Do we have to reduce zone 1 reach solely based on System Impedance Ratio –SIR?

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Abstract
There were several presentations done in various forums on pulling back the reach or even disabling under reaching zone, zone 1, depending on the Source to line impedance ratio, also known as System Impedance ratio. This paper examines relay performance based on the sensitivity of modern digital relays and the dependence on the type of instrument transformer providing the voltage input. Voltage discrimination, the difference in voltage between the line end fault and zone 1 reach location approach suggested in the industry is also reviewed. Several relays from manufacturers were checked in the laboratory at various SIRs ranging from 1 up to 60 with normal wound PT, CCVTS with active and passive filters. Results and conclusions from these tests are presented.

Index Terms—SIR, Zone 1, Voltage discrimination, Relay sensitivity

I. INTRODUCTION

Distance relays have been used for a long time as standard package to protect transmission lines. Relay operation isolates the faulted line section with high degree of reliability and security. They operate only for faults between the relay location and set reach based on impedance measurement which is proportional to the length of the line up to the fault location. The relay trips the line if the calculated impedance is less than the set value.

The impedance measurement is based on the ratio of the voltage to the current at the relaying point though different variations are used to determine the fault location and direction using relay inputs fed from current transformer and voltage transformer at the relay location. Figure 1 shows a simple electric network with generated voltage, E and impedances of the system behind the relay location, termed as source impedance Z_S and the line impedance up to the fault, Z_L. The voltage at the relay location is represented as V.

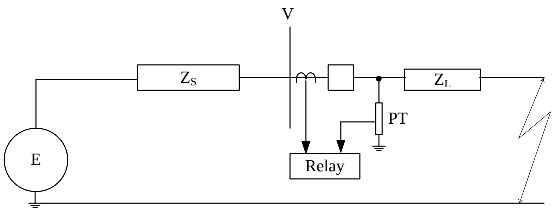


Figure 1: Relay Connections

The voltage at the relay location in Figure 1 is given by

$$V = \frac{Z_L}{(Z_S+Z_L)}E = \frac{E}{(\frac{Z_S}{Z_L}+1)} \quad (1)$$

If the relay is set to detect faults on the line up to Z_L, termed as reach of the relay, the relay will operate and trip the line if the measured impedance is less than Z_L and will not operate for faults beyond Z_L. The ratio Z_S/Z_L is defined as system impedance ratio, SIR.

For a fault at the reach point, the Voltage at the relay,

$$V = E / (SIR+1) \quad (2)$$

(a) Voltage at the relay for single line to ground fault

GE grid solutions protection and automation application guide [1] provides equations for determining the voltage at the relay location for single line to ground fault:

$$V = \frac{E}{[(\frac{Z_{1S}}{Z_{1L}})(\frac{2+p}{2+q})+1]} \quad ; \text{Where } p = \frac{Z_{0s}}{Z_{1S}} \text{ and } q = \frac{Z_{0L}}{Z_{1L}} \quad (3)$$

Thompson and Somani paper [2] analyses different methods used in the industry to determine SIR and discusses IEEE transmission line guide definitions of lines as short, medium and long based on SIR. The only relevance of these calculations is the voltage magnitude at the relay location for remote end faults and this has an impact on relay performance.

II. DISTANCE RELAY ZONES

Since distance relay is monitoring the impedance of the line from one end of the line, instantaneous clearing for faults on entire line section is not possible. This is due to errors associated with instrument transformers, line impedance and relay design. Basic distance protection will have an instantaneous unit known as under reaching relay or Zone 1 set to 80%-85% of the line impedance. The remaining line section is protected by a second time delayed unit known as overreaching relay or zone 2 and is set to 120% of the line impedance. Time delay is set to coordinate with relays on adjacent line section. Digital relays have several zones of protection providing both forward and reverse looking distance relays, referred to as distance elements.

III. RELAY PERFORMANCE

Zone 1 relay providing instantaneous operation for faults within 80-85% of the protected line has to be reliable and should not operate for faults beyond the remote end.

Based on this requirement, relay performance is examined based on:

- Voltage sensitivity
- Current Sensitivity
- Impedance settings sensitivity
- Relay Design

(a) Effect of Relay Voltage input

Magnitude of the voltage available to the relay depends on the source strength and SIR as per equations (1), (2) and (3). Our intent is to make sure that zone 1 relay does not operate for faults beyond the remote end.

SIR	1	5	10	30	40	60
V_{PU}	0.5	0.166	0.09	0.032	0.024	0.016
V@ $69V_{NOM}$	34.5V	11.45V	6.21V	2.2V	1.65V	1.13V
V@ $115V_{NOM}$	57.5V	19V	1035V	3.68V	2.76V	1.88V

Table 1: Voltage at the relay for remote end fault

Table 1 shows the available voltage to the relay for line end three phase fault. The voltage decreases with the increase in SIR and has at least 1.13V for remote three phase faults on a very weak system with SIR of 60.

Historically, 69V nominal was used on all electromechanical and static relays but, with modern microprocessor based relays, using 115 V nominal will provide higher voltages.

The accuracy and operating times of legacy relays, electromechanical and static versions, depended on the voltage magnitude. GE application guide provides historical perspective of relay accuracy and operating time dependence on voltage which is determined by SIR. It also shows graphs of how the relay errors increase with increase in SIR.

One of the inputs distance relay design is the compensated voltage (V-IZ) where Z is the relay setting. If the fault is at the reach point, the voltage V at the relay is equal to Current I times the line impedance Z and (V-IZ) would be zero for a fault without resistance. Electro mechanical relays used (V-IZ) as one of the inputs and the developed torque reduced as compensated voltage magnitude reduced resulting in slower operation for faults near the reach location as shown in Figure 2. The operating times of relays for static versions were shown as constant time contours showing operating times varying fault locations for different SIRs.

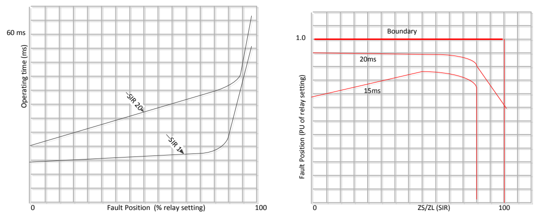


Figure 2: Typical Relay operating time–Constant Time Contour

Modern relays have flatter operating times than legacy relays and have better voltage sensing ability.

(b) Relay measurement Accuracy

Measuring sensitivity of digital relays depends on the number of A/D converter bits n, full scale measurement range, FSR.

Least significant bit is a measure of relay minimum voltage detection level LSB $=\frac{FSR}{2^{(n-1)}}$ though for accuracy purposes, we may use at least four LSBs as the minimum level. Table 2 provides an idea of how the relay sensitivity improves with higher bit converters and with lower full scale range.

Full Scale Range	12 bit A/D	16 bit A/D
150 V	LSB=150/2^{11}=73 mV	4.5 mV
250 V	112mV	7.7 mV
300 V	146 mV	9.16 mV

Table 2: Relay minimum voltage with reference A/D

Modern relays are available with full scale range up to 300V and if the user has a choice to select lower full scale range of 150V, the minimum voltage detection reduces to half the value at 300 V. However, the voltage available to the relay even at SIR of 60 shown in Table 1 is well above the LSB numbers in Table 2. Use of CCVTs creates other issues and this will be discussed later.

(c) Current and impedance sensitivity

Fault occurrence at voltage near zero generates current waveforms which are fully offset and may result in relay overreaching if the DC offset is not removed. Electromechanical relay designs with induction cup did not have issues with DC offset due their operating principle. Digital relays use filters and gapped core CTs to mitigate effects of DC on measurement accuracy.

Impedance setting is now available over a wide range from few 100^{th} of an ohm to over sixty ohms. The accuracy of measurement is well below the setting margins seen.

(d) Voltage Discrimination

Xcel Energy reviewed the practice of looking at the relay voltage difference between line end fault and end of zone 1 reach to evaluate the reliability of performance of zone 1 relay.

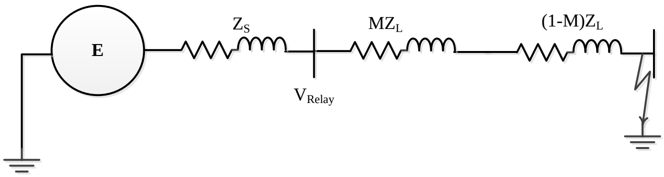


Figure 3: Single Line diagram showing Zone 1 Reach, $M*Z_L$

With reference to figure 3, the voltage at the relay for a fault at the Zone 1 reach is

$$V_{Zone1} = \frac{E}{(Zs+MZL)} MZL = \frac{E}{(\frac{SIR}{M}+1)} = \frac{M*E}{(SIR+M)} \qquad (3)$$

Voltage discrimination, ΔV is given by

$$\Delta V = \frac{E}{(SIR+1)} - \frac{M*E}{(SIR+M)} = \frac{E*SIR*(1-M)}{(SIR+1)*(SIR+M)} \qquad (4)$$

A criterion was set to pull back Zone 1 reach if the Voltage difference, termed as Voltage discrimination was below 1 V.

This philosophy was further analyzed considering the effect parallel paths in an interconnected system.

Figure 3 shows a protected 115 kV transmission line with the rest of the interconnected system impedance modeled as a parallel line with transfer impedance.

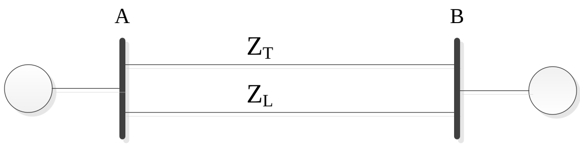


Figure 3: Two bus equivalent of the interconnected system

Z_L- Transmission line under study

ZT - Transfer impedance after system reduction

For different ratios of Z_T/Z_L, voltage difference between remote end bus fault and voltage for a fault on the line (varied from 0-100%) was plotted. This exercise was repeated by varying the local and remote end source strengths. One such plot is shown in figure 4 to illustrate that for $Z_T = 2*Z_L$, the discrimination voltage is less than 1V for faults at 70% or less in a very strong system (SIR=1). Similar relationship was seen varying transfer impedance and source impedance values.

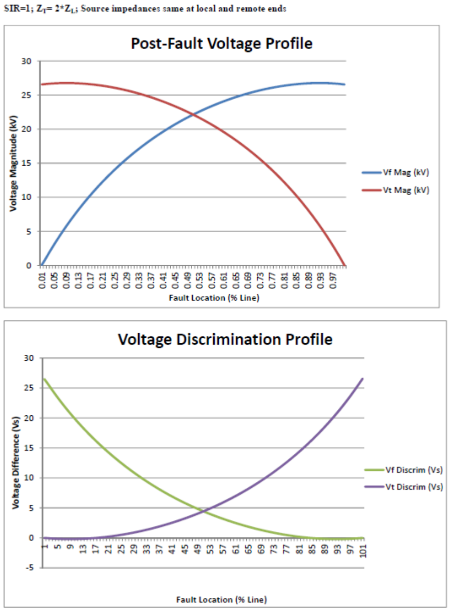


Figure 4: Voltage at relay location for sliding fault
And voltage difference discrimination plot.

Observations from these tests indicated that a) the voltage discrimination is dependent on the transfer impedance of the parallel path; b) dependent on the source strengths of local and remote ends.

Zone1reach setting based on voltage discrimination was determined to be unreliable in an interconnected system.

(e) Examination of compensated voltage input, (V-IZ)

Replacing M*Z_L with the relay reach, Z_R for zone 1 element, the compensated voltage input for zone 1element is (V-IZ_R). Instead of calculating the ΔV, examination of the compensated voltage, (V-IZ_R) provides a better review of the performance of zone 1 element.

Distance Elements operation is based on phase angle relationship between operating voltage, (V-IZ) and another reference voltage, known as polarizing voltage. This could be the faulted voltage or pre-fault voltage or positive sequence memory voltage.

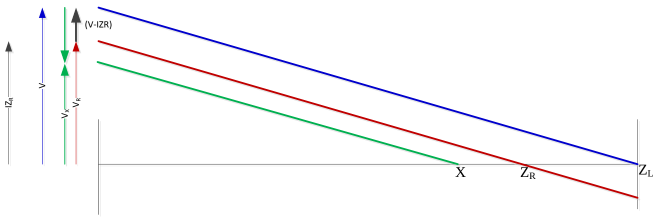


Figure 5: Phase relationship between V and (V-IZ_R)

The compensated voltage term can be expressed in terms of SIR as

$$(V - IZ_R) = \frac{(Z_L - Z_R)}{Z_L} * \frac{E}{(SIR+1)} \qquad (5)$$

This can also be expressed as

$$(V\text{-}IZ_R) = \frac{E*(1-M)}{(SIR+1)} \qquad (6)$$

As shown in figure 5, the Phase angle relationship between Voltage, V and the compensated voltage (V-IZ_R) reverses if the fault is within the set reach otherwise these input signals are in phase.

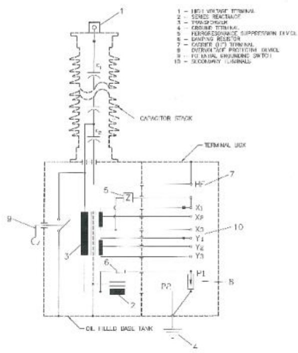
(V-IZ) is negative if the impedance up to the fault point is less than Z_R otherwise, it is positive.

If the magnitude of the voltage measured is lower than the actual value or if the current measured is larger than the actual value or if the set impedance is larger than the actual impedance, a fault closer to the remote end is seen as zone 1 fault.

15% -20% margin used in setting zone 1 reach should account for all errors in measurement or in impedance calculation.
Voltage instrument transformer, discussed in the next clause, plays a significant role in determining the effective margin for zone 1 element performance to be reliable.

IV. Voltage Instrument Transformer

Voltage transformers step down the system voltage to 69V/115V level to be used as relay input. Capacitive voltage Transformers (CVTs) provide a cost-effective way of stepping down primary system voltages to secondary voltages. CVT construction is as



shown in Figure 6.

Figure 6: CVT components

Since the arrangement is potential division of voltage using capacitors, sudden decrease in primary voltage due to a fault results in transient oscillations reflected on the secondary. This is due to the stored energy in capacitors trying to dissipate through the transformer and load on the secondary.

To suppress Ferro-resonance oscillations, a resistor is connected across the secondary winding through an L-C circuit (called Active Ferro-resonant circuit). Another variant of this is to connect a parallel combination of a resistance in parallel with a saturating inductor (called passive Ferro-resonance circuit). Figure 7 shows the representation of CVTs used in the studies at Xcel energy.

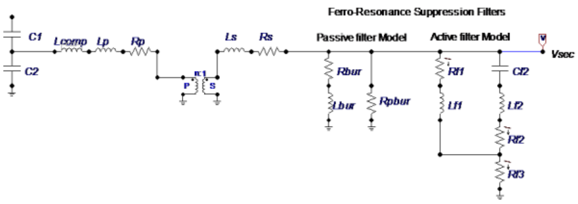


Figure7: CVT model

HV and EHV systems still have many installations with active Ferro-resonance filters due to their vintage as all CVTs sold today uses only passive Ferro-resonant filters.

CVT Secondary voltage waveforms for a close in fault are as shown in Figure 8 with an active Ferro-resonance filter and figure 9 for a passive Ferro-resonant filter. Transients tend to have lower magnitudes on CVTs with higher capacitance values than those with lower capacitance values.

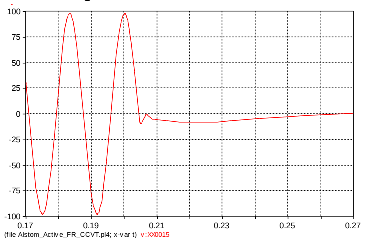


Figure 8: CVT with active filter $-V_{SEC}$

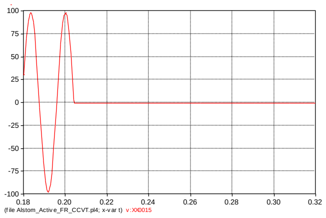


Figure 9: CVT with passive filter $-V_{SEC}$

GE document GER 3986 [3] provides a detailed analysis of transient overreach and speed of digital relays fed from CVTs with passive and active Ferro-resonant suppression circuits.

Based on their test results, a generic reach reduction curve similar to the curve in Figure 10 is published in the document.

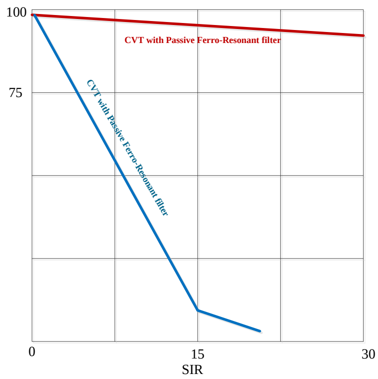
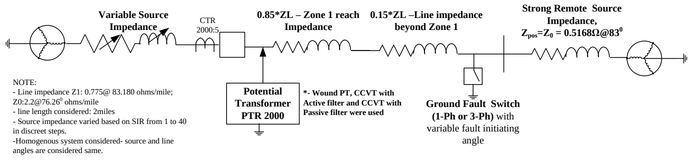


Figure 10: Suggested Reduction in Zone reach ref [3]

V. XCEL ENERGY STUDY

(a) PSCAD modeling

230 kV line was modeled in PSCAD with current Transformer ratio of 2000:5 and potential transformer ratio of 2000:1. One line of the system considered is as shown in figure 11.



One Line model of the System simulated in PSCAD

PSCAD simulations created COMTRADE output files for each case. COMTRADE files were used to test relays with Doble test set.

(b) Line length

All simulation cases were run with a 2 mile long 230 kV line modeled as two coupled PI sections each with 1.7 mile and 0.3 mile lengths. This could have been modeled as one section as no cases were run with faults at 85% of the line.

(c) Source Impedance

The local end source impedance was varied from 1.55 ohms (SIR=1.0) to 93 ohms (SIR =60) in discrete steps for SIRs of 5, 10, 20, 30, 40 and 60. X/R of source impedance was kept same as that of line impedance ($\tan 83^0$). The zero sequence impedance was set equal to the positive sequence impedance providing a solidly grounded source.

Remote end source was modeled as a very strong source with 0.5 ohm positive and zero sequence impedances. The intent was to reduce the zero sequence contribution from the local end for single line to ground fault cases producing lesser voltage input than for three phase faults at remote end.

(d) Fault Switch Fault initiation angle

Three phase fault simulations were run with fault at the remote end of the line for all cases with SIR varying from 1 to 60.

Ground fault switch closing point on wave was varied with reference to A-Phase from 0^0 to 180^0 in steps of 30 degrees.
Variation of fault initiation angle was to create varying amounts of DC offsets in current waveform.

Single line to ground fault simulations were run with SIR of 40.

(e) Voltage Transformer

Ideal wound PT with 2000:1 ratio was modeled to create a base case for comparison with cases run modeling CVTs with active and passive Ferro-resonance filters.

(f) Relay settings

Five relay types from two manufacturers were used in simulation studies. Zone 1 reach was set to 85% of the line impedance and zone 2 was set to 120% of the line impedance.

Relays with CVT transient suppression settings were tested by enabling and disabling the setting to determine the impact on zone 1 operation.

Relays were monitored for zone 1 operation for remote end faults and relay captured event files were downloaded.

VI. SIMULATION RESULTS

Zone 1 relays set to 85% of the line impedance did not operate for line end three phase and single line to ground faults for simulations with wound PT and CCVT with passive Ferro-resonance filter even with SIR of 60.

Relay Zone 1 response for simulations with CVTs using active Ferro-resonance circuits did not operate for SIRs up to 20.

Misoperations were recorded on relays without CVT transient suppression capability or when this feature was disabled. They were at few fault initiation angles. No misoperations were seen on relays up to SIR of 40 when CVT transient suppression setting was enabled.

Further testing is under way to determine whether delaying Zone 1 trip or reducing zone 1 reach will prevent overreaching issues.

VII. Conclusions

The response of Zone 1 relay for line end faults depends mostly on the type of voltage transformer installed. Wound PT and CVTs with passive resonance filters do not seem to create overreaching problems when Zone 1 relay is set to protect 85% of the line.

Ground distance element settings need to be corrected for the effects of mutual coupling.

On relays connected to CVTs with active Ferro-resonance filter, zone 1 reach needs to be pulled back or delayed to prevent overreaching problem. This is being investigated.

VIII. Acknowledgement

Several student interns at Xcel Energy were involved in the development of PSCAD model and generation of COMTRADE files in testing new generation and legacy microprocessor relays in Xcel Energy lab. Special acknowledgement goes to one of them, Jacob Gutzmann for the initial efforts in developing PSCAD model, setting up test cases and performing testing of most of the relays.

References

[1] PROTECTION & AUTOMATION Application Guide – GE Grid Solutions -2016 (This book was formerly known as Network Protection and Automation Guide- ALSTOM)

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Authors

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