Factors influencing CT saturation and its implications on Distance Protection Scheme- Analysis and Testing

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***Abstract*—The behavior of the Current Transformer (CTs) is of utmost importance for protection engineers to ensure reliable operation of power system. CT magnetic saturation is a well-known phenomenon when analyzing its performance characteristics. Nevertheless, transient conditions in the system might be different every time. A good understanding of the magnetic saturation of different CT designs and the effect of saturation on the protection schemes is imperative for developing a robust and dependable protection system.**

In this paper, various factors that affect CT saturation like X/R ratio, large current magnitudes, DC offset, burden and magnetization remanence are discussed. Analysis of CT saturation based on changes to burden and remanence is performed. In addition to that, the effect of saturation due to these factors on distance protection are presented with test results and analysis. Saturation conditions are analyzed on mho distance elements during phase to ground and three phase faults. Finally, a practical approach to efficiently test the performance of protection schemes under CT saturation conditions is proposed using COMTRADE play back. COMTRADE play back files for various scenarios of CT saturation conditions are generated and used for testing the performance of the protection scheme.

I. Introduction

The fundamentals of current transformer (CT) help in better understanding the concept of CT saturation. As per IEC 60044-1 standard, a CT is defined as an instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections. Two sets of windings around an iron core, which are magnetically coupled by the flux produced in the core, constitute a CT. When voltage is applied to the primary winding, a magnetic flux is produced in the core due to which, a voltage is induced in the secondary winding to produce the secondary current. To understand further, a current transformer can be represented by an equivalent circuit, referred to the secondary, as shown in Figure 1 where:

I_P: primary current

V_S: secondary voltage

I_S: secondary current

I_{ST}: secondary total current

I_E: excitation current

Z_E: exciting impedance

R_S: secondary resistance

X_L: leakage reactance

V_B: voltage across the burden

Z_B: burden impedance

N_1, N_2: CT turns on primary and secondary

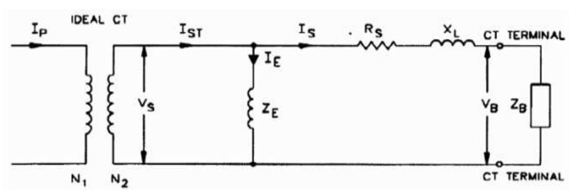

Figure 1 - Equivalent circuit of a CT

Z_E defines the magnetization behavior of the CT core and is non-linear in nature. In an ideal CT, I_P is proportional to I_{ST} as per the ratio of the CT as:

$I_{ST} = I_P(N_1/N_2) = I_P / n$

Where:

$n = \frac{N_2}{N_1}$: CT ratio

Using the secondary currents I_{ST} can be also be represented as:

$$I_{ST} = I_E + I_S$$

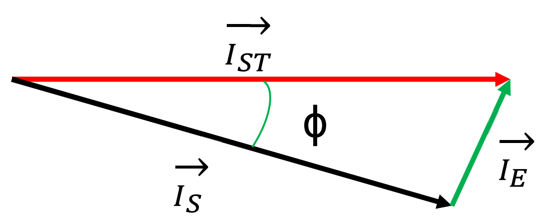

Figure 2 Vector diagram of CT currents

When I_E is close to 0, then $I_{ST} = I_S$ and the phase of the secondary current through the burden is very close to the actual phase of the current we intend to measure. Conversely the higher the excitation current I_E the greater the error in both magnitude and phase. From the equivalent circuit we can see that the excitation current can be calculated as:

$$I_E = \frac{I_{ST}\ (R_S + jX_L + Z_B)}{Z_M + (R_S + jX_L + Z_B)}$$

Since the magnetization impedance, Z_M, is much greater in value than the burden impedance, Z_B, we can see that the excitation current is directly proportional to the burden connected to the secondary of the CT, Z_B, and inversely proportional to the excitation impedance Z_M.

What this means for practical purposes is that the greater the burden the higher the excitation current of the CT and therefore the error incurred during the measurement.

On the other hand, the magnitude of the magnetization impedance Z_M depends on the status of the magnetic circuit of the CT which has a nonlinear behavior expressed by the magnetization curve as explained in section II.

As the CT core approaches saturation, the excitation current increases, thereby increasing the CT error. After the CT enters saturation the secondary current would no longer linearly follow the changes in the primary current. Section II explains such behavior in greater detail.

II. CT SATURATION

A CT is considered to be saturated when there is increase of magnetic flux in the core, which leads to non-linear

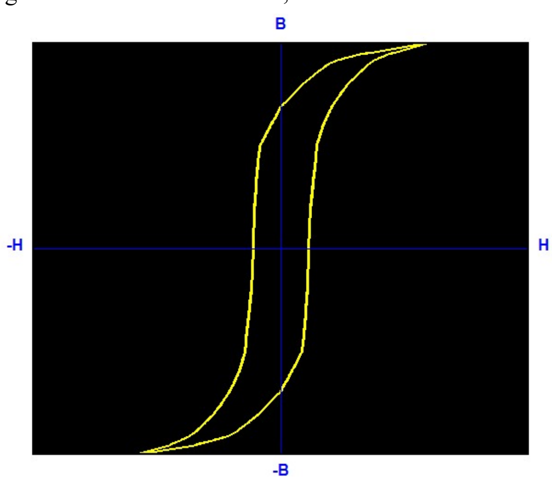

Figure 3 - B-H Curve

performance of the CT secondary output with respect to primary. The magnetic flux density (B) that impacts the performance of the CT depends on the magnetic field (H) that is generated across the cross-sectional area of the core. This relationship between the magnetic flux density and the magnetic field of the core can be represented by B-H curve as shown in Figure 3. These curves can vary between different core materials based on their ability to handle the magnetic field. Many external and design factors impact CT saturation.

The IEEE PSRC committee responsible for "C37.110 IEEE Guide for the Applications of Current Transformers Used for Protective Relaying Purposes" created a CT saturation calculator which uses inputs like system X/R, burden resistance, primary fault current etc. to generate simulated CT secondary waveforms. [4] Figure 4 shows the output from the CT saturation calculator where the graph represents CT secondary currents in amps vs time. The blue waveform represents the ideal curve and black waveform represents the actual output. CT saturation can be classified into symmetrical saturation and asymmetrical saturation. High magnitude symmetrical currents which cannot be handled by the CT core can cause symmetrical saturation, which is also referred to as steady-state saturation. Asymmetrical saturation occurs when there is presence of DC component in the primary currents through the CT. Due to DC offset; the peaks of the curve are not symmetrical on either side of zero crossing.

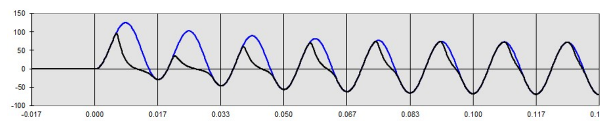

Figure 4 - Current Waveforms

A. Factors affecting CT Saturation

Various factors affect the saturation of a CT such as X over R ratio, remanence, CT secondary burden, current magnitude etc. It is important to choose the right CT with appropriate design factors for the protection application. [4] Factors that are considered in the CT saturation simulator tool are – Inverse of Saturation Curve Slope, RMS voltage at 10A excitation current, turns ratio, winding resistance, burden resistance, burden reactance, system X/R ration, per unit offset in primary current, per unit remanence and symmetrical primary fault current.

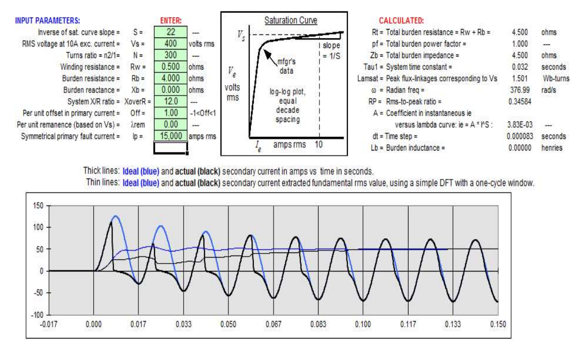

Figure 5 - Case 1 Saturation

To understand how these factors affect the CT saturation, cases with different parameters were studied. Case 1, as shown in Figure 5 is for a class C400 CT with 1500:5 CT ratio. It can be clearly seen that the CT starts saturating at these specified conditions within half a cycle. It should be observed that the remanence in this case is assumed to be 0 percent. Case 2 in Figure 6, shows the CT secondary response for a class C400 CT with 1500:5 CT ratio with some remanence present in the core.

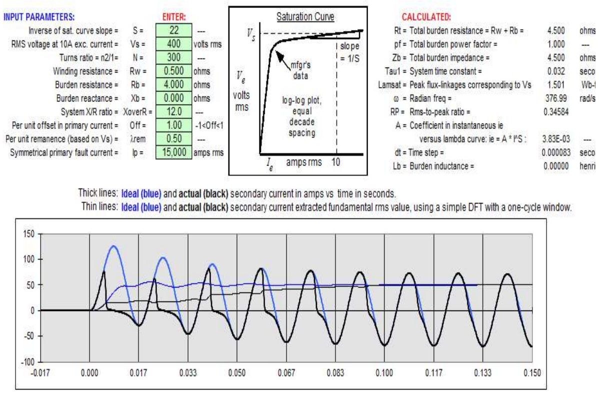

Figure 6 - Case 2 Saturation

It can be seen in the waveforms that due to remanence; the CT saturation occurs faster than in the previous case where the CT core was completely de-magnetized (remanence = 0). Hence, remanence plays a very important factor in CT saturation. The higher the remanence in the core, lower the fault current required to saturate the CT which then impacts the operation of the protection element. Next cases put light on different CT secondary burdens.

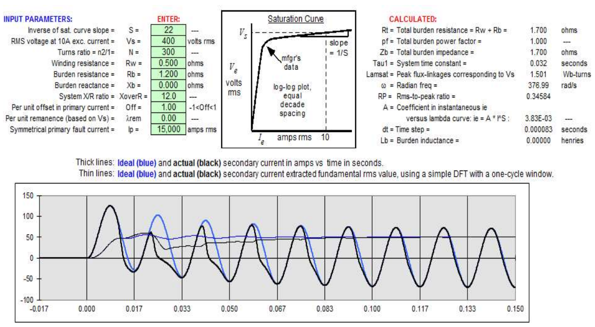

Figure 7 - Case 3 Saturation

Case 3 as shown in the Figure 7 represents the secondary waveforms for a class C400 CT with 1500:5 CT ratio with a burden resistance of 2 ohms as opposed to 4 ohms in Case 1. Comparing the secondary outputs of Case 1 and Case 3 show that, when the burden was reduced to 1.2 ohms, CT started saturating later than when the burden was 4 ohms. It is imperative that appropriate burden relays, wires, components be chosen as part of the secondary circuit to the CT. Distance of the relay from the CT location matters as resistance of the wire increases with length. Care should be taken to consider these factors when choosing the CT and designing the protection. CT class also plays an important role in saturation. For Case 1, if C800 CT was chosen instead of C400, the response during saturation would be as shown in Figure 8. It can be seen that CT takes longer to start saturating with C800 as opposed to C400. Certain factors like available fault current in the system, system X/R ratio cannot be changed or adjusted due to their nature. Hence, the engineer would have to work with factors that can be controlled like burden, CT class, ratio to provide the best CT for their system.

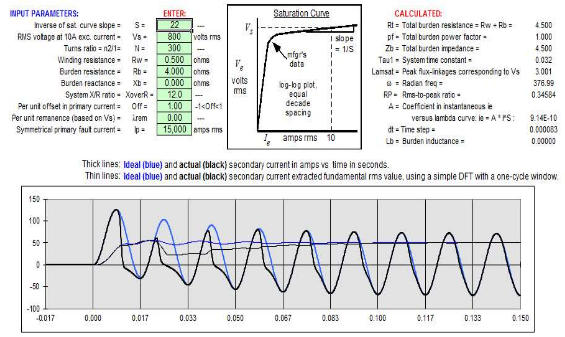

Figure 8 - Case 1 Saturation with C800

III. Impact of CT Saturation on Protection

Protection elements make decisions based on the current magnitude and phasor read from the secondary of the CTs. When the CT core goes into saturation, the secondary current is no longer linear with respect to primary current. Chances of protection element mis-operating for this case are extremely high and can be disastrous for the reliability of the power system network. Distance (mho characteristic) protection element is considered for studying the impacts of CT saturation in this paper.

A. Distance Element

Distance protection is widely used to protect transmission lines. Distance element operates based on impedance calculations derived from the currents and voltages measured from CT and PT circuits which are then compared with an impedance set point in the relay.

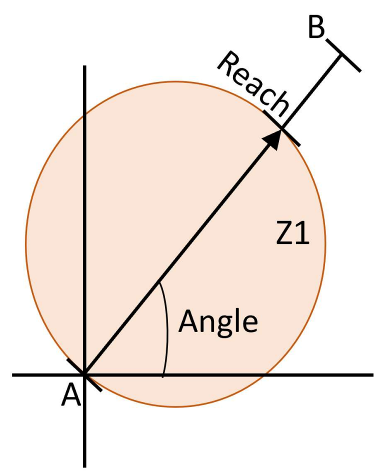

Figure 9 - Mho Characteristic

Mho characteristic is one of the characteristics used by protection engineers to implement distance protection. This characteristic is defined on a R-X plane where a circle represents the zone of protection for transmission line being protected. The origin of the R-X plane represents the relay location. The diameter of the circle represents the reach setting in ohms. The angle at which the reach is maximum with respect to the R axis, is referred to as the maximum torque angle (MTA) or the relay characteristic angle (RCA). When the measured impedance of the line falls within the mho characteristic (circle), the distance element operates. When CT saturates, the distance element may operate on underreach or overreach depending on the remanent flux in the core. This also impacts the operating time of distance elements which is key factor in zone 2 and 3 protection.

IV. CASES: TESTS & ANALYSIS

In this section, the system under test consideration, relay settings and CT specifications as well as test scenarios for distance and differential protection for various CT saturation conditions are discussed.

A. Test System

The system under test was modeled in a simulation software which consists of generators G1 and G2 rated at 100 MVA, 161kV. Transformer T1 which is a YY unit rated at 20 MVA, 161kV/69kV is present in the system. Differential relay 87T protects the transformer between station A and station B.

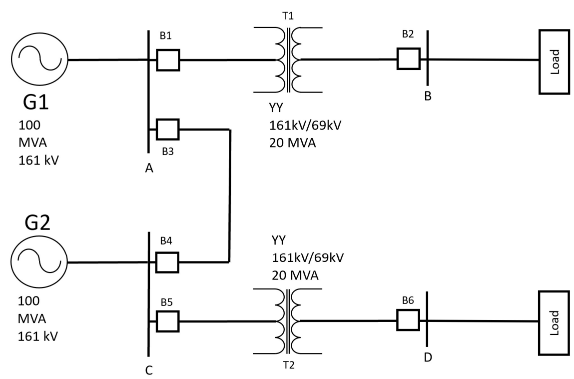

Figure 10 - Test System

Burden Specifications –
CT1 (At B3 breaker)
CT Ratio – 100:1 (C500 CT)
Winding resistance – 0.237 ohms
Burden resistance – 4.5 ohms
Burden reactance – 1.7 ohms

Distance relay(21) at station A protects the transmission line that connects station A and station C. Settings used in the distance relay is as follows –

Z1Mag	7.8	Pos Seq Line Impedance Mag
Z1Ang	83.97	Pos Seq Line Impedance Angle
Z0Mag	24.79	Zero Seq Line Impedance Mag
Z0Ang	81.46	Zero Seq Line Impedance Angle
LL	100	Line Length
CTR	100	CT Ratio
PTR	1610	PT Ratio
DIR1	F	Direction Zone 1
DIR2	F	Direction Zone 2
Z1P	6.24	Impedance Reach Z1
Z2P	9.36	Impedance Reach Z2
Z1PD	0	Zone 1 Phase Time Delay
Z2PD	25	Zone 2 Phase Time Delay
Z1G	6.24	Impedance reach Z1
Z2G	9.36	Impedance reach Z2
Z1GD	0	Zone 1 ground time delay
Z2GD	25	Zone 2 ground time delay

Table 1 - Distance Relay Settings

B. Test Set-up

The test system discussed in the previous section was modeled in a simulation software. COMTRADE files were generated for different fault types with CT saturation conditions. These COMTRADE files were used to playback to the relays under test to validate the scenarios. Three phase test equipment was used with COMTRADE playback capability. Analog currents and voltages were injected to the relay from the test equipment. Binary input on the test equipment was used to monitor the output contact on the relay for Trip.

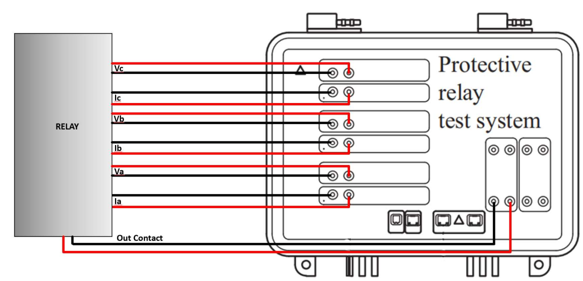

Figure 11 - Test Set-Up

COMTRADE playback test method was used to inject analog values to relays. COMTRADE files consist of oscillography data related to transient power system disturbances. These files can be generated either in the protective relay or using a simulation software. For the purpose of this paper, COMTRADE files were generated using a simulation software. These files were played back to the relay using test equipment software. The relay used for testing is of microprocessor type with capability to produce the event records.

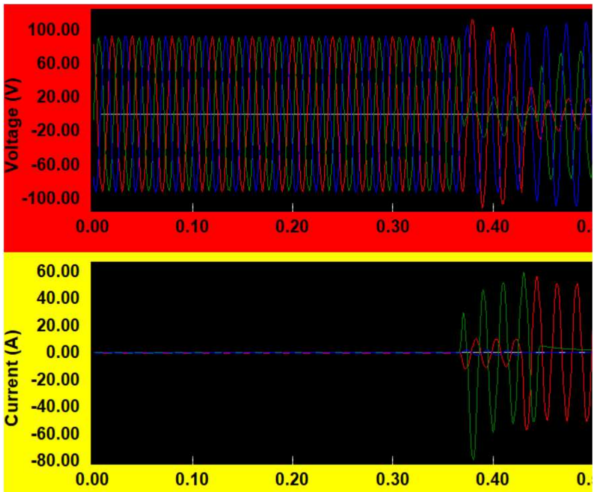

Figure 12 - COMTRADE Playback Waveforms

C. Test Scenarios – Distance Protection

For distance protection case, different scenarios were created for both three phase faults and single line to ground faults for nominal burden and high burden to the CT. Nominal burden refers to 100% of the burden rating of the CT whereas high burden simulation was created by using a burden about 60% higher than the nominal. Faults simulated in these scenarios were mid-line fault at about 75% and 85% of the transmission line as seen by distance relay at station A. Different scenarios were also created with respect to no remanence and high remanence in the CTs during the fault simulations.

1) 3-Phase Fault at 75% with High Burden condition

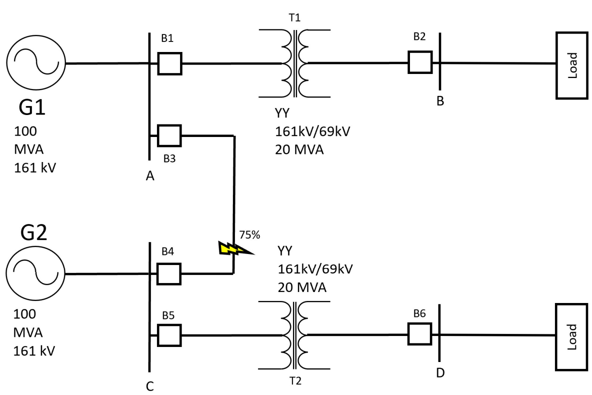

Figure 13 - Fault Simulation at 75% of the line

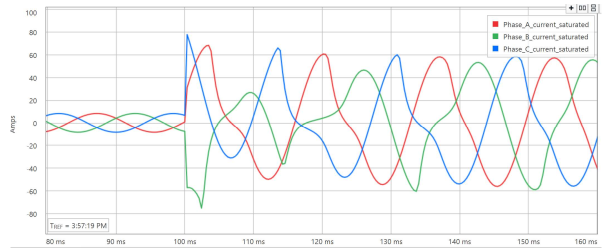

Figure 14 - Saturated current waveforms for 3P fault

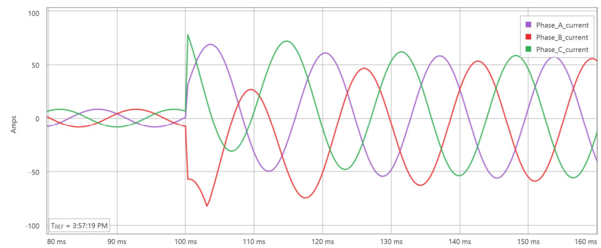

Figure 15 - Unsaturated current waveforms for 3P fault (Ideal - nominal burden)

In this scenario a three-phase fault was simulated at 75% on the transmission line as seen by the relay at Station A. COMTRADE files containing waveforms for saturated and unsaturated currents were produced for each case.

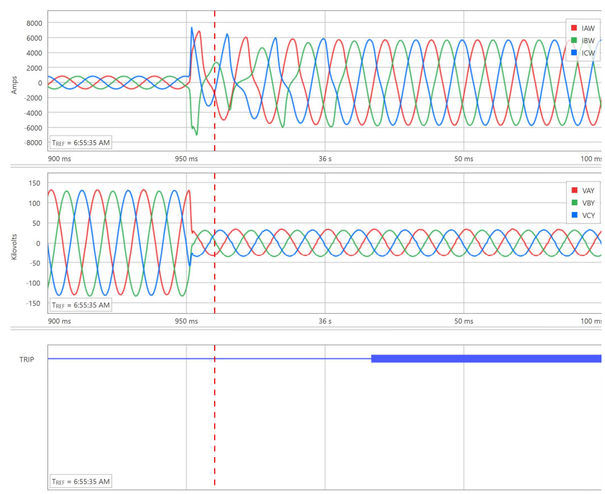

Figure 16 - Trip results after COMTRADE Playback of saturated waveforms

The COMTRADE file was generated for the three-phase fault with high burden condition and then this file was played back to the distance protection relay to observe the behavior of the protective element. For the saturated waveforms playback, element operated at 57.5 ms as seen in Figure 16. For the unsaturated waveforms playback, element operated at 19.5 ms. The fault simulated was a zone 1 fault at 75% (reach set at 80% of the line), which ideally would be an instantaneous trip.

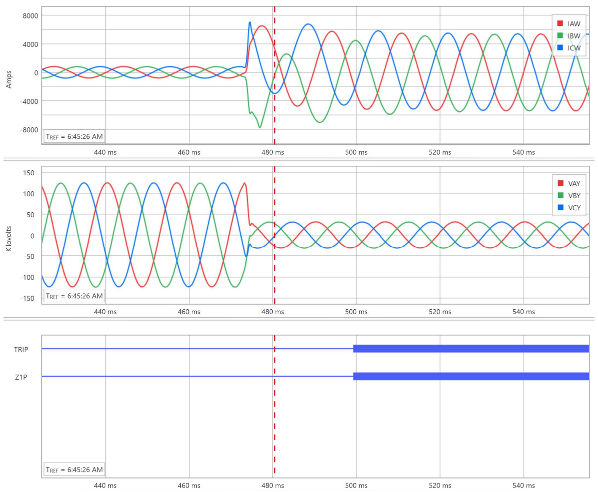

Figure 17 - Trip results after COMTRADE waveforms of unsaturated waveforms

The difference between the trip times for saturated and unsaturated conditions was found to be greater than two and a quarter cycles. This difference is due to the high burden condition to the CT during the fault.

2) 3-Phase Fault at 85% with High Burden condition

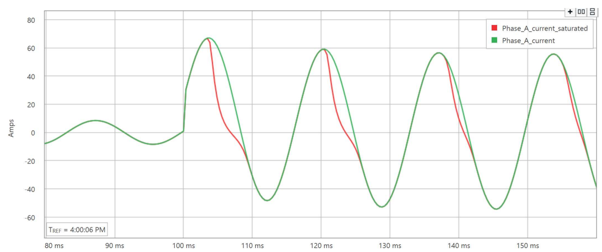

Figure 18 - Current waveforms for 85% 3P fault with high burden

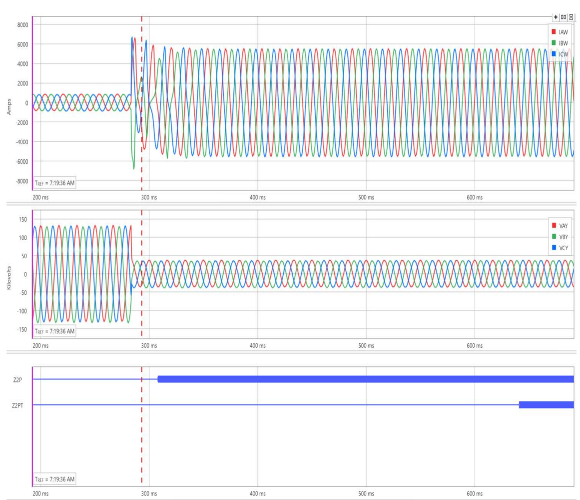

Figure 19 - Trip results after COMTRADE playback for Sc.2

3) SLG fault at 75% with High burden condition

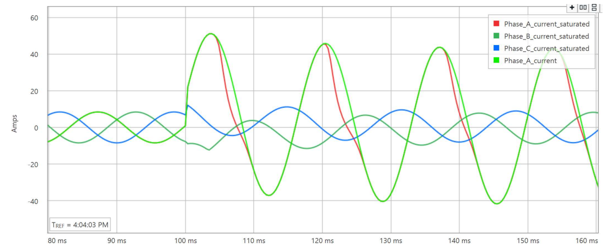

Figure 20 - Current waveforms for 75% SLG fault with high burden

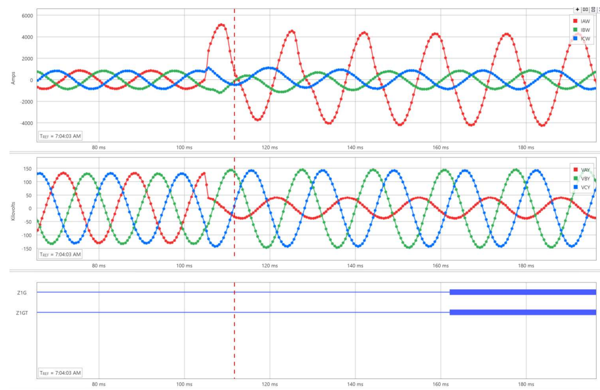

Figure 21 - Trip Results after COMTRADE playback for Sc. 3

4) SLG fault at 85% with High burden condition

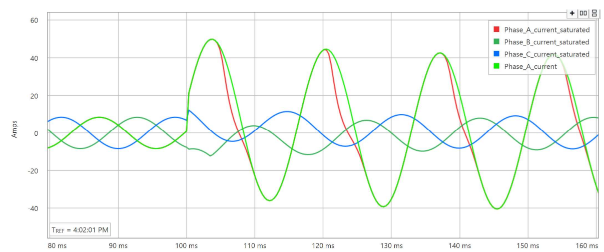

Figure 22 - Current waveforms for 85% SLG fault with high burden

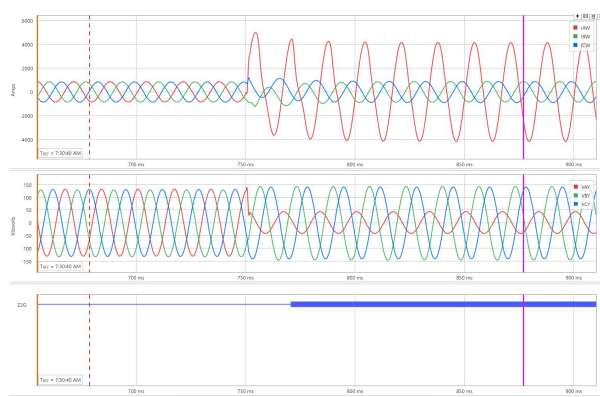

Figure 23 - Trip Results after COMTRADE playback for Sc.4

5) 3-Phase fault at 75% with High remanence condition

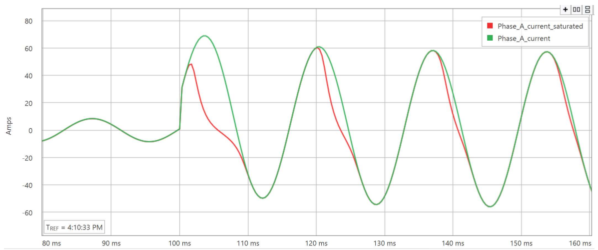

Figure 24 - Current waveforms for 75% 3P fault with high remanence

In this scenario a three-phase fault was simulated at 75% on the transmission line as seen by the relay at Station A. High remanence condition of about 75% in the CT was simulated during the fault. COMTRADE files contained waveforms for saturated and unsaturated currents.

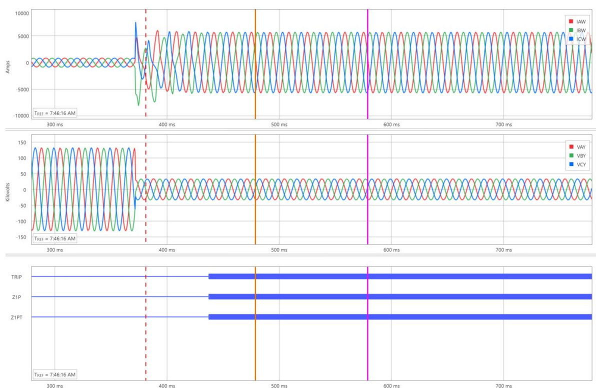

Figure 25 - Trip results after COMTRADE playback for Sc. 5

For the saturated waveforms playback, Zone 1 element operated at 55 ms as seen in Figure 25. For the unsaturated waveforms playback, Zone 1 element operated at 15 ms. The difference between the trip times for saturated and unsaturated conditions was found to be around two and a quarter cycle. This difference is due to the high remanence condition in the CT during the fault.

6) 3-Phase fault at 85% with high remanence condition

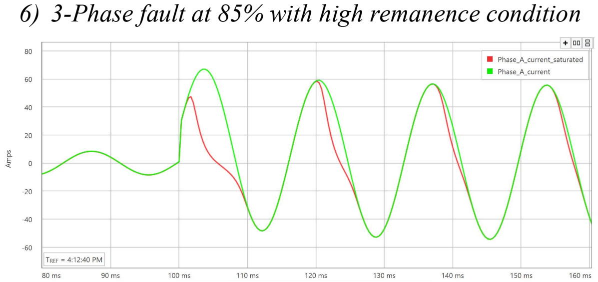

Figure 26 - Current waveforms for 75% 3P fault with high remanence

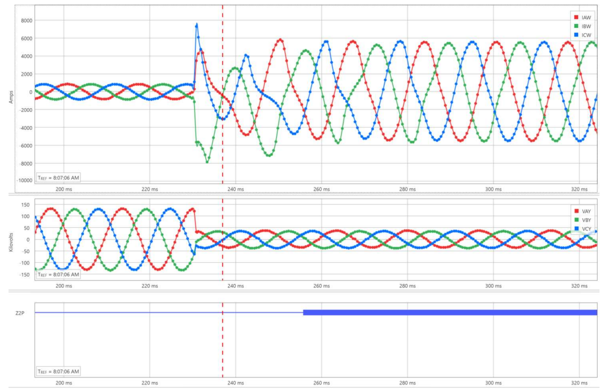

Figure 27 - Trip results after COMTRADE playback for Sc.6

7) SLG fault at 75% with high remanence condition

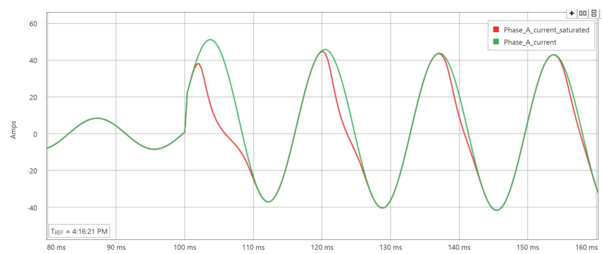

Figure 28 - Current waveforms for 75% SLG fault with high remanence

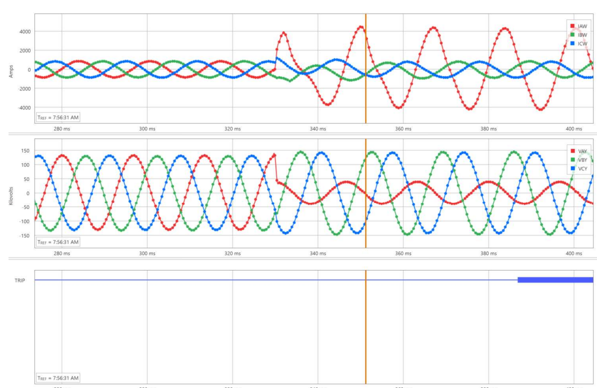

Figure 29 - Trip results after COMTRADE playback for Sc.7

8) SLG fault at 85% with high remanence condition

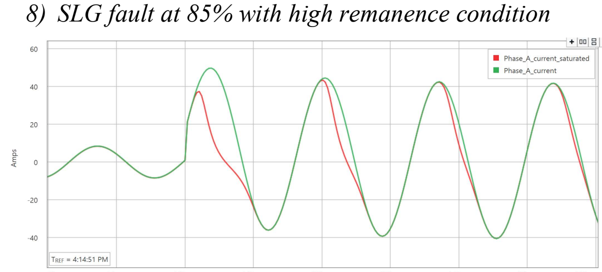

Figure 30 - Current waveforms for 85% SLG fault with high remanence

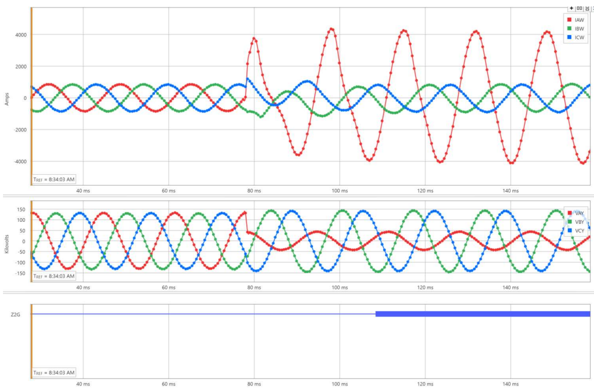

Figure 31 - Trip results after COMTRADE playback for Sc. 8

The transient behavior of the rms value of the current at the beginning of the fault can be seen in Figure 32 and Figure 33 for a non-saturated and saturated waveform respectively. Notice the high level of oscillation shown by the rms value resulting from the saturated waveform of Figure 33. Figure 34 shows the oscillations in the value of impedance calculated from saturated and non-saturated waveforms.

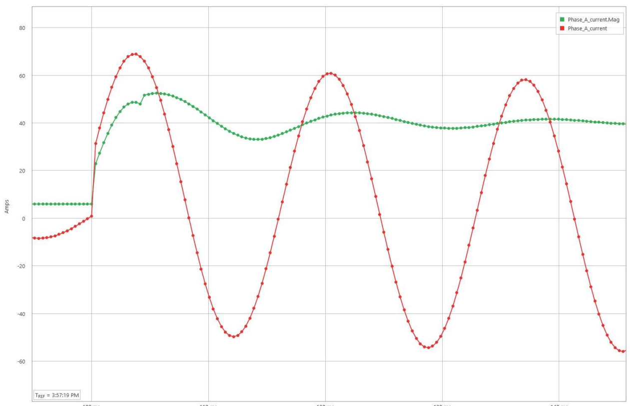

Figure 32 Transient rms value of non-saturated waveform

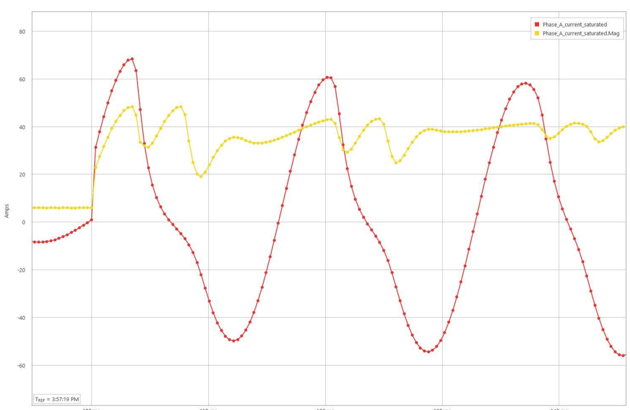

Figure 33 Transient rms value of saturated waveform

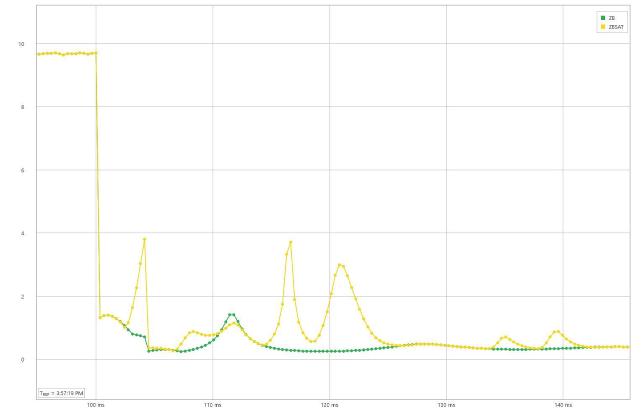

Figure 34 Instantaneous single phase Impedance saturated vs non saturated

A comparison table of the test results is presented below.

	HIB 75% 3P	HIB 75% SLG	HIB 85% 3P	HIB 85% SLG	HIR 75% 3P	HIR 75% SLG	HIR 85% 3P	HIR 85% SLG
Flt Loc Det (in ms)								
Sat	9	7	10		11		7.5	
Unsat	7.5	7	7				9	
Z1P&T (in ms)								
Sat	57.5	51	NA	NA	55	56.6	NA	NA
Unsat	19.5	19	NA	NA	15	16	NA	NA
Z2P (in ms)								
Sat	15		15.5	20	14.5	25.5	19	30
Unsat	15.5	13.5	15.5	19.8	10	13	13	20
FaultLocation (in miles)								
Sat	75.6	75.35	85.7	85.56	75.9	76	85.8	85.2
Unsat	75.7	75.24		85.16	75.7	75.1	85.6	85.2

HIB – High Burden
HIR – High Remanence
Flt Loc Det – Fault Location Detection

The results for fault location detection, Zone 1 trip time, zone 2 trip time, and fault location are classified for 2 categories – Saturated and Unsaturated. Actual trip times (~1 to 1.5 cycles) for Zone 1 operation for 75% faults relate to the ideal instantaneous tripping. However, for the saturated waveforms, the zone 1 operation was delayed by at least 2.5 to 3 cycles as compared to the unsaturated playback trip times. These findings imply to both high burden and high remanence test scenarios.

V. Recommendations

Above sections discussed the effect of both asymmetrical CT saturation with DC offset and symmetrical CT saturation caused by single-line-to-ground faults on distance elements.

Observations were made which highlighted the fact that DC offset is inevitable in one or more phases during a three-phase fault. Further analysis depicted that saturation can have adverse impact on traditional protection elements. It is therefore imperative to carefully select CTs for protection applications. Some of the recommendations are as follows.

Proper CT Sizing

A. Symmetrical CT Saturation

Understanding secondary terminal voltage rating of a CT is essential to generate some criterion for avoiding symmetrical CT saturation which could be seen during single-line-to-ground faults. The secondary terminal voltage rating is the voltage that the CT delivers to a standard burden at 20 times rated secondary current, without exceeding a 10 percent ratio error.

$$V_{STD} = 20\, I_{S\ RATED}\ Z_{B\ STD}$$

where:
V_{STD} is the secondary terminal voltage rating.
$I_{S\ RATED}$ is the rated secondary current.
$Z_{B\ STD}$ is the standard burden
Users can study the CT secondary excitation characteristic to determine or verify the CT voltage rating and the corresponding C or K classification. For Class C or Class K CTs, the ratio error will not exceed 10 percent if the secondary terminal voltage V_S is not greater than the secondary terminal voltage rating V_{STD} -

$$V_S \le V_{STD}$$

Applying Kirchhoff's voltage law for excitation voltage and replacing secondary current with fault current referred to secondary yields the below condition -

$$I_f\ Z_b \le 20$$

where:
Z_b is the CT burden in p.u. of the rated burden ($Z_b = Z_B/Z_{B\ STD}$)
I_f is the fault current in p.u of the CT secondary rated current ($I_f = I_F/I_{S\ RATED}$).
I_F is the symmetrical fault current referred to secondary

Above equation can be used to determine either the maximum allowable symmetrical fault current for a given burden or the maximum allowable burden for a given fault current.

B. Asymmetrical CT Saturation

To meet the criterion for avoiding asymmetrical CT saturation, the required transient performance for a current transformer can be specified by calculating the minimum required saturation voltage. Generally, different standards as IEC 185, BS3938, or ANSI/IEEE C5713 fix this voltage through the general expression:

$$V_s = K_0 K_s K_R I_2 R_2$$

where:

V_s = saturation voltage defined by the intersection of the extensions of straight-line portions (unsaturated and saturated regions) of the excitation curve
I_2 = symmetrical fault current in secondary amps.
R_2 = total secondary resistance burden including CT secondary, wiring loop
resistance, lead resistance, and load resistance.
K_0 = the effect of the offset present during the fault
K_R = remanent flux factor
K_s = saturation or transient factor

The offset present during the fault (K0) is a function of the time when the fault occurs, being maximum at zero voltage (0° or 180°). Incidence angles of the faulted voltage near 90° generally produce a lower offset effect. Therefore, this factor applies in those cases where offset exceeds 0.5 p.u.
The saturation or transient factor Ks is essentially the factor required for saturation-free operation for a fully offset waveform at a given instant of time. The equation is derived from the necessary flux in the CT to avoid saturation assuming that the secondary load is essentially resistive [5]. The use of this factor recognizes that protection elements may operate before the CT enters saturation. It is expanded as follows -

$$K_s = \frac{\omega T_1 T_2}{T_1 - T_2} e^{-\frac{t_s}{T_1}} - e^{-\frac{t_s}{T_1}} - \sin\omega t$$

where:
T2 = secondary time constant
T1 = time constant of the DC component of the fault component; this is proportional to the X / R ratio of the system
ω = system angular frequency
ts = time to saturation; this is equal to or greater than the relay operating time

Some relays are fast enough to operate before the CT saturation inception. Time to saturation may be on the order of 1 or more cycles, but in some cases, it can be in the range of half a cycle. The time-to-saturation value depends on many factors, such as the degree of fault current offset, the fault current magnitude, the CT core remanence level, the CT secondary circuit impedance, and the CT saturation voltage and turns ratio. In general, if the operating time is longer, then a larger Ks is required, and a better CT is needed. If the relay operating time and time constants are known, the protection engineer can determine Ks.
There is another method to size CTs for asymmetrical saturation that recognizes the significance of the area under the voltage sine wave corresponding to the voltage rating. It represents the CT saturated flux density. This volt-time area signifies the threshold of saturation and marks the boundary of CT saturation under a 10 percent ratio error. The method is discussed in detail in [6], [7], [8]. As per the method, following condition should be met to avoid asymmetrical saturation -

$$\frac{I_f\ Z_b\left(\frac{X}{R}+1\right)}{1-\text{remanence (pu)}} \le 20$$

where:

Z_b is the CT burden in p.u. of the rated burden($Z_b = Z_B/Z_{B\ STD}$)

I_f is the fault current in p.u of the CT secondary rated current ($I_f = I_F/I_{S\ RATED}$).

I_F is the symmetrical fault current referred to secondary

X is the primary faulted system equivalent reactance

R is the primary faulted system equivalent resistance

Remanence can be removed by applying a pure AC voltage source to the CT secondary terminals and ramp the source up to the knee point and then gradually back to zero. It is therefore strongly recommended to minimize remanence in the core of the CT after regular testing.

C. *Advanced Relaying Algorithms*

Sometimes saturation cannot be avoided by CT sizing requirements due to system constraints. Modern day microprocessor relays are capable of customizing their algorithms to mitigate the effect of CT saturation. Various advancements, such as the use of short window filters and incremental quantities, have pushed the operating speed of distance elements into the sub-cycle range [9]. Improved operating times have beneficial impacts on performance during CT saturation. Details are not in the scope of this paper.

VI. Conclusion

This paper sheds light on effects of CT saturation on protection schemes as well as factors that influence CT saturation. Important factors that affect saturation of a CT are remnant flux, burden x/r ratio. CT history, CT design and manufacturing, operational conditions as well as previous tests run on a CT. Various scenarios were simulated and tested to study the impact of CT saturation on distance protection relay. Based on the test result findings, it was observed that the effects of CT saturation were greater when CT had a relatively high level of remanent flux in the core. When a CT is saturated as a result of a fault; there is a greater chance of relay mis-operation for subsequent faults as result of the remnant flux. Another factor that gravely affects performance of a CT is burden to the CT. Test result findings also attest to the impact of burden to the performance of a CT. CT saturation can be mitigated with proper CT selection and adequate design of the connected burden. It is very important to consider burden test as part of the CT testing procedure, which helps in validating the design of connected burden. All the test cases that mimics real situation of the CT in the field should be part of the commissioning and maintenance test procedures. COMTRADE playback is one of the test methods that helps in testing real-world conditions with regards to the behavior of protection systems.

VII. References

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VIII. Biographies

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