Modeling of a Capacitive Voltage Transformer for Evaluation of Transient Response in Conformity with the IEC 61869-5 Standard

Felipe Luis Probst, Mauricio Valencia Ferreira da Luz, Stefan Tenbohlen

***Abstract* -- This paper presents the implementation of a nonlinear model of a Capacitive Voltage Transformer (CVT) to evaluate the transient response in conformity with the international standard IEC 61869-5. The work is divided into three main steps: electrical tests to measure the CVT parameters and frequency response; implementation of linear mathematical modeling and an optimization algorithm to estimate unmeasured parameters; and implementation of nonlinear modeling in a simulation program for electromagnetic transients. First, the requirements of the IEC standard about the transient response of CVT are presented. Then, some important aspects of CVT modeling are discussed. Afterward, a linear model of a CVT is used to estimate the parameter not measured in the laboratory. Then, a nonlinear model is implemented in ATP. The model is validated in the time domain by comparing the simulation results with some signals measured in the laboratory. Finally, simulations of the transient response tests are made following the IEC 61869-5. The results show that the model developed in this work is reliable and can be used for the simulation of ferroresonance and transient response tests following the IEC 61869-5 when no laboratory structure is available.**

***Keywords*: Capacitive Voltage Transformer, EMTP Simulation, Frequency Response, IEC 61869-5, Transient Regime Modeling.**

I. Introduction

The Capacitive Voltage Transformer (CVT) has the task of reducing high voltages to a level suitable for protective relays and measuring systems. It must be designed to operate both in a steady state and during transient events, which can be caused by lightning discharges, short circuits, and switching operations, among others [1]. Thus, international standards specify some design requirements as well as test procedures to certify the proper operation of the equipment.

Ferroresonance and transient response tests are two relevant tests for assessing the behavior of the equipment in electromagnetic transients [2]. Over the years, many papers have been written on modeling CVTs. Most of these papers attempt to determine an equivalent circuit that can be used to model a CVT [3]-[12]. Others present sensitivity studies for device parameters [11]-[14], that is, how changing the values of certain parameters, such as capacitances or inductances, affects the simulation results.

Power generation and transmission companies have old CVTs that have not been tested and certified by the IEC 61869-5 standard [2]. In case of equipment failure related to transients, one option is to send the CVT to the manufacturer to perform new tests and investigate the causes of the failure. However, this procedure involves high costs for the companies.

Another way to investigate failure is to use mathematical models. The contribution of this paper is the application of a methodology for evaluating a CVT using a circuit model in which most of the parameters are measured and one parameter is estimated. The model can be used for simulating ferroresonance and transient response tests according to the IEC 61869-5 or for other transient studies, such as simulations of short circuits in power systems.

A CVT with a rated voltage of 145 kV was chosen for the application of the methodology. Initially, some parameters of the CVT were measured and the saturation curves of the nonlinear components were obtained in a high-voltage laboratory. Then, the frequency response of the equipment was measured in a frequency range from 10 Hz to 10 kHz with three different voltage levels. Afterward, a linear model was extracted from the measured parameters and frequency response. Then, an optimization algorithm was used to estimate the parameter that could not be measured. After that, combining the linear model with the measurements of the nonlinear components, a nonlinear model was implemented in a simulation program for electromagnetic transients. The model was validated in both frequency and time domains.

II. Transient Response Requirements Following the IEC 61869-5

The transient response of a CVT is the ability to reproduce fast variations in the primary system to which it is connected. It is defined by the behavior of the secondary voltage after the occurrence of a primary short circuit.

Many of the CVT parameters affect the transient response, such as the equivalent capacitance of the capacitive divider, intermediate voltage, burden, and Ferroresonance Suppression Circuit (FSC). For example, using a capacitive divider with higher equivalent capacitance reduces the transient voltage in the secondary, although damping becomes slower.

F. L. Probst and S. Tenbohlen are with the Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart, 70569 Stuttgart, Germany (email: felipe-luis.probst@ieh.uni-stuttgart.de; stefan.tenbohlen@ieh.uni-stuttgart.de).
M. V. Ferreira da Luz is with the Department of Electrical and Electronic Engineering, Federal University of Santa Catarina (UFSC), CEP 88040-900, Florianópolis, Brazil (email: mauricio.luz@ufsc.br).

Paper submitted to the International Conference on Power Systems Transients (IPST2023) in Thessaloniki, Greece, June 12-15, 2023.

The IEC 61869-5 proposes to assess the transient response by calculating the maximum error between the output voltage after and before a short circuit, according to (1).

$$\varepsilon(\%) = \frac{|U_s(t)|}{\sqrt{2}\, U_s}\ 100\ \% \qquad (1)$$

where U_s is the secondary voltage before the short circuit and U_s(t) is the secondary voltage at time Ts after the short circuit.

The IEC standard defines three transient response classes: T1, T2, and T3. They are associated with the accuracy class. The evaluated CVT was specified with class T1, where the maximum acceptable error is 10 % at 20 ms or more after applying a primary short circuit.

There are two types of test methods to assess whether the device meets the specification: one considers the complete circuit and the other considers the equivalent circuit configuration with capacitors C_1 and C_2 connected in parallel. For the test, a voltage U_p is applied to the complete circuit, whereas a voltage U, calculated according to (2), is applied to the equivalent circuit.

$$U = U_p\ \frac{C_1}{C_1+C_2} \qquad (2)$$

Then, a short circuit is applied to the primary and both primary and secondary voltages are registered during the test. Fig. 1 shows the schematic diagram of the test considering the equivalent circuit configuration.

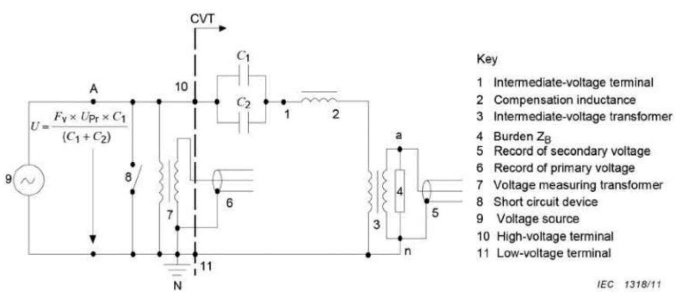

Fig. 1. Transient response test in the equivalent circuit configuration [2].

After defining the test configuration, the following guidelines must be observed:

- To apply the voltages U_p: 1.0 U_{Pr}, 1.2 U_{Pr}, and F_v U_{Pr};
- The burden of 100 % and 25 % or 0 % of the rated burden;
- Pure resistive burden or with an inductive power factor of 0.8;
- The test shall be made twice at peak and twice at zero crossing of the primary voltage.

III. CVT Modeling

The schematic diagram of the CVT used in this study is shown in Fig. 2. It consists of a capacitive voltage divider (C_1 and C_2), a compensating reactor (L_c), a voltage transformer (VT), a ferroresonance suppression circuit (FSC), an earthing switch (ES) and a burden connected to the secondary winding. It has three secondary winding, but only one is represented.

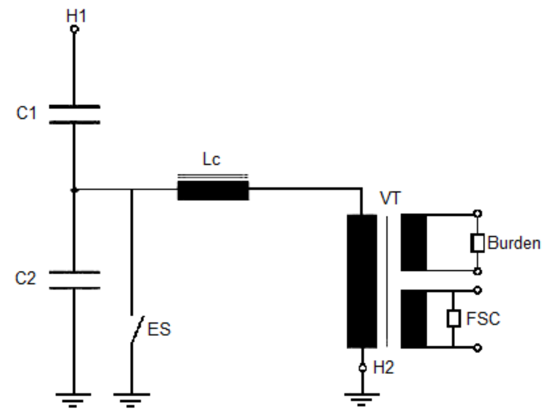

Fig. 2. CVT schematic diagram.

The FSC is a fundamental frequency-blocking filter type, which presents a high impedance for the fundamental frequency (60 Hz), whereas signals at other frequencies are absorbed by the damping load. Since ferroresonance usually has harmonic components, the filter provides an additional load to eliminate the effect [3]. Two metal oxide varistors are connected in parallel to the filter to limit voltage peaks.

The studies report a small influence in the frequency range from 10 Hz to 10 kHz for the following parameters: stray capacitance of the secondary winding, stray capacitance between primary and secondary windings, the ohmic resistance of the secondary, and leakage inductance of the secondary. However, the parameters C_1, C_2, stray capacitance of the compensating reactor (C_c), stray capacitance of primary winding (C_p), the FSC, and burden influence significantly the frequency response of the equipment. The stray capacitance C_c causes a rejection frequency between 500 Hz and 3 kHz, whereas C_p changes the response for frequencies above 1 kHz. As a result of the sensitivity studies, a simplified circuit is proposed for CVT modeling, as shown in Fig. 3.

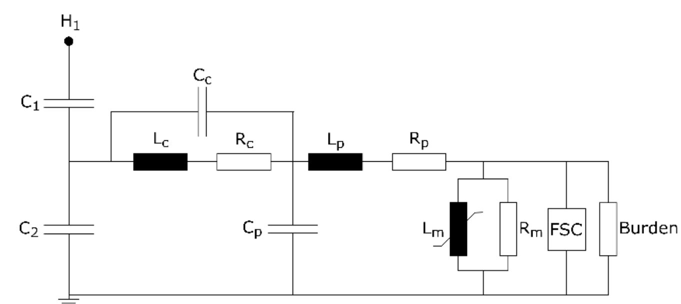

Fig. 3. Simplified circuit for CVT modeling.

This is currently the most commonly used circuit for modeling CVTs for studies in transient regime. It is important to note that, in addition to the stray capacitances present in the circuit, it is also important to represent the nonlinearities of the ferromagnetic core elements and voltage-limiting components if present. These data are not readily available from the equipment manufacturer and some of these parameters cannot be measured directly, requiring the use of techniques to estimate the unknown values.

IV. Measurements

To obtain the parameters for modeling the CVT, some tests were performed in a high-voltage laboratory.

A. *Measurement of CVT Parameters*

The parameters of the CVT were first measured to implement the linear modeling of the device in the frequency domain. Some of them could be measured directly:

- Capacitances of the voltage divider (C_1 and C_2) and the FSC (C_{rlc});
- The ohmic resistance of compensating reactor (R_c), VT primary winding (R_p), and FSC (R_d and R_{rlc});
- The inductance of compensating reactor (L_c) and FSC (L_{rlc});
- Stray capacitance of the compensating reactor (C_c).

The ohmic resistances were measured with a digital Kelvin Bridge instrument Instrum, model KB-10. The capacitance C_{rlc} and inductance L_{rlc} were measured with an LCR meter Minipa MX-1010. The capacitances C_1 and C_2 were measured with a power factor test set Tettex 2816, with an applied voltage of 10 kV on UST mode (Ungrounded Speciment Test). Fig. 4 shows the schematic diagram for measuring C_1 and the insulator with the capacitive divider.

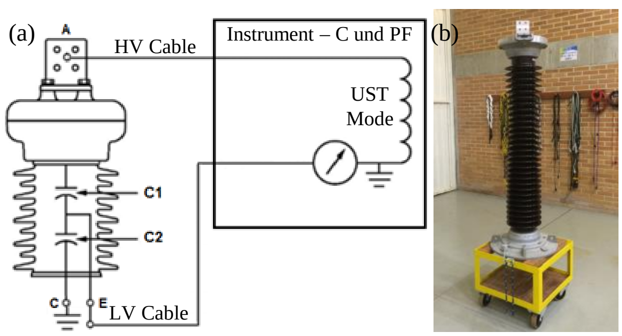

Fig. 4. Measurement of the voltage divider capacitances. (a) The schematic diagram for measurement of C_1. (b) Insulator with the voltage divider.

It is important to point out that some components, such as the compensating reactor, are not always accessible for direct measurement, but this was possible for the evaluated equipment. The inductance L_c and stray capacitance C_c of the compensating reactor were measured using a Quadtech 7600 precision LCR meter with an applied voltage of 5 V. L_c was determined by measuring the impedance at 10 Hz because the parallel stray capacitance has a high impedance at low frequencies and therefore the measured impedance is predominantly inductive. In contrast, C_c was determined by measuring the impedance at 2 MHz.

Other parameters were measured indirectly. The open circuit test with 115 V applied to the secondary was executed to measure the magnetizing inductance (L_m) and the core loss resistance (R_m). The short circuit test was done to obtain the leakage inductances of VT primary and secondary windings.

The circuit shown in Fig. 3 was chosen for the CVT modeling. Thus, the only parameter that was not possible to measure was the stray capacitance of the primary (C_p). An estimated value of 300 pF was initially assumed. The relevant measured and estimated parameters are listed in Table I.

TABLE I
Measured and Estimated CVT Parameters

Parameter	Measured Value	Parameter	Measured Value	Estimated Value
C_1	12730.00 pF	C_p	---	300.00 pF
C_2	83780.00 pF	L_m	735.43 mH	---
L_c	69.20 H	R_m	160.36 Ω	---
R_c	174.50 Ω	L_{rlc}	236.43 mH	---
C_c	119.29 pF	R_{rlc}	40.40 Ω	---
L_p	3.93 H	C_{rlc}	28.72 μF	---
R_p	690.00 Ω	R_d	251.00 Ω	---

B. *Measurement of Saturation Curves of the VT, Compensating Reactor, and FSC Reactor*

The saturation curves of the VT, compensating reactor and FSC reactor were measured to evaluate the nonlinear characteristics of the elements with a magnetic core. For these measurements, an instrument developed by the Federal University of Santa Catarina was used, which can apply voltage up to 1920 V. First, the VT saturation curve was measured in the secondary winding, as shown in Fig. 5.

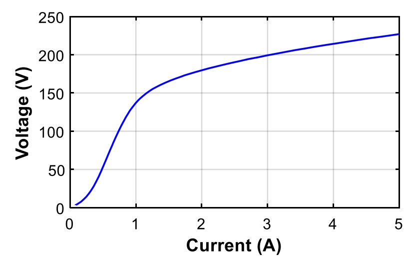

Fig. 5. Saturation curve of the VT.

The VT has an effectively nonlinear behavior. It presents a saturation characteristic for voltages above 150 V.

The saturation curve of the L_c was then measured. Although linear for most measured voltage levels, it has a nonlinear characteristic for voltages below 100 V, as shown in Fig. 6.

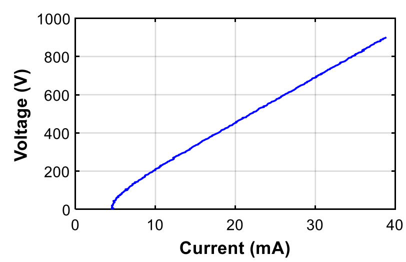

Fig. 6. Saturation curve of the compensating reactor (L_c).

Afterward, the saturation curve of the FSC reactor was measured. The results are presented in Fig. 7. It exhibits linear behavior over the entire measured range.

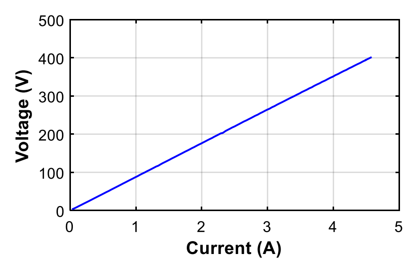

Fig. 7. Saturation curve of the FSC reactor.

C. Frequency Response Measurements

After measuring the CVT parameters and saturation curves, the frequency response was measured in the frequency range from 10 Hz to 10 kHz. A Fluke 5200A precision AC voltage calibrator and a 5205A power amplifier were used, which provide accurate voltages up to 1100 V at frequencies from 10 Hz to 100 kHz. However, the tests were limited to 10 kHz because of the high attenuation expected at higher frequencies due to the inductive characteristics of the VT. Similarly, high attenuation is expected at very low frequencies (below 10 Hz) due to the capacitances of the voltage divider (C_1 and C_2).

The measurements were performed in three different configurations:

- 100 V applied in the complete circuit;
- 1 kV applied in the complete circuit;
- 1 kV applied in the equivalent circuit configuration.

First, a sweep frequency response measurement was done by applying 100 V to the high-voltage terminal H_1. The amplitude of the primary voltage V_{in} and the secondary voltage V_{out} were registered, as well as the phase shift between the two signals. Then, the gain V_{out}/V_{in} was calculated in dB and normalized to the 60 Hz gain. Fig. 8 shows the schematic diagram of the test. The power amplifier was not used.

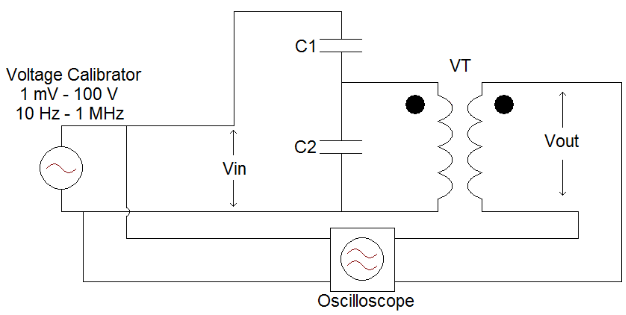

Fig. 8. Setup for frequency response test with 100 V in the complete circuit.

The second measurement was also performed in the complete circuit configuration, but using the AC calibrator with the power amplifier to apply 1 kV to the high-voltage terminal H_1. A high-voltage differential probe was used to measure the primary voltage with the oscilloscope.

Finally, the frequency response was measured with 1 kV applied to the CVT in the equivalent circuit configuration. For the evaluated equipment, 1 kV applied to the equivalent circuit corresponds to 7.53 kV in the complete circuit. The test circuit is shown in Fig. 9 and the measured frequency responses are presented in Fig. 10.

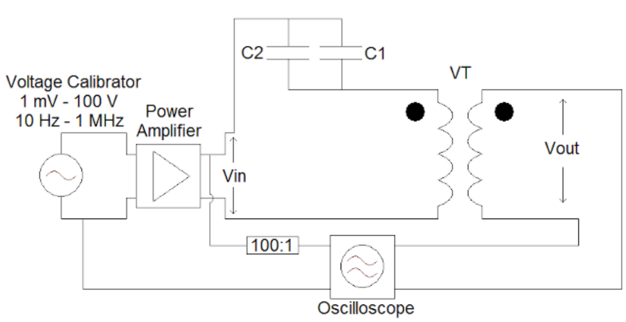

Fig. 9. Setup for frequency response test with 1 kV in the equivalent circuit.

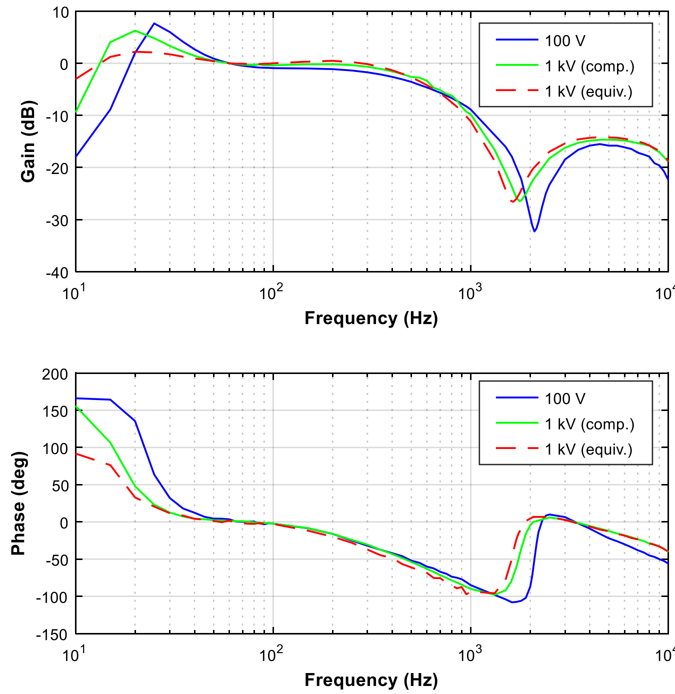

Fig. 10. Measured frequency responses with different applied voltages.

The comparison of the three results shows that they present a relevant difference for almost the entire frequency range investigated. The deviation is more significant at the resonant frequency between 1500 Hz and 2200 Hz and at frequencies below 40 Hz. The resonance frequency is caused by the compensating reactor L_c with its stray capacitance C_c. It has a different value for each measurement because L_c varies, as the inductance can change at low applied voltages due to the operating point on the magnetization curve. A similar reason explains the difference in responses at frequencies with higher gains in the range from 10 Hz to 40 Hz. The value of the magnetizing inductance has a strong influence on the low-frequency response of the CVT.

V. Modeling

A. Linear Modeling

After the measurements in the laboratory, a linear model of the CVT was implemented in Matlab. This model represents the transfer function of the CVT obtained from the circuit shown in Fig. 11. The circuit is represented by the measured parameters and the estimated value of 300 pF for the parameter C_p. All parameters are referenced to the primary side. Varistors and nonlinearities of the ferromagnetic core are not considered in this linear model but are implemented later for the simulations in the transient regime.

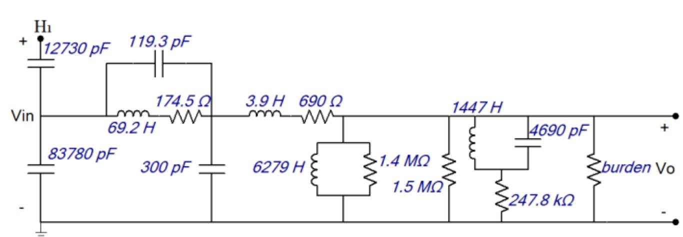

Fig. 11. Linear model of the CVT.

Then, the frequency response of the model implemented in Matlab was compared to the measured frequency responses. Fig. 12 shows these curves.

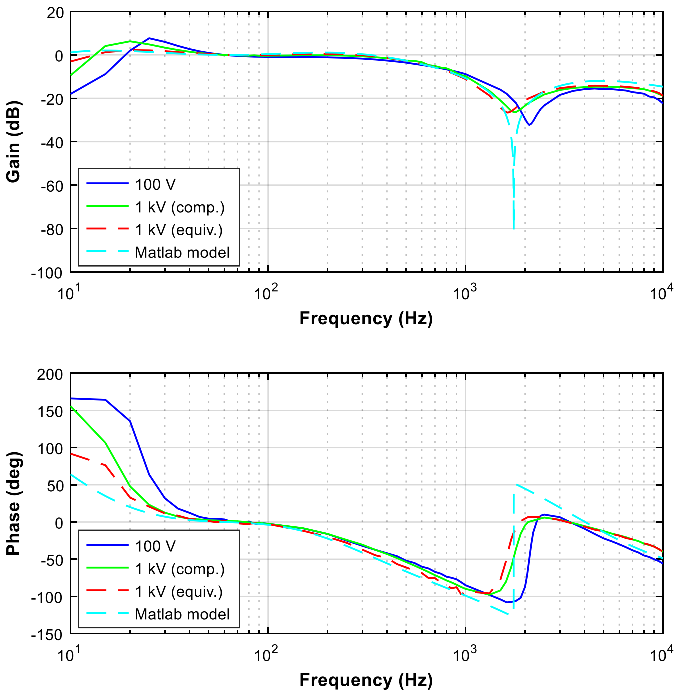

Fig. 12. Frequency response of the Matlab model compared to the three measured responses.

To check which measured curve best approximates the simulated one, the mean square error (MSE) and the mean percentage error (MPE) between the simulated and measured signals were calculated. The results are shown in Table II.

TABLE II
MSE AND MPE BETWEEN MEASURED AND SIMULATED SIGNALS

Test	MSE	MPE
100 V	$1.77 \cdot 10^{-7}$	– 40.28 %
1 kV (complete circuit)	$7.62 \cdot 10^{-8}$	– 2.24 %
1 kV (equivalent circuit)	$1.03 \cdot 10^{-8}$	– 1.56 %

As shown in Table II, MSE and MPE decrease with increasing applied voltage. The smallest error occurs when the equivalent circuit is tested with 1 kV.

From this result, the curve with the smallest error was used to estimate the unknown parameter C_p, minimizing the MSE for frequencies above 2 kHz, since the influence of this parameter occurs for frequencies above the resonance frequency between C_c and L_c.

The value of C_p obtained after optimization was 408.91 pF, and the MSE between the model and the measured curve with 1 kV in the equivalent circuit was reduced to $9.61 \cdot 10^{-9}$. A sensitivity analysis of C_p was not performed but may be considered for further investigation.

B. Nonlinear Modeling

Based on the linear model built in Matlab, a nonlinear model was developed in ATP by adding the nonlinearities of the voltage transformer, compensating reactor, and metal oxide varistors of the FSC. The magnetizing inductance of the VT was modeled by a nonlinear inductor represented by a curve λ - i (flux linkage - peak current) consisting of straight lines only in the positive cycle.

Considering the values measured in the laboratory and the VT design parameters, the calculated maximum value of magnetic flux density was 0.98 T, which is still far from the saturation point of the material. Then the equivalent point of flux linkage was calculated for a magnetic flux density of 2 T, considered as the value of magnetic flux density of core saturation. A few more points were added to the saturation curve until the saturation flux linkage value was reached, using a logarithmic extrapolation of the positive part of the curve λ - i. Finally, another point was added considering the air core inductance of the winding. The curve implemented in ATP is shown in Fig. 13.

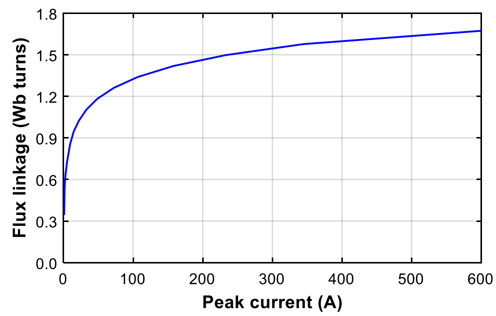

Fig. 13. Saturation curve of the VT implemented in ATP.

The compensating reactor is expected to exhibit linear behavior under normal operating conditions, but nonlinear characteristics were observed in the measurements for voltages below 100 V. The component is also expected to exhibit nonlinear behavior in the saturation region of the ferromagnetic core. Therefore, the same nonlinear inductor model was used for representing the compensating reactor. The curve implemented is presented in Fig. 14.

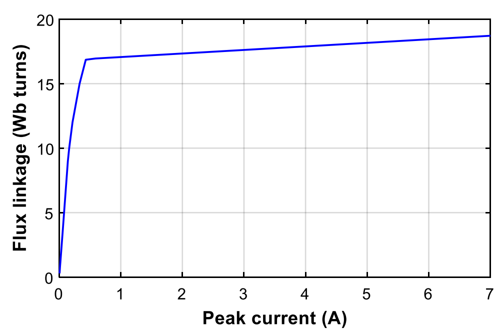

Fig. 14. Saturation curve of the compensating reactor implemented in ATP.

The two varistors of the FSC were modeled by the nonlinear resistor. The operating curve v - i from the catalog of the manufacturer was used as input data.

Given the model definition and the appropriate parameters for modeling the nonlinear elements, the circuit was implemented in ATP for studies in transient regime. For this purpose, the CVT was represented as its complete circuit, with the nonlinearity of the VT in the primary circuit, and the FSC in an exclusive circuit, as shown in Fig. 15.

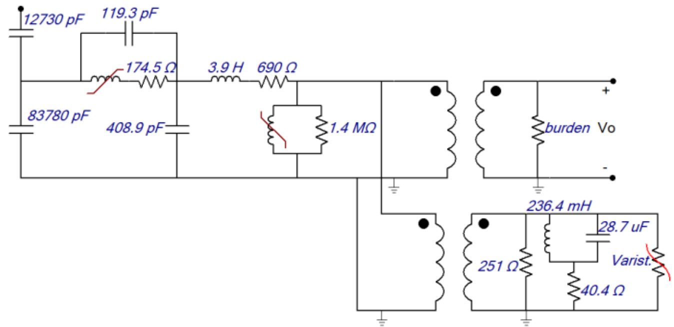

Fig. 15. Nonlinear circuit of the CVT implemented in ATP.

VI. Model Validation in Transient Regime

To assess whether the proposed model responds similarly to real devices, a series of time domain tests were simulated with a time-step of 5 µs. Previously, a ferroresonance test was performed in the manufacturer's laboratory on a CVT with the same technical specifications according to the procedures defined in the IEC 61869-5. The results were then compared. Fig. 16 shows the comparison between measured and simulated signals for a short circuit in the secondary applied at 30 ms and removed at 143.2 ms.

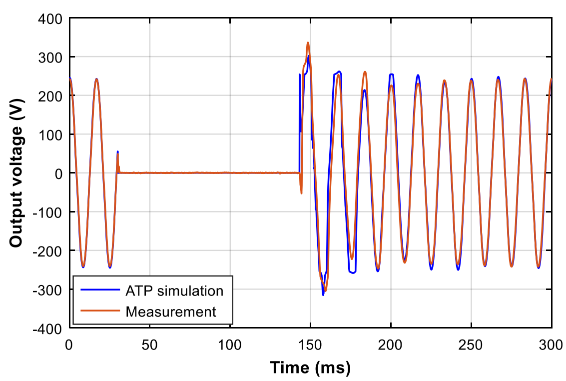

Fig. 16. Ferroresonance test - ATP simulation and measurement.

The response of the ATP model shows a good correlation with the one measured in the laboratory, and both meet the criteria of the IEC standard, although some differences can be seen in the first periods. The maximum measured voltage was 336.4 V, whereas the simulation presented a maximum voltage of 302.1 V, which represents an error of 10.2 %. Other signals were compared and the results were also satisfactory.

VII. Simulation of the Transient Response Test Following the Standard IEC 61869-5

After validating the model, the transient response test was simulated following the IEC 61869-5, considering the limits established for class T1. The test simulation was performed with a short circuit at peak voltage and zero crossing with an applied voltage of 100 % of the rated voltage and no secondary burden. The results are shown in Fig. 17.

When the short circuit occurs at the voltage peak, the response meets the criteria specified in IEC 61869-5. However, if the fault occurs at zero crossing, the response does not meet the criteria because it has an error of about 13 % after 20 ms, above the 10 % limit. Thus, the simulation shows that the model under study does not meet the specifications for transient response by the criteria of IEC 61869-5.

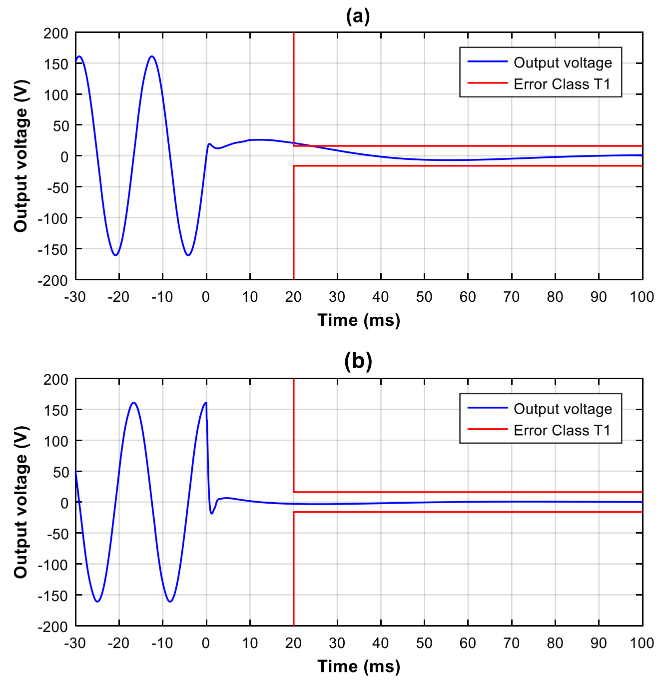

Fig. 17. Simulation of transient response test with an applied voltage of 100 % and burden of 0 %. (a) Short circuit at zero crossing. (b) Short circuit at peak.

A. *Design Improvement*

In terms of design, the transient response can be improved by using a lower equivalent capacitance C_{eq}. To confirm this hypothesis, capacitances C_1 and C_2 were changed to values of 6000 pF and 39487.8 pF, respectively, resulting in a C_{eq} of 45487.8 pF. The transient response test was performed again under the same conditions. The results are shown in Fig. 18.

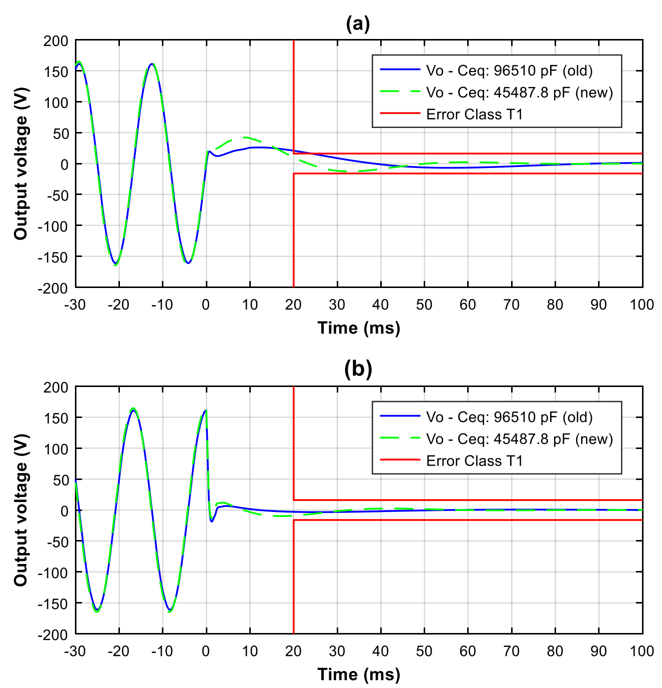

Fig. 18. Simulation of transient response test after changing C_{eq}. (a) Short circuit at zero crossing. (b) Short circuit at peak.

As can be seen, the circuit shows more oscillations with a lower C_{eq}, but the response remains within the limits specified by the IEC standard. This is a simplified approach to improve the transient response since changing the C_{eq} also affects the design of other elements.

VIII. Discussion

A. Frequency Response Measurement

Some authors argue that an applied voltage of about 1 % of the rated voltage is sufficient to measure the frequency response for modeling purposes, whereas others say that the magnetic components of the CVT must be close to their nominal state during the test. This work has shown that the best results can be obtained by applying higher voltages. Therefore, the use of commercial sFRA instruments is not suitable for this purpose, as they can usually apply up to 10 V.

It was also demonstrated that measurement with the CVT in the equivalent circuit configuration is a good method to "increase" the voltage applied to the equipment.

A. Modeling of Nonlinear Components

Modeling the nonlinear components is critical for transient studies. In this work, different nonlinear components were tested and it was found that the responses can vary significantly depending on the type chosen [1].

IX. Conclusions

To simulate the transient response test in conformity with the IEC 61869-5 standard and perform other transient studies, a reliable model should be developed in a simulation program for electromagnetic transients. In this paper, we presented a CVT model based on the measurement of parameters and frequency response that is suitable for this purpose. The nonlinear model has been shown to reproduce signals measured in the time domain.

Therefore, the developed model can be used for the simulation of ferroresonance and transient response tests by IEC 61869-5, when no laboratory structure is available to perform these tests or for other studies in the transient regime, such as short circuit simulations in electric power systems. The methodology has been applied to different CVTs. Thus, the model can be considered generic.

Finally, it should be noted that the modeling presented in this paper can be challenging. Special attention is required when performing the measurements and the availability of a high-voltage laboratory has proven to be very valuable for this purpose. In addition, the modeling of the nonlinear components is essential and should be done with great diligence.

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