Analyzing the Impact of Shunt Reactor Switching Operations Based on DFR Monitoring System

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***Abstract*—Cross Texas Transmission (CTT) uses 345kV shunt reactors to regulate the high voltages during lightly loaded conditions on its long transmission lines spanning over 100 miles on a regular basis. Initially, the company experienced a few challenges during reactor energizations due to inrush conditions. As a result, CTT implemented a Digital Field Recorder (DFR) monitoring system to capture and examine inrush waveform conditions. Actual field data recorded from DFRs over a period of 14 months is analyzed to present and discuss the behavior of reactor switching due to inrush and other observed effects for different operating conditions. This paper has diverse, practical scenarios to offer in the form of waveforms during reactor energization which help understand and avoid misoperations.**

Keywords—Inrush Current; CT Saturation; DFR Monitoring System; Harmonic Restrain/Blocking, Differential Protection, Instantaneous Ground Overcurrent

I. Introduction

Shunt reactors improve the efficiency of the power system by compensating for the reactive power generated by the line capacitance and preventing overvoltages at a lightly loaded grid. So is the case with CTT owned transmission lines, shared with an adjacent utility which spans over 100 miles.

Fault recording has been in practice for a long time and it is mainly used to record system events and to monitor the performance of the power system. Fault records are very important in terms of evidence that an event analyst can use during event investigations. This practice, if implemented, provides the reasons for premature equipment failure, the status of equipment behavior during an event and can offer necessary information to perform post-fault event analysis. Even though fault records are captured by microprocessor relays these days, they are subject to a limited sampling rate and inadequate record length. Digital fault recorders offer specialized, specific, and delicate microprocessor equipment with far superior sampling rates, remarkable record lengths, and unfiltered recording abilities. This helps the protection engineers to analyze the event in a better way [1]. The DFR monitoring system installed at CTT substations has helped identify and analyze peculiar events and has even assisted in avoiding misoperations. In this paper, approximately 380 DFR records from November 2017 to December 2018 are analyzed to discuss inrush scenarios, share potential situations that may trip the equipment, and advise methods to avoid them.

Section II briefly discusses the type of shunt reactors based on its core as well as its magnetic characteristics. It also analyses the cause for inrush currents during reactor energization and demonstrates different scenarios captured through DFR monitoring system installed at CTT substations.

Section III explains the impact of CT saturation (sometimes caused by high inrush currents) on the reactor protection, which is supported by actual observation. This section also discusses various methods to identify CT saturation using waveforms captured by DFR monitoring systems.

Section IV demonstrates how inrush currents and CT saturation following a reactor switching can cause a misoperation in particular protection functions, and it also analyzes the safety measures a protection engineer should take in protecting the shunt reactors and the connected transformer or transmission line.

This paper demonstrates the use of the DFR monitoring system in analyzing various phenomenon that happen during switching operations of reactors and helps avoid unwanted misoperations.

II. Shunt Reactors and Inrush Phenomenon During Energization

Shunt reactors used in transmission lines can be classified based on two attributes: construction (dry-type or oil-filled) and the type of core used. The type of core employed determines if the reactor is affected by inrush on energization [2]. HV/EHV shunt reactors based on the type of core can be categorized as coreless (air core) and gapped iron-core shunt reactors. Most air-core shunt reactors have a magnetic circuit which surrounds the coil to contain the flux within the reactor tank. Air-core reactors, since they do not have a material core, do not saturate and thus are not prone to magnetizing inrush currents. This diminishes the probability of CT saturation and also eliminates the reactor as a source of saturation in the case of event analysis. Shunt reactors with gapped iron core facilitates a longer range of linear operation before core saturation occurs, and thus have a far smaller magnetizing reactance than power transformers in the transmission system. In addition, they are typically designed with a lower flux density (higher saturation level) than transformers. The magnetic circuit of a gapped iron-core reactor is constructed similarly to that used for power transformers with the exception that small gaps are introduced in the iron core to improve the linearity of the inductance of the reactor, to reduce residual or remnant flux and to reduce the harmonic content that the reactor injects back into the power system. More information on types of shunt reactors can be found in [2].

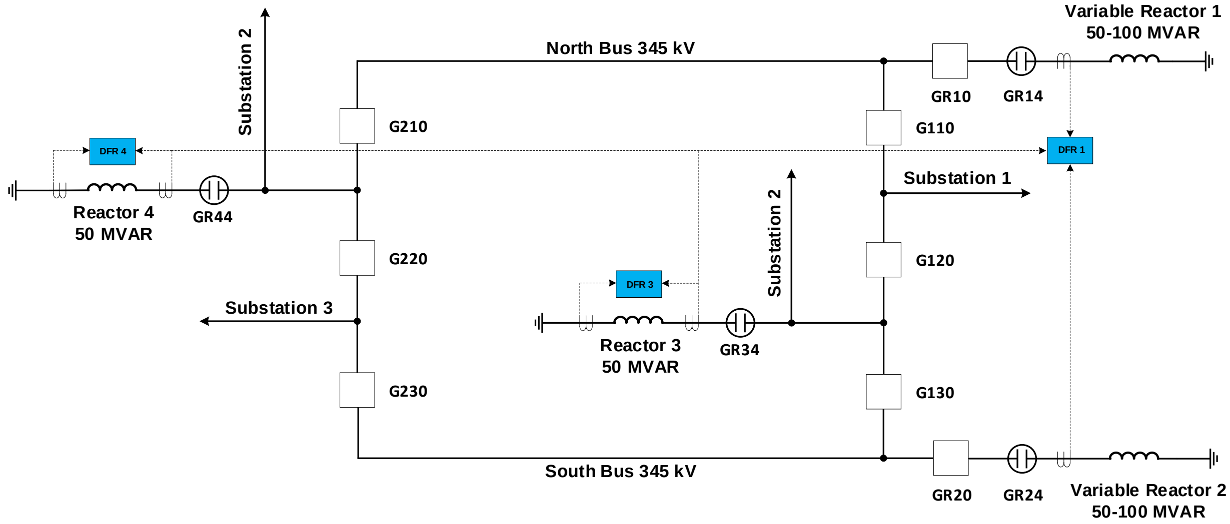


Figure 1. System One-line of CTT substation along with DFR monitoring system in place

Figure 1 shows the system one-line of CTT substation where 4 shunt reactors are in service. Two of the shunt reactors (Reactors 3 and 4) are installed to switch directly onto the transmission lines that are over 100 miles long. The other reactors are installed to switch onto the buses. Reactors 3 & 4 are monitored (currents & voltages) by using separate DFRs (DFR 3 and DFR 4) whereas Reactors 1 & 2 are monitored using DFR 1 as shown in Figure 1. A separate DFR, DFR 2 (not shown in Figure 1), is installed specifically to monitor the currents through breakers and voltages on transmission lines going out of the CTT substation shown above. These DFRs help in identifying and analyzing unusual events and have even assisted in avoiding misoperations.

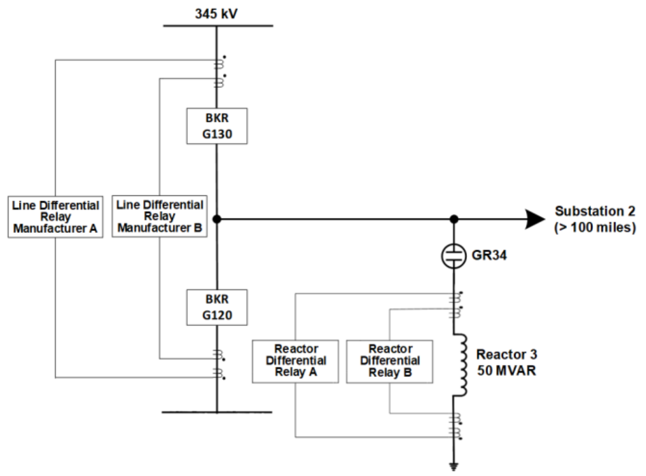


Figure 2. Reactor and line protection arrangement at CTT substation

A shunt reactor can have a fixed or a varying reactive power rating, and CTT uses both types of reactors at their substations. The waveforms discussed in this paper are those gathered from DFR 3 monitoring 345 kV, fixed 50 MVAR, oil-immersed shunt reactor with a gapped iron-core. Reactors 1 and 2 are 345kV, 50 – 100 MVAR, dry-type variable shunt reactors that have air-cores. Reactors are energized through the circuit switcher (GR#4) many times a day depending on the need to regulate the voltage. Each reactor is protected using primary and backup relays as shown in Figure 2. These relays are programmed to trip on differential and overcurrent elements.

The current waveforms observed by the shunt reactors upon energization are not always smooth, and an unwanted DC offset is often produced during reactor switching operations. The level of the DC component is most influenced by the point of the voltage waveform at which the reactor is energized. The effect of the phase angle of the voltage waveform on the observed DC component in the current waveforms following reactor energization is demonstrated with practical scenarios in this section. This DC offset often takes several seconds to decay because of the low losses exhibited by the reactor (high X/R ratio) and can cause saturation of current transformers (CTs) (discussed in detail in section III), as well as saturation of local power transformers. Because the different phases of a saturated reactor draw unbalanced inrush currents in the three phases, the neutral carries zero sequence current that might cause issues for zero-sequence protection elements [3]. The effects of these scenarios on protective relaying as observed through the DFR monitoring system is explained in section IV.

Contrary to inrush current observed on transformer energization (rich in 2^{nd} and 5^{th} harmonics), inrush current in gapped iron-core reactors is only slightly distorted even with significant DC offset because of its magnetic characteristics. As mentioned earlier, shunt reactors magnetic curves have a greater operating range in the linear region and a higher knee point. The gaps introduced in the core of the reactors help limit the change in slope of the magnetic curve beyond its knee point which in turn helps draw less harmonic content compared to a transformer. Figure 3 reproduced from Figure 11 from [4], shows the magnetizing characteristics of both coreless and gapped iron-core shunt reactor designs. The harmonic content in the current waveforms following reactor switching is also shown in the scenarios analyzed below.

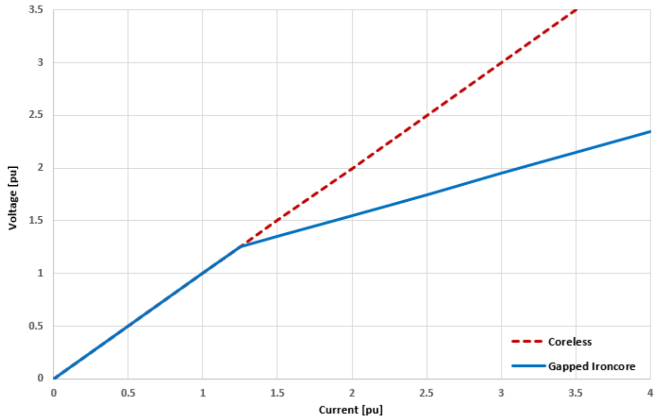


Figure 3. Magnetization characteristics of Coreless (air-core) and Gapper Iron-core shunt reactors [4]

Before we discuss various scenarios observed at CTT substations, we'll look at the theoretically derived reactor current equation and discuss possible extremities it can achieve based on phase angle on voltage during the energization. The shunt reactor can be simply modeled as an inductance in series with a resistance. The resistance is always present and is included to account for the losses. Assuming the line voltage is $V(t)$, current, $I_{Reactor}(t)$, flowing through the shunt reactor following energization can be derived as shown below.

$$V(t) = \sqrt{2}V_{rms}\sin(\omega t + \delta)$$

$$I_{Reactor}(t) = \frac{\sqrt{2}V_{rms}}{|Z|}\sin(\omega t + \delta - \theta) - \frac{\sqrt{2}V_{rms}}{|Z|}\sin(\delta - \theta)\, e^{\frac{-t}{L/R}}$$

Where, $$|Z| = \sqrt{R^2 + (\omega L)^2}$$

$$DC\ offset\ time\ constant = \frac{L}{R}$$

$$\delta = phase\ angle\ of\ voltage;\ \theta = arctan(\frac{\omega L}{R})$$

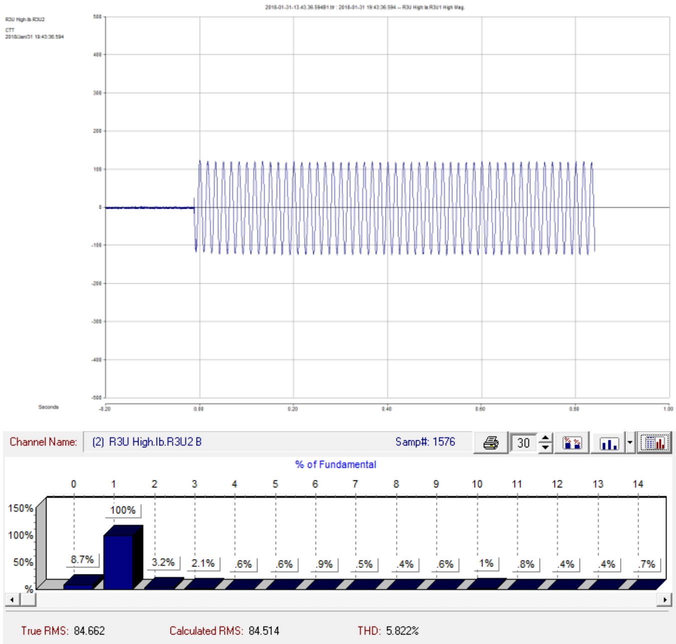
In the above-derived reactor current equation, the first term represents the steady-state value and the second term represents the transient value that has the damping DC offset. Since inductors oppose the sudden change in currents, in order to observe a smooth reactor switching, the circuit breaker should be closed when the transient value (second term) of the current is zero i.e., $\delta = \theta$ (the closing instance on voltage waveform matches the phase difference in voltage and current waveform). This can be simplified to presuming the resistive part of the impedance be zero, which results in $\theta = 90^{\circ} = \delta$. Thus, a smooth shunt reactor switching can be achieved with the transient part of the current being zero if the circuit breaker closes when the voltage reaches the maximum value ($\delta = 90^{\circ}$). Since the DC offset observed will be negligible in this scenario, the rms voltage should be almost constant from the time the reactor is energized. Scenario 1 shows a few instances of such shunt reactor energizations.

A. Scenario 1: Energization at peak voltage crossing

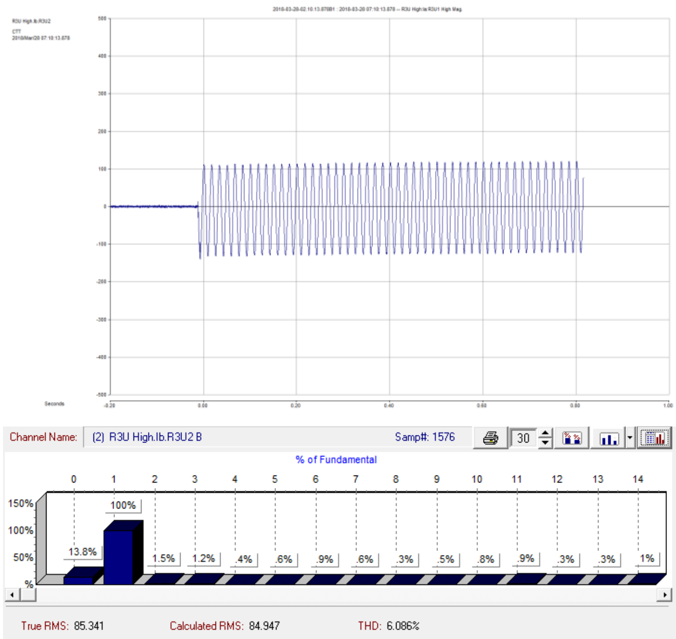
Voltage and current equations when $\delta = \theta = 90^{\circ}$ are derived below:

$$V(t) = \sqrt{2}V_{rms}\sin(\omega t + 90^{\circ})$$

$$I_{Reactor}(t) = \frac{\sqrt{2}V_{rms}}{|Z|}\sin(\omega t)$$



(a)



(b)

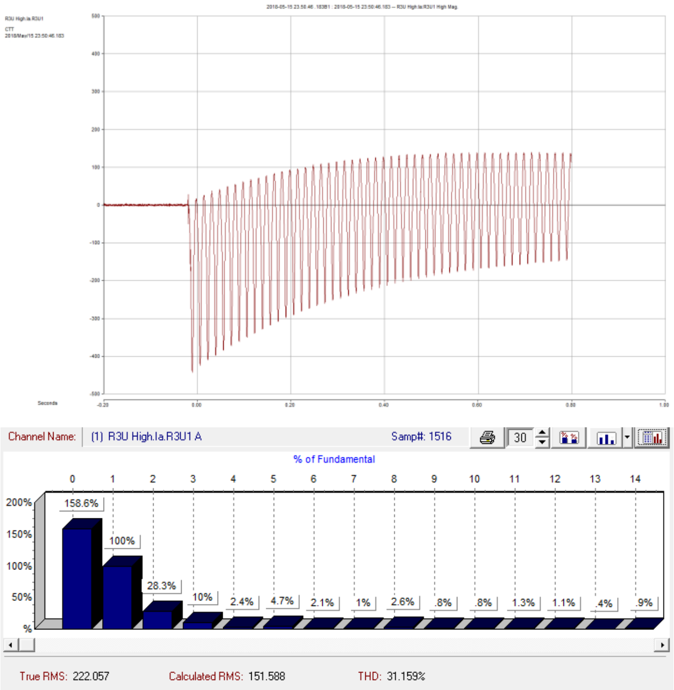
Figure 4. (a) Phase B current waveform of reactor energizing on peak voltage on 1-31-2018 along with Harmonic content of 1st cycle; (b) Phase B current waveform of reactor energizing on peak voltage on 3-28-2018 along with Harmonic content of 1st cycle

As observed in Figure 4, the DC offset observed on energizing shunt reactor on peak voltage is 8.7% (7.28 A) and 13.8% (11.55 A) in two corresponding instances. It should also be observed that the harmonic content is minimal for this kind of shunt reactor energization.

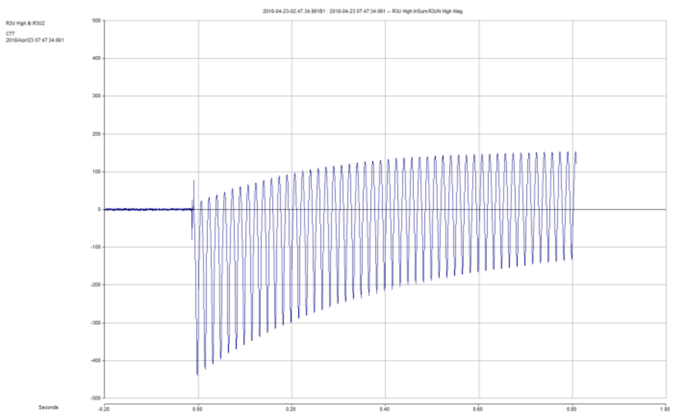
B. Scenario 2: Energization at zero voltage crossing

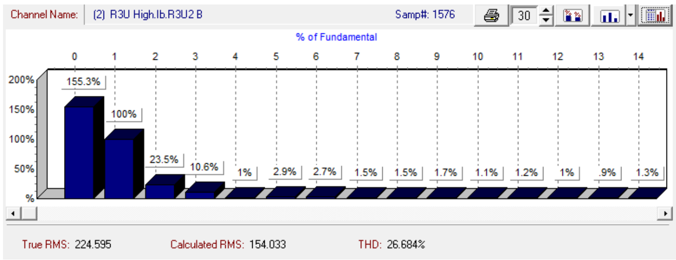
Now, opposed to the previous scenario, the transient term will be maximum if the circuit breaker closes when $\delta - \theta = \pm 90^{\circ}$. This can be simplified as $\delta = 0^{\circ}$ which implies the voltage waveform is crossing zero. The current observed by the reactor is as shown below:

$$I_{Reactor}(t) = \pm \frac{\sqrt{2}V_{rms}}{|Z|}\left(\cos(\omega t) - e^{\frac{-t}{L/R}}\right)$$



(a)





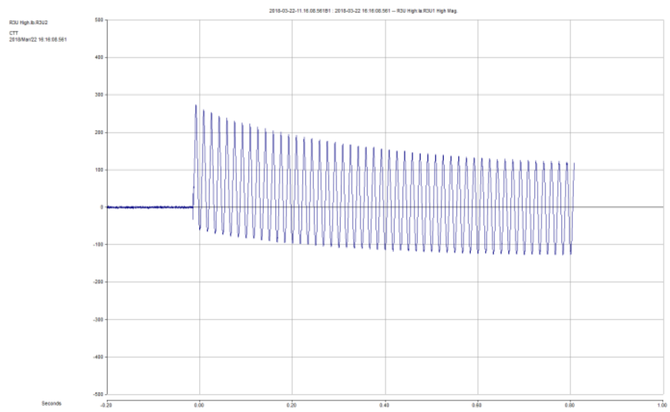
(b)

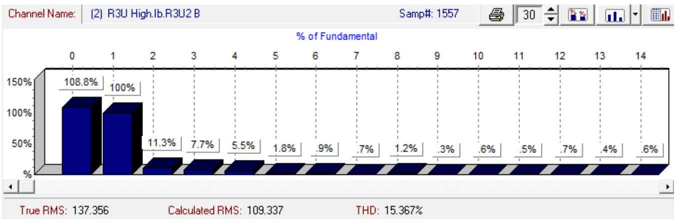
Figure 5. (a) Phase A current waveform of reactor energizing on zero voltage on 5-15-2018 along with Harmonic content of 1st cycle; (b) Phase B current waveform of reactor energizing on zero voltage on 4-23-2018 along with Harmonic content of 1st cycle

According to Figure 5, the DC offset observed on energizing the shunt reactor on zero voltage crossing is 158.6% (132.7 A) and 155.3% (129.95 A) in two corresponding instances. It should also be noted that, unlike transformer inrush current, the reactor inrush is fairly sinusoidal with low values of higher order harmonics but with a significant DC offset. The DC offset observed after 50 cycles for the above-discussed instances is 18% (15.06 A) and 39.6% (33.13 A) respectively. It is common for shunt reactors to have time constants close to 1 second whereas the transformers may have DC time constants up to a couple of hundred milliseconds (6~18 cycles) [4]. If the DC offset is dominant on the same polarity over time in consecutive energizations, and given that shunt reactors have long time constants, CTs are pushed into the saturation region. The effect of CT saturation on reactor protection is discussed in detail in Section III.

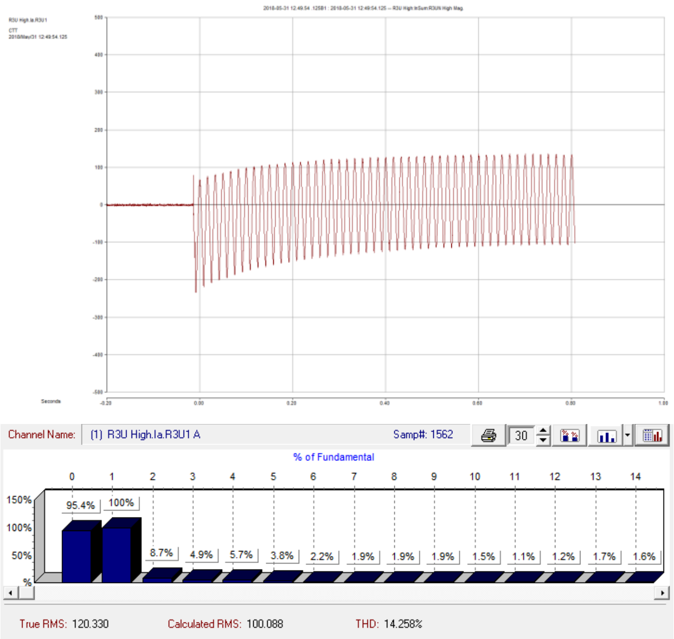
The following scenario is shown to compare the differences between the previous two scenarios. In this scenario, the reactor is energized when the voltage is neither at zero or at its peak.

C. Scenario 3: Energization when the voltage is neither at zero nor at its peak





(a)



(b)

Figure 6. (a) Phase B current waveform of reactor energizing on voltage @ 55˚ on 3-22-2018 along with Harmonic content of 1st cycle; (b) Phase A current waveform of reactor energizing on the voltage @ 244˚ on 5-31-2018 along with Harmonic content of 1st cycle

As observed in Figure 6, the DC offset observed on energizing shunt reactor is 108.8% (91.04 A) when the voltage is at 55˚ and is 95.4% (79.82 A) when the voltage is at 244˚ in corresponding instances. The DC offset in the second instance damped to less than 10% (12 A) within 8 cycles while it took 17 cycles in the first instance.

The inrush and high DC offsets during energization (and CT saturation caused by it) can be avoided if synchronized switching (point-on-wave) can be installed at the substations.

Protection engineers should be aware of the effects of inrush current when developing relay settings for reactor protection. In fact, due to the need of reactive power consumption for voltage control and power system safety, line reactors should never be tripped alone, whole transmission line should be taken out of service in the case of a reactor fault. Therefore, any sensitive instantaneous elements (especially instantaneous differential and zero sequence ground overcurrent elements) can result in taking reactor and transmission line along with it out of service if the above-mentioned effects are not considered during relay setting development. The effects of inrush currents during shunt reactor switching are discussed in section IV based on waveforms obtained through the DFR monitoring system at CTT substations.

III. Effect of CT Saturation on the Shunt Reactor Protection

A. *CT Operation*

CT is comprised of two sets of windings (primary winding and secondary winding) around an iron core. When the current flows through the primary winding, it generates the alternating magnetic field, which corresponds to the magnetic flux around the core [5]. This magnetic flux induces the voltage across the secondary winding. Depending on the load connected across the secondary winding, this voltage causes current to flow in the secondary winding.

B. *CT Saturation*

The primary current generates the magnetic field strength which produces the magnetic flux shared by both the windings. As more current flows, more field strength is generated and thus flux density also increases. This flux density increases to a maximum point depending on the material of the core. At this point CT gets saturated. Ideally, the secondary current is equal to the primary current divided by the number of turns. During the CT saturation, secondary current does not replicate the primary current accurately. There are two types of CT Saturation viz. Symmetrical saturation and Asymmetrical saturation [5].

Symmetrical saturation is caused due to the large symmetrical primary current being applied to the CT. Asymmetrical saturation is caused due to the DC offset present in the applied primary current. CTs in the shunt reactor get saturated mainly because of the DC offset present in the primary current during the Shunt Reactor switching. Figure 7 shows an example of a saturated CT.

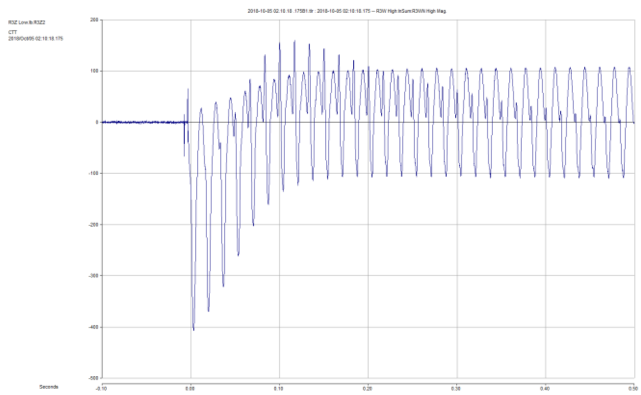


Figure 7. Phase B current waveform monitored through a saturated CT on 04-10-2018.

C. Identifying CT saturation with help of DFR [5]

1) Based on the difference in the characteristic waveform

Saturated CT waveform is different than the characteristic sinusoidal waveform due to the presence of harmonics. Figure 8 shows the saturated CT waveform in red and unsaturated CT waveform in blue (two different phases) superimposed on each other. It can be observed that saturated CT waveform characteristics are different than the characteristic sinusoidal waveform.

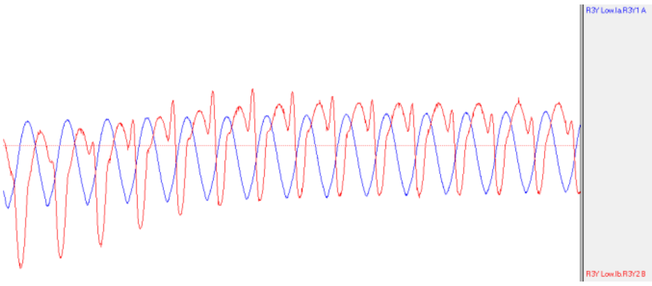


Figure 8. Comparing phase B (saturated) and phase A (unsaturated) current waveforms monitored on 04-10-2018.

2) Based on presence of harmonics

Saturated CT would have large amounts of harmonics present in the measured current. Thus, analyzing the CT waveform for the harmonics gives a good indication of whether the CT is saturated or not.

Figure 9 below shows the harmonic content during the reactor switching which is just before this CT is about to saturate. The 2nd order harmonic content observed at this instant is about 29.1% (24.35 A).

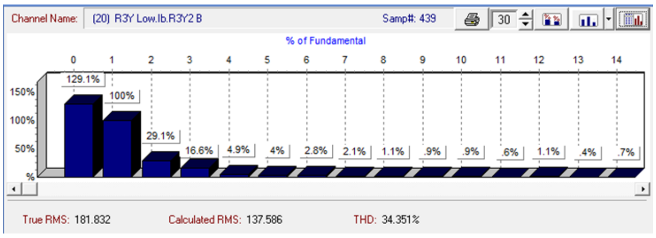


Figure 9. Harmonic analysis of phase B current waveform before CT saturation on 04-10-2018.

Figure 10 below shows that the 2nd order harmonic content of the observed waveform increases to 61.3% (51.3 A) when CT saturates.

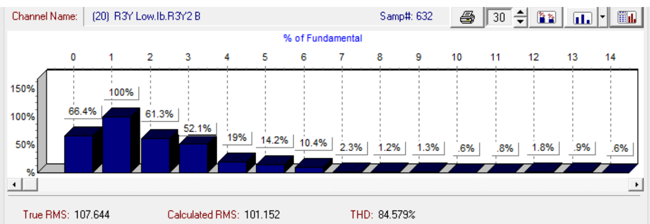


Figure 10. Harmonic analysis of phase B current waveform during CT saturation on 04-10-2018.

Figure 11 below shows the low magnitudes of harmonic content on all orders of the observed waveform when CT desaturates.

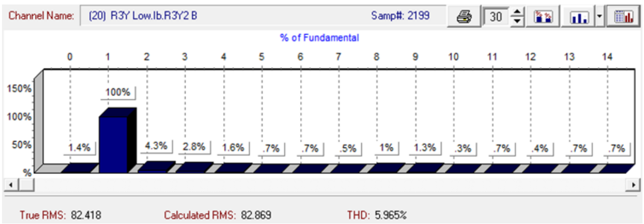


Figure 11. Harmonic analysis of phase B current waveform after CT desaturates on 04-10-2018.

3) Based on difference in high side and low side currents

Ideally, during the normal operation of shunt reactors, high side winding current is equal in magnitude and 180 degrees out of phase with low side winding current. Thus, the differential current is zero.

When CT on either side of the shunt reactor is saturated, the differential current appears. Figure 12 below shows the unsaturated high side CT current, saturated low side CT current, and the differential current. It can also be observed that as the low side CT gets desaturated, differential current starts reducing and eventually becomes approximately zero.

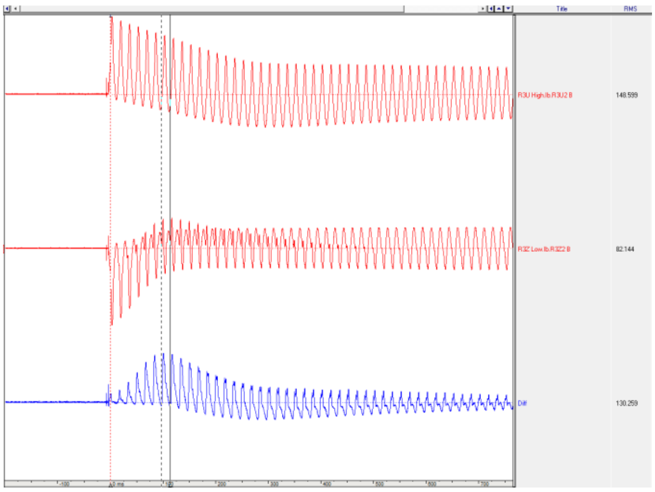


Figure 12. Phase B current waveforms on the high and the low side of shunt reactor where low side CT saturated on 04-10-2018. Resulting calculated differential current is also displayed.

D. Effects of CT Saturation on Reactor Protection

CT saturation can cause relay misoperations if the relays are not correctly set. For one of the records, which detected CT saturation, we observed that the differential current almost crossed into the operating region. The differential plot for that record is shown in Figure 13 below.

While developing the differential relay settings for reactors and transformers like slope, instantaneous pickup etc., a protection engineer should take the effect of CT saturation into account. If not, the relay can misoperate.

Effects of CT saturation on shunt reactor protection are discussed in detail in section IV.

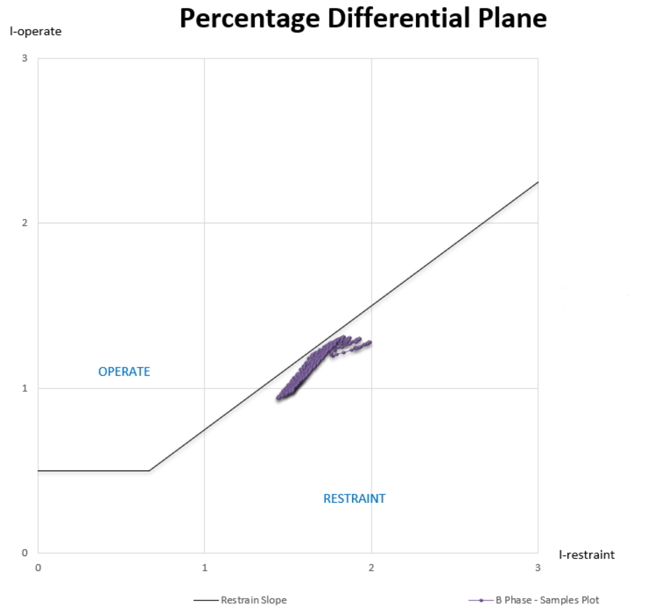


Figure 13. Differential plane showing the instance where CT saturation drives the relay close to the operating region.

IV. Avoiding Misoperations during Abnormal Conditions

Elements that can make relays misoperate due to inrush current and CT saturation are the differential and instantaneous ground overcurrent elements. This section discusses the philosophy to avoid relay misoperations due to the above-discussed effects.

A. Differential Element [6,7]

Developing relay settings for shunt reactors includes restrained and unrestrained element pickups with harmonic blocking and harmonic restraint functions. The harmonic restrained element has dual slope characteristics. The slope 1 should be set in such a way that the relay avoids misoperations due to the CT errors, losses, high load conditions etc. The slope 2 setting further increases the restraint region of the relay. It must be set in such a way that the relay doesn't misoperate because of the CT saturation. As discussed in the prior sections, inrush currents have high amounts of 2^{nd} order harmonics present (> 10%). Harmonic blocking and restrained elements can be set at ~10% such that it prevents the differential element from tripping.

As observed from the DFR records, saturation of the CTs on either side of the reactor produces high differential current. Instantaneous differential pickup should be set by taking CT saturation into consideration.

B. Instantaneous ground overcurrent element [6,7]

Due to asynchronized switching of the reactors, zero sequence current flows through the reactor. From the DFR records analyzed, it is observed that neutral current during switching can go as high as 1.38 pu. Instantaneous ground overcurrent element pickup should be set such that the relay does not operate during the reactor switching. The second harmonic blocking element can also be enabled for the instantaneous ground overcurrent element to avoid tripping during the reactor switching.

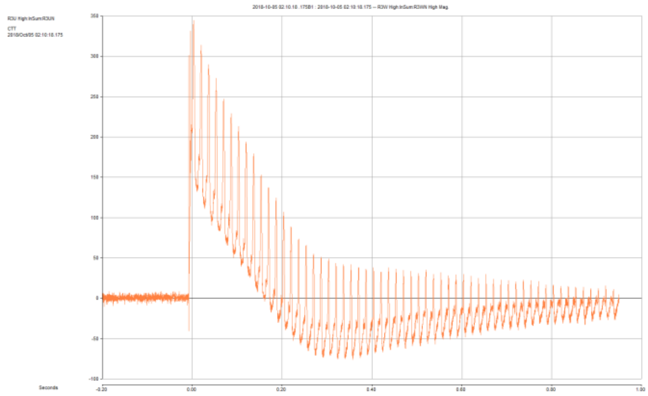


Figure 14. A high magnitude of neutral current flowing during asynchronous reactor switching on 04-10-2018.

V. Conclusion

The DFR monitoring system enables us to analyze and study the actual operation of the shunt reactor and its effect on shunt reactor protection. The effect of the phase angle of voltage during reactor energization on inrush current magnitudes was discussed in detail with demonstrations, and it was determined that peak voltage energization results in smooth reactor switching. CT saturation and its effect on reactor protection was discussed. Methods to identify CT saturation in the DFR waveforms was also discussed. Effect of inrush currents and CT saturation on working of the differential element and instantaneous ground overcurrent element respectively were described. Pointers to be considered when developing relay settings for these elements were mentioned.

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VII. Author Biographies

Lalit Ghatpande received his BE in Electrical Engineering from the University of Pune in 2013 and an MSEE degree from the Michigan Technological University in 2017. Since 2017, he has worked at SynchroGrid as a Relay Setting Engineer.

Naveen Ganta received his MS in Electrical Engineering from the University of Texas at Austin in 2017 and B.Tech degree from the Indian Institute of Technology, Bhubaneswar in 2015. Since 2018, he has worked as a Relay Settings Engineer with SynchroGrid, working on various engineering analysis projects.

Joe Perez received his B.S. degree in Electrical Engineering from Texas A&M University in 2003. Joe is the author of many relay application notes and has presented technical papers at WPRC, Texas A&M, and Georgia Tech Relay Conferences. Joe is the owner of SynchroGrid, a registered professional engineer in the state of Texas, and a member of PSRC, IEEE, and PES. Joe resides in the Bryan/College Station area. He can be contacted at jperez@synchrogrid.com.

Jerry Burton joined Cross Texas Transmission in November 2013 and has over 18 years of experience in the electrical field on projects in the residential, commercial, oil and gas, process and generation/transmission industries. Mr. Burton has filled several positions from apprentice to general foreman, senior relay technician and, most recently, Substation Superintendent. Mr. Burton has a wide variety of knowledge as it pertains to relay testing, commissioning, preventive maintenance, and substation construction. Mr. Burton currently holds a Texas Department of Licensing and Regulation Journeyman Electrician license and a Substation Journeyman Electrician certificate through the US Department of Labor.