

Effects of Low Resistance Measurement Instruments on Protection and Control Devices

Abstract:

Low resistance micro ohm measurement is a routine diagnostic test performed on Circuit Breakers (CB) and bus bars in medium and high voltage substations. This test is important to check the integrity of CB contacts and detection of high resistance joints and terminations for installed bus work. Although the test is very simple and easy to perform, it can prove problematic for other devices connected to the same circuit.

The DC current used for measuring the low resistance can affect the protection and control circuitry in adverse ways. Typical problems encountered are Current Transformer (CT) magnetization, accidental tripping of differential relays and inconsistent and unreliable low resistance measurements. The paper will address the root cause of these encountered problems. It will recommend precautions to take prior to performing the test and discuss in detail the recommended practices to avoid any misoperation of connected protection and control devices.

The recommended practices will be supported by both a real life case study and lab simulations to thoroughly explain the impact of quality of DC current used for the low resistance measurements, effect of in service tap CT ratio, and associated settings of connected relays. Paper will provide an insight into the factors that can go wrong during micro ohm measurements and how to prevent those using a proactive approach.

Low Resistance Testing

An electrical conductor is one of the most important elements in any electrical system. It is the part of the system that carries the current flow and its quality mainly depends on factors such as material, geometry (cross sectional area and length) and temperature, which all together define the resistance of the conductor.

The operation of electrical equipment depends on the controlled flow of current within the design parameters of a given piece of equipment. Depending upon the electrical asset, current flow under normal operation can range from a few amps to many hundred amps. Any increase in resistance can result in loss of energy in the form of heat in accordance with the formula $W=I^2R$. For instance, a bus joint resistance measured upon commissioning at $50 \mu\Omega$ is considered to be an acceptable measurement, but over time due to corrosion and lack of maintenance, if the resistance of the joint goes up to $500 \mu\Omega$; the power dissipated in the joint also increases tenfold.

The big difference in dissipated power will result in excessive heating and if left unattended, it can lead to catastrophic failure of that electrical equipment. External factors like environmental and chemical attacks, electrical stresses (over voltages or impulses) and mechanical stresses as well, can all contribute to the degradation of joints, contact surfaces and low resistance connection points. High resistance not only

causes unwanted heat, but it also causes energy losses which increase operating costs; this is the reason why utilities and other industries are aware of the importance of performing low resistance measurements. The application range of low resistance measurements is very wide and some of the most common applications include motor windings, coils, ground bonds, welded joints, lightning conductors, small transformers, bus bar connections and circuit breakers.

A resistance measurement is considered to be of low resistance when the resulting value of the test is below 1.000Ω . The lower ranges of many low resistance ohmmeters measure down to $0.1\ \mu\Omega$, which is required when conducting tests on breaker contacts and bus joints. At this level of resistance it is important to use the correct test equipment and method that will minimize the introduction of errors due to test lead resistance, contact resistance between the probe and the specimen under test, as well as other phenomena like standing voltages across the item being measured (e.g. thermal EMFs at junctions between different metals). This is achieved by means of a four terminal measurement (two current and two potential leads) as shown in Figure 1 below. It is important to ensure that the potential leads are placed between the current leads for most accurate measurements.

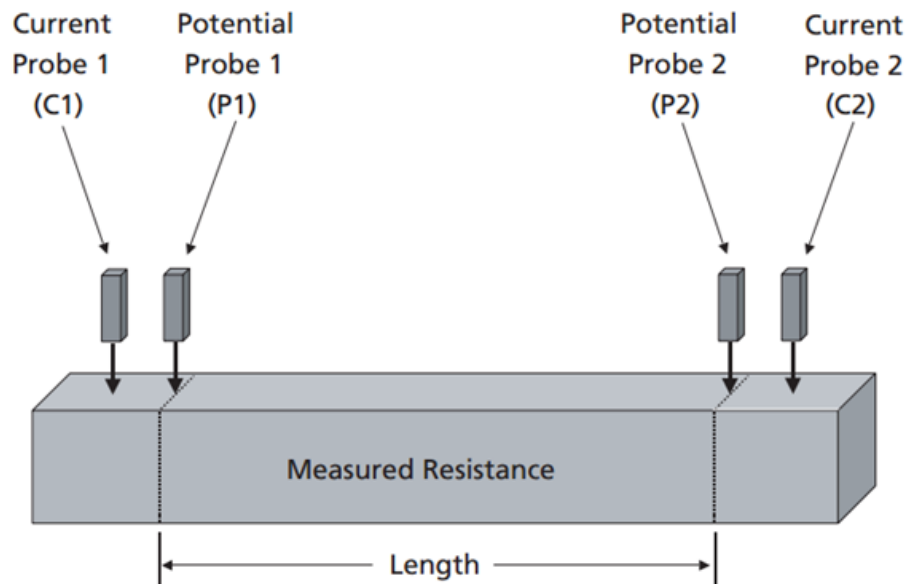


Figure 1. Four Wire Resistance Measurement

Circuit Breakers

The basic function of a CB is to interrupt current flow in a circuit when a fault condition is present. However, sometimes it is forgotten that under normal operating conditions a CB needs to act as a very good conductor for the circuit it is part of. The contact resistance has to remain under a certain value to ensure a good conductive path for the current flowing through it to avoid heating and hence energy losses. Regular maintenance programs include contact resistance testing in accordance with standards ANSI

C37.09 and IEC62271-100, which specify minimum current values to carry out the low resistance measurement.

Special care should be taken when measuring contact resistance of CBs with CTs that are still connected to a protection scheme. Figure 2 shows a typical single line representation of a CB with CTs.

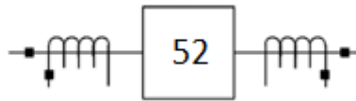


Figure 2. Circuit Breaker with bushing CTs

Differential Scheme

A differential protection zone is defined by the location of CTs and in an ideal case this scheme will work on the premise that the total input current of the system (protected zone) will be equal to the total output current. It will determine whether a fault is present within the protected zone if the difference between input and output currents is above a predetermined set value. This threshold and the proper configuration of the protection scheme are affected by certain characteristics of the CTs, like protection class, CT ratio, saturation levels and nonlinearities.

Differential protection scheme is generally recommended for all buses as it provides sensitive and fast phase and ground-fault protection. One of the most common approaches used is High-Impedance Voltage Differential, which will use zone CTs connected in parallel with a high impedance element inside the relay. All the CTs used for this application must have the same ratio, similar magnetizing characteristics and a relatively high knee point, in order to avoid a false operation for a given burden. Figure 3 shows a common differential protection scheme for bus and transformer protection.

The voltage threshold for a differential element should be set balancing two considerations; first, a low-value setting for maximum sensitivity for in-zone faults or second, a high-value setting to ensure stability for a saturated CT due to a fault present outside the protected zone.

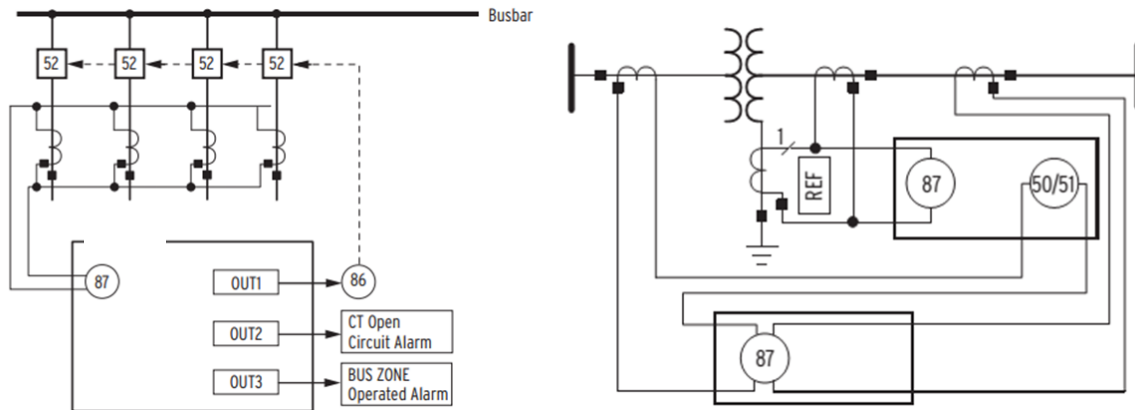


Figure 3. Differential Protection Scheme for a) Bus and b) Transformer

Effect of DLRO on the differential protection scheme:

A low resistance micro ohm measurement on each phase of medium and high voltage CBs is a routine maintenance test. The DC current applied for the test is passed through the breaker contacts and the voltage drop is measured to determine the breaker contact resistance in micro ohms. The majority of HV circuit breakers in North America are dead tank type breakers. As shown in Figure 4, these breakers have CTs mounted on their bushings. The primary of the bushing CT is basically a center conductor passing through the CT which then gets connected to the breaker interrupting chamber that encapsulates the fixed and moving contacts of the breaker.

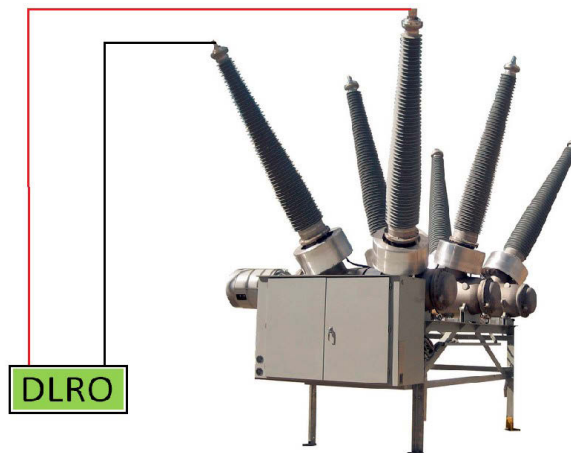


Figure 4. DLRO test connection to a dead tank CB

When performing a Digital Low Resistance Ohmic (DLRO) measurement, the DC current applied passes through the CT primary. In theory, it being a DC quantity, no current should be reflected on the secondary side of the CT. However, based upon the method used and quality of the applied DC current, in some cases, there is a reflection of that onto the CT secondary circuit. The duration and magnitude of the secondary current will depend upon a number of factors. Some of those include rate of rise and fall of

applied DC current, method used to generate DC current such as half wave rectified, full wave rectified or generation using a regulated power supply. A rapidly changing DC current output with ripple content or presence of harmonic components can be interpreted as a fault signal (AC quantity) by the relay and protection devices connected to the CT secondary circuit. Additionally, when the bushing CT is part of a differential protection scheme, this secondary current could be interpreted by the protection scheme as an operating quantity. One other side effect of a DLRO measurement is every time a DC quantity is passed through CT primary, it magnetizes the CT and alters the CT performance. If the current magnitude and time is substantial enough one could saturate the CT and introduce ratio errors during CT operation.

Disconnect CT to avoid tripping of differential protection

False tripping of relay or protection devices can take out a portion or complete system offline and can cause unreliable and unpredictable system operation. In cases where bushing CTs are part of transformer or bus differential scheme, if the unwanted CT secondary current due to DLRO test is greater than the threshold limits of relay settings, it can accidentally trip the system. To avoid any possibility of inadvertent relay tripping situation, the ideal method is to disconnect the CT secondary from the protection circuit and short the CT secondary. This has to be performed for any CT secondaries whose primary is part of the low resistance measurement circuit. One of the practical challenges at many utilities is the substation crew is different than the protection and control crew and is not allowed to change any protection circuits. Additionally, there is always a precaution of not changing existing circuits as it might cause wrong rewiring, incorrect selection of CT tap and accidentally leaving the CT secondary open. Because of all those reasons, although being an ideal method, CT secondaries are typically not disconnected for low resistance measurements.

CT Demagnetization

After exposing CTs to a DC current flowing through the primary it is possible that CTs may have residual magnetism; it is highly recommended to perform a demagnetization procedure on all the CTs involved in the circuit to ensure proper performance after DC testing has been carried out. The following example shows how the excitation curve for a given CT is affected by DC current injection in the primary circuit.

A protection class C200 multi tap CT with a full CT ratio of 600:5 (X1: X3) was used for this test.

First, a demagnetization procedure was carried out to ensure the CT had no residual magnetism and then, the first saturation test was run as shown in Figure 5. A knee point of 210.26V was measured for X1-X3 tap (full secondary winding).

Secondary Voltage Injection

Tap	X1-X2	X1-X3	X2-X3
Knee Volt.(V)	136.14	210.26	71.149
Cur.(A)	0.1371	0.0940	0.2850

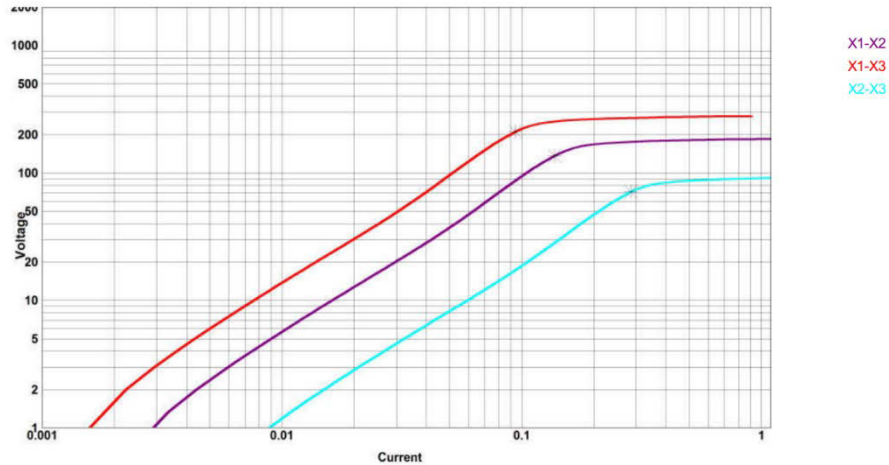


Figure 5. Saturation test after first demagnetization

A DC current was injected through the primary of the CT to see the effect on saturation characteristics of the CT. 400 A was injected through the primary of the CT using a DLRO as shown in Figure 6.

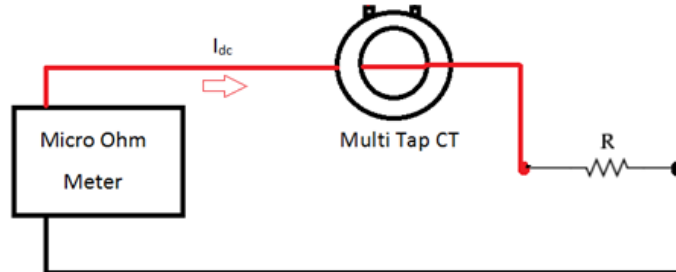


Figure 6. Application of DC current to CT primary

Without demagnetizing the CT, another saturation test was performed. In this case, the knee point was measured at 227.11V. As observed in Figure 7, in addition to knee point voltage change, there was a shift in the saturation curve as well. DC current altered the saturation characteristics of the CT.

Secondary Voltage Injection

Tap	X1-X2	X1-X3	X2-X3
Knee Volt.(V)	150.89	227.11	76.118
Cur.(A)	0.1561	0.1042	0.3130

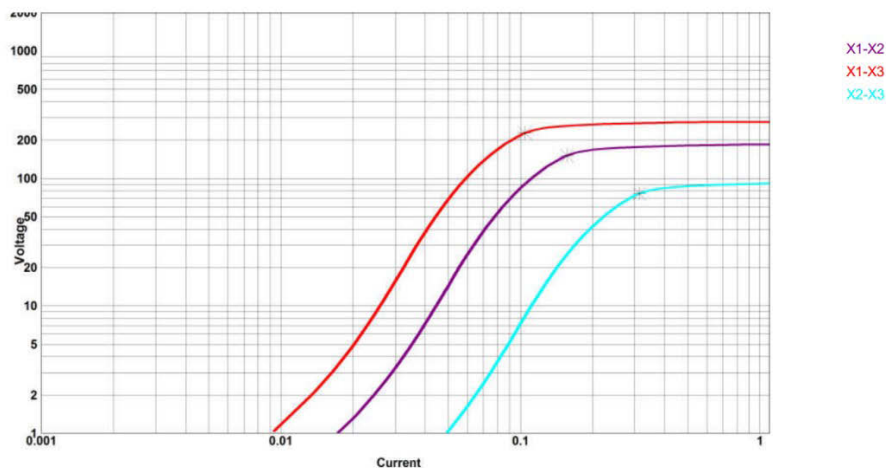


Figure 7. Saturation test after resistance measurement (primary)

A demagnetization process was performed and another saturation test was run thereafter. Figure 8 shows the curve after the demagnetization. In this measurement the knee point was observed at 208.30 V which was similar to first test results.

Secondary Voltage Injection

Tap	X1-X2	X1-X3	X2-X3
Knee Volt.(V)	134.48	208.30	70.130
Cur.(A)	0.1354	0.0930	0.2803

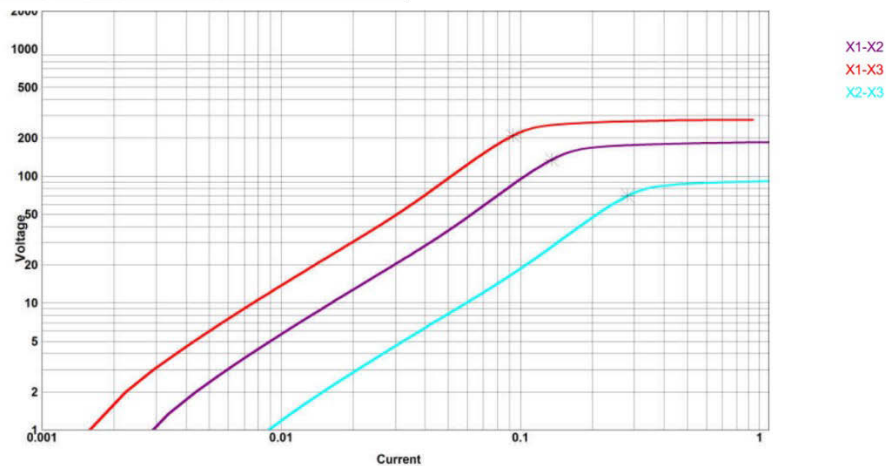


Figure 8. Saturation curve after resistance measurements followed by demagnetization procedure

DC current can magnetize the core of the CT and if not addressed properly can leave residual flux in the core. Under extreme cases it can even saturate the CT. These measurements demonstrate the importance of demagnetization processes after performing DC testing on any circuit that has CTs, especially the ones connected to a protection scheme.

Case Study:

In a normal differential scheme, one could expect multiple CT secondaries connected and compared for detecting an in-zone fault. When a portion of the circuit is taken offline for maintenance purposes, the Kirchhoff's current law still holds good and differential scheme works normally. In an ideal scenario, the current from the CT taken offline should be zero. When the offline CT secondary injects an accidental signal current (from injected DLRO DC current into the CT primary) into the differential circuit, pending the magnitude and duration of the current, it can trigger the differential protection scheme.

An incident occurred at one of the largest Investor Owned Utility (IOU) with more than 6 million customers and operating in seven different states. The bus differential relay tripped while performing the micro ohmmeter testing on a 138 kV circuit breaker. The technicians attempting the test had difficulty obtaining a good contact resistance measurement, and made multiple test attempts prior to the one that caused the trip. The circuit breaker under test featured integrated CTs that were not isolated from the bus differential protective scheme.

The DC current injected for the measurement was 100 A. The high impedance relay used for differential protection was set at a pick up voltage setting of 100 V with no intentional time delay. During the trip event, it was reported that the relay registered a voltage of 132 V. This prompted an investigation to determine the root cause of the incident to avoid any such future misoperation of the protection scheme. In order to observe how the relay responds to application of DC current through CT primary, field conditions were simulated in a lab environment by using the same make and model of high impedance relay along with the relay settings, CT of similar class and ratio and same micro ohmmeter test instrument with different levels of current.

Following instruments and parameters were used as variables to observe different aspects of the problem.

- Tests were performed at different levels of current (100 A - 200 A) for varying time duration (0.6 sec - 3 sec)
- Two different multi tap CTs of class C800 and C200 were used
- Different taps of the CTs were used (2000:5 and 4000:5)
- High Impedance relay settings from the relay events log with different trigger settings of 20V, 50 V, 75 V and 100 V were used for the analysis

The block diagram for the setup used in this relay tripping investigation is shown in Figure 9.

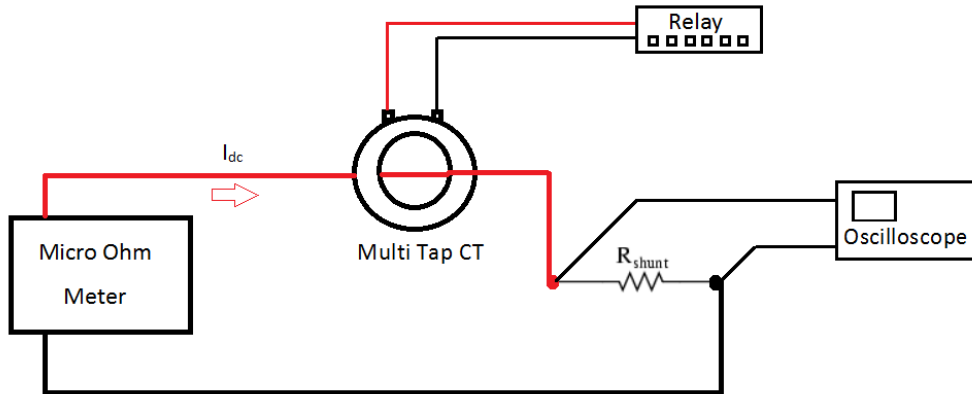


Figure 9. DLRO, CT and relay setup for lab investigation

Observations and Analysis:

Observation 1: Relay settings

An initial test was performed to simulate the field conditions with similar CT class, ratio and relay settings. No relay trip occurred at a setting of 100 V. The trip settings were then reduced to 75, 50 and 20 V for further analysis. Relay trip occurred at 20 V trigger setting. As expected relay settings play an important role in the tripping of the differential protection scheme.

Test Current	CT Class	CT Tap Position	Ratio	Relay Voltage Setting	Relay Trip Voltage
100	C800	X1-X3	2000:5	20	31
100	C800	X1-X3	2000:5	20	32
100	C800	X1-X3	2000:5	20	20
100	C800	X1-X3	2000:5	20	35
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	75	DNT
100	C800	X1-X3	2000:5	75	DNT
100	C800	X1-X3	2000:5	75	DNT
100	C800	X1-X3	2000:5	75	DNT
100	C800	X1-X3	2000:5	100	DNT
100	C800	X1-X3	2000:5	100	DNT
100	C800	X1-X3	2000:5	100	DNT
100	C800	X1-X3	2000:5	100	DNT

Table 1. CT: C800-2000:5

*DNT= Did Not Trip

Observation 2: DC current output characteristics

Different DLRO test instrument may have different quality of DC output based upon the method used to generate DC current from an incoming AC source. There are many factors that can cause the relay to sense initial DC input current as a potential fault current signal. A sudden spike at the start or end, very high level of harmonic components, or ripple current riding over the DLRO DC output are some of the examples that could cause a false trigger of protection scheme.

Ideally, a DC output should ramp up to the target current at a pre-defined ramp rate and follow the same method while ramping down at the end of the test. Additionally, it should have a smooth DC output during the measurement period. If a sudden spike is observed in the output, a relay might see the rising or decaying DC signal as one single narrow pulse and would trip the relay if the magnitude of the filtered output, after passing through one cycle cosine filter, exceeds the relay voltage setting.

Below are some of the examples:

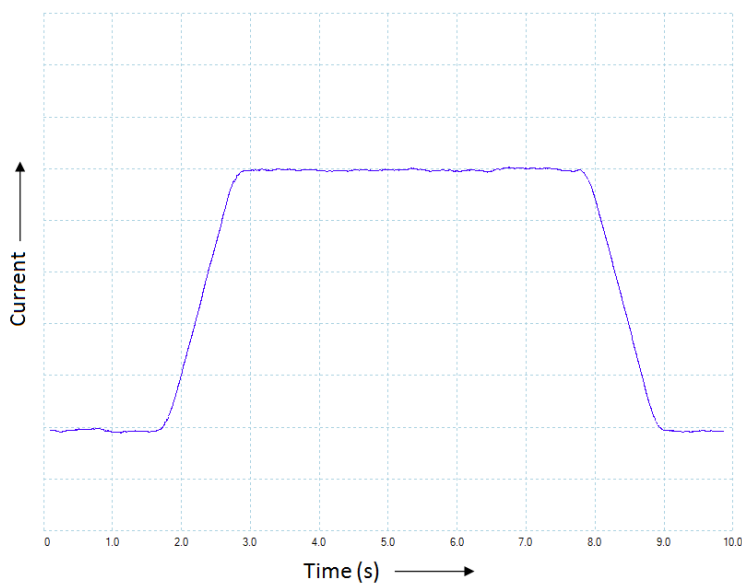


Figure 10. DLRO output current characteristics 1

Figure 10 above shows a smooth DC output with no ripple current and a ramp function at the start and end of the current injection.

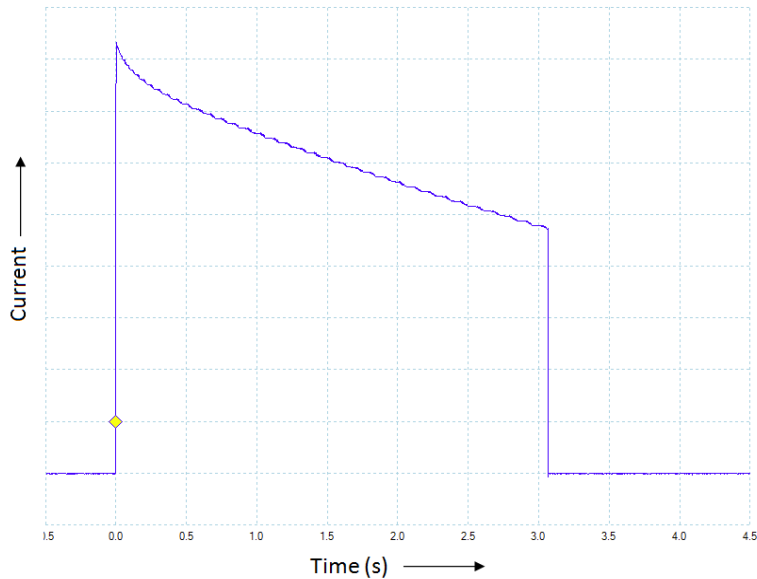


Figure 11. DLRO output current characteristics 2

Figure 11 above shows a decaying DC output without any intentional time delayed ramp function.

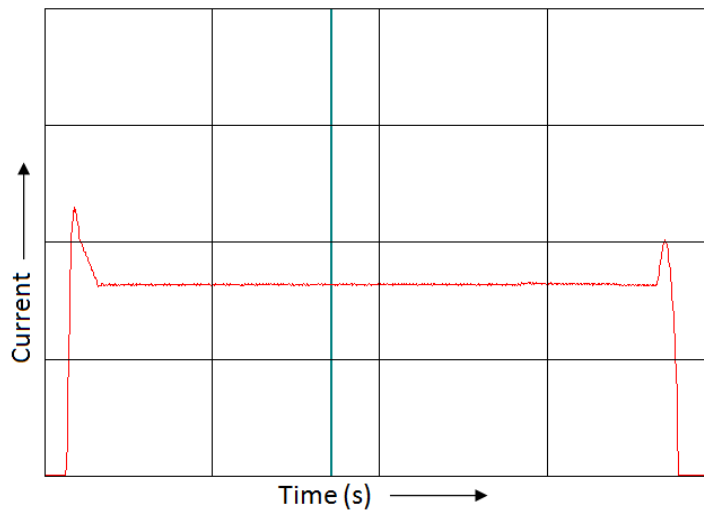


Figure 12. DLRO output current characteristics 3

Figure 12 illustrates an output with spikes at both the start and finish of the test.

Observation 3: Class of the CT

Two different protection class CTs with C200 and C800 were used as per the connections in Figure 9. Relay settings and DLRO test current were kept the same for two tests. Same CT ratio of 2000:5 was used for both of the CTs. It was observed that with a relay pick up setting of 20 V, C800 relay tripped and

C200 did not. Class of CT can affect the response of the relay. The higher the CT class, the more sensitive the relay trip circuit will be.

Test Current	CT Class	CT Tap Position	Ratio	Relay Voltage Setting	Relay Trip Voltage
100	C800	X1-X3	2000:5	20	31
100	C800	X1-X3	2000:5	20	32
100	C800	X1-X3	2000:5	20	20
100	C800	X1-X3	2000:5	20	35
100	C200	X2-X5	2000:5	20	DNT
100	C200	X2-X5	2000:5	20	DNT
100	C200	X2-X5	2000:5	20	DNT
100	C200	X2-X5	2000:5	20	DNT

Table 2. Variable CT class

Observation 4: Ratio of the CT

The highest ratio 4000:5 (X1-X5) of the C800 CT was used with different relay voltage settings. The relay tripped at pick up settings of 20 and 50 V, however, it did not trip at any setting above 75 V. At higher CT ratio (compared to Table 1), the relay tripped at 50 V setting. All other settings being equal, the CT ratio can impact the performance of the relay. The higher the CT ratio, the more sensitive the relay trip circuit will be.

Test Current	CT Class	CT Tap Position	Ratio	Relay Voltage Setting	Relay Trip Voltage
100	C800	X1-X5	4000:5	20	22
100	C800	X1-X5	4000:5	20	28
100	C800	X1-X5	4000:5	20	26
100	C800	X1-X5	4000:5	20	24
100	C800	X1-X5	4000:5	50	65
100	C800	X1-X5	4000:5	50	68
100	C800	X1-X5	4000:5	50	66
100	C800	X1-X5	4000:5	50	65
100	C800	X1-X5	4000:5	75	DNT
100	C800	X1-X5	4000:5	75	DNT
100	C800	X1-X5	4000:5	75	DNT
100	C800	X1-X5	4000:5	75	DNT
100	C800	X1-X5	4000:5	100	DNT
100	C800	X1-X5	4000:5	100	DNT
100	C800	X1-X5	4000:5	100	DNT
100	C800	X1-X5	4000:5	100	DNT

Table 3. CT: C800-4000:5

Observation 5: Different tap of the CT

Performance of two different taps (X1-X3 and X1-X5) of the C800 CT with same relay settings and test current was observed. As shown in Table 4 below, the relay only tripped on X1-X5 tap and not with X1-X3 tap.

Test Current	CT Class	CT Tap Position	Ratio	Relay Voltage Setting	Relay Trip Voltage
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X3	2000:5	50	DNT
100	C800	X1-X5	4000:5	50	65
100	C800	X1-X5	4000:5	50	68
100	C800	X1-X5	4000:5	50	66
100	C800	X1-X5	4000:5	50	65

Table 4. Variable tap of CT

Based upon the saturation test results performed on the C800 CT, X1-X3 knee point voltage was 394.50 V and X1-X5 knee point voltage was 788.86 V. As per the equation 1 from high impedance relay user’s manual, the minimum primary current required to trip the relay is dependent not only on the current flowing through the relay but also on CT excitation current I_{exc} and number of CTs connected in parallel to the relay.

$$I_{min} = (n * I_{exc} + I_r + I_m) * N \quad \text{Equation 1}$$

I_{min} = minimum primary current

n = number of current transformers in parallel with the relay, per single phase

I_{exc} = current transformer exciting current at relay setting voltage, Vs

I_r = current through the relay at relay setting voltage, Vs

I_m = current through the MOV at relay setting voltage, Vs

N = CT ratio

CTs with higher knee point voltage will have lower excitation current, making it more sensitive for the same relay trip voltage settings. This is shown in the Figure 13 below.

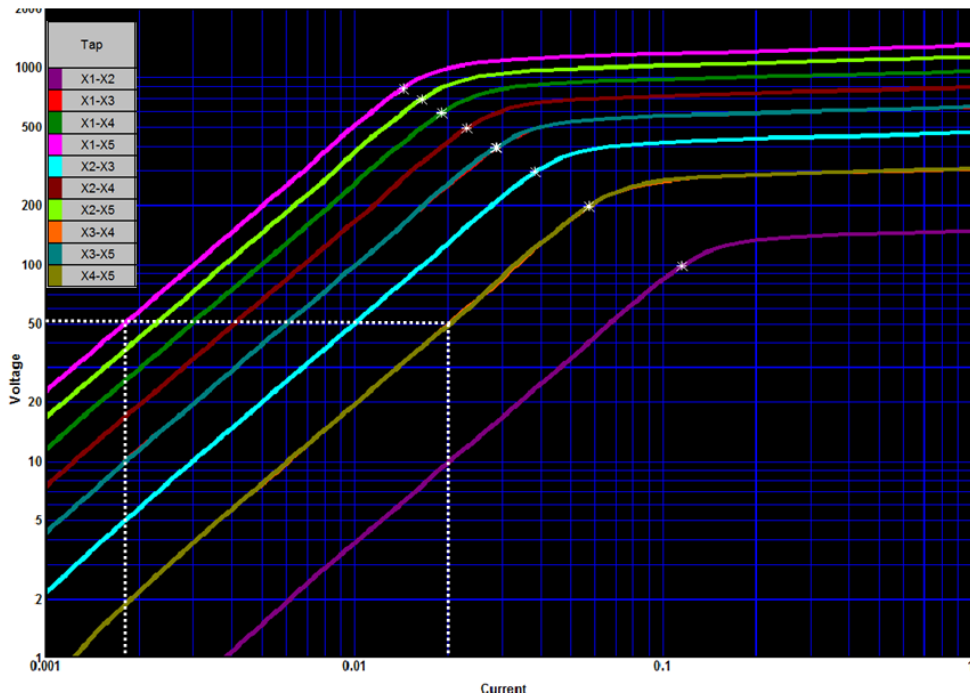


Figure 13. CT saturation curves for multi tap C800 CT

For any given relay voltage setting, the excitation current requirement is less for a higher tap CT. X1-X5 I_{exc} is less than I_{exc} for X1-X3.

Additionally, for same relay voltage settings, the number of CTs in the circuit would impact the sensitivity of the relay circuit. Protection schemes with less no. of CTs per phase connected in parallel to the differential relay would be more sensitive when compared against a scheme that has more CTs in parallel. Figure 14, shows a differential relay configuration on the right that is more sensitive compared to the one shown on the left.

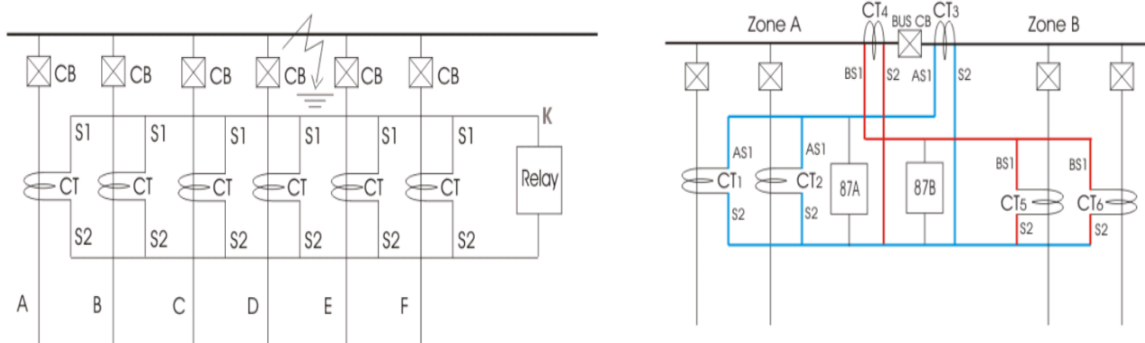


Figure 14. No. of CTs being part of differential protection scheme

Observation 6: Multiple repeat tests

Every time a DC current is injected to the CT primary, it magnetizes the core of the CT. This would result in either increase or decrease in CT excitation current requirements when compared against a demagnetized CT. Multiple repeat DLRO test in a short period of time could change the relay sensitivity because of CT core characteristics and make the relay operation unpredictable.

Observation 7: Pick up setting for a relay in service

During lab simulations, the relay never tripped for any voltage setting above 75 V for any possible combination of DC current, CT class or CT tap. However, during that accidental bus differential trip, the relay saw a voltage of 132 V. Some other factors such as burden associated with each CT, CT saturation and other design parameters could have contributed to final outcome. During investigation it was determined that even though the high impedance differential relay was set at a pick up setting of 100 V, as per the relay manufacturer's recommendation, the minimum relay pick up setting should have been 200 V for the high impedance differential relay in question.

Above observations and analysis indicated that there are several different factors that can contribute to inadvertent tripping of the differential relay. Some of the factors can be controlled by the user out in the field whereas others are defined by system design and settings. The case study and investigation gave an insight of which parameters can influence the outcome and factors to be considered before performing a DLRO measurement.

Solution and recommendations:

Instruments designed to measure contact resistance of CBs have incorporated methods to avoid the problems discussed in this paper. The first method implemented is having filtered DC outputs to eliminate any change in frequency that may be reflected on the secondary of any CT in the circuit, or even having instruments with pure ripple free DC outputs. A second approach, frequently used in conjunction with the first one, is the ability of an instrument to define a ramping rate at both the start and end of the test. A low resistance micro ohmmeter with this feature will slowly increase the injected current, starting from zero to the target current and at the completion of test, the same ramping rate is applied when reducing the current back to zero. This helps in preventing any sudden rise in DC quantity or spike that could possibly be interpreted by a relay as a fault signal.

The voltage differential setting in a relay can play a major role as well, as illustrated in a relay manufacturer's user manual: *"a low-voltage setting with no intentional time delay can have an adverse impact on the security of the differential elements for external faults. High-current external faults can result in enough unbalance current to cause operation of the differential elements for these low-voltage settings with no intentional time delay. A minimum instantaneous differential voltage setting of 200 V with no intentional time delay is recommended"*⁴.

When performing low resistance measurement out in the field on bus or breaker contact resistance, technicians have to be cautious and be aware of all the factors that can cause accidental tripping of relays.

Class of CT, CT ratio and CT tap in operation are few aspects although can't be altered, should be kept in mind. On the other hand, CT residual magnetism, demagnetization, unwanted repeated DLRO measurements, relay settings as per the manufacturer's recommendation and selection of the correct DLRO test instrument with smooth DC output and ramp rate option can certainly reduce the probability of any accidental trip.

Conclusion:

Low resistance micro ohm measurement is an integral part of regular substation asset maintenance practices. Breaker contact resistance and bus work installation will continue to be checked using this test method. The test, as simple as it is, comes with inherent critical issues that need to be addressed to avoid any inadvertent trips during this measurement.

This paper covered a real life case study and an analysis was made to discover the factors that can affect the protection scheme associated with the circuit under test. Understanding the CT performance and relay characteristics will prepare technicians better to take a proactive approach and perform the test in a risk free manner. Selection of the right instrument with proper DC output will go a long way in mitigating any possibility of accidental trip.

References:

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