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A NEW METHOD FOR THE CCVT PERFORMANCE ANALYSIS USING FIELD MEASUREMENTS, SIGNAL PROCESSING AND EMTP MODELING

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Abstract - This paper presents the results of an EPRI study on development of a new method for coupling capacitor voltage transformer (CCVT) frequency response measurements from the secondary side. The method is especially suitable for field measurements since it does not require any internal CCVT disassembly or access to its individual components. It has been verified by performing the field measurements on actual CCVTs installed in a substation. The results were compared with the results obtained by carrying out the CCVT frequency response measurements on the same type of CCVTs in a laboratory and using the method of frequency response measurement from the primary side. The proposed method is easy to use and gives accurate results. The method may be used for the EMTP-based CCVT model development and the CCVT performance analysis.

Keywords: Coupling Capacitor Voltage Transformer, CCVT, Frequency Response Measurements, EMTP Modeling

INTRODUCTION

CCVTs are widely used in power systems to obtain standard low voltage signals for protective relaying and measuring instruments. They are usually designed as stand-alone single phase units.

A typical circuit connection is shown in Figure 1.

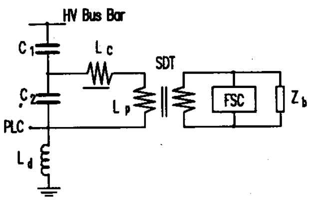

Figure 1. A CCVT Circuit Connection

C1, C2 - Capacitor Stack; PLC - Power Line Carrier Interface;
Lc - Compensating Inductor; Ld - Drain Coil;
SDT - Step Down Transformer;
Lp - STD Primary Winding Leakage Inductance
FSC - Ferroresonance Suppression Circuit; Zb - CCVT Burden

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To obtain high accuracy, CCVT components C1, C2, Lc and Lp are tuned to the fundamental frequency, making a parallel resonant circuit. An additional circuit, designed to suppress ferroresonance, is added at the secondary side. All these components make CCVT circuitry quite complex and have influence on its frequency response.

As of now, the transient performance of CCVTs is not covered by any standard. In addition to that, no convenient method for the CCVT performance analysis after some period of operation, which does not require any access to the internal components, has been published. Transient behavior of CCVTs is relevant for the application in protective relaying and an analysis of their transient responses is needed. This may be investigated by CCVT simulation using the EMTP program and by performing actual tests [1, 2]. The results show that CCVT frequency response is not flat in the wide frequency range and that it behaves as a filter [2].

Since the CCVT components have influence on the frequency response curve shape, an idea to use the frequency response curve as a base for the CCVT performance analysis is suggested. For CCVTs installed in a substation, access to their components is difficult or, in some cases, impossible. Therefore, a new method for the CCVT frequency response field measurements from the secondary side was developed. The proposed method is easy to use and gives accurate results. It does not require any internal CCVT disassembly or access to its individual components. The results can be used for two main purposes. The first application is for EMTP-based CCVT digital model development and performance analysis using EMTP program. Parameters required for the CCVT digital model implementation are obtained from the frequency response curve and the CCVT analytic expression, by using a curve fitting procedure. The curve fitting method is also developed and presented in this paper. The other application is for the CCVT diagnostic. It is found that the frequency response curve is very sensitive to its internal component variation. This enables an easy detection of the CCVT component degradation or changes in the CCVT design.

EMTP simulations and preliminary laboratory tests are described first. Next, a description of test methods and measurements performed in a substation is given. Analysis of the results is presented at the end.

EMTP SIMULATIONS AND LABORATORY TESTS

This section describes approaches used to verify that measurements from the secondary side give results which are very close to the results obtained by performing measurements from the primary side. To validate the method, two approaches were adopted as discussed below.

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[1] The work was done while the author was with Texas A&M University

EMTP Simulations

This approach included simulation of a CCVT frequency response as seen from the primary and then from the secondary side. Frequency response curves obtained by the simulations were identical in both cases, as predicted by the theory.

Measurements on an Actual CCVT

The second approach included measurements on an actual 138kV CCVT [3]. The test was performed in a laboratory, and carried out as described below.

Test I. To illustrate the advantage of the measurement method from the secondary side, three different test methods were compared. Simplified CCVT test connections are given in Figure 2. Simulation of current magnitude through the compensating inductor Lc was the base for the method comparison. Figure 3 shows the current magnitudes for the three different measurement configurations. The first (1) represents EMTP simulation with an 80kV test signal being applied to the transformer primary. The second (2) is obtained by applying a 115 V signal from the secondary side, while the third (3) represents a 115 V signal applied to the CCVT primary. The secondary side based measurement (Figure 3, Curve 2) although not entirely identical to the ideal case, as shown in Figure 3, Curve 1, provides a distinct advantage over the primary based low voltage method as presented in Figure 3, Curve 3. The problems of generating unreasonably high voltage test signals are avoided, as well as the pitfalls associated with signal levels that might not be sufficient to fully excite the transformer magnetic circuits (coercive force related effects). In some cases, the connection presented in Figure 2(c) may not be applicable for field measurements since it requires access to the internal CCVT components.

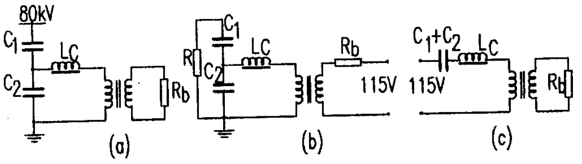


Figure 2. Simplified CCVT Connections for Simulation of Current Magnitudes through the Compensating Inductor Lc

Test II. This test included both, measurements from the primary side as shown in Figure 2(c), and from the secondary side as presented in Figure 2(b), with the coupling capacitor equivalent scheme instead of the actual stack. Frequency response curves are shown in Figure 4. Again, very good compliance between measurements from the primary side and from the secondary is observed. The results were encouraging for further development of a method intended for field measurements.

FIELD MEASUREMENT METHOD

This section outlines the methodology for field measurements of the CCVT frequency response with the excitation signal applied from the secondary side. Due to available measurement equipment capabilities, the measurements were restricted exclusively to the frequency response magnitude estimation. The phase response can easily be added if needed without changing the proposed methodology. The method for the CCVT frequency response field measurements is verified by performing tests in a substation.

Method Description

The general test circuit diagram is shown in Figure 5.

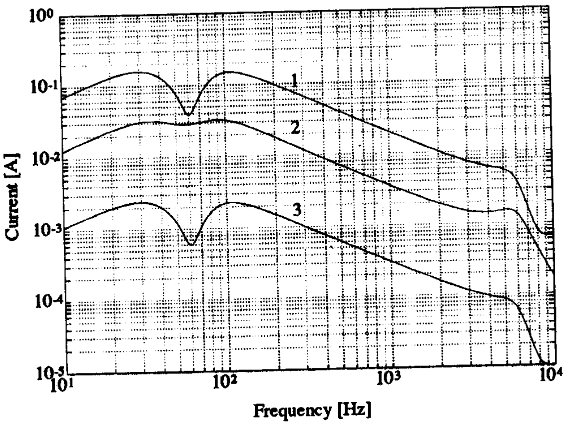


Figure 3. Comparison of Current Levels through the Inductor Lc for: (1) EMTP Simulation with a 80kV Test Signal Applied to Primary, (2) 115 V Test Signal Applied to the Secondary, and (3) 115 V Signal Applied to Primary (Simulation Data [3])

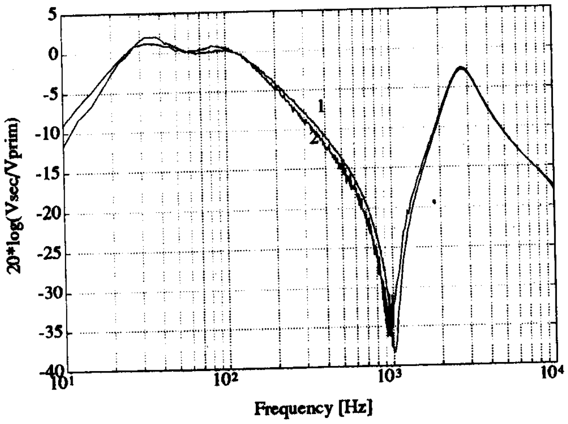


Figure 4. Typical 138kV CCVT Frequency Response Curves Obtained by Measurements, 1) From the Primary, 2) From the Secondary

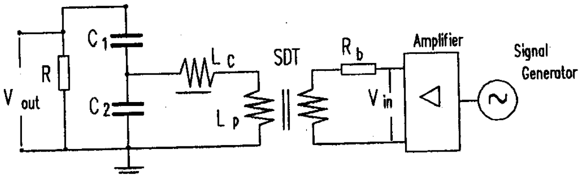
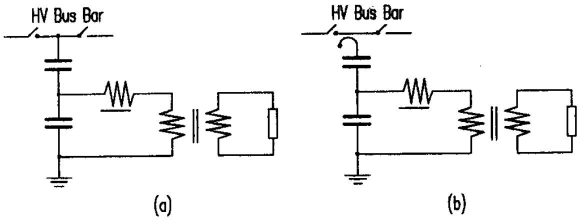


Figure 5. Circuit Diagram for the CCVT Frequency Response Measurements from the Secondary Side

On the CCVT primary side, a resistor R of 60Ω is connected. This value was selected in order to obtain sufficient output signal without affecting the CCVT response. Resistor Rb, representing the CCVT burden, is connected on the secondary in series with a voltage amplifier, which has low output impedance.

It should be observed that before performing the frequency response measurements, the primary bus bars where CCVTs are installed, must be de energized. CCVTs must also be disconnected from the bus bars on the primary side in order to minimize the "noise", caused by capacitively coupled voltages originating from the neighboring bus bars, which remain energized. Measurements have shown that induced voltage, in the part of bus bars where CCVTs are located, was typically 16 mV, measured on the resistor R. Circuit connection is presented in Figure 6a. When CCVTs were disconnected on the primary side, as shown in Figure 6b, the induced voltage was only 0.7mV.



(a) (b)

Figure 6. CCVT Position: (a) Connected to the HV Bus Bar; (b) Disconnected from the HV Bus Bar

A detailed block diagram of the CCVT connection and the measuring equipment is shown in Figure 7.

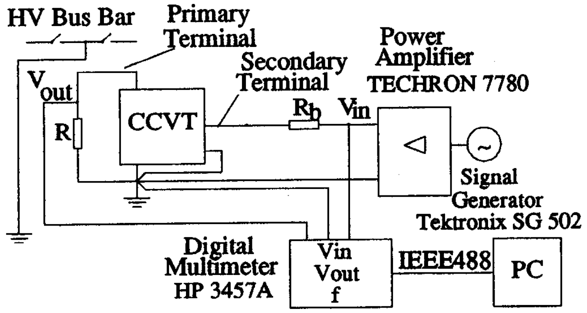


Figure 7. Block Diagram of the Method for the CCVT Frequency Response Field Measurements

The measurement method may be described as follows:

- the section of bus bars, where CCVTs are installed, must be de energized and grounded. The grounding serves both for operator protection and as an electrostatic shield lowering the measurement noise level,
- CCVT is disconnected from the HV bus bars,
- resistor R is connected on the CCVT primary side as shown in Figure 5,
- actual CCVT burden must be disconnected during the measurement,
- resistor, representing the CCVT burden, is then connected on the secondary in series with voltage amplifier, which has low output impedance,
- signal generator feeds amplifier and enables frequency change in the defined range,
- voltages Vin and Vout are measured at various frequencies and gain is calculated as:

$$G = 20\log(\frac{V_{out}}{V_{in}})$$

Field Measurements

Three 138kV CCVTs [4] connected in phases A, B and C of the same line were tested. The measurements were performed from the terminal box, where all three secondaries were connected as shown in Figure 8.

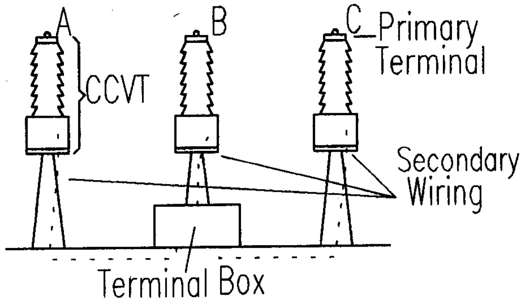


Figure 8. CCVT Layout and Location of the Terminal Box

In order to verify that the measuring results are correct, the frequency response curve waveshape was continuously monitored during the tests. The procedure was as follows: At each frequency step, voltages Vin, Vout and signal frequency were measured in sequence and the results were transferred, through an IEEE instrumentation bus, to the PC. Gain versus frequency was then automatically calculated and plotted on the screen by using the MATLAB software package [7]. The results of the frequency response measurements were compared with laboratory data obtained for the same type CCVT. This was the basis for the on-line method validation.

Typical circuit connection of a 138kV CCVT [4] is shown in Figure 9.

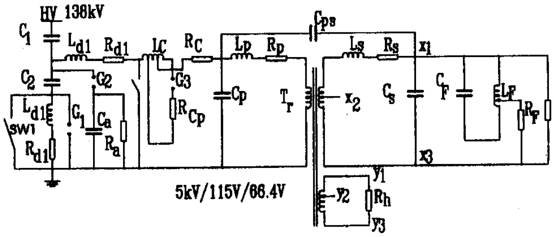


Figure 9. Typical Circuit Connection of a 138kV CCVT

In order to achieve the same CCVT operating condition as the one in a laboratory, measurements were carried out with switch SW1 closed and burden Zb disconnected. The results are shown in

Figure 10. Frequency response measurements performed in a laboratory, measured from the primary side are also shown in the same figure. It is evident that the results are very close to each other. The differences that exist in the region of deep attenuation (1.8 kHz) are due to the "base noise" level which was higher in the substation than in the laboratory. This has no effect on the resulting frequency curve. This effect can be further minimized, if necessary, by using a tracking filter and/or frequency selective voltmeter.

Other CCVT Frequency Response Measurements

In order to further verify the method, additional tests on two CCVTs of different types were performed. The selected CCVTs were of 138kV [5] and 345kV levels [6]. The measurements have been carried out in a laboratory. The "noise" level was measured prior to the tests. It was recorded to be as low as 0.06 mV. Frequency response measurements were performed as described in the previous section.

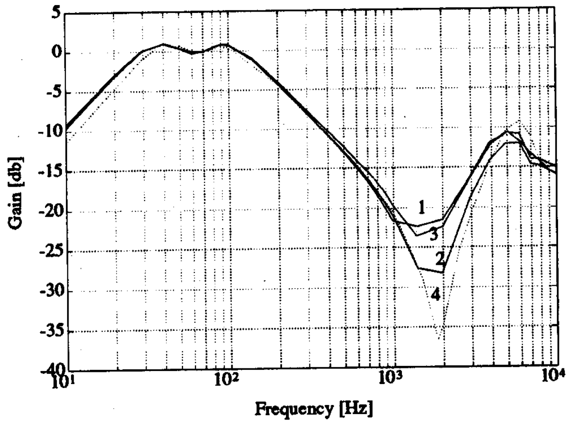


Figure 10. Frequency Response Measured in the Substation for 138kV CCVTs located in Phases: 1 - A, 2 - B, 3 - C; 4 - Frequency Response Measured in a Laboratory

First CCVT. This 138kV CCVT [5] was not equipped with drain coils. The results of the frequency response measurements are shown in Figure 11. The frequency response is as expected [2].

Second CCVT. This 345kV CCVT [6] was equipped with drain coils connected at the lower part of capacitor stack. Therefore, two measurements were performed. The first one, with drain coil in circuit, and the second one, with the drain coil bypassed. The results are shown in Figure 12. The differences are evident above 1 kHz, as expected [2].

By comparing frequency response of 138kV and 345kV CCVTs, it may be concluded that 345kV CCVT has a wider frequency bandwidth. This is due to the fact that tuning for higher voltage requires parameters which result in a lower Q factor than for 138kV CCVTs.

PERFORMANCE ANALYSIS METHOD

As it was outlined in the previous text, test results may be used for two main purposes described next.

EMTP-based CCVT Model Development

CCVT parameters can be estimated from the frequency response curve by using system identification methodology. Proper application of the system identification methods requires frequency response curves representing the magnitude as well as the phase response. Since, in our case, the phase response was not measured, a method that needs only the magnitude response was developed. Reference [9] investigates in detail the feasibility of complex transfer function estimation by using amplitude measurements only. It was found that the amplitude-only estimation gives acceptable results, although it shows larger relative error as compared to amplitude-phase estimation.

A simplified equivalent CCVT circuit shown in Figure 13 was adopted for the parameter estimation [2].

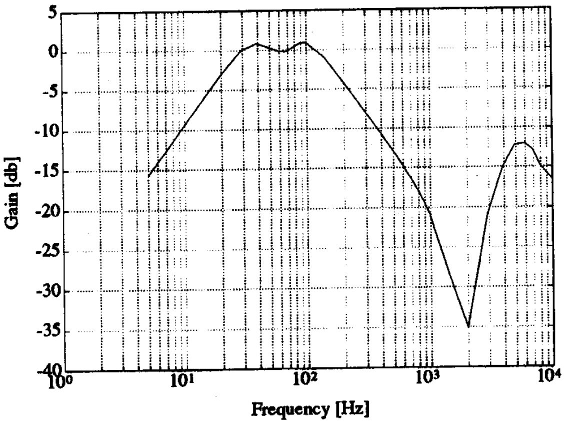


Figure 11. Frequency Response of the 138kV CCVT

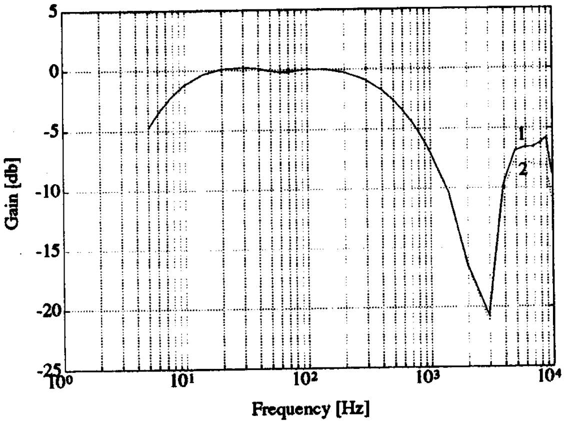


Figure 12. Frequency Response of the 345kV CCVT : 1 - With Drain Coil in Series with Capacitor Stack, 2 - Drain Coil Bypassed.

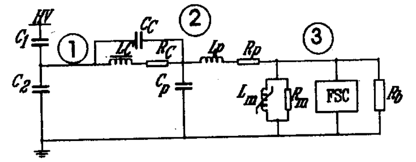


Figure 13. CCVT Circuit Representation Adopted for the Parameter Estimation

Some ferroresonant suppression circuits (FSC) are tuned to fundamental frequency. These circuits have high Q factor which was achieved by using inductance with a large mutual coupling [3,4,5,6] as shown in Figure 14a. EMTP-based model is described in paper [10]. The analytic model is represented in Figure 14b.

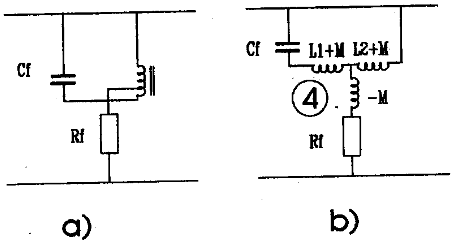


Figure 14. FSC Circuit Connection (a), Circuit Representation (b)

Nodal matrix for the CCVT model given in Figures 13 and 14 can be written as:

$$Y = \begin{vmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{vmatrix}$$

,where

$$Y_{11} = (jwC_1 + jwC_2 + jwC_c + \frac{1}{R_c + jwL_c})t^2$$

$$Y_{12} = Y_{21} = -(jwC_c + \frac{1}{R_c + jwL_c})t^2$$

$$Y_{22} = (jwC_c + \frac{1}{R_c + jwL_c} + jwCp + \frac{1}{R_p + jwL_p})t^2$$

$$Y_{23} = Y_{32} = -\frac{t^2}{R_p + jwL_p}$$

$$Y_{34} = Y_{43} = -\frac{1}{\frac{1}{jwC_f} + jw(L_1 + M)} - \frac{1}{jw(L_2 + M)}$$

$$Y_{33} = (\frac{1}{jwL_m} + \frac{1}{R_m} + \frac{1}{R_p + jwL_p})t^2 + \frac{1}{\frac{1}{jwC_f} + jw(L_1 + M)} + \frac{1}{jw(L_2 + M)} + \frac{1}{Rb}$$

$$Y_{44} = \frac{1}{\frac{1}{jwC_f} + jw(L_1 + M)} + \frac{1}{jw(L_2 + M)} + \frac{1}{R_f - jwM}$$

$$Y_{13} = Y_{14} = Y_{24} = Y_{31} = Y_{41} = Y_{42} = 0$$

, t - SDT ratio

$$I = \begin{vmatrix} jwC_1t & 0 & 0 & 0 \end{vmatrix}$$

Output voltage is calculated as:

$$E = [Y]^{-1} I$$

The parameter estimation procedure consists of two steps:

- measurement of the CCVT frequency response as described in the previous text
- parameter estimation using MATLAB software and the analytic method described

Frequency response curve should not include a large number of points, since due to measurement "noise" it may result with high error in parameter calculation. More points have to be included just in the region of interest.

In order to verify that this method has acceptable accuracy, two approaches were adopted. The first includes verification of parameter values for CCVTs measured in the laboratory [2]. The results are shown in Table I. Columns 2, 4 and 6 represent values obtained by measuring individual component parameters on a disassembled CCVT.

It should be recognized that individual component measurements include independent errors. In order to improve overall model accuracy, an additional step employing the nonlinear parameter fitting method was used. This method attempts to adjust parameters to match the model response to the frequency response measured on a fully assembled CCVT. The individual correction factors obtained by the parameter fitting method are shown in Table I. Columns 3, 5, and 7. The correction factors are close to unity with major deviations associated with the hard to measure capacitances Cc and Cp and the magnetizing branch elements Lm and Rm. Final parameter values can be calculated by multiplying columns 2&3, 4&5 and 6&7. It is evident that the suggested parameter fitting method can be used for EMTP-based CCVT model development. It is important to note that the transformer marked as Type 3. in Table I. employs somewhat different ferroresonance suppression circuit topology resulting in a different set of component parameters (T2, Lf, Rfs). Please refer to [8] for actual connection diagram.

The second approach included verification of the method using field measurements performed on the secondary side. This method was applied on the three 138kV CCVTs with the circuit connection shown in Figure 9. Table II shows the CCVT parameter values (Table I, Columns 2&3) obtained by laboratory measurement and measurement obtained for the same type CCVTs in a substation. Values listed were obtained after applying the fitting method.

Identified models were further used to demonstrate the frequency response variations among 4 units of the same type. The comparison is based on the results given in Table II. All models were simulated using EMTP program. Figures 15a and 15b present magnitude and phase responses respectively. Again, this method has shown a very good compliance with measurements (see Figure 10).

CCVT Diagnostics

The proposed method shows significant sensitivity of the CCVT frequency response to internal component variations. This enables an easy detection of the CCVT component degradation or changes in the CCVT design. As an illustration, two examples are included in the paper.

Example I illustrates PLC system influence on the frequency response. This was done by performing measurements, described in the previous text, with SW1 opened. The results for the CCVT located in Phase C, which had PLC system added, are shown in Figure 16. The differences in frequency response are evident in the region above 1 kHz as expected.

Example II is illustrative for the CCVT diagnostic. Figure 17 shows two frequency response curves for the same type CCVTs. One representing the "healthy" CCVT (curve #1) and the other, CCVT with a failure (curve #2). Additional measurements were performed in order to determine what is wrong with the second CCVT. It was found that the step-down transformer (SDT) V-I curve differs from the "healthy" one as shown in Figure 18. SDT ratio was unchanged.

The problem was pinpointed to the SDT core, which caused large losses. The same conclusion was reached by using parameter fitting procedure. Rm was found reduced to a value of 17kΩ.

As a conclusion, whenever the reference frequency response differs from the frequency response obtained after some period of the CCVT operation, CCVT should be de energized and tested in a laboratory.

Table I. CCVT Parameter Estimation from the Laboratory Measurements

	138kV CCVTs *					
	Type1 [4]		Type 2 [3]		Type 3 [8]	
Parameter	Measured	Corr	Measured	Corr	Measured	Corr
C1	5.65 nF	1.00	5.3 nF	**	6.75 nF	***
C2	81.1 nF	1.00	80 nF	**	84.11 nF	***
Lc	58.3 H	0.97	69 H	1.16	74.4 H	0.91
Rc	228 Ω	1.00	685 Ω	0.92	120 Ω	1.20
Cc	130 pF	0.98	250 pF	1.30	1.2 nF	1.18
Lp	2.8 H	1.02	8.9 H	0.83	2 H	0.57
Rp	400 Ω	1.00	830 Ω	1.00	230 Ω	0.83
Cp	140 pF	1.10	100 p	0.97	400 pF	1.05
Rm	1e6 Ω	1.00	1e6 Ω	1.20	1e6 Ω	0.87
Lm	1e4 H	1.00	1e4 H	0.13	1.6e3 H	0.95
t	40.5	1.03	43.5	1.01	47	0.92
M	0.16	1.02	0.16	1.01	-	-
L1	0.318 H	1.00	0.32	1.00	-	-
L2	0.084 H	1.00	0.084	1.00	-	-
Cf	9.6 µF	1.00	8 µF	1.00	-	-
Rf	37.5 Ω	1.00	40 Ω	1.00	8.9 Ω	1.00
T2	-	-	-	-	1.666	0.98
Lf	-	-	-	-	2.2 H	1.00
Rfs	-	-	-	-	74.6 Ω	1.00

* All CCVTs were rated 200VA, with relaying ratios and 1.2% accuracy [3,4,5,6,8]

** Not measured; capacitor stack was not available, values according to [3].

*** Not measured; capacitor stack was not available, values according to [8].

Table II. CCVT Parameter Estimation from the Field Measurements

	Laboratory	Field	Field	Field
Parameter		Phase A	Phase B	Phase C
C1	5.65 nF	5.75 nF	5.55 nF	5.86 nF
C2	81.1 nF	81.1 nF	81.1 nF	81.1 nF
Lc	56.5 H	75.9 H	75.6 H	73.4 H
Rc	228 Ω	243 Ω	254 Ω	228 Ω
Cc	127 pF	135 pF	112 pF	125 pF
Lp	2.85 H	2.25 H	1.85 H	2.13 H
Rp	400 Ω	453 Ω	489 Ω	401 Ω
Cp	154 pF	294 pF	310 pF	284 pF
Rm	1e6 Ω	3.7e5 Ω	4.3e5 Ω	3.6e5 Ω
Lm	1e4 H	7.5e3 H	5.5e3 H	6.3e3 H
t	41.7	46.6	45.6	47.5
M	0.163	0.162	0.162	0.161
L1	0.318 H	0.318 H	0.318 H	0.318 H
L2	0.084 H	0.084 H	0.084 H	0.084 H
Cf	9.6 µH	9.6 µH	9.6 µH	9.6 µH
Rf	37.5 Ω	37.5 Ω	37.5 Ω	37.5 Ω

It is evident that by having the referent frequency response curve and performing tests after some period of the CCVT operation, valuable results and conclusions about the CCVT performance may be established. One possible way of having a referent frequency response curves is to obtain them from the manufacturers.

The CCVT frequency response could be measured in the factory, after a CCVT is assembled and calibrated. The results can also be used for the production quality monitoring.

The other way is performing frequency response measurement immediately after a CCVT installation and keeping the results for future tests.

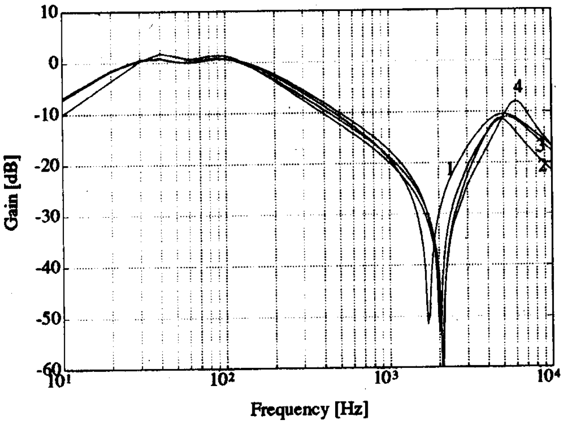


Figure 15a. Frequency Responses Magnitude of the 138kV CCVTs [4] obtained by using the Parameter Fitting Method and EMTP Simulations (1,2,3 - Field Measurements; 4 - Laboratory Measurements)

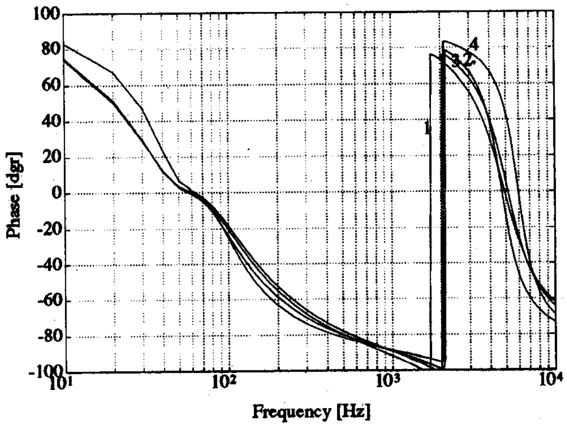


Figure 15b. Phase Response of the 138kV CCVTs [4] obtained by using the Parameter Fitting Method and EMTP Simulations (1, 2, 3 - Field Measurements; 4 - Laboratory Measurements)

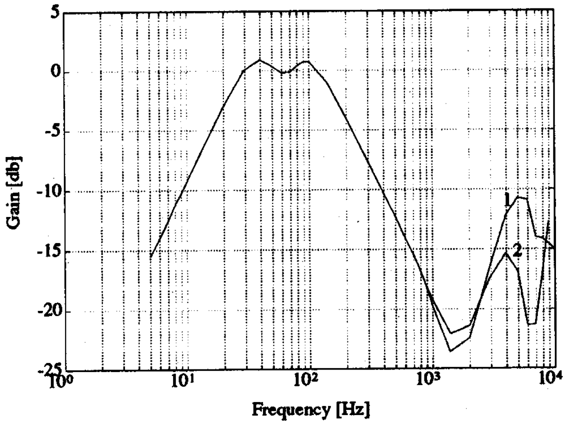


Figure 16. Frequency Response for the 138kV CCVT Located in Phase C: 1 - With PLC, 2 - Without PLC

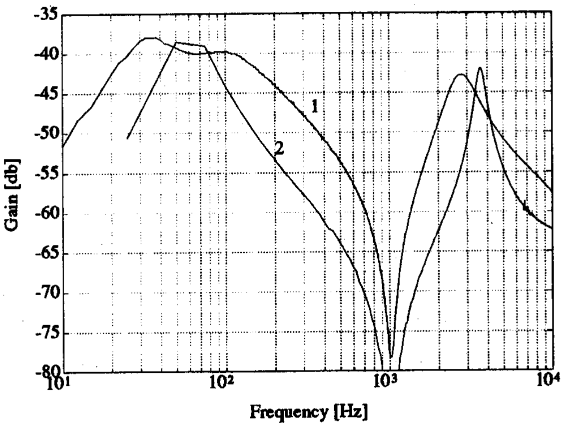


Figure 17. frequency response Curves Representing the Good CCVT (1) and the CCVT with Failure (2)

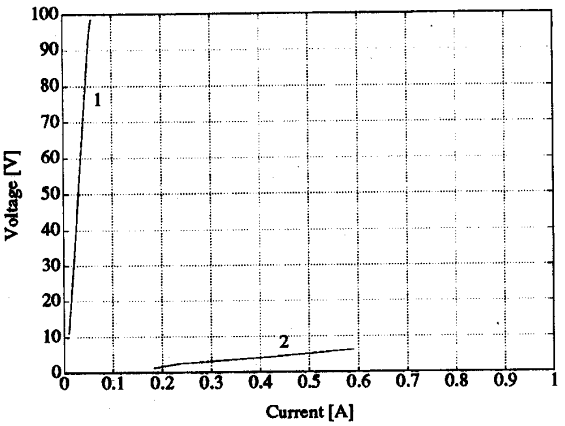


Figure 18. V-I Curves for the Good CCVT (1) and the CCVT with Failure (2)

CONCLUSIONS

The main conclusions of the paper are the following:

- A new method for the CCVT frequency response field measurements from the secondary side is developed. The proposed method is easy to use and gives accurate results. It does not require any internal CCVT disassembly or access to its individual components. The results can be used for two main purposes as described next.
- The first application is for EMTP-based CCVT digital model development and performance analysis using EMTP program. Parameters required for the CCVT digital model implementation can be obtained from the frequency response curve and the CCVT analytic expression, by using a curve fitting procedure. The curve fitting method is also developed and presented in the paper.
- The second application is for the CCVT diagnostic. Frequency response curve is very sensitive to its internal component variation. This enables an easy detection of the CCVT component degradation or changes in the CCVT design.

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DISCUSSION

Bruce A. Mork (Michigan Technological University, Houghton, MI): The authors have presented a practical method of obtaining field measurements of CCVT frequency response. These measurements are used to obtain the parameters for a simplified equivalent circuit which is then implemented in EMTP. Comments made here shall be directed toward the EMTP model and its application in transient studies:

The frequency response is measured at low linear levels of excitation. Could the authors explain why they avoid measuring the frequency response at "a large number of points?" If there is "noise" in the measurement, how can one be more confident of getting better parameter results if measurements are taken at wider frequency spacings? Smoothing a noisy set of closely-spaced measurements would seem preferable to the potential error introduced by noise in widely-spaced measurements.

The model has been developed, implemented, and verified at low linear levels of excitation. All work appears to have been done in the frequency domain. While this provides reassurance that the reduced equivalent circuit is topologically correct, it does not address the very important issue of magnetic saturation of the step-down transformer. How do the authors represent the nonlinearities in their model? How are these nonlinear parameters obtained? How must this model be modified before using it to simulate transient conditions involving system overvoltages? Has this model been verified by time domain simulations?

The model seems promising. It would be helpful to those who use EMTP as a tool to model transients if the authors could provide time domain verification results or point to a reference that contains some benchmarking results.

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Lj. Kojovic, M. Kezunovic, V. Skendzic, C. W. Fromen, D. R. Sevcik: The authors would like to thank Dr. Mork for his interest in this paper, and his valuable questions that make it possible for us to further explain our work.

With regard to the number of points used in the measurements it should be pointed out that parametric system identification requires the excitation signal energy to be concentrated at the frequencies which provide the greatest contribution to the knowledge about the parameters. As shown in [1] the minimum number of frequencies required to identify the n parameters describing a linear system is equal to $(n+1)/2$. Reference [1] also gives numeric procedures suitable for estimating the optimal frequency spacing (excitation signal) based on the preliminary transfer function measurements. The number of measurement frequencies determines the computation time needed for parameter estimation and may, if large, slow down the convergence process.

Smoothing the noisy set of closely spaced measurements may also smooth out an existing high Q resonance. It is much more appropriate to perform multiple measurements on the same (small) set of frequencies, and than use the available information to statistically determine the confidence interval (error bounds) for each individual frequency. Without resorting to *optimal* techniques [1], our experience shows that a set of 10 frequencies per decade, evenly spaced on the logarithmic scale provides excellent results when applied to CCVTs.

The statement that the model has been based on low level measurements is not entirely correct. By feeding the transformer from the secondary side, much higher voltage and current levels inside the transformer were obtained, closely simulating the actual operating conditions. The presented identification procedure however concentrates on obtaining the precise linear model.

Saturation effects, if needed, can easily be included by using EMTP saturable reactor models. Entering the required parameters is simple, provided that the saturation curves can be obtained from the manufacturer. An alternate approach would be to perform individual element measurements on a disassembled CCVT unit.

This model was also verified in time domain by using EMTP simulations. Results are reported in [2].

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