A SIMULATION ON THE TRANSIENT RESPONSE OF A CAPACITOR VOLTAGE TRANSFORMER USING MATLAB

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Abstract: This paper presents a study on the transient response behavior of a capacitor voltage transformer based on the simulation done using MATLAB. The adopted equivalent circuit is modeled in MATLAB using mathematical equations obtained through mathematical simplifications of the circuit. Based on this model, the effects of CVT components such as capacitor and ferroresonance suppression circuit, and the effects of fault type, point-on-wave and location on the CVT transient response are studied through observation on the MATLAB-generated transient responses. The ideal input voltage to the CVT is obtained from an ideal power transmission line system model in PSCAD/EMTDC.

Keywords: Capacitor Voltage Transformer (CVT), Ferroresonance suppression circuit (FSC), Matlab, Feroresonance

INTRODUCTION

In power systems the primary voltage and current signals are transformed to voltages of current for metering and protection purposes. These signals are required at adequately low level in order to suit the operation of instruments and relays. In order to obtain a low voltage level from high voltage source, a wound voltage transformer is normally used to step down the primary voltage. However, as the system voltage increases, the insulation cost makes this type of transformer inappropriate and other type of voltage sensing units are needed. The most commonly used voltage sensing unit is the CVT. CVT is commonly used in electricity distribution and transmission systems at high and extra high voltages.

Although the implementation of CVT is economical and good, it is not ideal. It loses some consistency in reproducing transient voltage variations due to the inductive, capacitive and nonlinear elements it contains. Transient response of a CVT refers to its ability to control the tendency to create irrelevant frequencies in the output. Electromagnetic voltage transformer could perform better in terms of transient response but it is again, costly.

Inconsistent transient response introduced by the CVT is mainly caused by a sudden change in the primary voltage especially when there are faults in the system. The CVT produces transient component in the secondary circuit in addition to the steady state value. The low frequency component, which tends to slow down the operation of relays, is dominant. This is due to the release of stored energy in the CVT circuit due to the burden current and the effective capacitance of the divider in resonance with the magnetizing inductance of the electromagnetic unit.

The performance of a CVT is also affected by a phenomenon called ferroresonance. It happens during certain transient conditions where the core of the tuning inductor of the intermediate transformer becomes saturated. A stable oscillation at system frequency is resulted from this phenomenon. To counter this phenomenon, the CVT will usually contain a ferroresonance suppression circuit (FSC). The performance of a CVT is largely influenced by the suppression of this stable oscillation. The stable oscillation basically results in large distortions of voltages and currents, and cause mechanical vibration of equipment.

The objectives of this project are:

- To study the design criteria of a capacitor voltage transformer and study the effects of stack capacitance and ferroresonance on its performance.
- To analyze the effect of CVT transient response to protection relay operation during different types of fault occurrences.
- To simulate the transient response of the CVT using Matlab.

CVT typically consists of coupling capacitors, compensating reactor, a step-down transformer and a ferroresonance suppression circuit (FSC), as depicted in Figure 1. The coupling capacitors of the CVT function as a voltage divider to step down the line voltage to an intermediate level voltage, typically 5 to 15kV. The compensating reactor cancels the coupling capacitor reactance at system frequency. This reactance cancellation prevents any phase shift between the primary and the secondary voltages at system frequency.

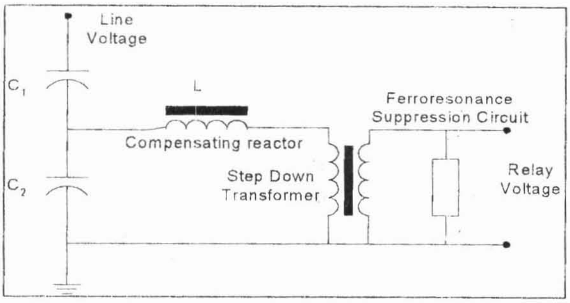

Figure 1: Typical Simplified Circuit Diagram of CVT

Theoretical study and tests carried out with cvt model and system protective relays show that it is possible to study the performance of protective relays fed by capacitor voltage transformers systematically [1]. This will enable the limits of the load for this particular type of cvt to be fixed before feeding the relays. Some examples are given in [1].

The results described in [1] show that a load represented by the parallel connection of a resistance and an inductance has a very harmful effect on the transient voltages of CVT. The amplitudes of the transient voltages are not sufficient to characterise the risk of disturbance in the performance of the relay.

Protective relays fed by CVT do not operate correctly if the secondary side voltage is not a direct replica of the primary side voltage [2]. In order to ensure correct operation of the relay, it is necessary for the secondary side voltage to be operated as accurately as possible to the primary voltage when the latter falls rapidly. The other conditions that the CVT must satisfy have been given in [2].

Sometimes a phenomena known as ferroresonance can occur in the CVT. Ferroresonance is a complicated non-linear electrical phenomenon, which can lead to transformer voltages being several times higher than the normal ratings. Ferroresonance occurs because the inductance in the circuit is ferromagnetic, meaning that it has a core made of ferromagnetic material, usually iron, for instance a transformer [3].

Ferroresonance in a power system can result in any or all of the following [4]:

- High-sustained overvoltages, both phase to phase and phase to ground.
- High sustained overcurrents.
- High sustained levels of distortion to the current and voltage waveforms.
- Transformer heating and excessively loud noise.
- Electrical equipment damage (thermal or due to insulation breakdown).
- Apparent mis-operation of protective devices.

To overcome the problem of ferroresonance a ferroresonance suppression circuit (FSC) has been introduced to the CVT circuit as shown in Figure 2. A ferroresonance suppression circuit is designed to prevent sub-synchronous oscillations due to saturation of the core of a step-down transformer during overvoltage conditions. As the circuit has a non-linear transient characteristic, three methods of damping are introduced to stabilise the ferroresonance phenomena. They are:

- Permanently connected resistive burden.
- Permanently connected tuned circuits.
- Switched damping circuits.

METHODOLOGY

Research study

The equivalent circuit of CVT and FSC are adopted from previous studies on CVT transient response (through research study). To have an idea on the direction of the project, research study are done on the factors affecting CVT transient response and also the ferroresonance phenomenon.

Implementation (Programming)

By using the mathematical analysis on the CVT equivalent circuit, the CVT is modeled in MATLAB to generate its transient response due to various effects such as CVT components and various types of fault occurrences. Two models of CVT are the CVT without FSC and the CVT with FSC connected

Analysis

Based on the transient responses of CVT generated by MATLAB [5], the behavior of the CVT is analyzed. Basically, the transient responses are compared with each other and finally, the effects of this transient to protection relay operation are analyzed.

RESULTS AND DISCUSSIONS

CVT is similar to an electromagnetic voltage transformer (VT). However, the addition of a capacitor divider circuit, which consists of a stack capacitor (C_s) and a base capacitor (C_t), distinguishes a CVT and VT. The values of the components in a CVT especially the stack capacitor influence the ability of the CVT to produce the desired response at the secondary side of the CVT. It is desired that the secondary side of the CVT be able to replicate exactly the voltage at the primary. Figure 2 shows the equivalent circuit of a CVT with FSC.

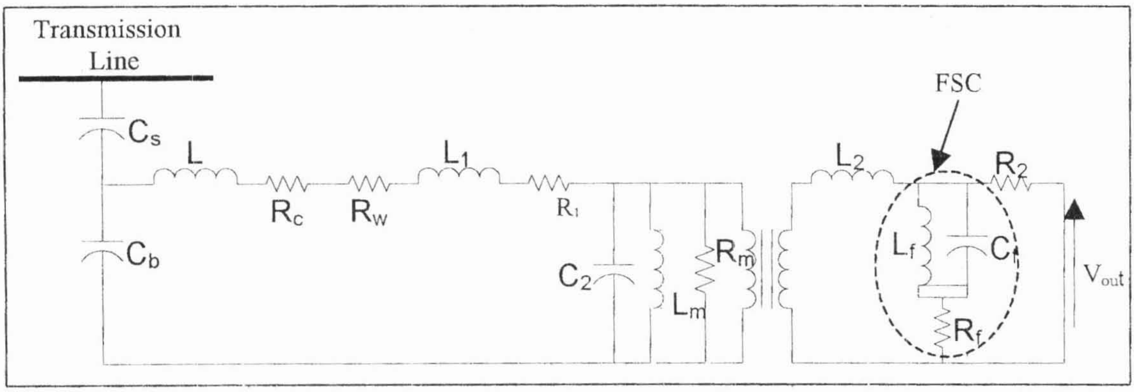

Figure 2: CVT Equivalent Circuit with FSC Connected (circled)

Table 1 lists the components of a CVT (without FSC) and its values. The value of these components affects the CVT output at the secondary. In order for the CVT to be able to replicate the voltage at the primary, the gain of the circuit should be unity.

Table 1 is a reduced mathematical analysis of the CVT equivalent circuit to obtain the gain function of the circuit.

Table 1: CVT Component Value

SYMBOL	COMPONENT	COMPONENT VALUE
C_s	Stack Capacitance	2000pf
C_b	Base Capacitance	0.084 µf
L	Tuning Inductance	1.056 H
R_c	Equivalent Core Resistance	2000Ω
R_w	Winding Resistance	239Ω
L_l	Primary Leakage Inductance	79.832 mH
R_l	Primary Resistance	1050Ω
L_m	V.T Magnetizing Inductance	27050 H
R_m	V.T Magnetizing Reactance	5.8MΩ
L_2	Secondary Inductance	0.168 mH
R_2	Secondary Resistance	0.162 Ω
C_2	Lumped Stray Capacitance	1060pF
R_L	Burden resistance	103997 Ω
K	V.T Ratio	12kV/63.5V

Figure 2 can be further simplified as shown in Figure 3. All the components are referred to the intermediate voltage level and capacitors Cs and Cb are group together to form a Thevenin equivalent voltage source. Refer to Figure 3

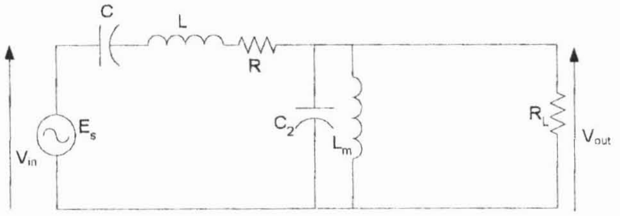

Figure 3: Simplified CVT Equivalent Circuit

- The resistor R is the total resistance of the primary, core and winding resistance. $R = R_l + R_c + R_w = 1050 + 2000 + 239 = 3289\ \Omega$.
- The capacitor C is the total capacitance of the base and stack.
  $C = C_b + C_s = 0.084e\text{-}06 + 2000e\text{-}12 = 86\ nF$.
- The inductor L is the total inductance of primary leakage inductance, tuning inductance and secondary inductance.
  $L = L_l + L + L_2 = 79.832e\text{-}03 + 1.056 +$
  $0.168e\text{-}03 = 1.136\ H$.

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{Z_2 Z_3}{Z_1 Z_2 + Z_1 Z_3 + Z_2 Z_3} \; .. \qquad (1)$$

Where;

$$Z_1 = \frac{1}{j\omega C} + j\omega L + R \; \ldots\ldots\ldots\ldots\ldots\ldots \qquad (2)$$

$$Z_2 = \frac{j\omega L_m \times j\omega C_2}{\frac{1}{j\omega C_2} + j\omega L_m} \; \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3)$$

$$Z_3 = R_L \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (4)$$

The FSC is introduced into the CVT circuit in order to eliminates the phenomenon of ferroresonance. Therefore FSC has been connected to the CVT circuit as shown in Figure 2. Table 2 shows parameters of the active ferroresonance components in the CVT circuit diagram shown in Figure 2.

Table 2: FSC Tuning Components Value

Component	Symbol	Component value
Tuning capacitance	C_f	0.285 nF
Tuning inductance	L_f	315.3 H
Tuning resistance	R_f	77379 Ω

After similar circuit simplification steps, we obtain:

$$H(\omega) = \frac{V_{out}}{V_{in}} = \frac{Z_2}{Z_1 + Z_2} \; \ldots\ldots\ldots\ldots\ldots \qquad (5)$$

Where;

$$Z_a = R_f + \frac{j\omega L_f C_f}{L_f + C_f} \; \ldots\ldots\ldots\ldots\ldots \qquad (6)$$

$$Z_b = \frac{j\omega C_2 L_m}{C_2 + L_m} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (7)$$

$$Z_c = \frac{Z_a Z_b}{Z_a + Z_b} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (8)$$

$$Z_1 = \left(\frac{1}{j\omega C} + j\omega L + R \right) \; \ldots\ldots \qquad (9)$$

$$Z_2 = \frac{Z_c R_2}{Z_c + R_2} \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (10)$$

Effects Of Changing Capacitance Value

Figure 4 shows the transient responses of CVT with two different values of capacitance, which is the typical and four times larger capacitance value. Theoretically, the capacitance value associated with high capacitance CVT decreases the CVT transient in magnitude. This is also depicted in Figure 5 where it shows that the transient response of a CVT with the Thevenin equivalent capacitance to be four times the typical value has a magnitude that is closer to the ideal VT response.

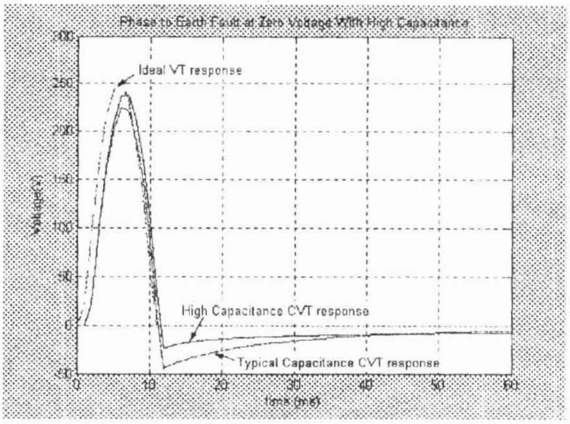

Figure 4: CVT Transient Response For Phase to Earth Fault At Zero Voltage With Varying Coupling Capacitance Value

Effects of Implementation of FSC

The connection of FSC in a CVT is important to prevent stable oscillation in the output. The FSC is like a bandpass filter and introduces extra time delay in the CVT secondary output. The energy storage elements in the FSC contribute to the severity of the CVT transient. Figure 5 and Figure 6 shows CVT transient response with and without the FSC connected, respectively. Based on Figure 7 and 8, it shows that magnitude of the output voltage at a fault occurrence is larger. However, the FSC causes the transient response of the CVT to damp faster. The transient response of the CVT with FSC during a phase to earth fault at zero voltage initiation follows the ideal VT response within 1.5 cycles after fault initiation. When fault occurs at the peak voltage, the CVT transient response followed the ideal VT response within 0.5 cycle after fault initiation.

Figure 6 shows the CVT transients at zero voltage fault initiations for a phase-to-earth fault type. For comparison, the ideal VT voltage output is shown in each figure. This ideal VT response is the response that the CVT should replicate.

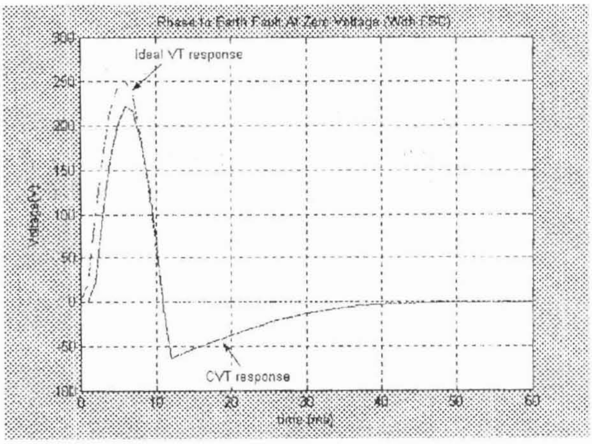

Figure 5: Phase to Earth Fault At Zero Voltage With FSC Connected

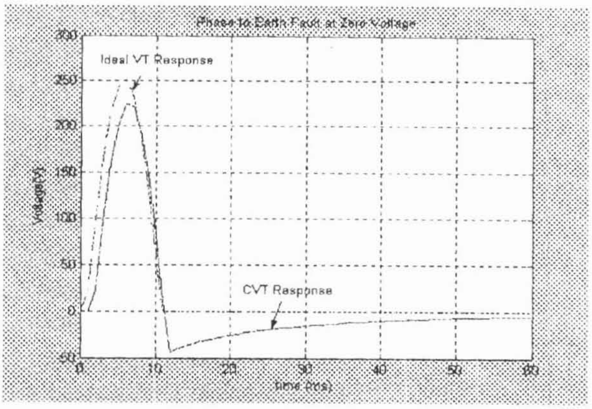

Figure 6: Phase to Earth Fault At zero Voltage Without FSC Connected

Effects of Fault Point-On-Wave (POW)

Based on Figure 7, the output of the CVT does not follow the ideal output voltage until approximately two cycles later. The transient response of the CVT has an 'overshoot' at the beginning of the fault initiation. This 'overshoot' delays the CVT response to follow of the ideal response closely.

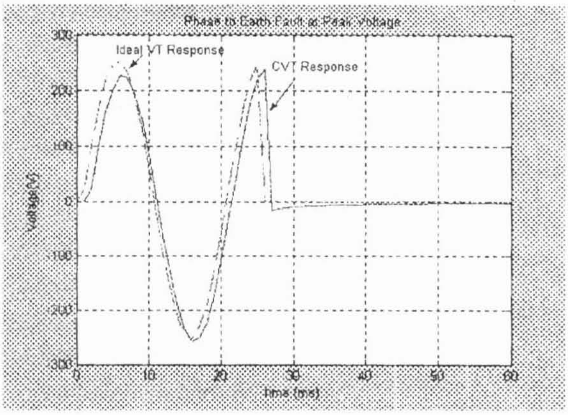

Figure 7: Phase to Earth Fault At Peak Voltage Without FSC Conected

Figure 7 shows CVT transient response for fault occurring at the peak or maximum voltage. Based on the figure, the CVT transient response shows similar behavior with the response when fault POW is at zero. The transient response of the CVT has a delay in which it does not follow the ideal output voltage until after approximately one cycle later. This indicates that when fault POW is at peak voltage, the response is similar with when fault POW is at zero but is also a better response as the overshoot introduced are of smaller magnitude and has a faster rate of restoration to the ideal response.

Effects of Fault Type

Two types of fault studied in this project are the phase-to-earth and the phase-to-phase fault. In power system, the more common type of fault is phase-to-ground. The transient responses plotted in this paper are with respect to phase A. During a phase-to-earth fault (Phase A to ground), the ideal voltage drops to zero immediately. Whereas during phase-to-phase fault (Phase A and B at fault), the voltage of the phases involved will reduce as the third phase voltage will increase. Comparing the transient responses in Figure 6 with Figure 8, it is found that both types of fault introduce delay in reaching the steady state. It can also be observed that the transient response of the CVT is closer to the ideal VT response during phase-to-phase fault compared to during phase-to-earth fault. However, when fault occurs at peak voltage (graphs not shown), the difference is not so obvious.

Effects of Fault Location

The location of fault is referred to as the distance between the relay and the source of fault. The distances studied in this project are at 20km, 80km and 100km.

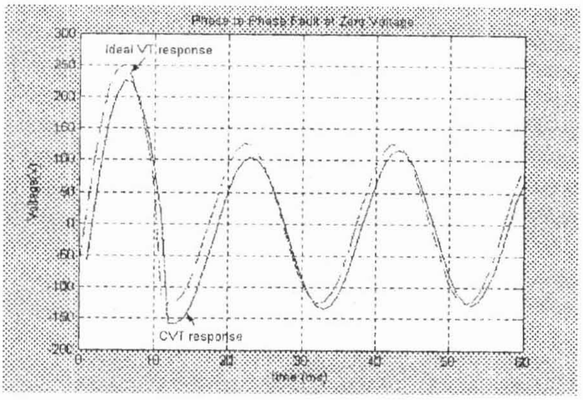

Figure 8: Phase-to-Phase Fault At Zero Voltage

Figure 9 shows the distance between the fault and the relay at 80 km. As the distance between the fault and the relay is increased the magnitude of the fault voltage also will increases and the transient response of the CVT worsen as well. The noise at the beginning of the transient is contributed by the load, which is inductive.

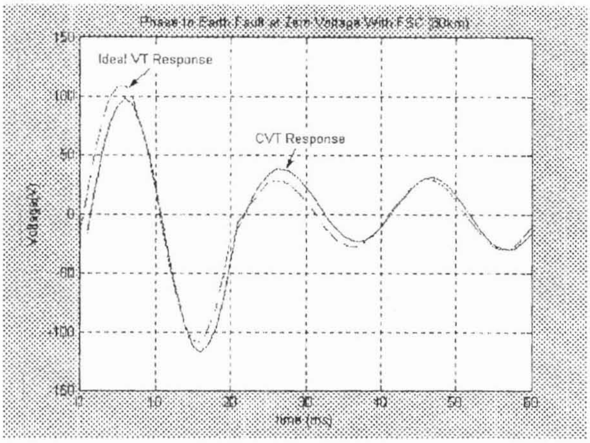

Figure 9: Phase-To-Earth Fault At Zero Voltage With FSC (Relay is 80km away from fault source).

CONCLUSION

In high voltage power transmission (>33kV), it is more economical to implement capacitor voltage transformer (CVT) for protection, measurement and control compared to electromagnetic voltage transformer (VT). However, in comparison with VT, CVT is not ideal and lose some fidelity in reproducing transient voltage variations when faults occur, leading to delay or incorrect relay operation. It is also affected by the ferroresonance phenomenon where stable oscillation is produced at system frequency due to the saturation of the tuning inductor at certain condition. This phenomenon can be reduced or eliminated by implementing ferroresonance suppression circuit at the secondary side of the transformer.

Basically the CVT transient is controlled by the sum of the stack capacitances, shape and parameters of the ferroresonance suppression circuits and point on wave when fault occurs.

RECOMMENDATIONS

Another factor that can be used to control the CVT transient is the total load of the CVT. It is possible to modify the total load of the CVT so as to avoid a transient voltage of a frequency or amplitude particularly ill adapted to a given type of relay. Therefore in the future try to investigate the performances of the relays by modifying the total load of the CVT.

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