Input Source Error Concerns for Protective Relays

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***Abstract*—Capacitive Coupled Voltage Transformers (CCVTs) and Bushing Potential Devices (BPDs) have supplied high voltage relay potential circuits for many years. The transient performance of a CCVT has been analyzed, and solutions for their transient performance have been incorporated in relaying systems since the 1970s. Little analysis has been performed on BPD transient performance. A BPD has been tested and characterized to determine the parameters that affect the output voltage during system fault conditions.**

Current Transformers (CTs) that saturate during system faults produce a nonsinusoid output that, when filtered, presents a reduced magnitude and phase shifted current to protective relays. The response of distance relays for various levels of CT saturation are analyzed and presented.

Finally, utility experience with relays sourced by CCVTs and BPDs with the intent of validating the models and relay setting adjustments for input source errors are presented.

I. Introduction

Electromechanical relays are reasonably tolerant of voltage source errors due to their inherent signal filtering and slower response. The filtering and response of solid-state and numerical relays have been tuned to provide fast response to fundamental frequency values. This fast response has enabled them to respond during the transient period of the voltage sources. CTs that were installed many years ago may be subjected to higher fault currents than originally contemplated. These CTs may saturate during the system faults, resulting in an erroneous signal being applied to the relay. Protection engineers may specify voltage and current source suitable for relaying performance on new construction. However, there are many relay retro-fit situations where the project budget will not tolerate replacement of voltage and current transformers.

This paper will review CCVT modeling, present a model for BPDs, analyze distance relay performance during CT saturation, and provide utility experience with CCVT and BPD performance and transient error mitigation.

II. Capacitive Coupled Voltage Transformer

A. CCVT Construction

A CCVT is a device that makes use of a capacitive voltage divider to reduce the primary voltage to a medium voltage level, e.g. 15 kV. The medium voltage is applied to a voltage transformer that delivers the common secondary 115 and 66 voltages.

The other components associated with the CCVT are a compensating reactor and ferroresonance suppression circuit. A typical CCVT with an active ferroresonant suppressing circuit and equivalent circuit are shown in Fig. 1 and Fig. 2, respectively. The equivalent circuit includes stray capacitance and winding resistance of the compensating reactor and also stray capacitance, winding resistance, and leakage inductance of the step-down transformer.

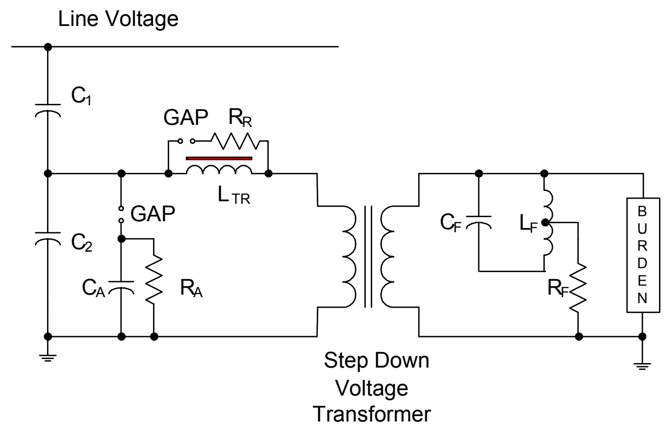

Fig. 1 CCVT circuit

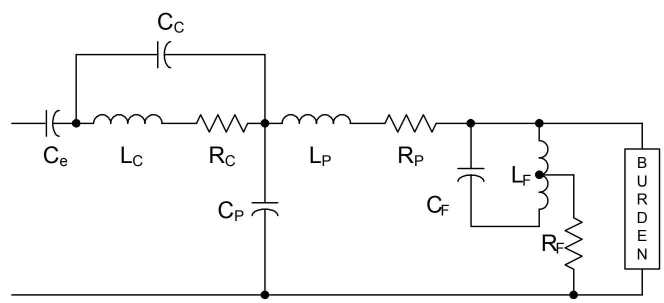

Fig. 2 CCVT equivalent circuit

B. CCVT Voltage Transient

For a few cycles following a voltage change, the output of a CCVT does not match the input. This output error is known as a subsidence voltage. The typical demonstration of subsidence voltage is to plot the voltage response for a short circuit occurring at voltage peak and zero as shown in Fig. 3 and Fig. 4, respectively. These transient voltage responses are from the equivalent active CCVT circuit shown in Fig. 2.

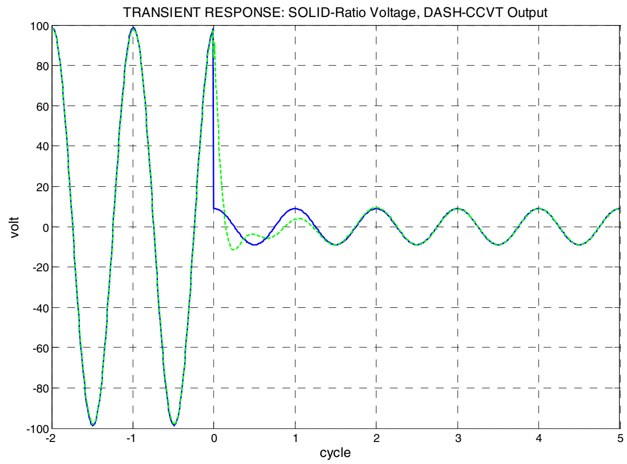

Fig. 3 CCVT peak voltage subsidence transient

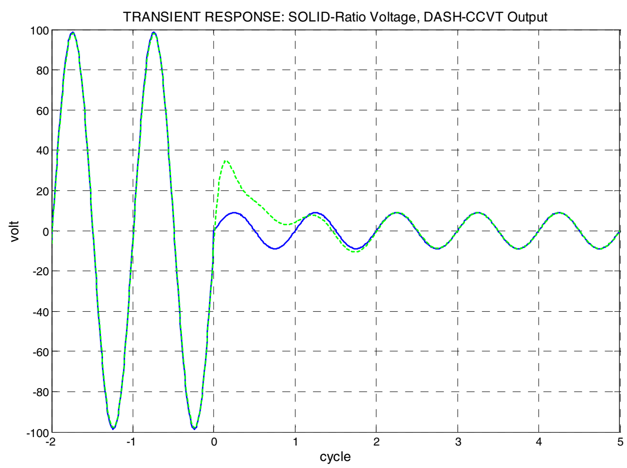

Fig. 4 CCVT zero voltage subsidence transient

C. *Explanation of Transient*

For a voltage peak transient, the capacitor is fully charged and is discharged with an associated RLC time constant into the short circuit. The resulting equivalent is an underdamped circuit that will result in a transient voltage that oscillates at a frequency greater than the fundamental as shown in Fig. 3. For a voltage zero transient, the transformer and compensating reactor are at peak flux. This stored flux is released through the capacitors to the short circuit with a RLC time constant. This results in an overshoot voltage that rings down to zero in a few cycles as shown in Fig. 4. A simplified equivalent circuit is shown in Fig. 5.

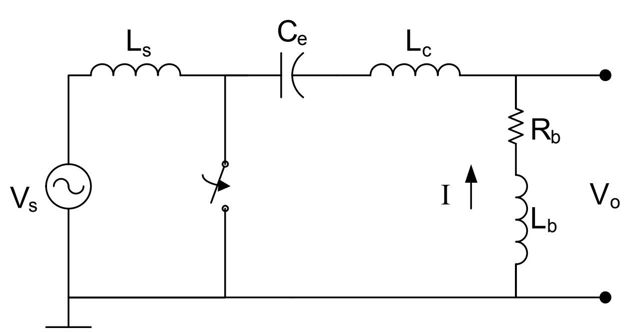

Fig. 5 Simplified CCVT equivalent circuit for a terminal short circuit

The subsidence voltage causes a measured voltage magnitude reduction and phase angle shift as shown in the polar plot, Fig. 6 and Fig. 7, for peak and zero voltage fault initiation. The numbers marked in the plots are the sequence that the fault voltage goes through after the fault initiation.

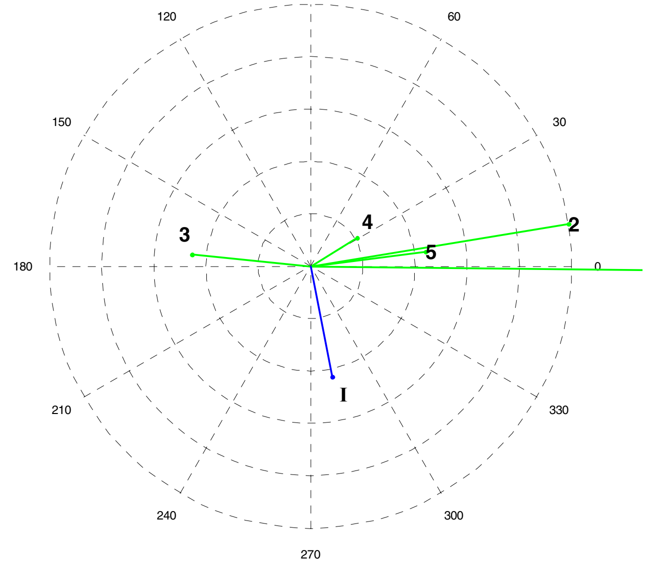

Fig. 6 CCVT voltage peak subsidence transient fundamental voltage

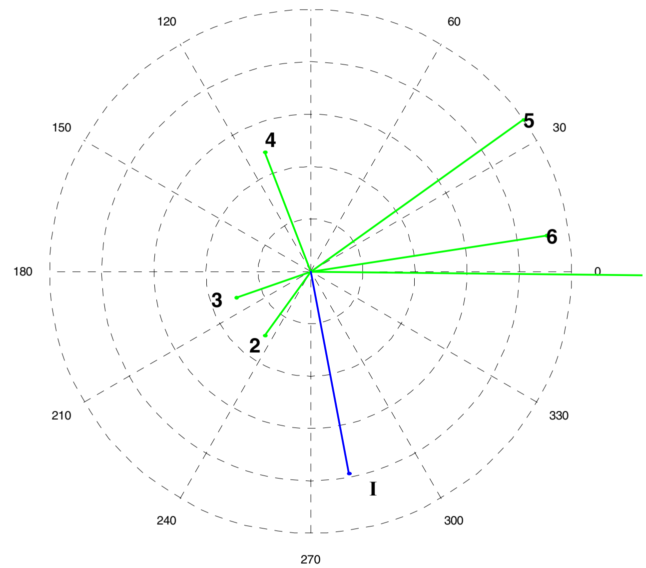

Fig. 7 CCVT voltage zero subsidence transient fundamental voltage

Notice how the voltage magnitude is severely reduced and significantly out of phase with the actual fault voltage, points 5 and 6, respectively in Fig. 6 and Fig. 7.

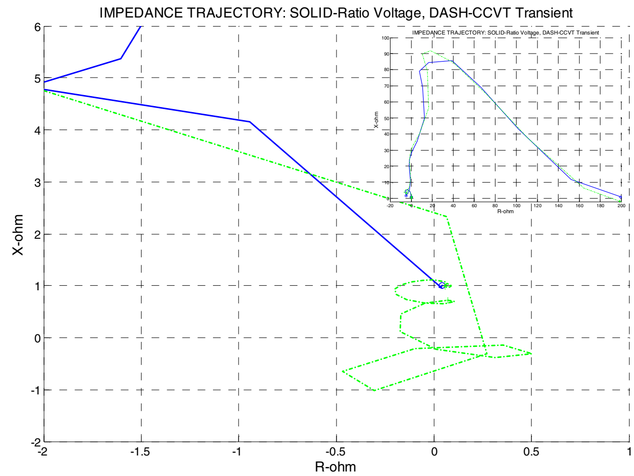

Fig. 8 CCVT output impedance trajectory of voltage-peak fault

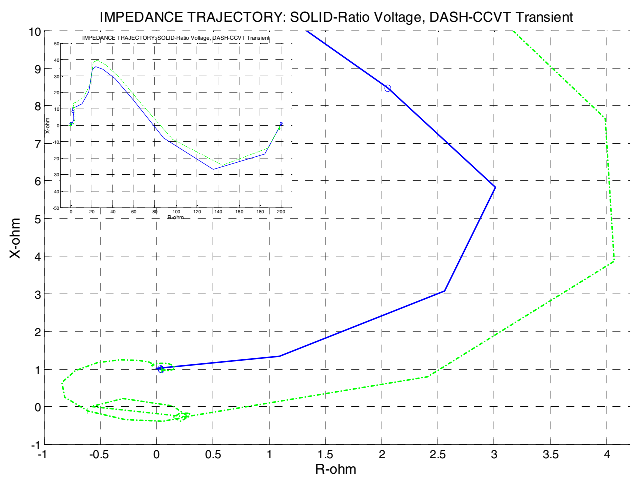

Fig. 9 CCVT output impedance trajectory of voltage-zero fault

This voltage error causes the relay measured impedance trajectory to present a negative-impedance reach before traversing through zero to the actual fault impedance as shown in Fig. 8 and Fig. 9, where the main graph shows the enlarged version of the entire impedance trajectory plotted in a small graph of the same figure. These examples present cases where the Zone 1 would have to be eliminated because it could not be set short enough to avoid misoperation.

D. *Parameters That Affect CCVT Transient Performance*

TABLE I
PARAMETERS THAT AFFECT CCVT TRANSIENT PERFORMANCE

Parameter	Small Transient	Large Transient
CCVT Capacitance	High	Low
Ferroresonance Suppression Circuit	Passive	Active
Transformer Ratio	High	Low
Burden	Resistive	Inductive
Bus Voltage Dip*	Small	Large

* The transient error is proportional to the change in bus voltage due to a fault.

E. *Utility CCVT Performance*

Two examples of CCVT performance are provided. In both cases the numerical relays are applied to the secondary, resulting in a low secondary burden. The first example is a failed circuit switcher contact on a line reactor that is selected to open for voltage control. The Phase B contact remains closed as the horizontal air break is opened toward Phase C creating a B-C fault. A remote Zone 1 relay, set to protect a 41-mile line with a SIR of 1.45, trips for this event. The CCVT sourcing the protective relay has an active ferroresonance suppression circuit. The resulting transient impedance lies within the Zone 1 reach due to the subsidence transient as shown in Fig. 11 and Fig. 12.

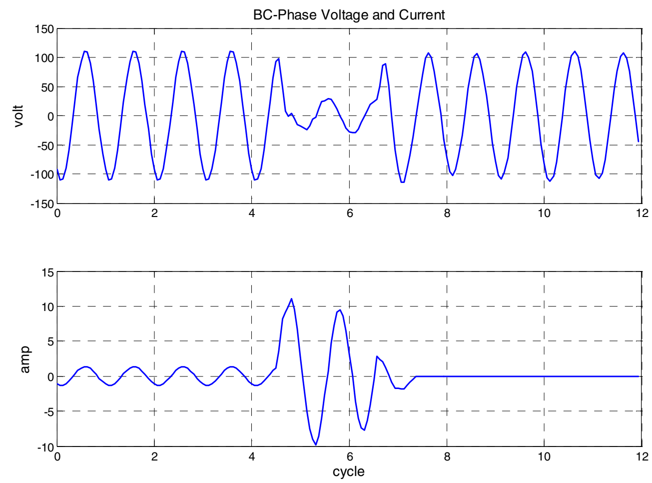

Fig. 10 B-C phase voltage and current for B-C fault

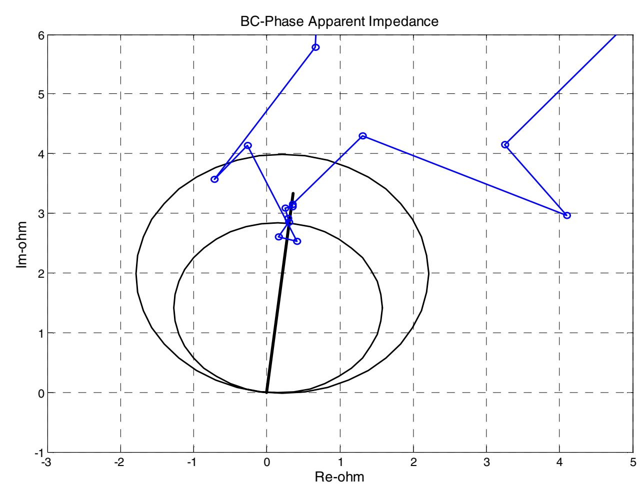

Fig. 11 Zone 1 overreach for B-C fault

The second case occurred when a breaker was closed into a three-phase fault. A remote Zone 1 relay, set to protect a 13-mile line with a SIR of 29, trips for this event. The resulting transient impedance lies within the Zone 1 reach due to the subsidence transient as shown in Fig. 12 and Fig. 13.

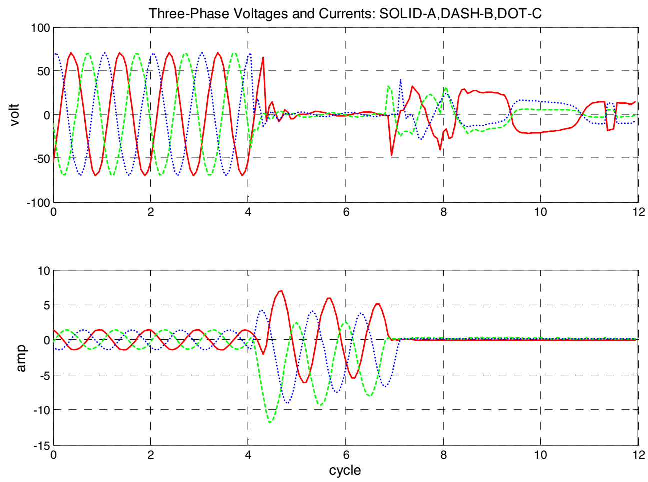

Fig. 12 Voltages and currents for three-phase fault

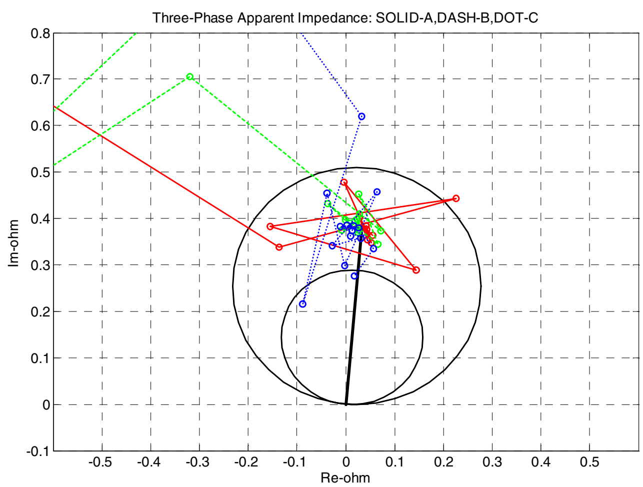

Fig. 13 Zone 1 overreach for three-phase fault

In the first case, the Zone 1 reach was reduced to eliminate the transient overreach. In the second case, a 1.75-cycle time delay was added to eliminate the overreach.

F. Recommended CCVT Specification

In order to minimize the CCVT subsidence transient, use the following criteria:

- High capacitance, e.g. 10 nano-fared
- Large transformer ratio, e.g. 15 kV / 115 / 66 V
- Passive ferroresonance circuit
- Resistive CCVT burden

III. Bushing Potential Device

A. BPD Construction

BPDs are manufactured to match a particular bushing type, e.g. GE "U" or "F" type. The BPD may be applied on a bushing type ranging from 69 to 230 kV. The construction of a BPD is based on tapping a point within the degrading insulation of a bushing. This makes use of the capacitive effect of a breaker bushing to produce a capacitive voltage divider. The BPD reduces the primary voltage to a medium voltage level, e.g. 4 kV, which is applied to a transformer to produce the secondary potentials of 115 and 66 volts.

The secondary of the BPD contains a coupling coil, phase angle adjustment capacitors, and power factor adjustment capacitors. The coupling coil and phase angle adjustment capacitors provide for aligning the secondary potential with the primary. This adjustment is required because the primary capacitance will vary based on the primary operating voltage. The power factor adjustment capacitors are to compensate the secondary burden to near unity power factor to minimize phase shift and voltage drop due to the burden. BPDs are notoriously difficult to adjust for electromechanical relaying burdens.

BPDs are designed to withstand overvoltage up to rated line-to-line voltage that result when neutral voltage shift occurs. Therefore, a ferroresonance suppression circuit is not required. A typical BPD and equivalent circuit are shown in Fig. 14 and Fig. 15, respectively. Refer to the Appendix for the model parameters.

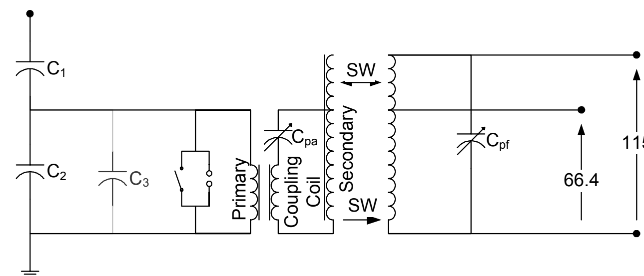

Fig. 14 GE KA-105 BPD circuit

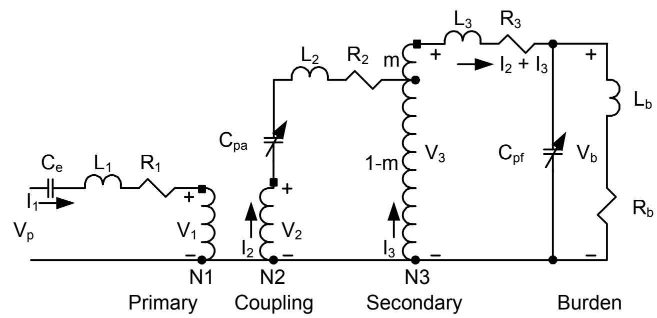

Fig. 15 GE KA-105 BPD equivalent circuit

B. BPD Voltage Transient

A BPD produces a similar response to a change in voltage to that of a CCVT. However, because the BPD employs a low step-down transformer ratio, the BPD response is more dependent on the secondary burden as shown in Fig. 16 through Fig. 19. A high inductive burden (low power factor) significantly increases the amount and duration of the transient error as shown in Fig. 18 and Fig. 19.

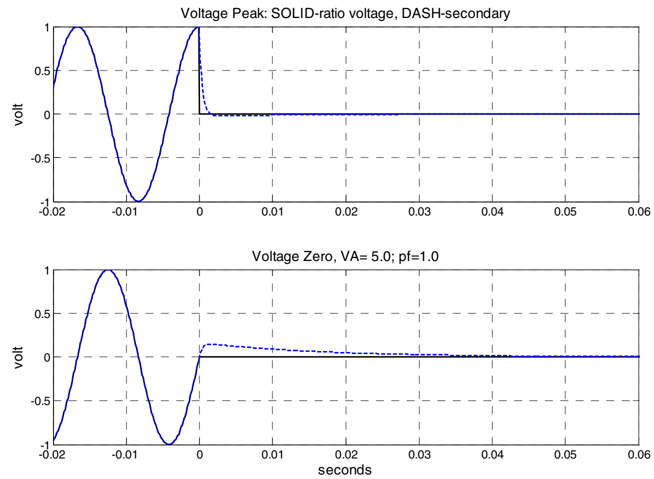

Fig. 16 BPD response for burden of VA=5 and pf=1.0 with exact pf compensation

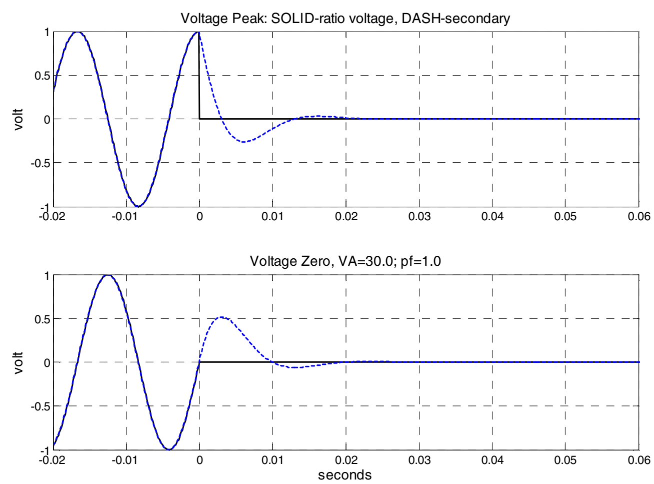

Fig. 17 BPD response for burden of VA=30 and pf=1.0 with exact pf compensation

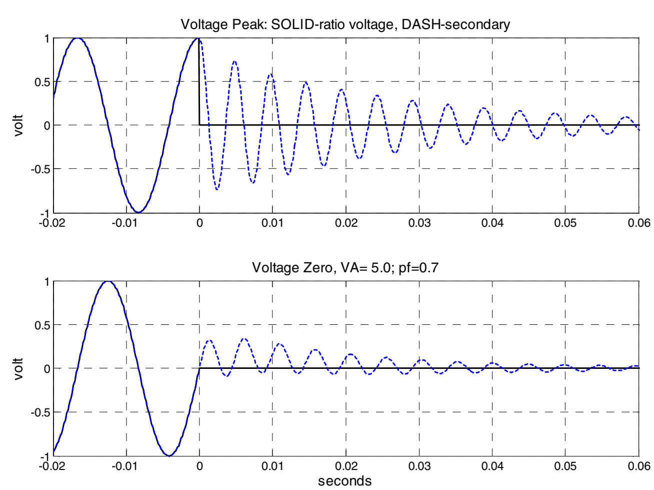

Fig. 18 BPD response for burden of VA=5 and pf=0.7 with exact pf compensation

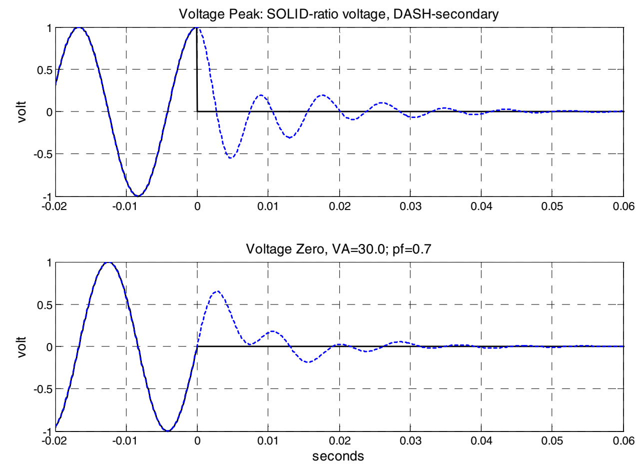

Fig. 19 BPD response for burden of VA=30 and pf=0.7 with exact pf compensation

C. Parameters That Affect BPD Transient Performance

- Burden: Inductive burdens result in worst transient performance.
- Transformer Ratio: A low step-down transformer ratio will result in a larger burden effect and produce greater transient error.
- Power Factor Adjustment: Compensating for any lagging power factor burden with capacitor C_{pf} will improve the transient performance.
- Bus Voltage Dip: The transient error is proportional to the change in bus voltage caused by a fault. Therefore, high source-to-line-impedance ratios result in these large voltage changes and transient error at Zone 1 boundary faults.

D. Utility BPD Performance

Two examples are provided demonstrating BPD performance. The first case involves a relaying system consisting of both numerical and electromechanical relays resulting in a high burden, 10 ohms at 65% power factor. The protected line is 40 miles long with an SIR of 5.8. A ground fault occurs 64% from a station. The large and slow decaying BPD transient results in an underreach for this fault as shown in Fig. 20 and Fig. 21.

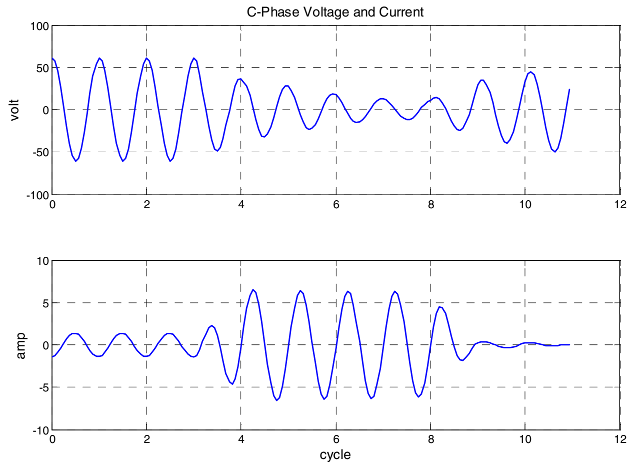

Fig. 20 Voltage and current for a C-phase fault at 64% of line length

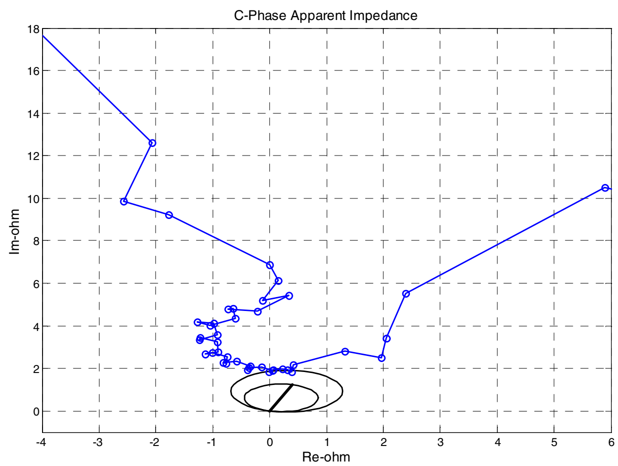

Fig. 21 Apparent impedance of a C-phase fault at 64% of line length

The second case involves all numerical relays presenting a low burden to the BPD. A remote Zone 1 relay, set to protect a 3-mile line with a SIR of 1.87, trips when a clamp fails, allowing Phase A to fall into Phase C on the station dead-end structure one station beyond the remote end bus. The resulting transient impedance lies within the Zone 1 reach due to the subsidence transient as shown in Fig. 22 and Fig. 23.

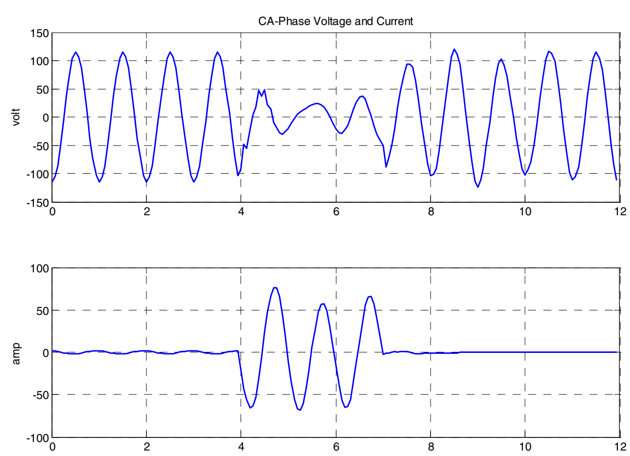

Fig. 22 C-A phase voltage and current

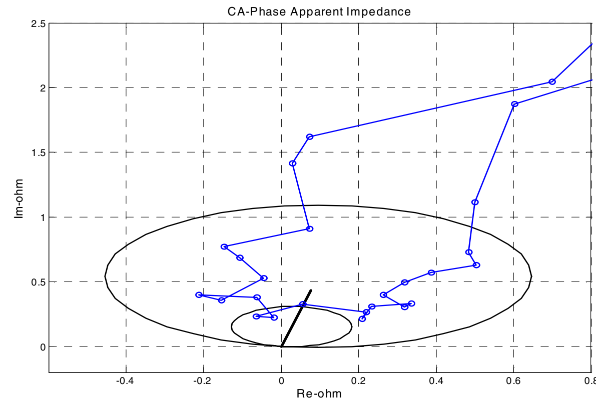

Fig. 23 C-A phase apparent impedance

E. Mitigation of CCVT and BPD Subsidence Transient

The characteristic of the CCVT and BPD subsidence transient is a reduction in fundamental voltage for a few cycles. This will result in a Zone 1 distance relay overreach for remote terminal faults. The preferred mitigation to apply depends on the fault clearing requirements of the transmission system. If the system can tolerate a few cycles for fault detection, then time delay the Zone 1 output by up to two cycles. However, for the system with stringent fault clearing times, the Zone 1 relay reach should be reduced based on the chart shown in Fig. 24. Fig. 24 is obtained using typical passive and active CCVTs with a resistive burden of 5 kΩ, representative of the load of several modern microprocessor relays and meters.

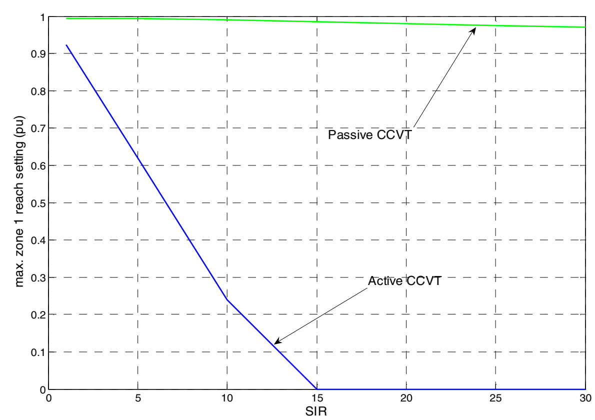

Fig. 24 Distance element performance as function of source impedance ratio

In some microprocessor relays, dedicated logic has been developed to deal with the transient overreach concerns from CCVT transients. The system impedance ratio (SIR) is estimated from the fault voltage and current, when this value is high and causes a concern of overreach, a time delay is added to the instantaneous tripping distance elements. The fault impedance is then closely monitored to detect any CCVT transient signatures. Therefore, on the detection of a high SIR, the relay applies the Zone 1 delay and monitors the voltage transient. If the transient signature is small and does not indicate overreach, the time delay is quickly removed to allow a quicker operation of the elements. The logic adapts to the quality of the CCVT used and only adds time delay when necessary.

IV. CURRENT TRANSFORMER

A. CT Saturation

CT saturation results in a reduction in fundamental magnitude and a leading phase shift. This error will cause distance relays to under reach a remote fault as shown in Fig. 25 through Fig. 30.

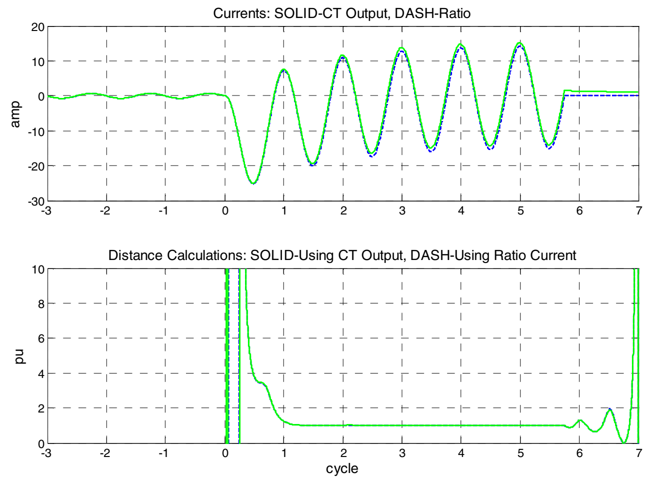

Fig. 25 CT output and distance measurement without saturation

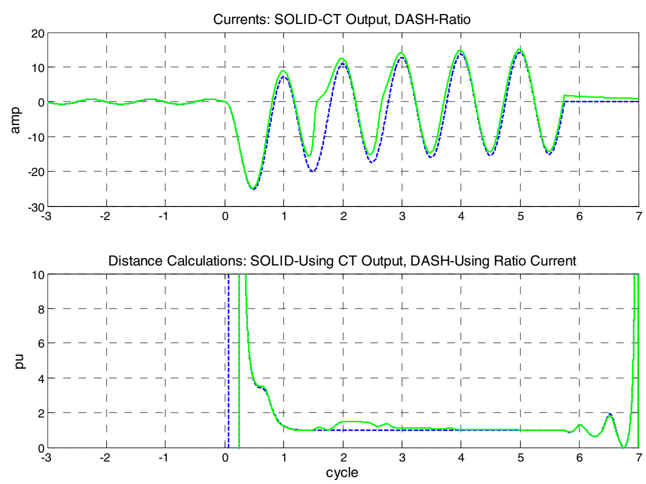

Fig. 26 CT output and distance measurement with minimal saturation

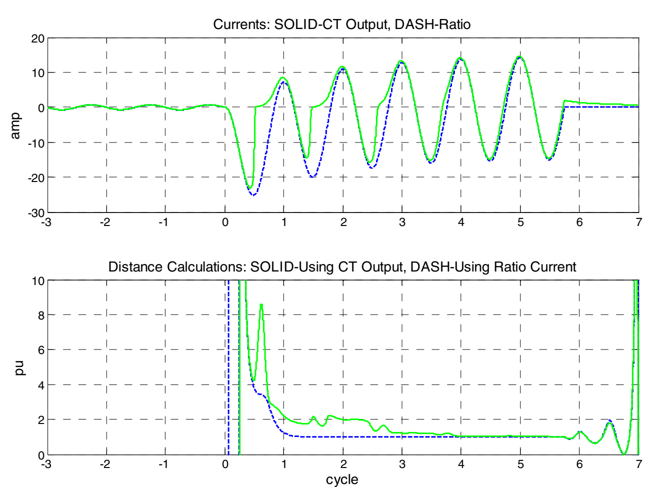

Fig. 27 CT output and distance measurement with 7.7 ms to saturation

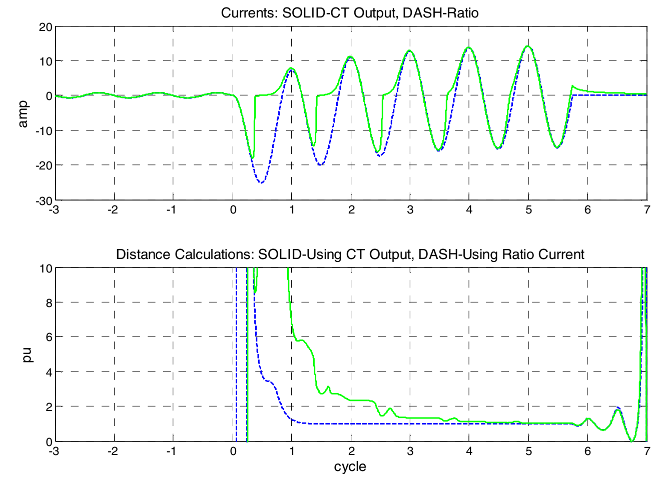

Fig. 28 CT output and distance measurement with 6.3 ms to saturation

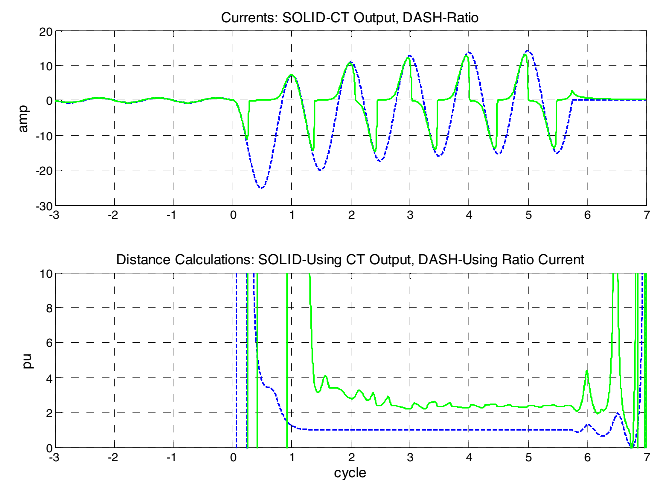

Fig. 29 CT output and distance measurement with 4.5 ms to saturation

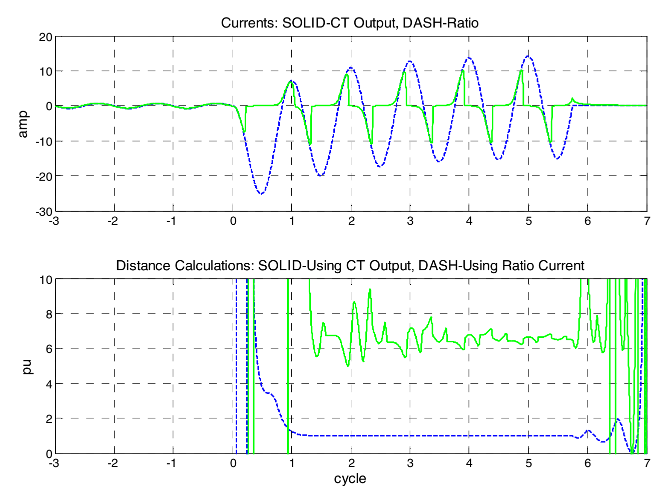

Fig. 30 CT output and distance measurement with 3.3 ms to saturation

The time to saturate determines the reduction in reach. Table II summarizes the reach reduction based on the time to saturate.

TABLE II
DISTANCE RELAY REACH DURING CT SATURATION

Time to Saturate (milliseconds)	**Reach (% at 1.5 cycles)**
No saturation in first cycle	100
7.7	50
6.3	33
4.5	25
3.3	17

B. Conclusion

Utility experience with CCVT transients has demonstrated that the CCVT model is accurate and can be used to determine mitigation methods. Both utility examples of reach reduction and time delay have produced satisfactory results for dealing with existing CCVT sources. Additionally, proper CCVT specifications will result in better performing CCVTs for new installations.

A model for BPDs has been developed and validated with captured events. The analysis of BPDs has determined that these devices do produce a subsidence transient. This transient is dependent on the burden attached to the device. Ultimately, BPDs are suitable for protective relaying applications using numerical relays and meters that present a low, near unity power factor burden.

CT saturation will cause distance relay underreach. Where CT saturation has been identified and there is no ability to mitigate the saturation with CT settings (e.g. changing the ratio or reducing the burden) or replacement, then the reach of the Zone 2 relays should be adjusted for this underreach.

V. APPENDIX

This appendix shows the equivalent circuit and parameters used to model a GE KA-105 Bushing Potential Device.

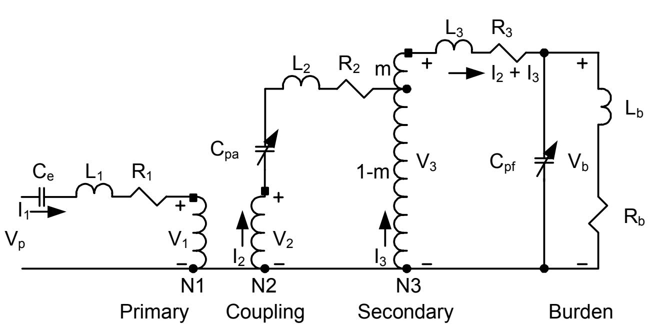

Fig. 31 BPD equivalent circuit

TABLE III

Parameter	Description	Value
C_e	Equivalent Capacitance (C_1+C_2)	0.0059 µF
L_1	Transformer Primary Leakage Inductance	0.263 mH
R_1	Transformer Primary Winding Resistance	0.22 Ω
C_{pa}	Phase Angle Adjustment Capacitance	12.9 µF
L_2	Coupling Coil Leakage Inductance	0.298 mH
R_2	Coupling Coil Winding Resistance	0.077 Ω
L_3	Transformer Secondary Leakage Inductance	3.836 mH
R_3	Transformer Secondary Winding Resistance	0.086 Ω
C_{pf}	Power Factor Adjustment Capacitance	Adjusted for burden

VI. REFERENCES

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[2] A. Sweetana, "Transient Response Characteristics of Capacitive Potential Devices," IEEE Transactions on Power Apparatus and Systems, Vol. 90, No. 5, September/October 1971.

[3] D. Hou and J. Roberts, "Capacitive Voltage Transformers: Transient Overreach Concerns and Solutions for Distance Relaying," presented at the 22nd Annual Western Protective Relay Conference, Spokane, WA, October 24–26, 1995.

VII. BIOGRAPHIES

David Angell graduated from the University of Idaho with a bachelors degree in electrical engineering in 1984 followed with a masters degree in 1986. He has 21 years of service with Idaho Power and two years with Bonneville Power Administration. David has 20 years experience in power system protection and communications. He has presented several papers on protection topics for conferences and university lectures. Presently, David is the manager of Planning and Load Research for Idaho Power and an adjunct professor at Boise State University.

Daqing Hou received BS and MS degrees in electrical engineering at the Northeast University, China, in 1981 and 1984, respectively. He received his Ph.D. in electrical and computer engineering at Washington State University in 1991. Since 1990, he has been with Schweitzer Engineering Laboratories, Inc., Pullman, Washington, USA, where he has held numerous positions including development engineer, application engineer, and R&D manager. He is currently a principal research engineer. His work includes system modeling, simulation, and signal processing for power systems and digital protective relays. His research interests include multivariable linear systems, system identification, and signal processing. He holds multiple patents and has authored or co-authored many technical papers. He is a Senior Member of IEEE.

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