

Where did those transients come from and how are we going to handle them? A fresh look at CCVT transients phenomena

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Introduction

Potential transformers and coupling capacitor voltage transformers (CCVT's) have been used successfully for providing voltage to the inputs of meters and relays since the 1960's. At voltage levels above 138kV economics dictate that CCVT's be used to provide secondary voltages to relays. As we'll see later CCVT's consist of a capacitive voltage divider along with a step down transformer and other associated equipment. Placing capacitance in series and shunt to the natural inductance of the power system leads to resonant circuits and RC time constants that affect the faithful reproduction of the primary voltage on the output terminals of the CCVT. These transients weren't a problem for electromechanical relays, but with the advent of faster solid state relays and modern microprocessor relays CCVT transients became a problem that needed attention. This paper will discuss coupling capacitor voltage transformer design. What factors in the design influence the transient behavior of the CCVT. What factors in the power system contribute to the transient behavior of the CCVT. How CCVT transient behavior affects relay performance. Finally, how relay manufacturers take this transient behavior into account in relay design. A Capacitive Voltage Transformer (CVT) is a CCVT without carrier accessories. The paper will use these terms interchangeably. Even though there is a slight difference between the two, the portion of the device in that pertains to the transient response is the same.

CVT Design

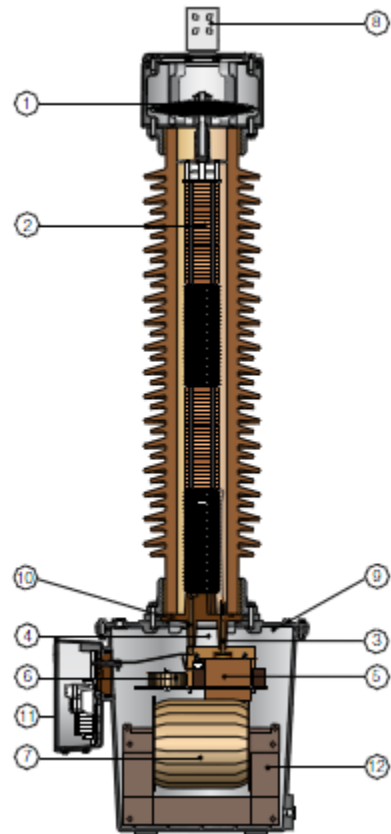
Figure 1 shows cut away view of a capacitor voltage transformer. The CVT has two major components: a capacitance voltage divider, and an electromagnetic unit. The capacitor voltage divider is used to take the line to ground voltage applied to the capacitor and reduce it to an intermediate voltage, typically $22/\sqrt{3}$ kV. The intermediate voltage is applied to the electromagnetic unit which consists of a step down transformer and a compensating reactor. The reactor is used to compensate for the capacitive reactance of the capacitor voltage divider. All capacitor voltage transformers (CVT's) need to incorporate some kind of ferroresonant damping, since the capacitance in the voltage divider, in series with the inductance of the transformer and the series reactor, constitute a tuned resonant circuit.

This circuit can be brought into resonance that may saturate the iron core of the transformer by various disturbances in the network. This phenomenon can also overheat the electro-magnetic unit, or lead to insulation breakdown.

A damping circuit is connected in parallel with one of the secondary windings. The damping circuit consists of a reactor with an iron core and a series resistor. Under normal use, the iron core of the damping reactor is not saturated, yielding a high impedance, so that practically no current is flowing through this circuit.

A coupling capacitor voltage transformer is similar except for the addition of a carrier coupling unit .

Figure 2 is an electrical schematic for the capacitor voltage transformer.



Capacitor Voltage Divider

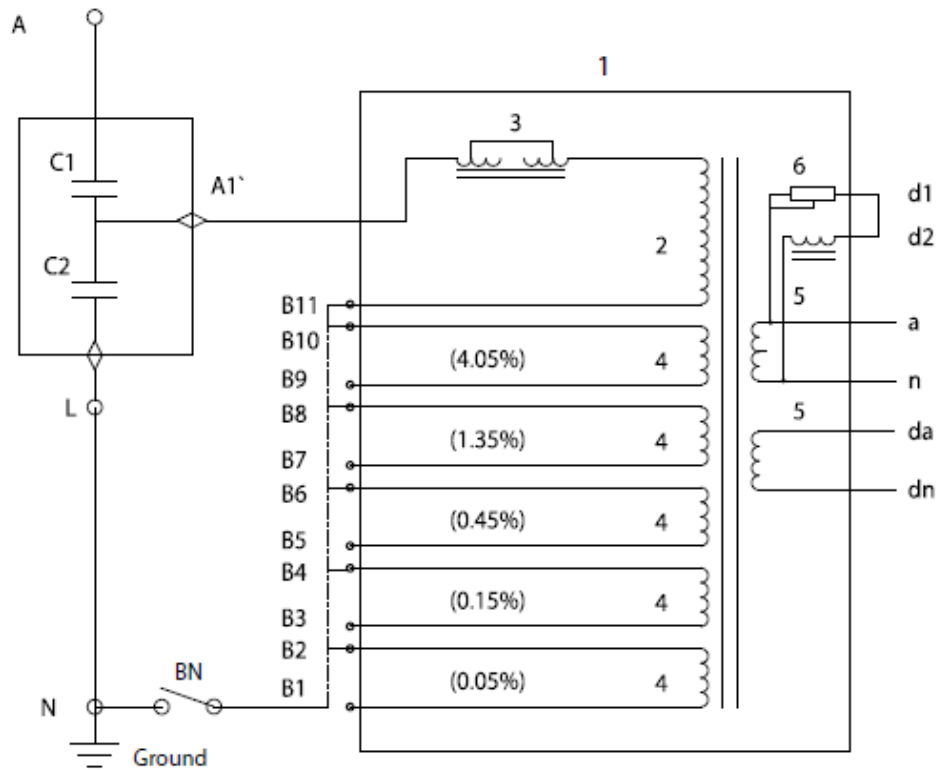
- 1 Expansion system
- 2 Capacitor elements
- 3 Intermediate voltage bushing
- 8 Primary terminal, flat 4-hole Al-pad
- 10 Low voltage terminal (for carrier frequency use)

Electromagnetic unit

- 4 Oil level glass
- 5 Compensating reactor
- 6 Ferro-resonance damping circuit
- 7 Primary and secondary windings
- 9 Gas cushion
- 11 Terminal box
- 12 Core

Figure 1

Capacitor Voltage Transformer



1. Electromagnetic unit (EMU): Intermediate voltage transformer with compensating reactor
2. Primary winding of the intermediate voltage transformer
3. Compensating reactor
4. Adjustment windings
5. Secondary windings
6. Ferro-resonance damping circuit

Figure 2

Schematic of Capacitor Voltage Transformer

The adjustment windings are used for factory calibration of the capacitor voltage transformer and aren't used for field use. The equivalent circuit for the CVT is shown in figure 3

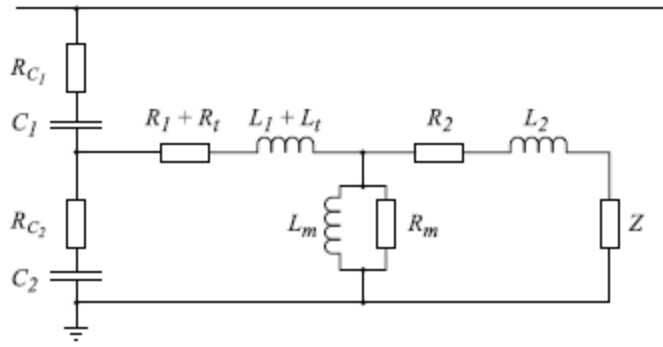


Figure 3

Equivalent circuit for Capacitor Voltage Transformer

The capacitance stack is represented by capacitances C_1 and C_2 with R_{c1} and R_{c2} being the losses in the capacitors. Since the losses in modern capacitors are less than 0.2%, they can be neglected. R_1 and L_1 are the resistance and inductance of the primary winding of the electromagnetic unit. R_2 and L_2 are the resistance and inductance of the secondary of the electromagnetic unit. R_t and L_t are the resistance and inductance of the tuning reactor. L_m and R_m are the inductance and resistance of the magnetizing branch of the EMU. Z is the burden connected to the CVT. The equivalent capacitance, C_{eq} , is a term often referred to when comparing various CVT's. C_{eq} is defined in equation 1.

$$C_{eq} = C_1 + C_2 \quad (1)$$

Since CVT's are composed of capacitors and inductors, the transient response of the CVT is much different than that of an inductive voltage transformer.

When there is a short circuit on the primary, the discharge of the stored energy in the capacitors and inductors will result in a transient oscillation in the secondary. This oscillation has two components; a high frequency component which can be between 900 and 4000 Hz, and a low frequency component that can be between 2 – 15 Hz. The high frequency component usually dies out in less than 10 milliseconds. The low frequency component can last much longer.

This response can cause problems for distance relays that rely on this voltage to make tripping decisions.

Transient Response

The transient response of a capacitive voltage transformer is the ability to reproduce rapid changes in the primary voltage. It's defined as the remaining secondary voltage after a specific time due to a short circuit on the primary voltage. Several factors influence this, they are; the equivalent capacitance of the stack, the tap voltage, the connected burden, and the type of ferroresonant suppression circuit.

Early work by Sweetana (2), and Rusnak(3) provide transient response curves for CVT's while varying the equivalent capacitance, tap voltage, method of ferroresonant suppression, and connected burden for 1970's vintage designs.

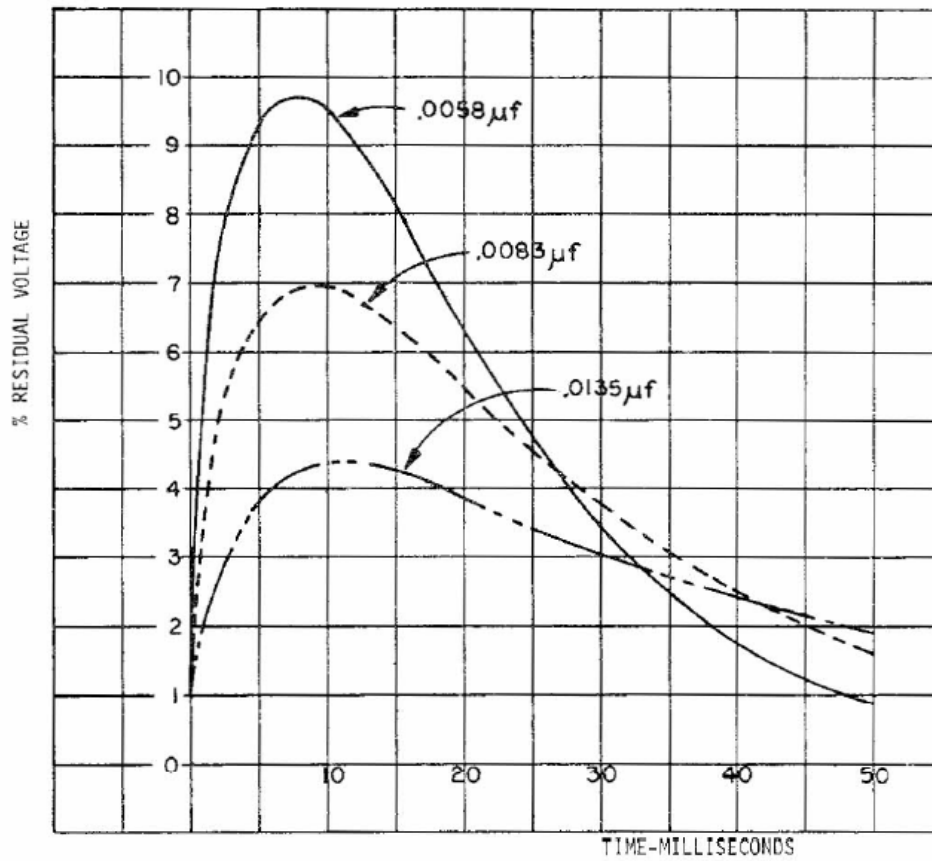


Figure 4

345kV PCA-7 Coupling Capacitor Voltage Transformer showing effect of equivalent capacitance.

Figure 4 demonstrates the effect of varying the equivalent stack capacitance. It shows the residual voltage on the secondary of the CVT after the primary voltage is removed. The higher the capacitance, the lower the magnitude of the residual voltage.

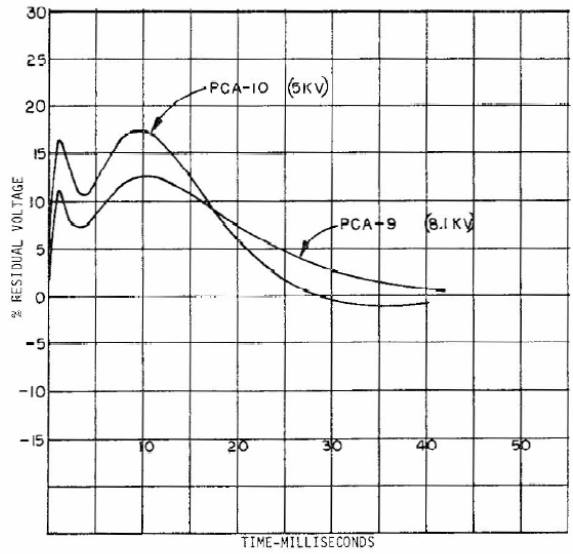


Figure 5

Transient Response of CVT for Different Tap Voltages

Figure 5 shows the transient response of two CCVT's. The primary voltage was suddenly removed and the secondary voltage was measured. Each is designed with a different tap voltage. The higher the tap voltage, the lower the magnitude of the transient response. In designing a CVT both the tap voltage and stack capacitance can be varied. Figure 6 shows the transient response for CVT's that have been optimized for various applications.

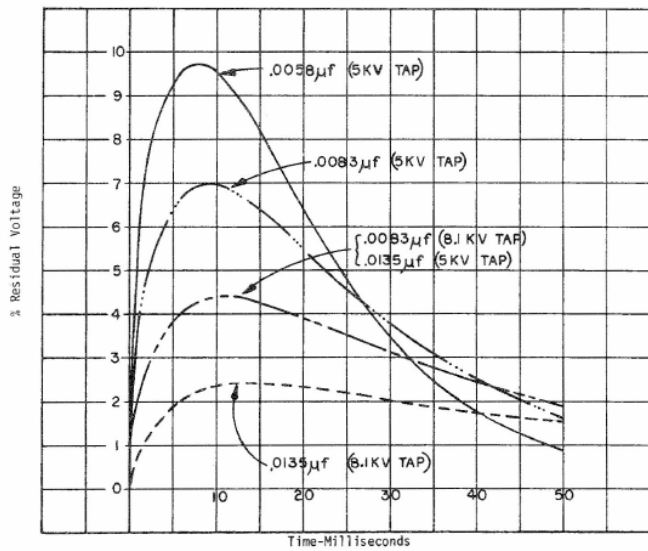


Figure 6

Transient Response of CCVT Designs with varied Tap Voltages and Capacitance

Another factor that affects transient response is the ferroresonant suppression technique used on the secondary of the CCVT. Figure 7 shows the transient response of CCVT's with various methods of ferroresonant suppression.

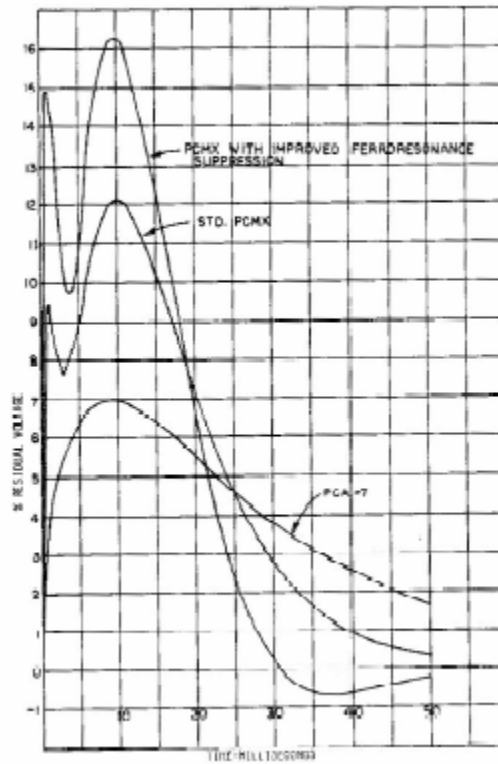


Figure 7

Transient Response for Different Types of Ferroresonant Suppression

All the above factors are under the control of the capacitor voltage transformer designer. A user can purchase a high capacitance design, but other factors such as the tap voltage, and ferroresonant circuit are in the designer's hands. The one factor that the user can control is the connected burden on the CCVT. Figure 8 shows the effect of different connected burdens on the transient response. The higher the burden, the greater the magnitude of the transient response.

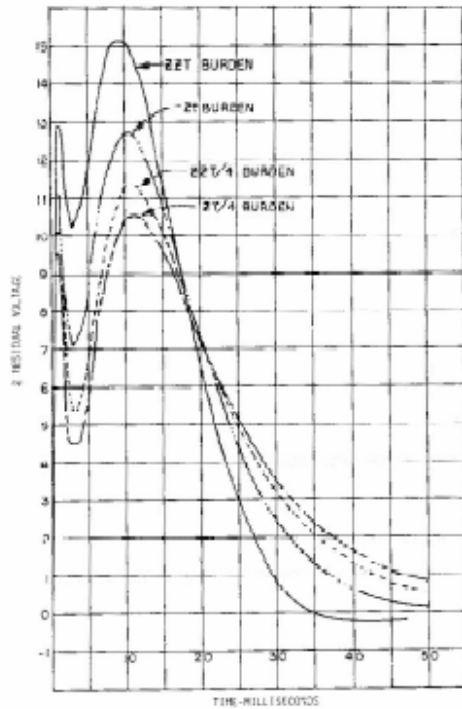


Figure 8

Transient response for various connected burdens

The previous curves were based on testing of Westinghouse design CVT from the 1970's and 1980's. They were used to illustrate the effect of various factors on the transient performance of the device. Since the physics doesn't change, they are still valid. There have been some changes in the design of the CVT's since that time. CVT's can be designed with higher tap voltages. Figure 9 shows a set of transient response curves for currently designed CVT's for comparison.

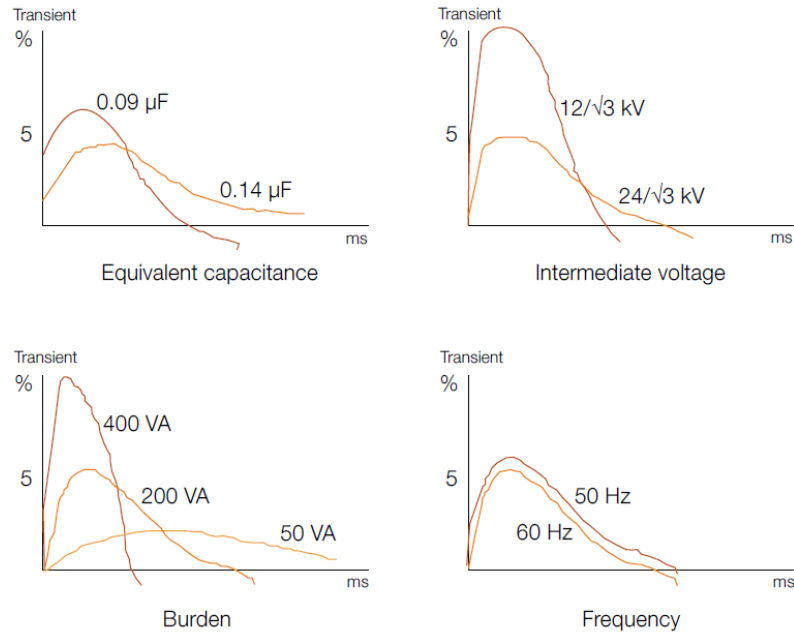


Figure 9

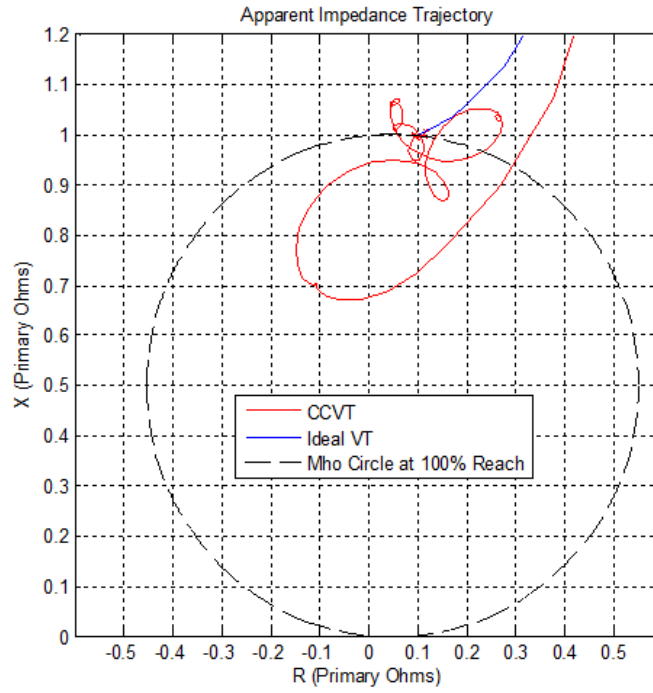
Transient Response Curves for a Current Design of CVT's

CVT Transient Response Effect on Distance Relays

Distance relays calculate the impedance to the fault and operate if the calculated impedance is within its reach setting. Correct analog inputs are necessary for a relay to make the impedance calculation. CVT transients cause incorrect information to be presented to the relay for a short period of time. Since zone 2 and zone 3 timers are much longer than the CVT transient period, zone 2 and zone 3 elements are not affected by CVT transients. Zone 1 elements operate with no intentional delay. Therefore, their operation is affected by the CVT transient.

If Franklin and Horton's paper (4) looked at how much the zone 1 setting of a microprocessor distance relay needs to be pulled back so it didn't overreach from a capacitor voltage transformer transient. The results were for CVT's with active (RLC) ferroresonant suppression networks. They found the worst case scenario for overreach to be a phase to phase fault on a heavily loaded line with load flowing toward the relay location and a fault occurring at voltage zero on the phase to phase voltage. Figure 10 shows the impedance trajectories for an ideal voltage source and a CVT for a fault with 1500Mw of load flowing into the relay location. This case is for a phase to phase fault with $SIR = 5$, and $Z_{Line} = 0.1 + j 1.0$. The maximum allowable reach so the relay wouldn't overreach for this fault would be 67% or 0.67 p.u. The fault impedance was $1m\Omega$

Figure 11 shows the relationship of the source impedance ratio (SIR) to the maximum zone 1 reach.



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Figure 10

Comparison of impedance trajectories for the ideal VT and CVT for the case of 1500MW into the relay location

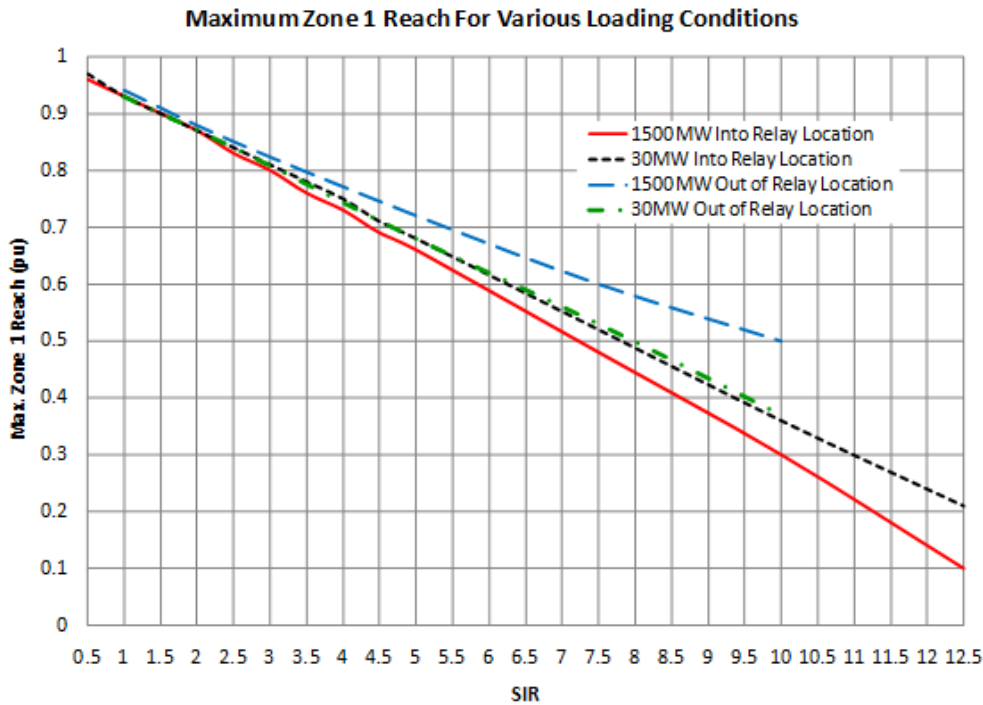


Figure 11

Maximum amount of relay reach to compensate for CVT transient

Many other factors contribute to the reach setting of a distance relay. Reduction in the setting due to CVT transients is only one of them.

The latest generation of microprocessor relays use a combination of low pass filtering techniques and counters to combat CVT transients. Security comes at the price of speed. The operation of the relay is delayed by up to 10 msec due to these measures. In cases where a conventional wire wound voltage transformer is used CVT Transient filtering may be turned off by a setting in the relay.

Selection of Capacitor Voltage Transformer

Manufacturers offer the user many options when purchasing CVT's. One of those options is the capacitance. Figure 12 illustrates the variation of capacitance available for different voltage level CVT's. When selecting a CVT from a transient response viewpoint, select the CVT with the highest capacitance.

| Capacitor voltage transformer CPB | | |
|-----------------------------------|--|---|
| Type | Standard capacitance For IEC test voltage | Net weight incl. oil Polymer/ Porcelain |
| | pF (+10; - 5%) | kg |
| CPB 72 ¹⁾ | 18200 | 190/200 |
| CPB 72 ¹⁾ | 24900 | 210/240 |
| CPB 72 ²⁾ | 24900 | 280/310 |
| CPB 123 ¹⁾ | 11200 | 200/220 |
| CPB 123 ¹⁾ | 15400 | 230/280 |
| CPB 123 ²⁾ | 15400 | 300/350 |
| CPB 145 ¹⁾ | 9100 | 210/280 |
| CPB 145 ¹⁾ | 12900 | 230/300 |
| CPB 145 ²⁾ | 12900 | 300/370 |
| CPB 145 ²⁾ | 20200 | 350/440 |
| CPB 170 ¹⁾ | 7800 | 220/250 |
| CPB 170 ¹⁾ | 10800 | 240/320 |
| CPB 170 ²⁾ | 10800 | 320/400 |
| CPB 170 ²⁾ | 17000 | 350/440 |

Figure 11

Capacitor Voltage Transformer Capacitance variations for different voltage levels

EMTP Studies

Several models for the CVT have been developed for use with the Electromagnetic Transients Program.(5) Models have been verified by field tests. To understand what the predicted response of the CVT will be on a given power system, and how it affects relay operation, it is recommended that a EMTP study be done.

Conclusion

This paper reviewed capacitive voltage transformer design, and showed how some design parameters affect the transient response. The higher the equivalent capacitance of the CVT, and the higher the tap voltage of the capacitor stack the lower the magnitude of the transient. The user can specify a high capacitance CVT when ordering, thus reducing the magnitude of the transient.

CVT transients affect the operation of distance relays. Due to the time delays associated with zone 2 and zone 3 relays, they are not affected by the CVT transient. Zone 1 distance relays with no intentional delay are susceptible to overreach as a result of CVT transients. Zone 1 relay reach settings need to be reduced

based on the SIR of the line. The latest version of microprocessor relays use filtering techniques to lessen the affects of CVT transients.

EMTP studies are recommended to look at CVT transient response for specific system conditions.

References

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- (3) Accuracy, Transient Response, and Carrier Characteristics of Capacitor Voltage Transformers, Fred Brown, George Rusnak 1981 Electric Utility Engineering Conference, March 22 – April 3, 1981
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Biography

Roger graduated with a BSEE from Marquette University, and a Masters degree in Electrical Engineering from the University of Pittsburgh. Roger is Relay Development Consultant for ABB. He guides the development of relay products for the North American market. Roger is also a regional technical manager for the central area of North America. Roger is a IEEE senior member, and Vice Chair of the IEEE Power Systems Relay Committee. Roger has authored or co authored many papers in power systems protection.