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DIGITAL MODELS OF COUPLING CAPACITOR VOLTAGE TRANSFORMERS FOR PROTECTIVE RELAY TRANSIENT STUDIES

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Abstract– This paper describes an EPRI development of digital Coupling Capacitor Voltage Transformer (CCVT) models that are intended for digital simulation of fault transients. Experimental techniques for laboratory measurements of the CCVT parameters are outlined. A sensitivity study is performed to identify the influence of various CCVT parameters on the transient behavior relevant for the relaying studies. Finally, digital models of three different CCVTs are given and their transient behavior is compared to the behavior of the actual transformers.

Keywords: Coupling Capacitor Voltage Transformer, CCVT Transient Response, Digital Simulation, EMTP.

INTRODUCTION

This paper introduces digital models of Coupling Capacitor Voltage Transformers (CCVT) that are based on the Electromagnetic Transients Program (EMTP) modeling techniques [1]. These models can be used in EMTP based simulators to study transient behavior of CCVT as it affects protective relaying. The models are being incorporated in a digital simulator developed for protective relaying system studies [2, 3].

The steady state performance of current and potential transformers (including CCVTs) is well understood [4]. However, the transient performance is not covered by any standard. Specifically for CCVTs, which have complex circuitry, attempts have been made to define some acceptable transient performance specifications [5]. A number of studies have been conducted to investigate the transient behavior phenomena [6–10]. An analog model of a CCVT was developed and the time response was studied using this model [6]. Some experiments were also conducted to obtain harmonic response of the actual CCVTs [7]. Several studies were concentrating on the influence of the CCVT characteristics on the protective relaying performance [8, 9]. The mentioned studies gave considerable insight into the CCVT transient behavior as well as some understanding of the influence of this behavior on the protective relaying performance. Based on these results, it can be concluded that a detailed representation of the CCVT transient behavior may have to be taken into account for application testing of protective relaying systems.

Recent development of digital simulators for relay testing has enabled the use of EMTP modeling techniques for generation of fault transients [2, 3]. The need to represent the transient behavior of the CCVT has prompted investigation of digital modeling techniques for development of EMTP based CCVT models. Previous attempts to develop improved CCVT models for relaying studies have not included some of the CCVT stray capacitances and the variations of ferroresonance suppression circuit designs relevant for detailed analysis of the CCVT response to the fault transients [10–12]. The most recent papers on the digital simulator development for relay testing did not report any new CCVT model developments [13–15].

This paper describes a procedure for development of detailed digital models of CCVTs. Models have been developed for three CCVT designs. Experimental techniques for laboratory measurement of the relevant CCVT parameters are outlined and the results are given. The identified parameters have been used to develop EMTP based models of the CCVTs. Several cases of the CCVT behavior in frequency domain have been investigated by comparing results measured on the actual CCVTs with the results obtained by simulations using digital models. It is demonstrated that the digital models provide quite accurate representation of the transient CCVT behavior relevant for protective relaying studies.

The first part of the paper introduces measurement techniques for identification of the important CCVT parameters. The model development is given in the next section, and model validation is discussed at the end.

MEASUREMENT TECHNIQUES

This section outlines measurement techniques, used to obtain CCVT parameters, and the analysis needed for the model development. The aim of this study was to develop a relatively simple measurement approach that can be carried out in a laboratory equipped with readily available instrumentation.

The example used to illustrate the measurement techniques is obtained using a PCA-5 CCVT [16]. The same measurement approach is used to obtain the parameters of interest for the other two CCVT models.

CCVT Measurements

A generic model of a CCVT is shown in Figure 1. The R, L, C parameters were measured using a direct measurement approach. Some of the stray capacitances have been measured by an indirect approach. This measurement procedure is described below.

Step Down Transformer (SDT) short circuit measurements have been done in order to estimate the resistive and inductive portion of the primary and secondary winding impedances. The stray capacitances of the windings were calculated from the known leakage inductances and the resonance frequencies.

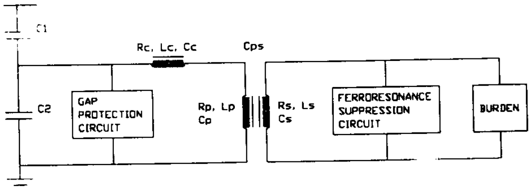

Figure 1. Generic CCVT Model.

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The data needed for SDT primary winding leakage inductance calculation was obtained by measuring the input impedance as seen from the primary side, with the secondary side short circuited. The same procedure was then repeated for the secondary winding leakage inductance. Both measurements are shown in Figure 2. Secondary impedance is referred to the primary. It can be seen that the resonance frequency for the primary winding is much smaller than for the secondary.

For the SDT primary winding, a leakage inductance L_p was measured and found to be $L_p = 2.8H$. As it can be seen from Figure 2, the resonance frequency f_r for primary winding is $f_r = 8kHz$. The calculated value for the SDT primary winding stray capacitance is then:

$$C_p = \frac{1}{L_p(2\pi f_r)^2} = 140pF$$

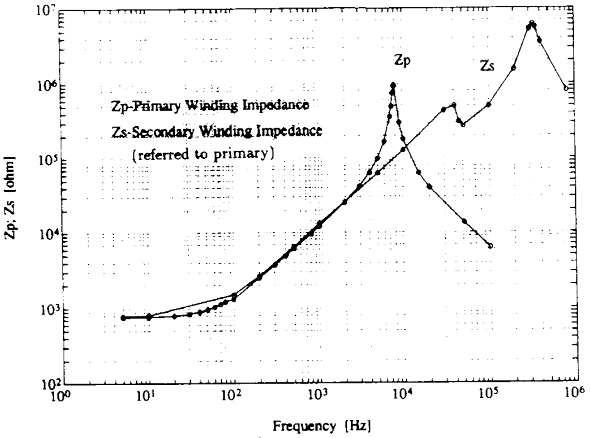

Figure 2. Measurements of the CCVT Step Down Transformer Short Circuit Winding Impedance vs. Frequency.

In order to define the stray capacitance of the coupling inductor winding, measurement of its impedance as a function of frequency has been performed. The result is shown in Figure 3. The winding stray capacitance was calculated from the measured inductance and the resonance frequency. The measured inductance is $L_i = 58.35H$, the resonance frequency is $f_r = 1830Hz$. The calculated value for the stray capacitance is then: $C_c = 130pF$.

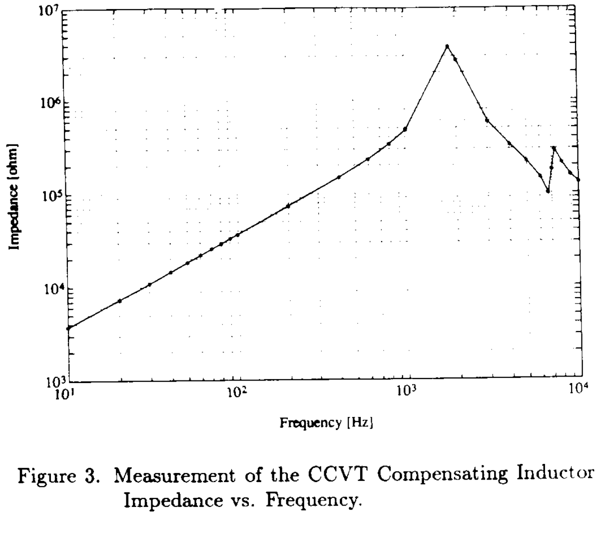

Figure 3. Measurement of the CCVT Compensating Inductor Impedance vs. Frequency.

CCVT Frequency Response Measurements

The frequency response measurement is needed for sensitivity analysis of CCVT parameters and for model validation. This measurement can be done using various approaches. The following measurement techniques have been evaluated in this study:

a) sine waveform signal generator with continuous frequency control capability, as shown in Figure 4. The tests were done using 100V sinusoidal signal in the 10 Hz to 10 kHz frequency range with a resistive burden of 100Ω,

b) dynamic signal analyzer (HP 3561), as shown in Figure 5. The tests were done using an input signal of $30V_{RMS}$ in the 10 Hz to 100 kHz frequency range with a resistive burden of 100Ω,

The main problem in the frequency response measurements was to provide acceptable test signal voltage level over the broad frequency range (10 Hz–10 kHz). It was also recognized that an instrument for direct measurement of the frequency response would be highly desirable.

A readily available solution to the voltage level problem was the use of a solid state power amplifier which can provide up to 100 Vrms. In order to obtain an acceptable ratio between the test voltage and the rated CCVT primary voltage, an equivalent of the CCVT stack capacitor was used. The stack capacitor circuit and its equivalent are shown in Figure 6. This has reduced the rated primary voltage down to the 5kV–15kV level in the cases studied. Experiments were conducted to verify the measurement accuracy as a function of the voltage level. The results have shown that test voltage in the order of 1% of the reduced rated primary voltage provides good measurement accuracy. This confirmed results from previous studies [17]. Therefore, the first measurement technique using a signal generator provides acceptable accuracy and hence this technique has been used.

Since the sensitivity study had required a number of frequency response measurements to be taken, it was found that the second measurement technique was more convenient. The dynamic signal analyzer provides voltage test signals for all the frequencies in the range simultaneously. This results in a reduced voltage level at each of the frequencies. The measurement accuracy of this technique has been shown to be acceptable for the sensitivity study measurements. However, the model validation measurements had to be performed using the first technique.

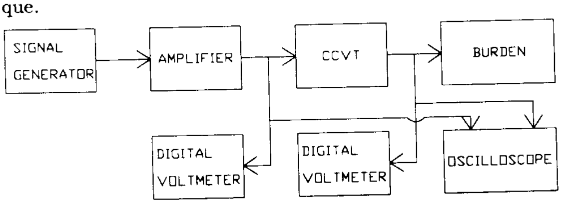

Figure 4. Measurement of CCVT Frequency Response by Using a Signal Generator.

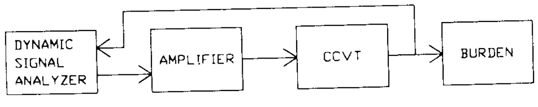

Figure 5. Measurement of Frequency Response from CCVT Primary Side by Using a Dynamic Signal Analyzer

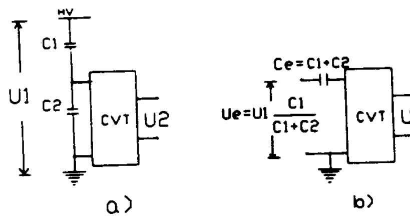

Figure 6. **Coupling Capacitor** Circuit: a) Real; b) Equivalent

MODEL DEVELOPMENT

The approach taken for the model development was to begin with a general CCVT model. It was validated based on a frequency response comparison between the measurements on an actual CCVT and the EMTP simulations. Sensitivity study of the frequency response was carried out in order to identify the CCVT parameters that are most relevant for the transient behavior representation. This resulted in a simplified model which appears to be quite appropriate for relaying studies. The PCA-5 CCVT type is used in this section to illustrate the model development approach.

General CCVT Model

A general CCVT model can be represented as shown in Figure 7. It consists of elements such as: compensating inductor (R_c, L_c, C_c), step-down transformer (R_p, L_p, C_p, C_{ps}, R_s, L_s, C_s, L_m, R_m), ferroresonance suppression circuit (R_f, L_f, C_f), drain coils (Ld_1, Ld_2), and other circuits with L,C elements and gaps which in many cases are non-linear. These elements can influence the transient response of the CCVT and can considerably distort the secondary signal. Their detailed representation results in a complex CCVT model requiring data that is not readily available. Detailed CCVT modeling may require considerable computation time as well.

In order to reduce the CCVT model complexity, a sensitivity study of the influence of various parameters on the CCVT frequency response was performed. The results of this study are given next.

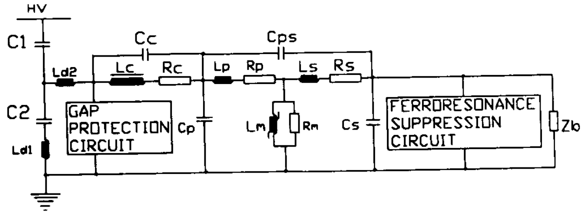

Figure 7. General CCVT Model

Sensitivity Analysis in Frequency Domain

The sensitivity analysis has been performed by changing the selected CCVT parameters and observing the frequency response. The coupling capacitor ($C_1 \parallel C_2$), compensating inductor stray capacitances (C_c), and step down transformer primary winding stray capacitance (C_p) influences are shown in Figures 8, 9 and 10 respectively. It can be observed that the mentioned parameters have significant influence on the CCVT transient response. The same behavior is obtained by the EMTP based model of the basic CCVT circuitry shown in Figure 7. The EMTP based simulation results are shown in Figure 11 (C_c)

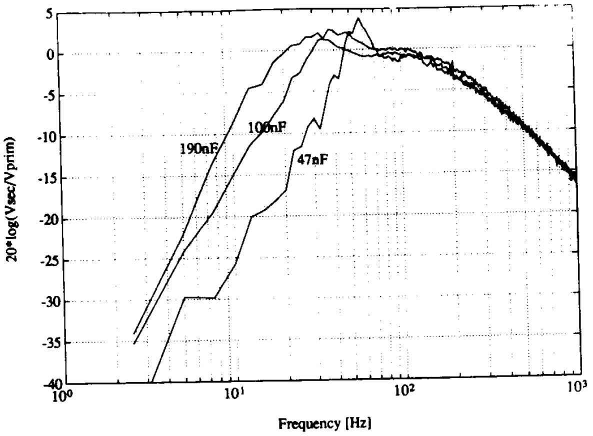

Figure 8. CCVT Coupling Capacitor Influence on Frequency Response (Measured by Using Dynamic Signal Analyzer).

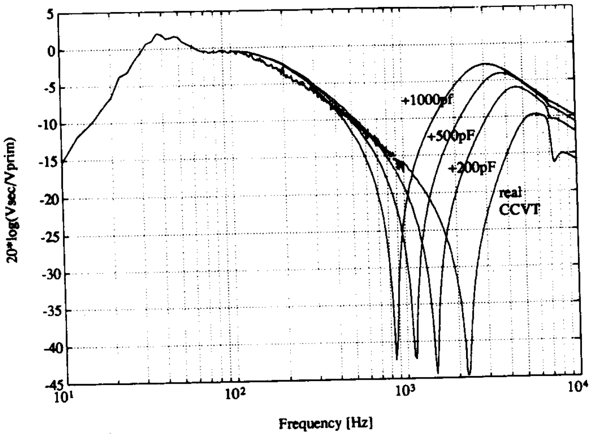

Figure 9. Influence of Compensating Inductor Stray Capacitance on CCVT Frequency Response (Measured by Using Dynamic Signal Analyzer).

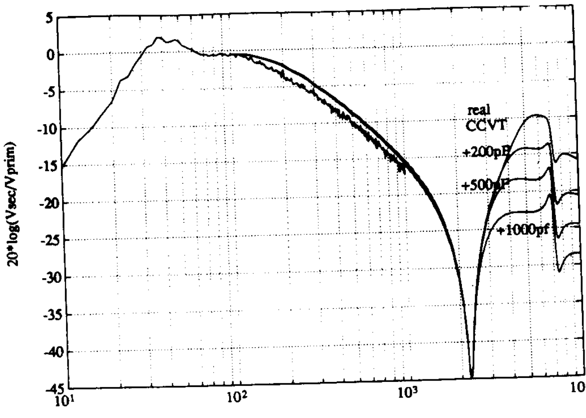

Figure 10. Influence of SDT Primary Winding Stray Capacitance on CCVT Frequency Response (Measured by Using Dynamic Signal Analyzer).

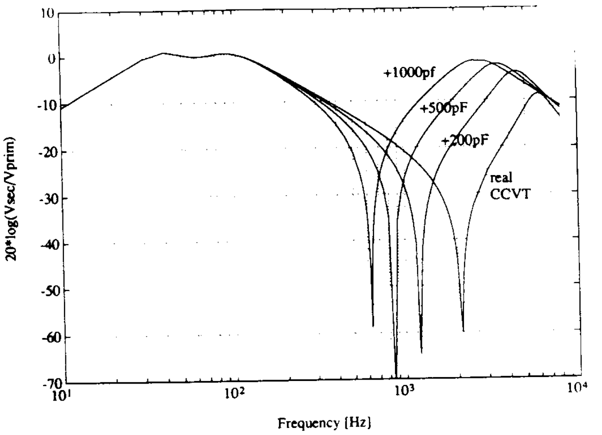

Figure 11. Influence of Compensating Inductor Stray Capacitance on CCVT Frequency Response (Simulated Using the EMTP Model).

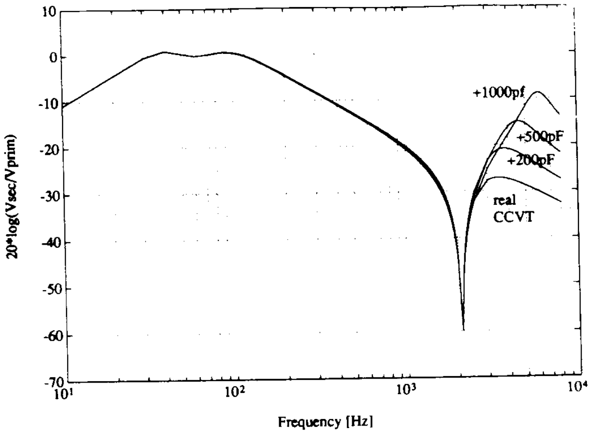

Figure 12. Influence of SDT Primary Winding Stray Capacitance on CCVT Frequency Response (Simulated by Using the EMTP Model).

and Figure 12 (C_p). The influence of the secondary winding stray capacitance (C_s), stray capacitance between primary and secondary windings (C_{ps}), secondary winding resistance (R_s), leakage inductance (L_s), and drain coils (Ld_1, Ld_2) was determined to be small in the range up to 10kHz. The gap protection circuit has no influence on the frequency response unless over voltage occurs. The effect of the over voltage has not been taken into consideration at this time since it may not be relevant for most of the relaying studies. The influence of the step down transformer iron losses (R_m) can not be directly measured and this had to be investigated using EMTP simulations.

The existing EMTP subroutine "TRANSFORMER" has been used to represent the CCVT step–down transformer. The use of this subroutine also requires selection of values for R_s and L_s.Since the influence of those elements is small, some measurement time can be saved by arbitrarily adopting some small values as shown in Figures 18, 20 and 22.

The simulation results for R_m are shown in Figure 13. It can be observed that influence of R_m may be neglected for values over $1M\Omega$. Finally, an EMTP simulation was carried out to demonstrate that the influence of the CCVT burden on the transient behavior may be significant, as shown in Figure 14.

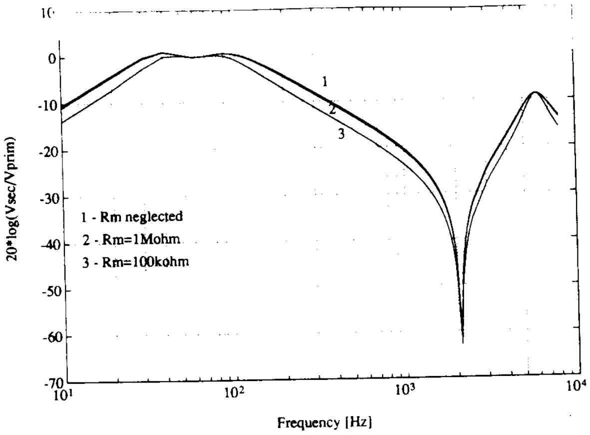

Figure 13. SDT Iron Loss Influence on CCVT Frequency Response (Simulated by Using the EMTP Model).

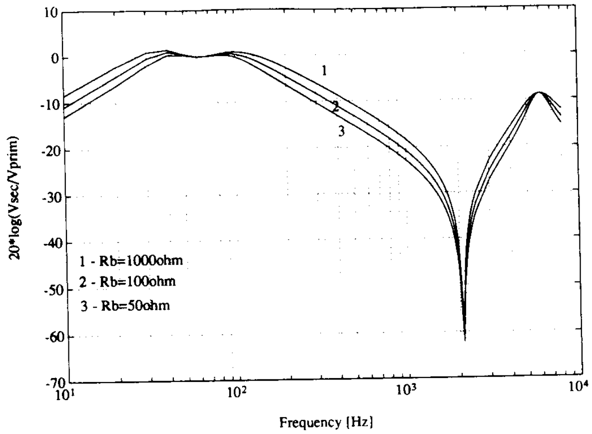

Figure 14. CCVT Burden Influence on Frequency Response (Simulated by Using the EMTP Model).

As a result of the sensitivity analysis, the general CCVT model given in Figure 7 was reduced to a simplified model given in Figure 15. This model was used to perform further analysis of the CCVT transient behavior.

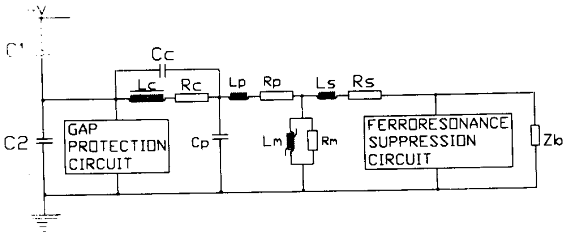

Figure 15. Simplified CCVT Model

Further Analysis of the Frequency Response

The purpose of this additional analysis was to demonstrate the importance of stray capacitance (C_c, C_p) and ferroresonance suppression circuit (FSC) representation in the model.

The simulation results that demonstrate the model frequency response when C_c and C_p parameters are neglected are shown in Figure 16. If the stray capacitances combined with the ferroresonance suppression circuit are neglected, the frequency response is given in Figure 17.

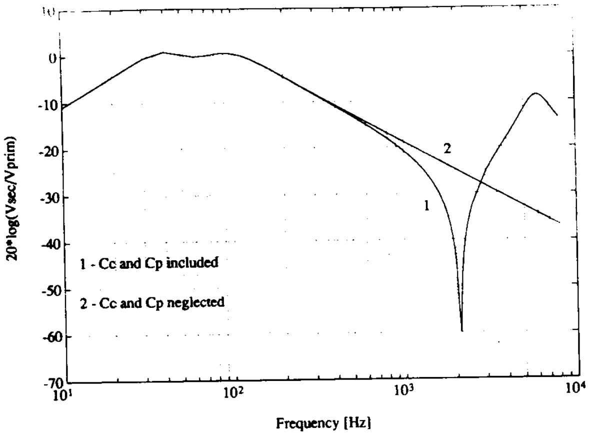

Figure 16. Influence of C_c and C_p Parameters on the Frequency Response of the Simplified CCVT Model.

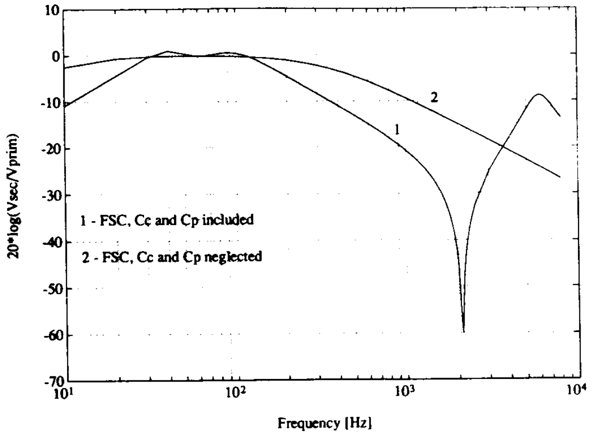

Figure 17. Combined Influence of the C_c, C_p and FSC on the Frequency Response of the Simplified CCVT Model.

The simulation results gave an indication that the stray capacitances (C_c, C_p) and the ferroresonance suppression circuit (FSC) need to be taken into account if a study of CCVT transient behavior is to be performed for the protective relay application testing purposes.

MODEL VALIDATION

This section of the paper describes validation of the CCVT models which were developed. The validation is based on comparison of the frequency responses obtained by measurements with the ones obtained by EMTP simulations. The value of the burden used for the comparison study was 100Ω resistive.

Digital Model of the PCA-5 CCVT

After all the CCVT parameters were measured, an PCA-5 model was developed. The circuit diagram that is the basis for the EMTP model is shown in Figure 18.

Comparison between the measured frequency response and the one obtained from EMTP simulation is shown in Figure 19.

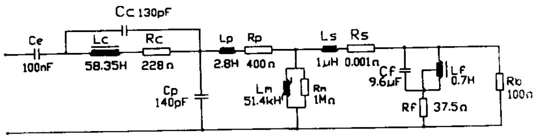

Figure 18. EMTP Model of the PCA-5 CCVT Circuit Design

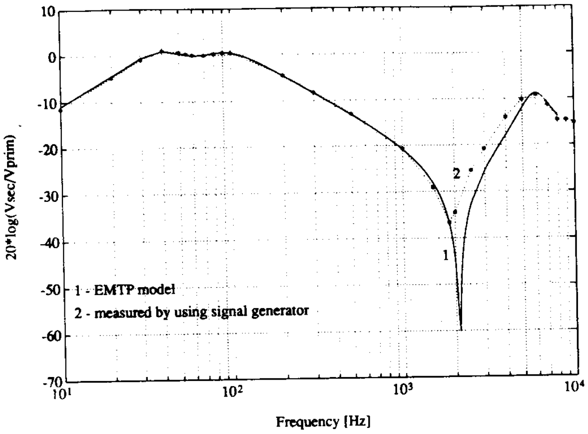

Figure 19. PCA-5 CCVT Frequency Response (Measured vs. EMTP Simulation).

Digital Model of the GE CD-31B CCVT

A CCVT circuit diagram adopted for the EMTP model of the CD-31B is given in Figure 20 [18]. Comparison between the measured frequency response and the one obtained from EMTP is shown in Figure 21.

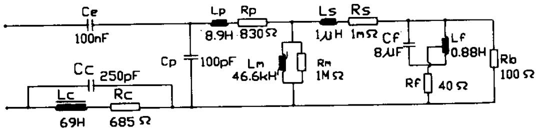

Figure 20. EMTP Model of the CD-31B CCVT Circuit Diagram.

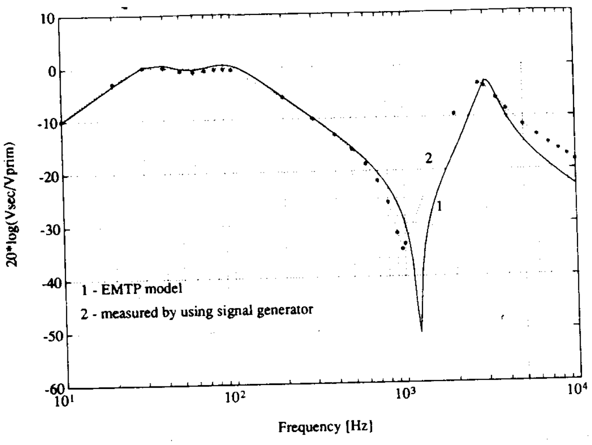

Figure 21. CD-31B CCVT Frequency Response (Measured vs. EMTP Simulation).

Digital Model of the Trench Electric TEHM 345 CCVT

The circuit diagram used for the digital model development is shown in Figure 22 [19]. The ferroresonance suppression circuit is designed by using a gap and a small resistance value connected at the secondary. Due to this design solution, the ferroresonance suppression circuit does not have any influence on the frequency response unless over voltage occurs. Therefore, the effect of the ferroresonance suppression circuit is not taken into account in the EMTP based model simulation. Comparison between the frequency response obtained by measurements and the one obtained from EMTP simulations is shown in Figure 23. It should be noted that the CCVT circuitry in this unit is immersed in oil, which was drained out at the time of measurements.

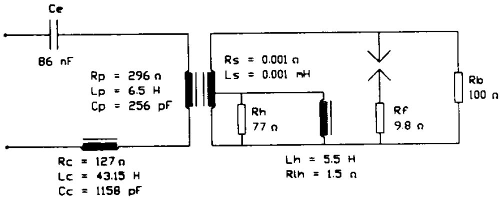

Figure 22. EMTP Model of the TEHM 345 CCVT Circuit Diagram.

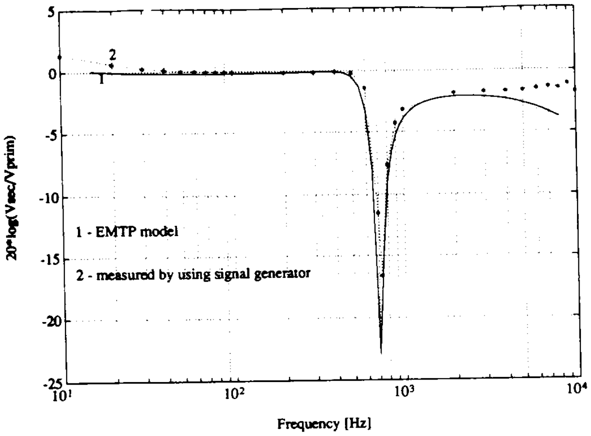

Figure 23. TEHM 345 CCVT Frequency Response (Measured vs. EMTP Simulation).

Validation Assessment

In all of the three cases the results show that the simulated values are almost identical to the measured values in the frequency range from 10 Hz up to 1 kHz. The main difference between simulated and measured values is at the points of high Q–factor resonance. This is due to the fact that the EMTP simulation does not take into account iron losses during the frequency response calculations while the measurements reflect them. The difference at higher frequencies comes from limited accuracy in the stray capacitance measurements. This may be due to the neighboring components influencing the measurements as well as to the L_C inductance being frequency dependent in the range. The EMTP simulation did not take this effect into account.

CONCLUSIONS

The results presented in this paper show the following:

- detailed digital models of CCVTs for transient relay studies can be developed using a relatively simple measurement approach combined with the modeling capability of an EMTP.
- the level of the modeling detail needed for relaying studies requires accurate representation of some of the stray capacitances and the ferroresonance suppression circuit, which has not been widely recognized in the past.
- analysis of the transient behavior for the three CCVT models indicates that all of the CCVT designs have significantly different transient response.

Acknowledgments

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From 1984 to 1989 he was with the Electrical Engineering Department at the University of Split. Currently he is a graduate student at Texas A&M University.

Charles W. Fromen (M'68, SM'85) was born in Atlanta, Georgia, on March 11, 1944. He received a Bachelor of Science Degree in Electrical Engineering from Texas A&M University in 1968. Upon graduation, Mr. Fromen joined Houston Lighting & Power Company. He was assigned first to the Distribution Relay Protection Group in 1968. The he was assigned to the Transmission & Generator Relay Protection Group in 1972. Since 1984 he has had the title of Senior Consulting Engineer. He is the HL&P Co. technical representative for the East Tie HVDC Project.

Mr. Fromen has been the HL&P Co. representative to the IEEE Power Systems Relaying Committee since 1973 and is a member of that committee. He is a Registered Professional Engineer in the State of Texas.

Donald (Don) R. Sevcik (M'81) was born in El Campo, Texas in 1953. He received his Bachelor of Science Degree in Electrical Engineering from Texas A&M University in 1975.

Mr. Sevcik is employed by Houston Lighting & Power Company in 1975 and is presently a Lead Engineer. Has worked in the following areas: Power Plant Electrical Systems (1975 to 1977). System Studies (1977 to 1979), and Transmission and Generation Protection (1979 to present).

Mr. Sevcik is a Registered Professional Engineer in Texas. He is a former officer of the Houston Chapter of the Power Engineering Society.

Stig L. Nilsson (F'88) is a Senior Program Manager, Transmission Substations Program in the Electrical Systems Division, at the Electric Power Research Institute (EPRI) in Palo Alto, California.

Before joining EPRI in 1975, Nilsson worked for three years at the Boeing Company, assigned to the Boeing Electronic Utility Instrumentation and Control Department in the Portland, Oregon office. He spent the last six months with the company in the Computer Services Division as a Program Manager.

Between 1962 and 1972, Nilsson worked for ASEA Sweden, at first involved with simulation of HVDC systems. In 1963, he was assigned to the ASEA Konti–Scan HVDC project as Control Engineer, and in 1967 he was assigned to the ASEA–GE joint venture project for the Pacific HVDC Intertie Project.

Nilsson holds an E.E. degree, obtained at HTL, Malmoe, Sweden in 1960 and an MBA from Santa Clara University in 1985. He is the chairman of a working group of the Power Systems Relaying Committee, chairman of the DC Transmission Subcommittee in the Transmission and Distribution Committee and a member of CIGRE and CIGRE working groups. He received the Prize Paper Award from the IEEE Power Engineering Society in 1987.

Discussion

M. K. Glinkowski, (Rensselaer Polytechnic Inst., Troy, NY): The authors are congratulated for the work on modeling a CCVT for the relaying simulation of a power system. Instrument transformers are important components of the system. They might affect and distort the current and voltage signals supplied to the relay.

The devices like CCVT's are especially difficult to represent by a simple lumped-parameter equivalent circuit. Besides the typically large values of coupling inductors and small values of coupling capacitors, the fact that the 60 Hz resonant condition occurs can create additional complications. In addition, the nonlinear nature of the inductances prohibits the use of superposition property and Fourier/Laplace transform analysis.

In the light of the above comments I have two questions to the authors:

1) What is the effect of the nonlinear elements of their model (inductors) on the frequency response tests they performed?
2) The model derived from the frequency response tests is good in the range of some several Hz to ~ 1 kHz. Many transient effects in the power system are beyond this range, both in low and high frequency limits. My estimate would be to model the CCVT in the range of a few Hz to approximately 5–10 kHz. Did the authors run any comparative transient analysis of their model (10 Hz-1 kHz) versus an extended model or experiment? If yes, could they comment on the results?

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P. G. McLaren, W. W. L. Keerthipala, R. P. Jayasinghe, and **J. R. Lucas,** (University of Manitoba, Winnipeg, Manitoba): This paper has produced a wealth of detail on values for the various elements required for the simulation of CCVT's. It will certainly improve on the model we have been using to date in that we chose to ignore the stray capacitances of the various constituent parts [D1]. Our model did not therefore show the rejection "cusp" at frequencies around 1 kHz which the more complete model used by the authors exhibits. What our model did show, however, was the effect of burden and core model for the VT on the characteristics within the pass band of most relays. This present paper would be greatly enhanced if it demonstrated that the detailed model is capable of showing subsidence transients and ferroresonance effects under the appropriate system and burden conditions. Both of these phenomena depend on the core model for the VT. We found that our model did show both of these effects (see Figures 16 and 17 of [D1]) and that the tendency to ferroresonance showed through in the frequency response when the burden was very small. The peak in the frequency response was then around 4 Hz (see Figure 19 of [D1]) and is therefore outside the range considered by the authors. The measured response shown in Figure 23 of the present paper does indicate a rising trend as it passes through 10 Hz.

Would the authors care to comment on the performance of their *model* with respect to subsidence transients and ferroresonance.

Reference

[D1] Lucas, J. R., McLaren, P. G., Keerthipala, W. W. L., and Jayasinghe, R. P., "Improved simulation models for current and voltage transformers in relay studies," *IEEE Trans. on Power Delivery*, Vol. 7, No. 1, January 1992, p. 152.

Manuscript received February 11, 1992.

M. Kezunović, L. J. Kojović, V. Skendzić, C. W. Fromen, D. R. Sevcik, and **S. L. Nilsson**: Authors would like to thank discussers for their comments. The following are our responses.

Discussion by P. G. McLaren, et al., points out the importance of the core model for the PT. We agree that it would be nice to have a detailed model of the core, and our further study is concentrating on evaluating some of the existing core models available in the Electro-Magnetic Transients Program (EMTP). However, it is found to be expensive to acquire experimental data that can be used to validate the proposed models. Having that in mind, the authors find experimental and simulation results presented in reference [1] quite interesting. Unfortunately the results for the d.c. hysteresis model validation given in Figure 8 in the reference can not be easily compared with the given manufacturer's data due to different measurement units on the graphs. The same holds true for simulated and measured transient flux-current loops given in Figures 9 and 10 respectively, since the experimental data is presented without any scale.

Paper [1] also gives the simulation results for the CCVT behavior with and without the ferroresonance suppression circuit. The paper however does not provide experimental verification for the results given. Frequency response simulations with and without ferroresonance suppression circuit, are presented in Figures 18 and 19 of reference [1], for 200 VA and 20 VA burdens respectively. Figure 19 given in reference [1] shows the peak representing sub harmonic oscillations, but again no experimental data is provided to support the results. From our experience, the ferroresonance suppression circuit has the significant influence on the CCVT transient response. The suppression filter model presented in Figure 6 in reference [1] tends to have low Q factor and may have to be verified against the appropriate experimental results. We have investigated this problem, and the results are reported in reference [2].

At this time, we do not have access to experimental data to validate transient response of our CCVT models under "subsidence" and ferroresonance conditions. However, several simulations are performed to show time response of the models under the voltage collapse conditions as well as the influence of ferroresonance suppression circuit representation. These results are given in the reference [2].

The measurements performed at TAMU laboratories spanned a frequency range from 5 Hz to 50 kHz. The frequencies below 5 Hz were not measured due to an increasing measurement error caused by the low output signal levels. The frequencies above 10 kHz were not considered to be of the primary importance for two reasons:

- Most of the protective relaying studies do not require accurate representation of the frequency response in such a wide range.
- The CCVT response modeling in the range over 10 kHz becomes increasingly complex due to influence of various parasitic elements.

The two questions raised by M. Glinkowski deserve special attention. Regarding the nonlinear nature of the inductance, it is generally agreed that the existence of nonlinear elements in the system prohibits the use of superposition property, and Fourier/Laplace transform analysis. However, in the case of nonlinear systems with a limited number of nonlinear components, the transfer function can still be identified provided that the measurements are done in the 'linear' portion of the characteristic.

To simulate such a system, the circuit should first be represented by using linear models for all of the nonlinear elements. This is the base for the model validation used in our paper. The final model is than obtained by replacing the linear models with the nonlinear ones. This is in fact a standard practice in the EMTP studies where only a small number of nonlinear models is used to represent the elements.

The modeling procedure described provides a faithful representation of nonlinear effects only if:

- The equivalent 'impedance' the nonlinear element sees at it's terminals is adequately represented at all time instants.

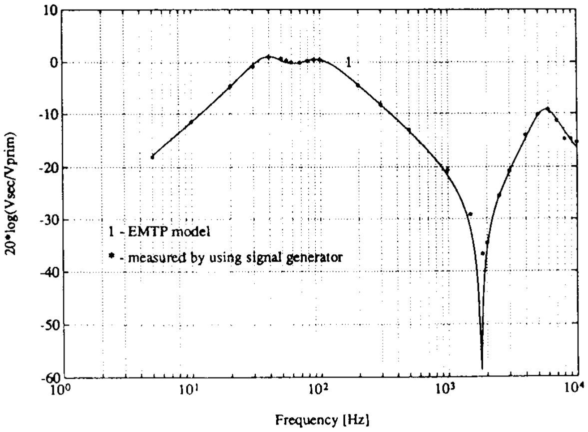

Fig. 1. PCA-5 CCVT Frequency Response (Measured vs. EMTP Simulation With Fitted Parameter Values)

- The nonlinear element is modeled with a sufficient level of accuracy.

As per first question of Mr. Glinkowski, it should be noted that the CCVT frequency response measurement method used must take into account the nonlinear nature of the tested device. The excitation signal shape and level must be carefully optimized in order to operate the device in the 'linear' portion of the characteristic [3]. In our case, this was ensured by conducting a frequency response sensitivity study with respect to the excitation signal level, as indicated in the paper. The same rule applies to the individual component value measurements.

As per second question, the results presented in the paper indicate the level of precision obtained by applying the proposed measurement methodology. As can be seen in the Figures 19, 21, and 23, the modeling error increases above 1 kHz. The further refinement of the models can be obtained by subjecting the results to the nonlinear parametric fitting techniques which are currently being investigated at TAMU. The preliminary results of the fitting process performed on the PCA-5 CCVT, show excellent agreement with the measurements, as indicated in Figure 1.

It should be noted that CCVT is a complex structure, making it virtually impossible to measure all of the individual model parameters with the same level of accuracy. This is especially true for the stray capacitance measurements.

The fitting procedure greatly reduces the individual component measurement errors by adjusting desired parameters in order to minimize the model error with respect to the CCVT frequency response which was separately recorded. The final results were used as data for the EMTP simulation shown in Figure 1.

As a conclusion related to all of the questions raised, we would like to emphasize the following:

- The modeling approach used in our paper faithfully reflects the actual CCVT element topology. It is therefore easy to include the nonlinear core saturation effects by simply substituting the inductor L_m with an EMTP saturable inductor model. The data needed for such a simulation can be readily obtained from the transformer manufacturer.
- By using the outlined approach it can be observed that *our model* covers both the "subsidence" transients and ferroresonance effects. The final error is dependent primarily on the EMTP hysteresis modeling precision.

References

[1] J. R. Lucas, P. G. McLaren, W. W. L. Keerthipala, and R. P. Jaysinghe, "Improved Simulation Models for Current and Voltage Transformers in Relay Studies," IEEE/PES, Summer Meeting, SM 317-8, July 1991.

[2] Lj. Kojović, M. Kezunović, and S. Nilsson, "Computer Simulation of a Ferroresonance Suppression Circuit for Digital Modeling of Coupling Capacitor Voltage Transformers," ISMM *Int. Conf. on Computer Applications in Design, Simulation and Analysis,* Orlando, Florida, March 1992.

[3] J. Schoukens and R. Pintelon, "Identification of Linear Systems —A Practical Guide to Accurate Modeling," Pergamon Press, Fairview Park, Elmsford, New York 10523, ISBN 0-08-040734, 1991.

Manuscript received May 28, 1992.