported in Table 7, are much higher of the required sensitivity.

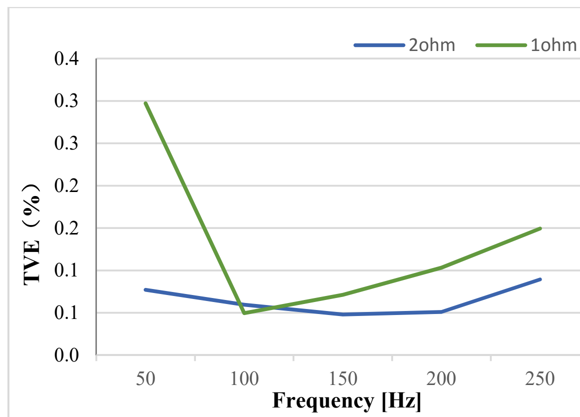

Fig. 3. *Total vector error differences of each condition considering NR as a reference (FR case).*

The Fig. 4 depicts the TVE evaluated under the same conditions of Fig. 3, but using the proposed non-linear model. The error bars in the plot represent the expanded standard deviations in the TVE evaluation at a given frequency. As clearly pointed out by the plot, not only the error at the second harmonic is correctly evaluated, but also the three different conditions are well identified, especially at 50Hz and 250Hz. Moreover, the severity of the fault can be easily correlated to the TVE value.

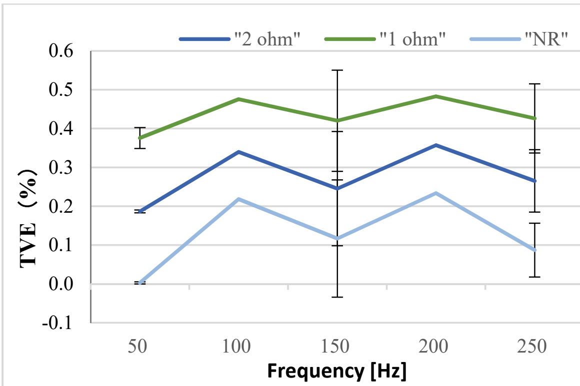

Fig. 4. *Total vector errors estimated by the proposed non-linear approach for different emulated fault conditions.*

VI. CONCLUSION

In this paper, a simplified Volterra model of VT is used in order to represent its nonlinearities. It has been demonstrated that this model accurately represents the VT in real working conditions. The model can be used as a benchmark in order to check the efficiency status of the device, with an in-site procedure. The tests presented in this paper show that this approach features sensitivity higher than that obtained by using the common frequency response analysis in detecting inter-turn faults. The preliminary results are very promising and open the way to the on-line monitoring of all kinds of measurement transformers (including current ones).

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