Identification of Parameters for Coupling Capacitor Voltage Transformers

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Abstract - **A method to obtain the coupling capacitor voltage transformer (CCVT) model parameters from frequency response curves is presented. Frequency response measurements of magnitude and phase, in the range from 10 Hz to 10 kHz, were carried out for a 230 kV CCVT at our high voltage laboratory and used as input data to a full Newton-type fitting routine to estimate the CCVT parameters. Analytical CCVT functions were fitted to the measured data. The magnitude and phase errors, in the whole frequency range, are fairly small. The nonlinear behavior of the voltage transformer (VT) magnetic core is also taken into account. The obtained CCVT model may easily be used in connection with the EMTP (Electromagnetic Transients Program).**

Keywords: Coupling Capacitor Voltage Transformer, Nonlinear Fitting, CCVT Model, EMTP.

I. INTRODUCTION

Electric utilities, for many years, have used coupling capacitor voltage transformers (CCVTs) as input sources to protective relays and measuring instruments. However, problems have yet been traced to incorrect inputs.

The fundamental principle of CCVT is the fidelity with which the secondary voltage follows the primary voltage under all operating conditions. Under steady-state conditions, this requirement may be achieved based on the design and tuning of the CCVT. However, the fidelity of CCVT decreases under transient conditions due to inductive, capacitive and nonlinear components [1]. Therefore, the CCVT transient behavior must be well known.

Many works including field measurements, laboratory tests and digital simulations, have been conducted to study the performance of the CCVT. Some studies have been concentrated on nonlinear behavior of the voltage transformer (VT) magnetic core to accurately simulate the transient response of CCVT [2, 3, 4].

Other works have considered the effect of stray capacitances in some CCVT elements to explain the measured frequency responses in the linear region of operation [5, 6, 7]. There are some problems in obtaining the CCVT parameters. In [5] and [7], the used measurement techniques need disassembling the CCVT and in [6], a method was developed to measure the CCVT frequency response from the secondary side without the need to access its internal components.

In Brazil, some electrical energy companies have reported unexpected overvoltage protective device operations in several coupling capacitor voltage transformers leading to failures of some units. The reported overvoltages occurred during normal switching conditions [8, 9].

In the present study, a first step consisting on building a CCVT model for transient studies, is given towards the solution of some CCVT problems reported by CHESF (Companhia Hidro Elétrica do São Francisco). The model includes the nonlinear behavior of the VT magnetic core.

The goal is to obtain a method to estimate the model parameters (resistances, inductances and capacitances) from the frequency response curves. In order to achieve this, frequency response measurements of magnitude and phase, in the range from 10 Hz to 10 kHz, were carried out for a 230 kV CCVT in the high voltage laboratory and used as input data to a full Newton-type fitting routine. The analytical CCVT functions (magnitude and phase) were fitted to the measured data.

II. FUNDAMENTAL PRINCIPLES

The basic electrical diagram for a typical CCVT is shown in Fig. 1. The primary side consists of two capacitive elements C_1 e C_2 connected in series. The voltage transformer provides a secondary voltage v_o for protective relays and measuring instruments. The inductance L_c is chosen to avoid phase shifts between v_i and v_o at power frequency. Small errors occur due to the exciting current and the CCVT burden (Z_b) [1, 2].

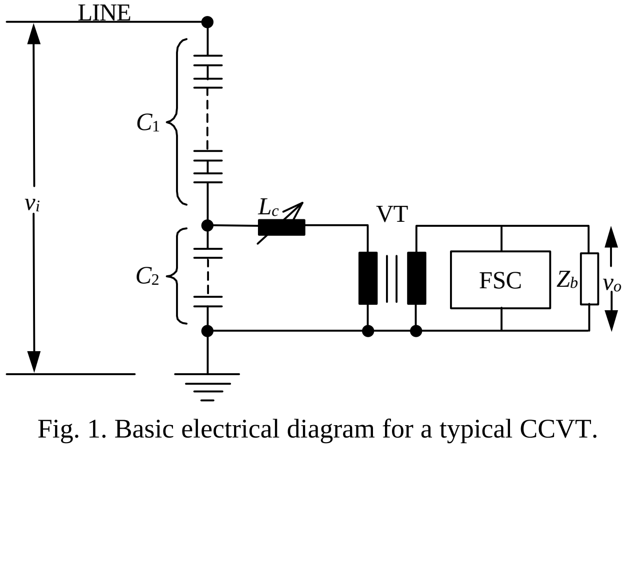

Fig. 1. Basic electrical diagram for a typical CCVT.

Ferroresonance oscillations may take place if the circuit capacitances resonate with the iron core nonlinear inductance. These oscillations cause undesired information transferred to the relays and measuring instruments. Therefore, a ferroresonant suppression circuit (FSC) is normally included in one of the CCVT windings.

Circuits tuned at power frequency (L in parallel with C) and a resistance to ground have been often used as ferroresonant suppression circuits [4, 6] because they damp out transient oscillations and they require small amount of energy during steady-state.

III. DEVELOPED ANALYTICAL METHOD

The diagram shown in Fig. 1 is valid only near power frequency. A model to be applicable for frequencies up to a few kilohertz needs to take the VT primary winding and compensating inductor stray capacitances into account [3, 4, 5, 6].

In this work, the circuit shown in Fig. 2 was used to represent the CCVT. It comprises: a capacitor stack (C_1, C_2); a compensating inductor (R_c, L_c, C_c); a step down transformer (R_p , L_p , C_p , L_m , R_m) and a ferroresonant suppression circuit (R_f, L_{f1}, L_{f2}, $-M$, C_f) [5, 6, 10].

The FSC design is shown in Fig. 3a. A nonsaturable iron core inductor L_f is connected in parallel with a capacitor C_f so that the circuit is tuned to the fundamental frequency with a high Q factor [10]. The configuration of FSC digital model is shown in Fig 3b. The damping resistor R_f is used to attenuate ferroresonant oscillations.

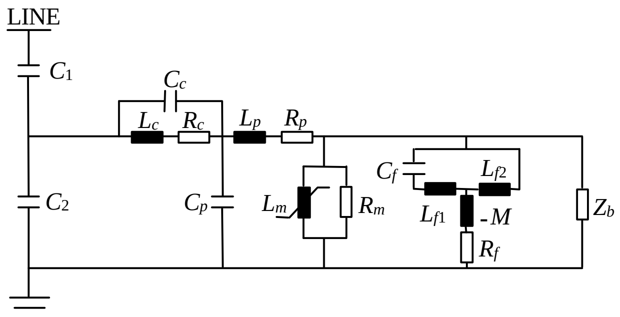

Fig. 2. CCVT model for identification of parameters.

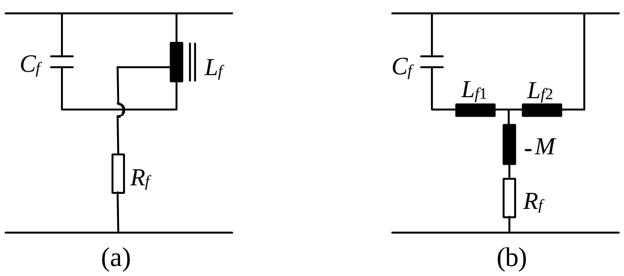

Fig. 3. (a) FSC design. (b) FSC digital model.

A. Mathematical Model Development

In order to develop the analytical expressions of CCVT model, we considered only the linear region of the VT magnetic core because in the frequency response measurements, the core was not saturated. The nonlinearity will be only included in time domain simulations to improve the representation of the transient effects in CCVT. The circuit shown in Fig. 2 is considered with specific blocks of impedances Z_1, Z_2, Z_3, Z_4, Z_5 and with all the elements referred to the voltage transformer secondary side, according to Fig. 4.

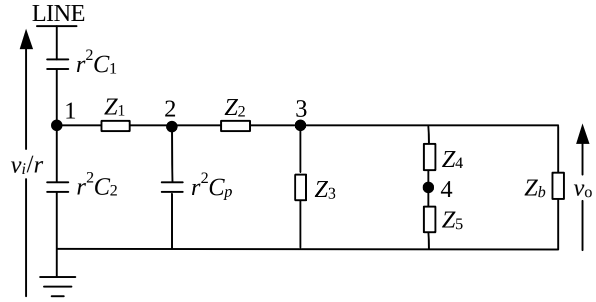

Fig. 4. CCVT model with specific blocks of impedances.

The expressions for the impedances in the s domain, with $s = jw$, are:

$$
\begin{aligned}
Z_1 &= \left[(R_c + sL_c)/r^2\right] // \left(1/r^2 sC_c\right);\\
Z_2 &= \left(R_p + sL_p\right)/r^2 ;\\
Z_3 &= \left(R_m/r^2\right) // \left(sL_m/r^2\right);\\
Z_4 &= \left(sL_{f1} + 1/sC_f\right) // \left(sL_{f2}\right);\\
Z_5 &= R_f - sM.
\end{aligned}
\tag{1}
$$

Where, r is the VT ratio and the symbol // means that elements are in parallel.

The CCVT model parameters R, L, C should reproduce the transfer functions of magnitude and phase represented by v_o/v_i. They are calculated using the technique described below for the minimization of nonlinear functions.

B. Minimization of Nonlinear Functions

Methods for minimizing nonlinear functions are usually iterative, that is, given an approximate solution x_i, an estimate of the solution x^* is obtained. The technique used here is based on Newton's method which uses a quadratic approximation to the function $F(x)$ derived from the second-order Taylor series expansion about the point x_i. In two dimensions, the second-order Taylor series approximation can be written in the form:

$$
\begin{aligned}
F(x_1 + p_1, x_2 + p_2) &\approx F(x_1, x_2) + \begin{bmatrix} p_1 & p_2 \end{bmatrix} \begin{bmatrix} \dfrac{\partial F(x_1, x_2)}{\partial x_1} \\ \dfrac{\partial F(x_1, x_2)}{\partial x_2} \end{bmatrix} \\
&+ \frac{1}{2} \begin{bmatrix} p_1 & p_2 \end{bmatrix} \begin{bmatrix} \dfrac{\partial^2 F(x_1, x_2)}{\partial x_1^2} & \dfrac{\partial^2 F(x_1, x_2)}{\partial x_1 \partial x_2} \\ \dfrac{\partial^2 F(x_1, x_2)}{\partial x_2 \partial x_1} & \dfrac{\partial^2 F(x_1, x_2)}{\partial x_2^2} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \end{bmatrix}
\end{aligned}
\tag{2}
$$

And for n dimension, the expression above in matrix/vector form is:

$$F(\boldsymbol{x}+\boldsymbol{p}) \approx F(\boldsymbol{x}) + \boldsymbol{p}^T \nabla F(\boldsymbol{x}) + \frac{1}{2}\boldsymbol{p}^T \nabla^2 F(\boldsymbol{x})\boldsymbol{p} . \quad (3)$$

To obtain the step $\boldsymbol{p}$, the function F is minimized by forming its gradient with respect to $\boldsymbol{p}$ and setting it equal to zero. Then,

$$\nabla^2 F(\boldsymbol{x})\boldsymbol{p} = -\nabla F(\boldsymbol{x}). \quad (4)$$

The approximate solution $\boldsymbol{x}_{k+1}$ is given by:

$$\boldsymbol{x}_{k+1} = \boldsymbol{x}_k + \boldsymbol{p} = \boldsymbol{x}_k - \left[\nabla^2 F(\boldsymbol{x}_k)\right]^{-1} \nabla F(\boldsymbol{x}_k) . \quad (5)$$

Newton's method will converge if $[\nabla^2 F(\boldsymbol{x})]^{-1}$ is positive definite in each iterative step, that is, $z^T[\nabla^2 F(\boldsymbol{x})]^{-1} z > 0$ for all $z \neq 0$. The technique used here is the full Newton-type method [11,12]. It is a modification of Newton's method for that iteration in which $[\nabla^2 F(\boldsymbol{x})]^{-1}$ is not positive definite: $\nabla^2 F(\boldsymbol{x})$ is replaced by a "nearby" positive definite matrix $\overline{\nabla}^2 F(\boldsymbol{x})$ and $\boldsymbol{p}$ is computed by solving $\overline{\nabla}^2 F(\boldsymbol{x})\boldsymbol{p} = -\nabla F(\boldsymbol{x})$.

Our objective is to minimize the merit function $c^2(\boldsymbol{x})$

$$c^2(\boldsymbol{x}) = \sum_{i=1}^{n} \left[\frac{y_i - y(w_i; \boldsymbol{x})}{s_i} \right]^2 , \quad (6)$$

where w_i is the $\boldsymbol{i}$-th measured frequency value and y_i is the i-th measured frequency response value of the n data points. s_i is the standard deviation for each y_i. $\boldsymbol{x}$ is the vector which contains the parameters R, L, C to be determined and $y(w_i; \boldsymbol{x})$ is the analytical model function.

A FORTRAN code was written to minimize the merit function $c^2(\boldsymbol{x})$ using the method described above. Besides the function $y(w_i; \boldsymbol{x})$ it is necessary to know its first and second derivatives with respect to each parameter of the vector $\boldsymbol{x}$. The algorithm is given below:

1. Supply the CCVT frequency response values y_i for each frequency w_i and enter with a guess for the parameters R, L, C (vector $\boldsymbol{x}$);
2. Determine $c^2(\boldsymbol{x})$ and evaluate $c^2(\boldsymbol{x} + \boldsymbol{p})$;
3. Save the value of $c^2(\boldsymbol{x} + \boldsymbol{p})$ and for a user defined number of iterations m, compare the actual value of the merit function to its old value m iterations before:
4. If the difference is greater than a user defined tolerance, go back to step 2. Otherwise, stop the iterative process.

IV. LABORATORY TESTS

Frequency response measurements of magnitude and phase were carried out for CCVT. The rms $v - i$ nonlinear curve for the VT magnetic core was measured as well.

A. 230 kV CCVT Manufacturer Data [10]:

- Primary voltage: $230{:}\sqrt{3}$ kV;
- Intermediate voltage: $30{:}\sqrt{3}$ kV;
- Secondary voltage: 115 V and $115{:}\sqrt{3}$ V;
- CCVT ratio: 2000 – 1154.7 : 1;
- Capacitances: C_1 = 9660 pF and C_2 = 64400 pF;
- Frequency: 60 Hz.

The configuration of the CCVT intermediate voltage transformer is shown in Fig. 5.

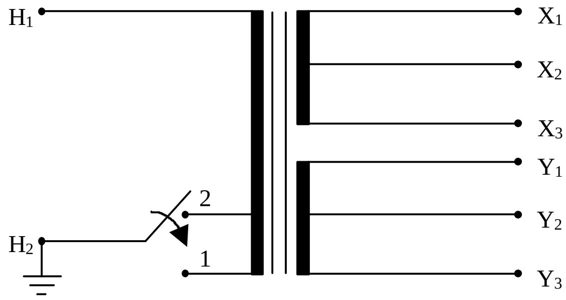

Fig. 5. 230 kV CCVT voltage transformer.

In this configuration, H_1 is the primary terminal, H_2 is the ground terminal and X_1, X_2, X_3, Y_1, Y_2, Y_3 are the low voltage secondary terminals. Terminals 1 and 2 can be connected to ground.

B. Frequency Response Measurements

Frequency response measurements, magnitude and phase, were carried out for the 230 kV CCVT. A low-pass filter was required to attenuate high frequency noises. A 3rd order RC active filter with a cut-off frequency of 15 kHz, was used [10]. A signal generator feeding an amplifier whose maximum peak-to-peak voltage is 2000 V, was connected between the high voltage terminal and the ground, according to Fig. 6.

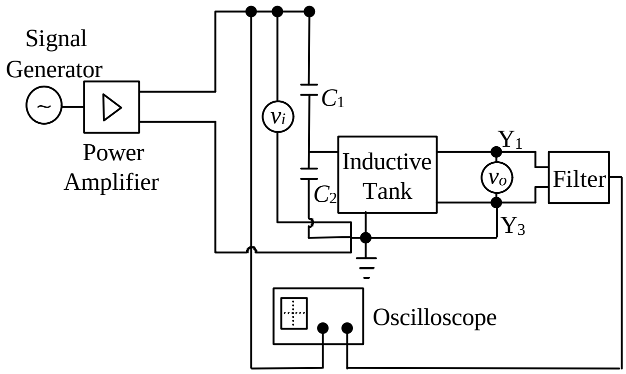

Fig. 6. Frequency response measurements for the 230 kV CCVT.

C. VT Nonlinear Characteristic Measurements

A sinusoidal voltage source was applied across terminals $X_1 - X_3$ up to 2.2 p.u. and rms voltage and current data points were obtained. The rms $v - i$ data were converted into the peak $\lambda - i$ data shown in Table 1 by using a routine developed in [13].

Table 1. Nonlinear characteristic of the VT magnetic core.

Peak Current (A)	**Peak Flux (V.s)**
0. 076368	0.025772
0.720881	0.189066
1.429369	0.396889
2.147414	0.638099
2.511675	0.748388
2.989304	0.806533
3.662012	0.863553
4.587227	0.903317
5.712037	0.942706

V. ANALYSIS OF THE RESULTS

The nonlinear fitting routine was used for two CCVTs. To check if the code was correct, 138 kV CCVT data reported in literature [5, 6] were used as a benchmark. Measurements were performed for a 230 kV CCVT at our high voltage laboratory.

A. 138 kV CCVT Benchmark Case

From the 138 kV CCVT parameters of Table 2 [6], the frequency response magnitude and phase were computed using MICROTRAN® [14]. The magnitude and phase data were used as an input file to the full Newton-type fitting routine and the parameters were recalculated back. One set of the initial guesses is shown in Table 3. The recalculated parameters are shown in Table 4.

Figs. 7 and 8 show the analytical and fitted curves for magnitude and phase, respectively. The curves are nearly the same. The fitting errors are shown in Table 5.

The routine converges even for sets of initial guesses far away from the final values. Although differences may occur for some recalculated circuit parameters, for each set of initial guesses the obtained analytical frequency response curves are nearly the same [10].

The gain is calculated as:

$$Gain = 20\log\left(\frac{41.7v_o}{v_i}\right), \tag{7}$$

where 41.7 is the VT ratio. The voltages v_o and v_i were measured at several frequencies.

The CCVT phase is the phase shift between applied signal and secondary signal as follows:

$$phase = \angle v_o - \angle v_i\,. \tag{8}$$

Table 2. 138 kV CCVT parameters [6]

R_c = 228.0 Ω	L_p = 2.85 H	L_{f2} = 247.0 mH
L_c = 56.5 H	R_m = 1.0 MΩ	R_f = 37.5 Ω
C_c = 127.0 pF	L_m = 10.0 kH	M = 163.0 mH
C_p = 154.0 pF	L_{f1} = 481.0 mH	–
R_p = 400.0 Ω	C_f = 9.6 μF	–

Table 3. 138 kV CCVT initial guess parameters

R_c = 174.0 Ω	L_p = 7.0 H	L_{f2} = 270.0 mH
L_c = 17.0 H	R_m = 34.0 MΩ	R_f = 40.0 Ω
C_c = 58.0 pF	L_m = 10.0 kH	M = 193.0 mH
C_p = 5.0 pF	L_{f1} = 650.0 mH	–
R_p = 3.0 kΩ	C_f = 7.0 μF	–

Table 4. 138 kV CCVT recalculated parameters

R_c = 3.25 Ω	L_p = 2.88 H	L_{f2} = 274.34 mH
L_c = 56.55 H	R_m = 1.47 MΩ	R_f = 36.80 Ω
C_c = 126.86 pF	L_m = 10.98 kH	M = 192.7 mH
C_p = 151.44 pF	L_{f1} = 649.78 mH	–
R_p = 833.55 Ω	C_f = 7.53 μF	–

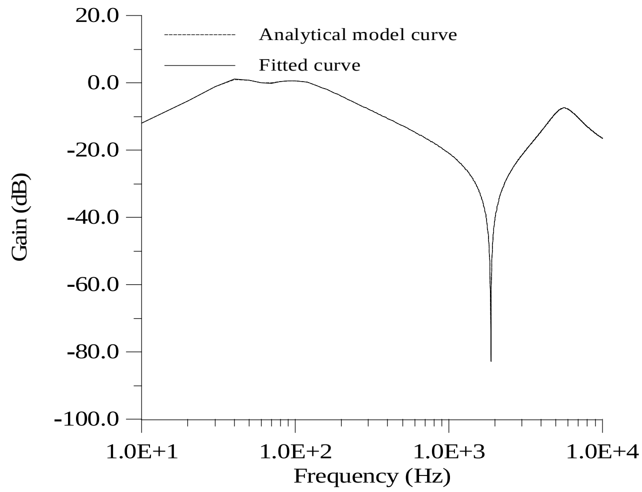

Fig. 7. 138 kV CCVT magnitude curves obtained from the original parameters and the nonlinear method.

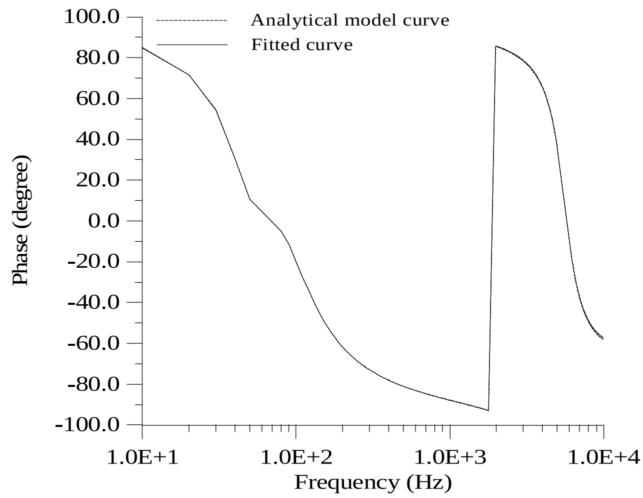

Fig. 8. 138 kV CCVT curves of phase obtained from the original parameters and the nonlinear method.

Table 5. Magnitude and phase errors for 138 kV CCVT.

Magnitude Error		**Phase Error**	
Average	Maximum	Average	Maximum
0.026 %	0.13 %	0.39°	0.86°

For the initial guesses shown in Table 3, the routine converged in 6 iterations. This is one of the most important characteristics of the full Newton-type method: fast decrease of the merit function in the initial iterations [10, 12]. In other words, $c^2(\boldsymbol{x})$ reached quickly a value nearly 300,000 times lower than its initial value.

From these results, the CCVT magnitude and phase can be reproduced by the fitted curves with very small errors.

B. 230 kV CCVT Parameters from Measurements

The 230 kV CCVT parameters were estimated from frequency response data points of magnitude and phase measured in laboratory. The 230 kV CCVT initial guesses and the fitted parameters are shown in Table 6 and 7, respectively. The measured and fitted magnitude and phase curves are shown in Figs. 9 and 10, respectively.

Table 6. 230 kV CCVT initial guess parameters

R_c = 16.0 kΩ	L_p = 91.0 H	L_{f2} = 95.0 mH
L_c = 50.0 H	R_m = 2.0 MΩ	R_f = 4.0 Ω
C_c = 46.0 nF	L_m = 7.0 MH	M = 10.0 mH
C_p = 60.0 pF	L_{f1} = 10.0 mH	–
R_p = 62.0 kΩ	C_f = 140.0 μF	–

Table 7. 230 kV CCVT estimated parameters.

230 kV CCVT estimated parameters		
R_c = 6.71 kΩ	L_p = 114.7 H	L_{f2} = 43.03 mH
L_c = 86.16 H	R_m = 27.94 MΩ	R_f = 4.63 Ω
C_c = 584.6 nF	L_m = 16.3 kH	M = 9.19 mH
C_p = 0.23 nF	L_{f1} = 11.06 mH	–
R_p = 10.5 kΩ	C_f = 173.15 μF	–

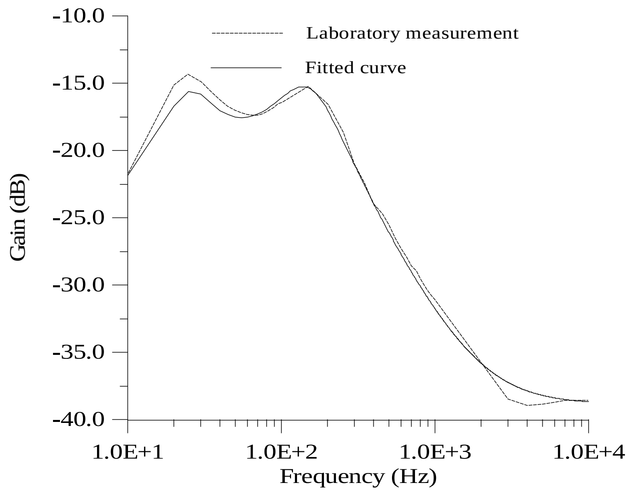

Fig. 9. 230 kV CCVT curves of magnitude measured and fitted by nonlinear method.

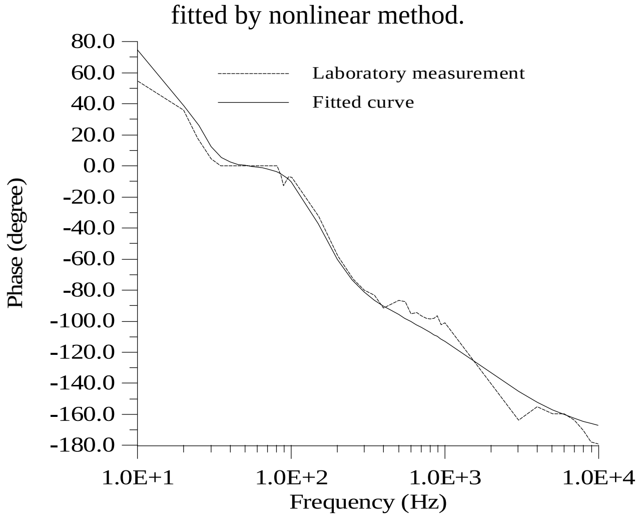

Fig. 10. 230 kV CCVT curves of phase measured and fitted by nonlinear method.

The 230 kV CCVT gain is given by:

$$Gain = 20\log\left(\frac{152.6v_o}{v_i}\right), \tag{9}$$

where 152.6 is the VT ratio measured in laboratory, considering the secondary terminals $Y_1 - Y_3$.

The CCVT phase was obtained from the same expression given in (8). The fitting errors for the magnitude and phase are shown in Table 8.

Table 8. Magnitude and phase errors for 230 kV CCVT.

Magnitude Error		**Phase Error**	
Average	Maximum	Average	Maximum
5.1 %	16.09 %	5.53^{o}	20.3^{o}

Based on Figs. 9 and 10 and Table 8, magnitude errors are fairly small for frequencies up to 2 kHz. Near 60 Hz the magnitude and phase errors are very small. This is the region in which the CCVT operates most of the time.

C. 230 kV CCVT Transient Simulations

Time domain simulations were performed with MICROTRAN® to evaluate the importance of the FSC. The CCVT is connected to the power system by a switch. An open-close switch operation was simulated. Fig. 11 shows the CCVT voltage waveform at the CCVT secondary side when the FSC is removed. Fig. 12 shows the same case with the FSC included in the model. The switch opened at 12.5 ms and closed at 50 ms. It can be seen that the transient was damped out if the FSC is in.

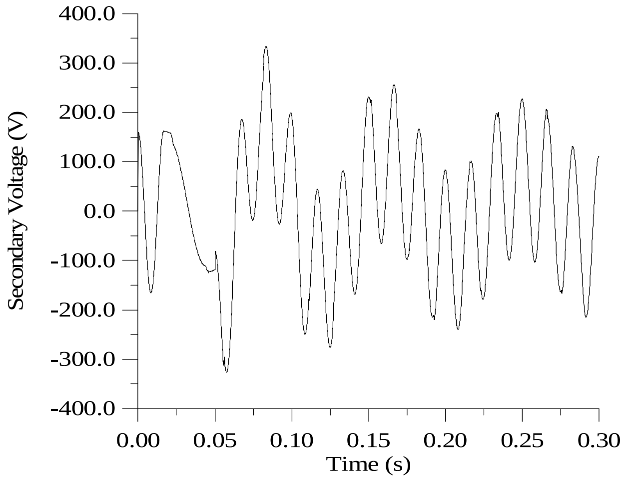

Fig. 11. Secondary voltage waveform of the 230 kV CCVT without the FSC.

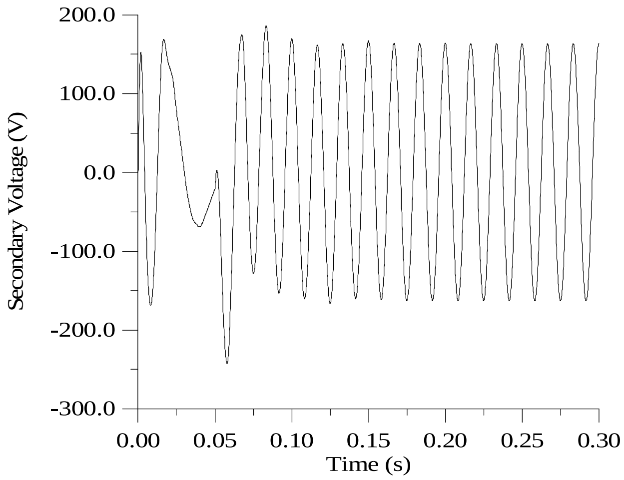

Fig. 12. Secondary voltage waveform of the 230 kV CCVT with the FSC.

VI. CONCLUSIONS

In this work, is given a first step to solve some CCVT problems reported by CHESF. A routine has been implemented to estimate the CCVT model parameters from the frequency response curves of magnitude and phase in the range from 10 Hz to 10 kHz. The analytical CCVT functions of magnitude and phase were fitted simultaneously to the measured data. Laboratory measurements were carried out to validate the used methodology.

The adopted CCVT model includes the nonlinear characteristic of the voltage transformer and it may be used in connection with the EMTP.

ACKNOWLEDGMENTS

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