Study of Transient Behaviour of the Capacitor Voltage Transformer

Amit Kumar[1], Dr. A. G. Thosar[2], Vivek Moroney[3]

PG Student [EPS], Dept. of EE, Government College of Engineering, Aurangabad, Maharashtra, India[1]

Assistant Professor and Head, Dept. of EE, Government College of Engineering, Aurangabad, Maharashtra, India[2]

General Manager, Crompton Greaves Limited, Nashik, Maharashtra, India[3]

ABSTRACT: Capacitive Voltage Transformers (CVTs) are widely used as source of voltage signals for monitoring, protection relays and control application at transmission and sub transmission voltage level. The main component of the CVT are the capacitive voltage divider, a tuning reactor, a step down voltage transformer, a Ferro-resonance suppression circuit and the burden made by the relay. CVT are used for protection of high voltage lines, substations and transmission of high frequency signals. These applications required low voltage signal, which is given by output of CVT. The CVT applications require fast and secure protection.

The energy storage elements like inductors & capacitors cause CVTs to exhibit transient behaviour. Further the performance of protection devices is also affected by the transient of CVTs. In steady state, the secondary voltage of a capacitor voltage transformer mirrors the primary voltage. Because of the energy-storage elements used, the transient output, caused by sudden change in primary voltage, is no longer a replica of the primary. Transient over voltages, which exceed insulation ratings can stress electrical insulation, leading to abrupt failure or gradual breakdown of the dielectric of electrical component. This paper attempts to study the effects of changes in capacitor values on the transient response of the CVT. Furthermore, the various method which affects the transient response are discussed by simulating the mathematical model using MATLAB.

KEYWORDS: CVT, Ferroresonance, Transient, MATLAB.

I.INTRODUCTION

Capacitive Voltage Transformers (CVTs) are the predominant source of voltage signals for monitoring, protection relays and control application at transmission and sub-transmission voltage level. Poor CVT transient responses causes serious concern for high-speed line protection. For faults that cause very depressed phase voltages, the CVT output voltage may not closely follow its input voltage due to the internal CVT energy storage elements. Because these element stake time to change their stored energy, they introduce a transient to the CVT output following a significant input voltage change.

Theoretically, the output waveform of a CVT should be an exact replica of the input waveform under all operating system conditions. This requirement can easily be satisfied under steady-state condition. However, electric power systems are subjected to many types of disturbances that results in electric transients due to lightning, system fault, line energization and de energization, switching of inductive or capacitive load. Under such transient conditions, the CVT output waveform may not follow closely to its input waveform due to internal storage elements such as capacitive, inductive and non-linear components (saturable magnetic core) of the CVT. The phenomenon of Ferroresonance is of particular concern during CVT transients because it may cause thermal overstress and consequently deterioration of CVT components due to transient over voltages produced inside the CVT [1].

This type of related work are carried in the [2] In order to have a better access to the above issues, a thorough investigation of the CVT transient performance is needed. A typical 132kV CVT model to be used in connection with the ATP-EMTP is presented. Digital time domain simulations corresponding to system fault and Ferroresonance

condition are carried out. Besides that, frequency domain studies are conducted on the CVT model to investigate the frequency response of various parameters in the CVT system.

This paper presents the structure of a CVT and its transient response. The objectives of this work are to identify the CVT transient contribution factors and to investigate the transient impact on power system relay. A mathematical model is developed in MATLAB in such a way as to unveil the CVT transient voltages which will assist in assessing and evaluating the operational performance of CVTs. Section II follows the generic structure of CVT, Section III describes the mathematical model of a CVT. Transient response due to various factor are presented in Section IV. Finally, the conclusions are given in Section V.

II. GENERAL CVT STRUCTURE

Fig. 1.gives the general structure of the CVT. It consists of the following components: Coupling capacitor (C1 and C2), Compensating reactor (L), Step-down transformer, Ferro resonance-suppression circuit.
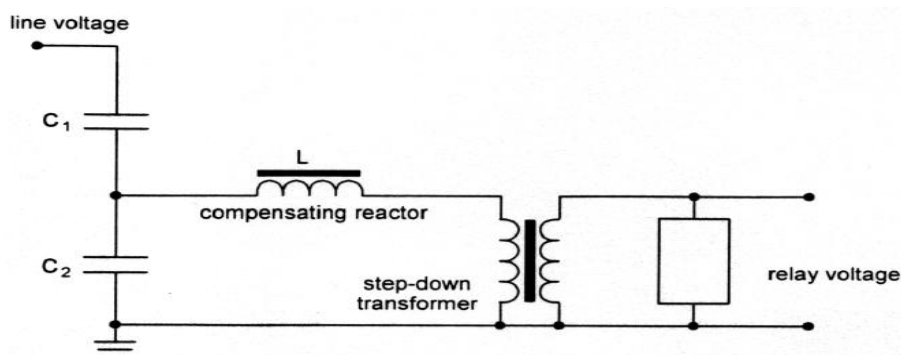

Fig.1. General Structure of CVT

The Capacitors of the CVT function as a voltage divider to step down the line voltage to an intermediate-level voltage, typically 5 to 15 kV. The compensating reactor cancels the capacitor reactance at the system frequency. This reactance cancellation prevents any phase shift between the primary and secondary voltages at the system frequency. The step-down transformer further reduces the intermediate-level voltage to the nominal relaying voltage, typically $115/\sqrt{3}$ volts. The compensating reactor and step-down transformer have iron cores. Besides introducing copper and core losses, the compensating reactor and step-down transformer also produce Ferro resonance due to the nonlinearity of the iron cores. For compensate the Ferroresonance phenomenon Ferro-resonance Suppression circuit normally used on the secondary of the step-down transformer. This circuit is required to avoid dangerous and destructive over voltages caused by Ferroresonance and at the same time it can aggravate the CVT transient. Whether or not this suppression circuit aggravates the CVT transient depends upon the suppression circuit design.

III.MATHEMATICAL MODELING OF CVT

CVT can be represented by the simplified equivalent circuit shown in Fig. 2, with its parameters referred to the primary side and the same model are used in the MATLAB.
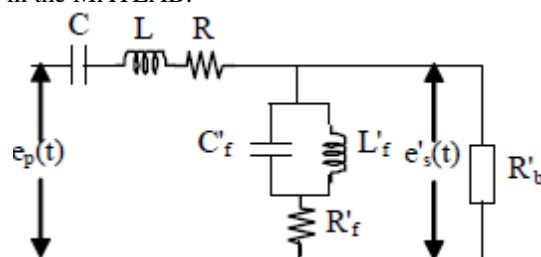

Fig. 2. CVT equivalent circuit model

where, R, L, C, R_f', L_f', C_f', R_b' and $e_s'(t)$ are the equivalent resistance and inductance of the compensating reactor, stack capacitance, Ferro resonance resistance, inductance and capacitance referred to the primary, resistive burden referred to the primary, secondary voltage referred to the primary respectively. R, L and C form a series resonance circuit while R_f, L_f and C_f form a series-parallel resonance circuit.

Computer simulation program was developed in MATLAB for the selected CVT. Considering the CVT equivalent circuit of Fig. 2. From Fig. 2 the equivalent resistance of the compensating reactor

$$R = \sqrt{Z^2 - (X_L - X_C)^2},$$

and R_f, L_f and C_f are the parameter of Ferroresonance circuit and form a series-parallel resonance circuit. So that,

$$R_f = \sqrt{Z_f^2 - (1/X_L^2 - 1/X_C^2)^2}$$

$$X_{Lf} = 2\pi f L_f,$$
$$X_{Cf} = 1/2\pi f C_f,$$
$$X = X_L - X_C,$$
$$X_f = \frac{1}{X_{Lf}} - \frac{1}{X_{Cf}}$$

where, $X, X_L, X_C, X_{Lf}, X_{Cf}$, X_f are the total series, series inductive, series capacitive, Ferroresonance inductive, Ferroresonance capacitive and total Ferroresonance reactance, respectively. The inductance, L, is a constant value dependent only on the capacitance used to set up the divider. At resonance, therefore,

$$L = 1/w^2 C$$

The transfer function is established the CVT model of Fig. 2 is:

$$\frac{e_s(S)}{e_P(S)} = \frac{A_3 S^3 + A_2 S^2 + A_1 S}{B_4 S^4 + B_3 S^3 + B_2 S^2 + B_1 S + B_0}$$

where,
$A_1 = R_f R_b C, A_2 = L_f R_b C, A_3 = L_f C_f R_f R_b C$

$B_0 = R_f + R_b,$
$B_1 = RC(R_f + R_b) + L_f + R_f R_b C,$
$B_2 = LC(R_f + R_b) + RCL_f + L_f C_f(R_f + R_b) + L_f R_b C,$
$B_3 = LCL_f + RCL_f C_f(R_f + R_b) + L_f C_f R_f R_b C,$
$B_4 = L_f C_f(R_f + R_b) + LC$

The state space representation of T.F. in canonical form of matrix, is as given below;

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_4 & -a_4 & -a_4 & -a_4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \end{bmatrix} [e_p(t)]$$

where,

$$e_s = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \beta_0 e_p;$$

$$e_p(t) = \hat{E}_p \sin(wt + \theta)$$

$$a_1 = \frac{B_3}{B_4}; \; a_2 = \frac{B_2}{B_4}; \; a_3 = \frac{B_1}{B_4}; \; a_4 = \frac{B_0}{B_4}$$

$$b_0 = 0; b_1 = \frac{A_3}{B_4}; b_2 = \frac{A_2}{B_4}; b_3 = \frac{A_1}{B_4}; b_4 = 0.$$

$$\beta_0 = b_0; \beta_1 = b_1 - a_1\beta_0; \beta_2 = b_2 - a_1\beta_1 - a_2\beta_0;$$
$$\beta_3 = b_3 - a_1\beta_2 - a_2\beta_0;$$
$$\beta_4 = b_4 - a_1\beta_3 - a_2\beta_2 - a_3\beta_1 - a_4\beta_0$$
$$\hat{E} = Maximum \; value \; of \; voltage$$

IV.CVT TRANSIENT

A CVT is made up of a number of capacitor units connected in series. The number of capacitor units depends on the applied primary voltage level. The CVT capacitance is represented by two values: one for the equivalent capacitance above the intermediate voltage point (C_1) and the other for the equivalent capacitance below the intermediate voltage point (C_2). The Thevenin's equivalent capacitance value ($C_1 + C_2$) is different from the total capacitance$(C_1 * C_2)/(C_1 + C_2)$.

CVT transients reduce the fundamental component of the fault voltage. This decrease in the fundamental voltage component results in a decrease in the calculated impedance. If the total capacitance C is high, the series reactance becomes smaller. It is found that the transient magnitude becomes smaller with the increase in the total capacitance. However, if the RC time constant is increased due to an increase in C, a lower magnitude with a longer time transient is exhibited. The Capacitor value is varied as 100nF, 200nF, 300nF, 400nF and 500nF. The transient response for the various capacitor values are studied.

There are many factors which affect the CVT transient such as: Capacitor values, Ferroresonance circuit, Tapping voltage and types of loading.

V. RESULT AND DISCUSSION

A) Effect of Ferro resonance suppression circuit design on CVT transient response:
A specific design of FSC is often treated as proprietary information and is seldom available. However, two generic models of FSC that are commonly used in CVT will be considered here. They are the active Ferroresonance suppression circuit (AFSC) and passive Ferroresonance suppression circuit (PFSC) as shown in Fig. 3 (a) and Fig. 3 (b) respectively.
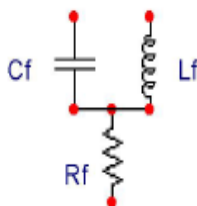

Fig. 3: (a) Active Ferroresonance Suppression Circuit
Active Ferroresonance Suppression Circuit contains the parallel connection of Inductor and Capacitor are in series with the Resistor.
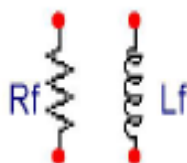
Fig. 3: (b) Passive Ferroresonance Suppression Circuit

Passive Ferroresonance Suppression Circuit contains the Inductor or resistor which is permanently connected to load side of electromagnetic transformer.

FSC is designed to avoid dangerous and destructive overvoltage caused by Ferroresonance. It loads a CVT and creates an extra path apart from the burden for dissipating energy. The AFSC acts like a band-pass filter and introduces extra time delay in the CVT secondary output. The energy storage elements in the AFSC contribute to the severity of the CVT transient. In contrast, the PFSC has little effect on the CVT transient.
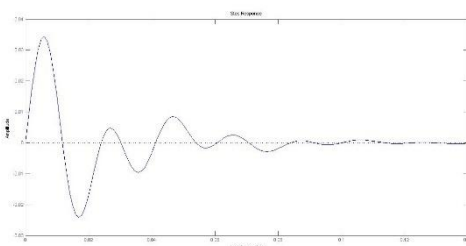
Fig. 4(a) CVT Transient with AFSC

The transient response of CVT with AFSC are shown above with percentage overshoot and settling time which is more than transient response of CVT with PFSC.
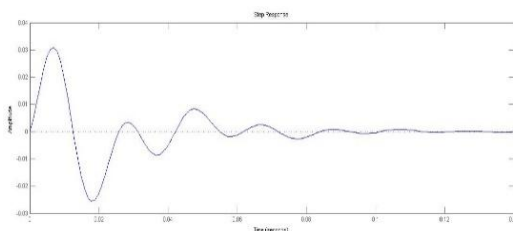

Fig. 4(b) CVT Transient with PFSC

The transient response of CVT with PFSC are shown inFig. 4(b) respectively. Note that the CVT with a PFSC has a better, less distorted transient response than the CVT with an AFSC.

B) Effect of types of burden on CVT Transient response:
Burden with high power factor or nearly resistive gives better transient response. However, the CVT transient response better with low resistive burden and the response worsens with high burden. The response shown in Fig. 5(a) and 5(b).
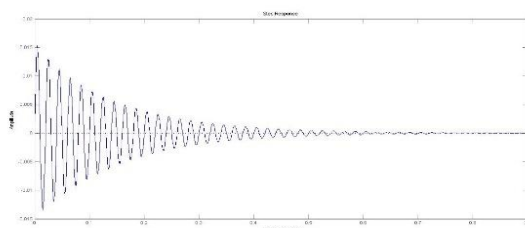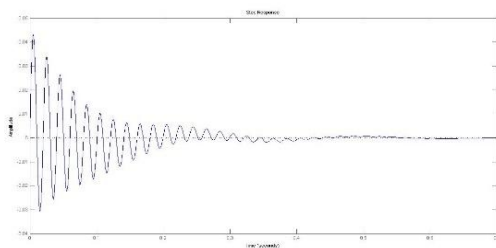

Fig. 5(a) CVT Transient with low burden

Fig. 5(b) CVT Transient with high burden

C) Effect of Capacitor value on CVT transient response:

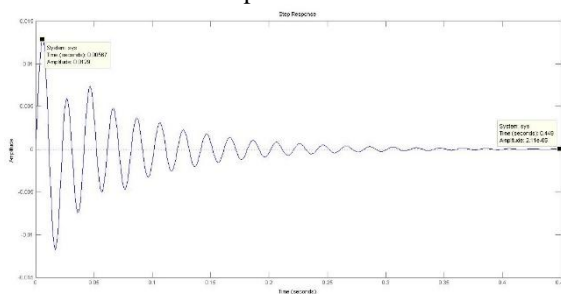Fig. 6(a) shows the transient response for the 100 nF capacitor.

Fig. 6(a) Transient response with 100nF capacitor value

For 100nF value of capacitor, Overshoot is 88% and settling time is 0.449 sec and this transient overshoot are enough to trip the power system relay because the relay are very sensitive to transient.
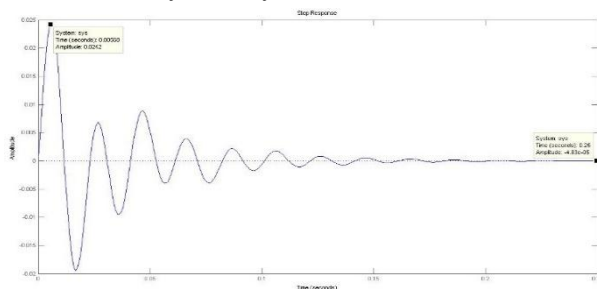

Fig. 6(b) Transient response with 200nF capacitor value

Fig. 6(b) shows the transient response for the 200nF capacitor. For this value of capacitor the overshoot is 77.4% and settling time is 0.25 sec.
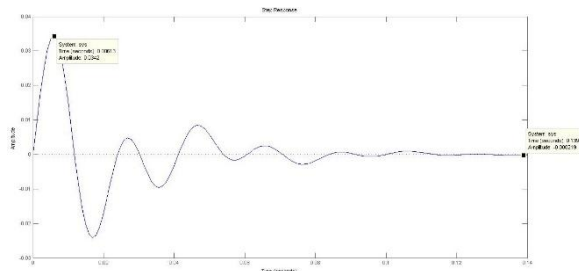

Fig. 6(c) Transient response with300nF capacitor value

Fig. 6(c) shows the transient response for the 300nF capacitor. For this value of capacitor the Overshoot is 68.1% and settling time is 0.139 sec.

Fig. 6(d) Transient response with400nF capacitor value

Fig. 6(d) shows the transient response for the 400nF capacitor. For this value of capacitor the Overshoot is 59.9% and settling time is 0.125 sec.
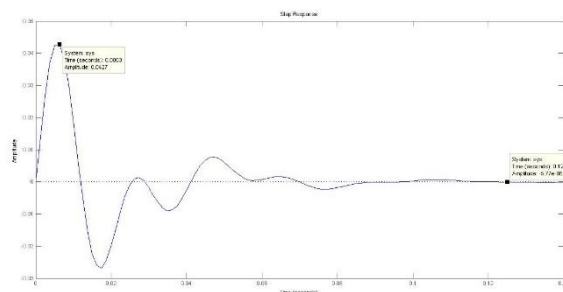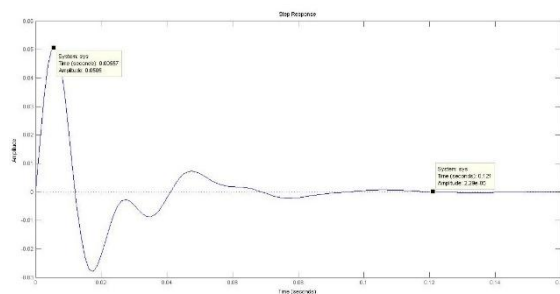

Fig. 6(e) Transient response with500nF capacitor value

Fig. 6(e) shows the transient response for the 500nF capacitor. For this value of capacitor the Overshoot is 52.6% and settling time is 0.121 sec.

After the same, study more in details with pole location. It is shown that the poles are shifted left from the origin with respect to increased value of capacitor.

Table 1. Location of pole with overshoot and settling time for various capacitor values

Capacitor value	Pole	Overshoot (%)	Settling time(sec)
100nF	$-12.8\pm j315$	88	0.449
	$-37.6\pm j116$		
200nF	$-25.7\pm j315$	77.4	0.250
	$-37.4\pm j115$		
300nF	$-38.5\pm j315$	68.1	0.139
	$-37.2\pm j115$		
400nF	$-51.3\pm j315$	59.9	0.125
	$-37\pm j115$		
500nF	$-64\pm j315$	52.6	0.121
	$-36.8\pm j115$		

The table shown the impact of capacitor on the transient. It is observed that overshoot is 88% and settling time is 0.449 sec for 100nF capacitor and the overshoot is 52.6% and settling time is 0.121 sec for 500nF capacitor.

If we are looking for transient performance, the highest value of capacitor are recommended for CVT. However, increasing the CVT capacitance value increases the CVT cost. Therefore, the users must strike a balance between CVT performance and CVT cost. Judging only from the magnitude of CVT transient, therefore, one should recommend CVTs with higher sum of stack capacitances to be used to feed distance relays.
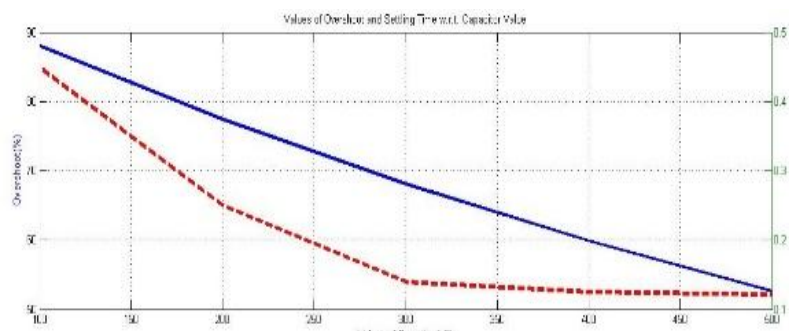
Fig. 7 shows the overshoot and settling time with various value of capacitor

Fig. 7 shows the overshoot and settling time with various value of capacitors in the graphical manner. It shows that the percentage overshoot and setting time decreased with increased values of capacitor. Smooth line shows overshoot and dotted line shows settling time w.r.t various capacitor.

VI. CONCLUSION

This paper has presented a CVT mathematical model addressing the transient performance of CVTs. The behaviours of CVT under transient conditions have been successfully studied, which confirms the validity of the developed model. The quantitative data obtained from the developed model will serve as a guide to predict how the relays and relay schemes will react to the CVT transients.This work observed the following:

The greater the CVTs equivalent capacitance (sum of stack capacitance), the smaller the amplitude and settling time of the transient oscillations.

The transient produced by CVTs with PFSC are much less than those produced by CVTs with AFSC.

Burden with high power factor or nearly resistive give better transient response.

REFERENCES

[1]Ab. Halim Abdul Bakar, Cheng Hock Lim, Saad Mekhilef "Investigation of Transient Performance of Capacitor Voltage Transformer" First International Power and Energy Conference PEC on 2006 509 November 28-29, 2006, Putrajaya, Malaysia

[2]M. Kezunovic, C. w. Fromen and S. L. Nilsson, "Digital Models of Coupling Capacitor Voltage Transformers for Protective Relay Transient Studies," IEEE Transactions on Power Delivery, Vol. 7, No.4, October 1992

[3] D.Hou and J. Roberts, "Capacitive voltage Transformer - Transient overreach concerns and solution for distance relaying," in Proc. 22nd Annual. Western Protective Relay Conference

[4] I. Sule, U. O. Aliyu, *Member, IEEE* and G. K. Venayagamoorthy, *Senior Member, IEEE* "Simulation Model for assessing Transient performance of Capacitive Voltage Transformers"Power Engineering Society General Meeting, 2006. IEEE, Publication Year: 2006

[5] K. Ogata, *Modern Control Engineerin*g, Third Edition, Prentice-hall International, Inc., 1997.