High-Impedance Differential Applications With Mismatched CTs

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Abstract—Applying high-impedance differential schemes with mismatched-ratio current transformers (CTs) is generally discouraged. However, in instances where facilities are being expanded, new circuit breakers and CTs may have different ratings than the existing equipment, making it necessary to modify purchase standards to match the existing equipment. Techniques have been developed to allow this application when necessary. Each of the methods has advantages and drawbacks that must be considered in determining the best solution for the application. One easy solution is to tap a higher-ratio CT at a matching tap. For this solution, general guidance has cautioned that those considering applying a high-impedance scheme across a partial CT secondary winding tap must evaluate the effect of the higher voltage on the insulation of the circuit components connected to the other terminals of the CT. This paper investigates the issue in detail, including results of testing CTs in a high-current test facility, to provide practical guidance to practicing engineers in determining the risks and application considerations.

I. INTRODUCTION

IEEE Standard C37.234-2009, IEEE Guide for Protective Relay Applications to Power System Buses, outlines the importance of power system bus protection and various considerations that need to be observed [1]. Apart from reliability, operational, economical and initial design considerations, another important consideration is how the chosen protection scheme can handle future changes after it is placed into operation.

Despite best attempts and intentions by the original bus protection design engineers, planned and unplanned events will challenge the flexibility of the chosen scheme. If the selected protection scheme is a high-impedance differential protection scheme, changes that require integrating new and existing current transformers (CTs) of mismatched full ratios can make the feasibility of this scheme challenging, if not questionable.

On the other hand, high-impedance differential protection schemes have many advantages, supporting good reasons for not simply choosing a different alternative. Some of the advantages are the following:

- High performance, including high speed, high sensitivity, and high security.
- Virtually no limit on the number of branch circuits on the bus.
- Simple CT wiring with CTs wired to a summing junction located in the yard and a single set of leads brought into the substation control enclosure.
- Extremely simple setting calculations.

This paper investigates this issue in detail and opens the possibility of using high-impedance differential protection with mismatched CTs provided certain design factors are considered.

II. BUS PROTECTION, A UTILITY'S PERSPECTIVE

Alliant Energy is an investor-owned Midwest Energy Company serving approximately 958,000 electric customers and 411,000 gas customers in Iowa and Wisconsin. Alliant Energy is primarily a distribution and generation asset owner and operator. As a company with distribution buses operating in the range of 12.5 kV to 25 kV and generation buses operating in the range of 35 kV to 345 kV, Alliant Energy has standardized on high-impedance differential protection over percentage-restrained (low-impedance) bus protection. Table I of [2] provides a good comparison of the two schemes. Scalability, setting complexity, panel space, and cost are key reasons in the decision to standardize on high-impedance differential protection. Alliant Energy's single, fixed distribution buses typically involve four to nine circuit breakers depending upon the need and location within the service territory. The ability for the high-impedance differential protection scheme to accommodate large quantities of circuit breakers while keeping a centralized design to a single relay and panel is the largest driving factor in the decision, with ease of setting the relay as close second.

There are many reasons why Alliant Energy encounters the need to use mismatched CTs for bus protection. The reasons can vary for each site, and at some locations, multiple factors are involved. The factors discussed in this section are a few of the primary drivers that have surfaced for Alliant Energy:

- **Multicompany ownership of bus protection assets.** Alliant Energy, like many other utilities, is no longer a vertically owned utility that owns and controls 100% of the bus protection equipment. With utility ownership split between generation, transmission, and distribution assets along with an increase in independent power producers, there is a prevalent percentage of co-ownership of protection systems as a whole. Not having complete control over all assets in question generally contributes and/or exacerbates many of the remaining factors discussed. Even if co-owners can agree and plan upgrades together, there is often sequencing of the upgrades. Sequencing can be necessary because of site physical space limitations

for construction crews and engineering limitations of shared design drawings, which prevents both companies from simultaneously designing upgrades for construction.

- **Standardization.** Alliant Energy was formed from a three-company merger of which some of the three predecessors were also derived from prior mergers. Operating a larger company that is a result of multiple smaller companies highlights the vast differences in designs and multitude of equipment choices. This background has driven a higher priority on moving forward with standardization and enforcing fewer options and variations. Where CTs are typically provided with power transformer, circuit breaker, and switchgear orders, there is a desire to specify a one size fits all approach in an effort to reduce variations.
- **Outage constraints.** Some upgrades require sequencing of work due to outage constraints. Taking an entire bus out of service to simultaneously replace all circuit breakers and CTs to a different ratio is not always possible.
- **Budget constraints.** Upgrades to a location can be limited to a portion of an overall plan and require a multiphase approach due to a single company's budget constraint or due to coordinating budgets for a multicompany upgrade.
- **Equipment failure.** Alliant Energy desired to have a limited number of spare equipment that could be universally applied when equipment failures occur.
- **Upgrades (ampacity, fault current interrupting capacity, CT saturation, asset life cycle, bus expansion).** Upgrades to circuit breakers for ampacity, fault current interrupting capacity, life cycle, and expansion are reasons where only a portion of the bus involved may require modifications that can result in mismatched CTs.

To highlight some of the reasons above, two recent examples at Alliant Energy occurred at the Green Street and Birchwood substations. Alliant Energy was completely rebuilding an existing two-bus distribution substation including high-side transformer circuit breakers at the Green Street location. However, the transmission company was not upgrading the 69 kV transmission bus equipment that sourced the Green Street substation. The transmission company owned the 69 kV high-impedance differential protective relays that incorporated 1200:5 CTs. Alliant Energy desired to purchase and install their standard 69 kV high-side circuit breakers with 2000:5 CTs available for the transmission company's differential protection. Because both owners were not simultaneously upgrading all the circuit breakers around the buses, the mismatched CT issue surfaced and originated the research on the feasibility of using mismatched CTs in a high-impedance differential protection scheme.

The Birchwood substation is a second example of a desire to use mismatched CTs that followed close in time after the Green Street substation project. At the Birchwood substation, Alliant Energy was adding a new distribution feeder onto an existing 25 kV distribution bus. The Alliant Energy standard for 25 kV feeder circuit breakers would normally specify 2000:5 CTs for bus protection. However, the existing distribution high-impedance differential protection scheme used a 1200:5 CT.

In the Green Street substation example, the bus protective relay was not owned by Alliant Energy; therefore, we had no control over whether the relay could be changed from a high-impedance to a low-impedance relay to accommodate the desired ratio difference.

The Birchwood substation project was wholly owned by Alliant Energy. Changing from a high-impedance relay to a low-impedance relay to accommodate the ratio difference was an option not pursued. Ultimately, enforcing one standard distribution bus protection design is favored over enforcing standards with less variation in CT ratios in our supplied equipment. The desire to retain the standard high-impedance differential protection while using mismatched CTs opens the possibilities for sequencing improvements or responding to equipment failure and reduces variations of standardized equipment for these projects.

III. BUS DIFFERENTIAL PROTECTION REQUIREMENTS

Bus protection must provide fast operation for all bus faults and high security for external faults. Differential protection operates on the sum of the currents entering the bus, also called the differential current. The relay trips the bus when it detects excessive differential current. Differential protection schemes must mitigate the risk of misoperation for external faults. Mainly, the concern is false differential current caused by CT saturation. Buses are typically protected by either high-impedance differential relays or percentage-restrained (low-impedance) differential relays. Table I summarizes Table 1 from [1] relative to Alliant Energy's application for these two alternative bus protection principles.

TABLE I
BUS PROTECTION SELECTION TABLE

Consideration	Application	High-Impedance	Percentage-Restrained
Bus arrangement	Fixed	R	R
Low short-circuit level	NA	R	
Dedicated CTs available	Yes	R	R
CTs with mismatched ratios	Yes	N[1]	R
CTs with low accuracy class	NA	R[2]	R[3]

R = Recommended, N = Not recommended, NA = Not applicable

Note 1: There are techniques for dealing with mismatched CTs in a high-impedance bus differential application, but other relay systems can more easily deal with this problem.

Note 2: Assuming that the burden voltage rating is great enough to satisfy both security and dependability criteria.

Note 3: Assuming that the differential relay has functionality to put it in high security mode if CT saturation is detected or the fault has been determined to be external.

The information in this table highlights that [1] does not recommend high-impedance bus differential protection for applications with mismatched CTs. As Note 1 (Note 2 in [1])

for the table says, "…other relay systems can more easily deal with this problem." As discussed in the previous section, Alliant Energy has many reasons beyond just protection guidance to want to standardize on using high-impedance differential protection. Therefore, Alliant Energy decided to further investigate the techniques for dealing with mismatched CTs in a high-impedance differential protection scheme.

IV. CT APPLICATION CONSIDERATIONS FOR HIGH-IMPEDANCE DIFFERENTIAL PROTECTION

A. High-Impedance Differential Scheme Operation

To determine the CT requirements for a high-impedance differential scheme, it is necessary to understand its basic operation. The high-impedance differential scheme introduces a high-value stabilizing resistor (e.g., 2,000 ohms) in the differential branch of the circuit to reduce the differential current resulting from heavy CT saturation during external faults. Fig. 1 shows the relay connection for a typical application [3].
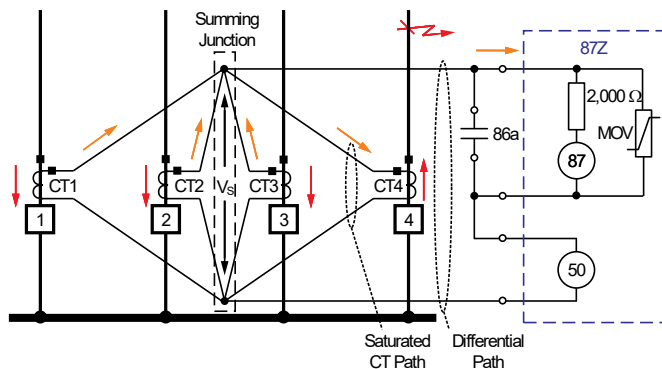

Fig. 1.   Bus high-impedance differential protection scheme

A low-impedance overcurrent element (87) senses the current flowing through the stabilizing resistor. The current through the 87 element is proportional to the voltage V_S across the relay.

If CT saturation occurs for an external fault, the high impedance of the relay will force the current through the lower impedance path of the saturated CT. Very little current will then flow through the 87 element. For this small current, the relay will not operate.

For internal faults, the significant current flowing through the 87 element causes the relay to operate; the resulting high voltage across the relay typically drives all CTs into saturation.

For internal faults, the voltage produced by the CTs to drive the differential current through the stabilizing resistor can reach dangerous levels. The relay circuit includes a voltage limiter, such as a metal-oxide varistor (MOV), to limit this voltage to a safe level (Fig. 1). The auxiliary lockout relay contact (86a) shown in this figure is typically applied to limit the energy absorbed by the stabilizing resistor and MOV by shunting current away from these components when the relay trips.

This scheme requires dedicated CTs on all bus terminals. Sometimes the CTs are paralleled in a summing junction box (Fig. 1), and then a single pair of leads is brought into the substation control enclosure. A good practice is to locate the junction box at a point close to and equidistant from each CT.

Reference [4] provides application guidelines for high-impedance bus differential relays. The following subsections summarize these guidelines. In the following discussion, we emphasize the premise that when protection engineers set a relay, they must consider both a security limit and a dependability limit to every setting [5].

B. Security Considerations

For an external fault (a fault occurring out of the differential protection zone), the currents sum to zero when the CTs perform adequately. To determine the security limit, we make an extreme simplifying assumption. If a CT saturates, the secondary of the CT becomes completely decoupled from the primary and the impedance in that branch of the differential circuit reduces to the burden resistance of the CT windings and leads from the CT to the differential summing junction. This is an unrealistic assumption, but it provides a conservative boundary condition. If the saturated CT contributes any secondary voltage at all, it improves the margin over the assumption of zero magnetic coupling.

The saturated CT path is in parallel with the differential path of the circuit and acts as a shunt for differential current. The stabilizing resistance is several orders of magnitude greater than the saturated CT shunt path so that near-zero current will flow to the relay. The lead resistance from the differential summing junction to the relay can be ignored because it is in series with the much larger relay burden (2,000 ohms in this example).

The relay minimum voltage setting (security limit) is set based on the boundary assumption that one of the CTs saturates completely for the external fault and produces no secondary voltage. The minimum secure voltage setting is based on the largest voltage drop from the summing junction to the saturated CT. To illustrate the concept, the four-CT bus shown in Fig. 1 is simplified to a two-CT circuit in Fig. 2 and Fig. 3. CT1, CT2, and CT3 are combined into a single current source connected to the summing junction, and CT4 on the faulted circuit is kept in the simplified circuit. For illustration purposes, we assume that R_{CT} and R_{LEAD} have the same values in all four branches. The composite of CT1, CT2, and CT3 is the parallel combination of these impedances so that branch has one-third the resistance as the CT4 branch. Because the fault is external on Circuit 4, the combined current of CT1, CT2, and CT3 is equal to the current in the CT4 branch.

In both examples, we assume that the combined CTs perform perfectly. Fig. 2 shows that the summing junction voltage, V_{JCT}, is zero if CT4 performs perfectly.

Fig. 3 shows the summing junction voltage when CT4 saturates completely. This voltage is used to determine the security limit of the relay. We must set the relay pickup voltage higher than this value with margin. Fig. 3 also shows that if CT4 does not saturate completely (provides a voltage greater than zero), the voltage profile line would move down, improving the margin of the setting based on the boundary assumption.
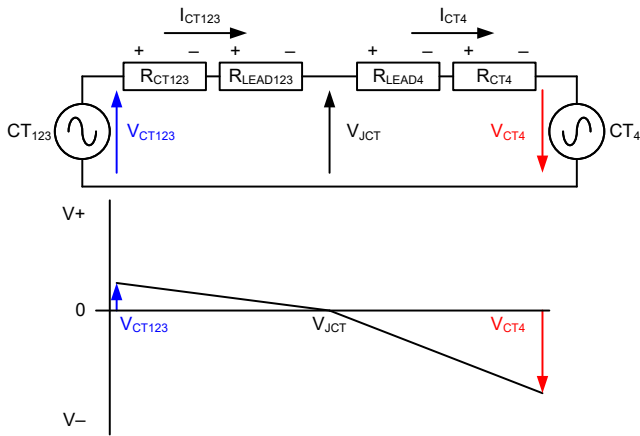
Fig. 2.   Summing junction voltage when all CTs perform perfectly (no saturation)
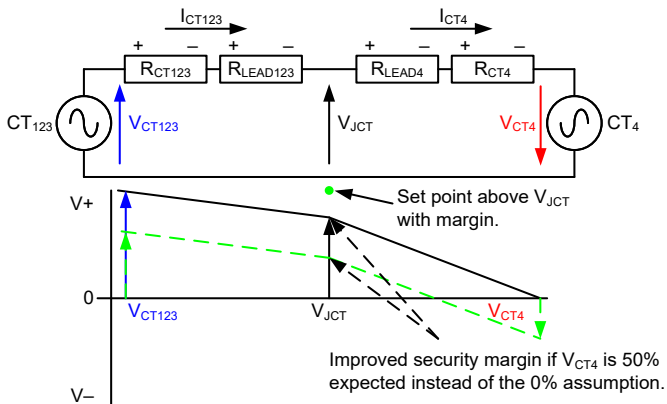

Fig. 3.   Summing junction voltage when the faulted branch CT saturates completely (produces zero volts)

This protection principle is popular because we can make an unrealistic simplifying assumption that a saturated CT produces no voltage contribution to the circuit. The relay is very easy to set and provides very high security, dependability, and sensitivity.

Rigorous analysis would include calculating the burden impedance times the maximum external fault current for each terminal of the bus zone. Typically, a conservative approach uses the internal fault current (which includes contributions from every terminal) and the largest CT lead length and CT internal resistance.

Security is of minor concern for through faults with this scheme when set with the conservative simplifying assumptions as described. However, because of its high sensitivity, differential current caused by some in-zone circuits can result in undesired operation.

One security issue involves in-zone surge arresters that can cause a trip under normal operation when they successfully conduct to clamp a surge [6]. Another issue involves faults on the secondary of in-zone station service transformers or voltage transformers [1]. Normally, it is not desired for the bus differential protection to trip before transformer primary or secondary fuses clear the secondary fault. In applications where transformer bushing CTs are used (creating the zone boundary), the transformer surge arresters can be in the protection zone and

the presence of the arresters should be considered in the relay setting.

C. Dependability Considerations

For an internal fault, the CTs must drive their ratio current through the high burden represented by the stabilizing resistor. This condition results in all CTs saturating. The voltage in the circuit is impressed across the secondary of all CTs. All CTs are affected because CT saturation is a function of the time integral of the voltage at the CT terminals (the volt-time area concept) [7].

Consider a 10 kA internal fault. If we use a 2000:5 CT ratio, the secondary current through the differential path would be 25 A secondary. The voltage across the relay would be 50,000 V root-mean-square (rms) if the CTs do not saturate. Even with the expected saturation, the voltage developed would be significant. The relay MOV (Fig. 1) limits the voltage in the circuit to a level (under 2,000 V_{Peak}) that will not damage the insulation of the CT, CT cables, terminal blocks, test switches, relay, etc. Thus, for an internal fault, the voltage in the circuit goes through the following stages:

- The voltage rapidly rises to the MOV conduction level. While the curve shape during this rise is sinusoidal, its steepness on the way to 50 kV makes it appear vertical.
- The MOV clamps the voltage by conducting the fault current until a CT in the circuit saturates.
- The CTs all have nearly the same voltage impressed upon them. If they all have the same C rating (or effective rating in the case of a tapped CT), they will all saturate at nearly the same instant. If a CT has a lower C rating, it will saturate when its volt-time area capability is exceeded.
- Once any CT saturates, the voltage in the circuit drops to nearly zero because the saturated CT effectively short-circuits the stabilizing resistor burden and none of the saturated CTs are driving current into the secondary circuit. Nonsaturated CTs are driving current into the saturated CT secondaries that are shunting the relay.
- Once the primary fault current crosses zero, the CTs come out of saturation and the process begins again in the opposite polarity.
- The resultant voltage signal that the relay measures is a series of positive and negative rectangular pulses with the magnitude determined by the MOV voltage and the width determined by the CT volt-time area capability, which is determined by the C rating. See Fig. 4 for an example. This is a reproduction of Fig. 36 from [4].
- A digital relay may sample this signal (e.g., at 16 samples per cycle) and estimate the magnitude using a half-cycle cosine filter [8].

From the previous analysis, we conclude that the signal measured by the relay for an internal fault is not a function of the fault current level. It is a function of the C rating of the poorest CT in the circuit. This conclusion is confirmed by the

superimposed waveforms shown in Fig. 4 of 20 kA, 40 kA, and 60 kA tests. The voltage measured by the relay is the same for all three tests. The dc offset of the primary fault current can have an effect because the zero crossings will not be evenly spaced a half cycle apart if the primary current is offset. The result is that the half-cycle cosine filter can have two pulses in its filter window and measure a larger voltage than for a symmetrical waveform where the pulses are evenly spaced.

Fig. 5 shows the output of the half-cycle cosine filter with the narrow voltage pulses that the relay samples for an internal fault. The figure shows one of the recordings from the test of a 2000:5, C400 CT discussed in Section VIII. The waveform labeled 87A corresponds to the raw samples. The waveform labeled 87FILTERED is the output of the cosine filter. The waveform labeled 87A.Mag is the magnitude of the estimated phasor. The waveform labeled 87PU is the 200 V element pickup setting. The bottom digital waveform shows the 87 element assertion in less than one cycle.
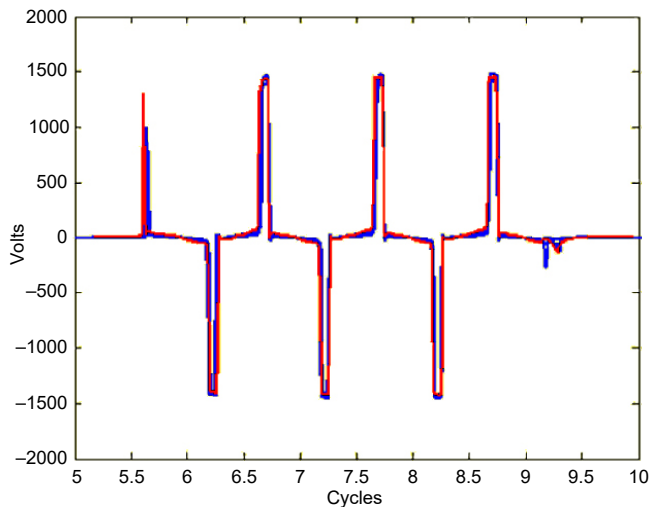

Fig. 4.   Superimposed relay voltages from 20 kA, 40 kA, and 60 kA internal fault tests with C200, 1200:5 CTs
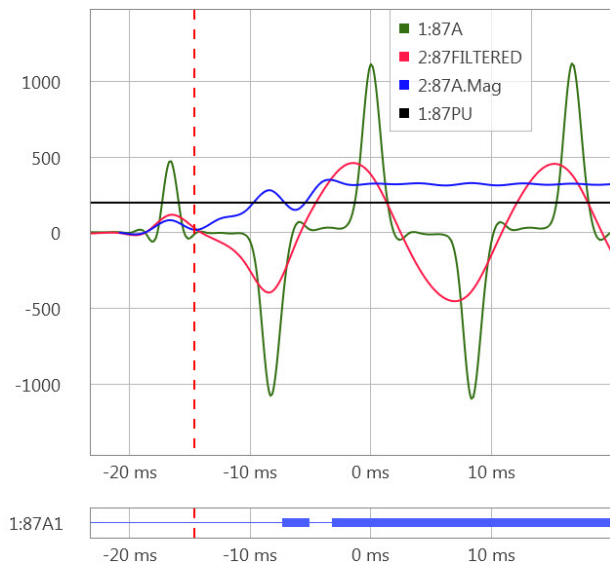

Fig. 5.   Response of the half-cycle cosine filter to pulses

High-current simulation and testing reported in [4] showed that, for internal faults, a C100 CT produces pulses too short to measure reliably at 16 samples per cycle. The C200 CT pulses provide a relay measurement of around 400 V; the C400 CT pulses provide a relay measurement of around 800 V.

From these results, we can conclude that, as long as the setting is greater than or equal to 200 V [9], the CTs are rated greater than or equal to C200, and internal fault currents are greater than the minimum required to create more than 200 V at the relay, there are no dependability concerns with regard to choosing the CT ratios.

A recommended setting greater than 200 V is based on balancing dependability versus security. The high-impedance differential principle inherently provides high sensitivity. Hence, based on using 50% margin on the voltage level measured by the relay for the minimum allowable accuracy class rating of C200, a minimum voltage pickup setting of 200 V is reasonable. Setting the relay lower to obtain adequate sensitivity is seldom required.

D.   Sensitivity Considerations

For very low levels of internal fault current (e.g., impedance-grounded systems), we must perform a different analysis to verify scheme sensitivity. When the current flowing for an internal fault is not high enough to cause the MOV to conduct, we have to look at the distribution of currents in every branch of the circuit for this low-grade internal fault. Recall that the voltage in the circuit is impressed upon every CT in the circuit. Thus, we have to account for the excitation current drawn by all paralleled CTs to determine the minimum internal fault that will cause the relay to operate. Reference [2] provides further discussion on determining minimum scheme sensitivity.

E.   Ratio Selection Considerations

The Alliant Energy standard requires multiratio CTs rated C800 and 2000:5 in the transmission system (e.g., Green Street substation application), and C400, 2000:5 CTs in the distribution system (e.g., Birchwood substation application). In an existing substation with 1200:5 CTs, an allowed deviation from the standard could be to purchase circuit breakers with 1200:5 multiratio CTs to match the existing CTs. However, purchasing nonstandard circuit breakers is discouraged.

Because the CTs are physically paralleled before being connected to the high-impedance differential relay, the ratios of all CTs must match. The high-impedance differential relay can typically withstand a steady-state overvoltage for only a very short time before the I^2R loss from the stabilizing resistor damages the relay.

The CT ratio should be chosen not to limit the loadability of the primary equipment, if possible. The CTs are specified with a thermal rating factor of two. Thus, the secondary windings are capable of continuously carrying 10 A. The primary rating of the CT would be sized to ensure that the current in the secondary windings of the CT do not exceed the secondary rating times the thermal rating factor.

V. Current Transformer Design and Construction

The requirement for C class CTs is to have ratio errors of less than 3% at rated current and 10% at 20 times rated current. Hence, the CT is designed with an adequate core cross section so that the magnetizing current is less than 10 A (10% of 20 times the 5 A rated secondary current) at the voltage across the magnetizing impedance, including the voltage drop of the CT winding, for 20 times rated current and a burden equal to the standard burden.

For high-ratio CTs it is not possible to perform the test at 20 times rated current accurately. However, by calculation it can be shown that if the composite error of the CT is less than 10%, then the CT will be in class. The CT composite error is the error in the secondary current as a percentage of the nominal secondary current [10].

The winding is wound by distributing the turns evenly to reduce the effect of flux leakage on the accuracy. Careful winding of the turns on the core reduces the leakage flux to an extent that leakage reactance can be neglected for the CT. C class CTs must have fully distributed windings as shown in Fig. 6. This is the reason that we only use the winding resistance in our calculations for this type of CT. When the CT is a multiratio CT with taps brought out, the windings between each tap must also be fully distributed.

Paper and polyester film, often used as insulation between the layers, is tested with induced voltage and open-circuit tests.
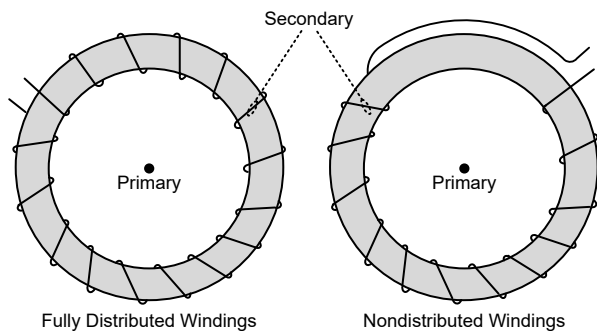

Fig. 6.   Distributed windings versus nondistributed windings on a toroidal iron core

VI. Application With Mismatched CTs

A. Reduced Accuracy Class

Because the high-impedance differential scheme requires matched ratio CTs, using mismatched-ratio CTs implies using taps of the higher-ratio CTs to match the ratios of the lower-ratio CTs. There are different ways of connecting mismatched-ratio CTs in a high-impedance differential scheme [11] [12]. Fig. 7 shows the connection where we simply connect the tap with the matching ratio of the mismatched CT to the summing junction.
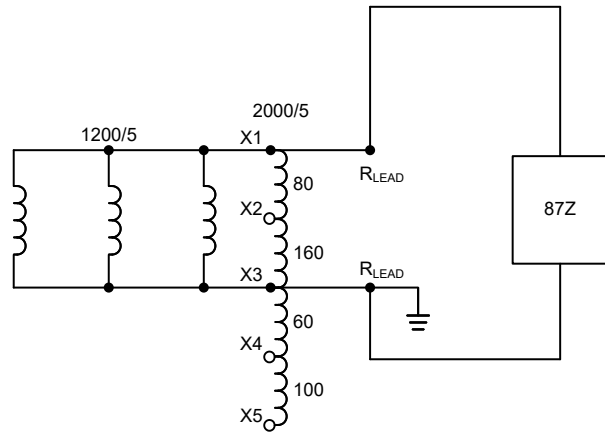

Fig. 7.   Connection of mismatched CT using the taps with a matching ratio to the other CTs [12]

From an accuracy class point of view, tapping a 400-turn C800 CT at 240 turns makes it equivalent to a C480 CT [(240/400) • 800 V = 480 V]. This equivalent C480 CT will be the limiting CT that defines the width of the voltage pulse for internal faults and thus the voltage measured by the relay. In the discussion in Section IV, Subsection A, we concluded that a C480 CT should provide voltage pulses of adequate width to the relay, so derating the CT by tapping it is not a concern in this application.

B. Induced High Voltage Across Full Winding and Leads

A CT behaves like any other transformer. In a protection class CT with distributed windings and low leakage flux, the volts per turn on the magnetic circuit are the same for the whole winding. For this reason, tapping the CT at less than the full ratio produces a proportionally higher voltage on the full winding terminal of the CT.

For example, let us consider a 400-turn multiratio CT tapped at 240 turns (Fig. 8). The CT develops voltage and drives the current in the loop. However, before the differential scheme CTs saturate for an internal fault, the current must flow all the way to the MOV in the relay panel where the voltage is clamped. Thus, there can be significant voltage drop between the CT and the MOV. For simplicity, we will ignore this voltage drop along the circuit. The voltage drop would increase the voltage over the value obtained in this simple analysis, as seen in Section VIII, which discusses the high-current laboratory tests. Therefore, we advise to use adequate margins in their analysis.

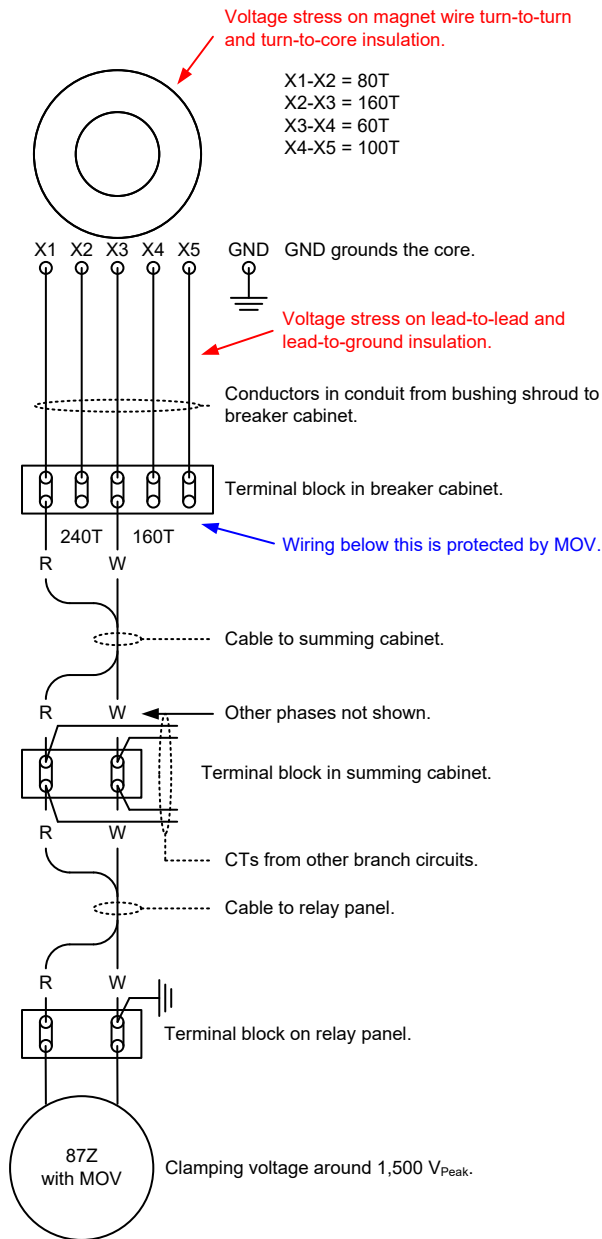Turns X1-X2, X2-X3, X3-X4, and X4-X5 are fully distributed on the core to achieve low leakage reactance.

Voltage stress on magnet wire turn-to-turn and turn-to-core insulation.

X1-X2 = 80T
X2-X3 = 160T
X3-X4 = 60T
X4-X5 = 100T

X1 X2 X3 X4 X5   GND   GND grounds the core.

Voltage stress on lead-to-lead and lead-to-ground insulation.

Conductors in conduit from bushing shroud to breaker cabinet.

Terminal block in breaker cabinet.

240T   160T

Wiring below this is protected by MOV.

R   W

Cable to summing cabinet.

R   W   Other phases not shown.

Terminal block in summing cabinet.

R   W

CTs from other branch circuits.

Cable to relay panel.

R   W

Terminal block on relay panel.

87Z with MOV   Clamping voltage around 1,500 V_{Peak}.

Fig. 8.   Wiring diagram of a 400-turn CT, tapped at 240 turns

During an internal fault, the voltage at which the MOV clamps (around 1,500 V_{Peak} as shown in Fig. 4), will be impressed between the X1 and X3 terminals of the CT. Note the relay manual specifies the MOV clamping voltage is 2,000 V, which is from the MOV supplier specifications and is for worst-case laboratory conditions. The numbers used in this paper are based upon actual high-current laboratory test data for the relay as applied [4].

The volts per turn will be:

$$1,500 \text{ V}/240 \text{ turns} = 6.25 \text{ V/turn}$$

In this case, the voltage between X1 and X5 will be approximately:

$$400 \text{ turns} \cdot 6.25 \text{ V/turn} = 2,500 \text{ V}_{Peak}$$

In the Green Street and Birchwood substation applications, we are fortunate that the X3 terminal is connected to the common neutral of the circuit and grounded. In this case, the voltage from X1 to ground will be:

$$240 \text{ turns} \cdot 6.25 \text{ V/turn} = 1,500 \text{ V}_{Peak}$$

The voltage from X5 to ground will be:

$$160 \text{ turns} \cdot 6.25 \text{ V/turn} = 1,000 \text{ V}_{Peak}$$

In other applications, the grounded terminal of the tapped CT may not be in the middle of the winding and the insulation to ground may be overstressed. The example illustrated in the Appendix is one such application. In the high-current laboratory testing discussed in Section VIII, the test configuration deviated from the conditions described here in that the X1 terminal was grounded for that test.

However, inside the CT or in the lead wiring between the CT and the terminal block in the circuit breaker cabinet, the turn-to-turn or tap-to-tap lead insulation can be stressed by the higher voltage and result in shorted turns. A voltage of 2,500 V_{Peak} could cause the turn-to-turn insulation inside the CT to fail if windings connected to the X1 terminal are in close proximity to a winding that is connected to the X5 terminal. This condition is likely given the distributed way the conductors are wound on the core. As mentioned in Section V, paper and polyester film are often used between layers to improve the ability of the CT to withstand an induced voltage test.

Similarly, this high voltage could cause the lead-to-lead insulation of the wiring between the CT and the terminal block in the control cabinet to fail if the lead on the X1 terminal is in close proximity to the lead on the X5 terminal of the CT.

If turns or leads are short-circuited, damage may occur and the CT and/or wiring may need to be repaired or replaced. However, the main concern is that, if turns are short-circuited in the secondary winding of the CT, the voltage in the differential circuit will be depressed and the relay may fail to operate, resulting in a dependability failure.

The Appendix provides a similar analysis for the case of mixing 600:5 CTs and tapped 1200:5 CTs in a high-impedance differential scheme.

C.   CT Insulation Evaluation

To fully assess the risk of turn-to-turn or lead-to-lead insulation failure, additional information on the voltage withstand capability of the 600 V class insulation used in these CTs and wiring is required. IEEE Standard C57.13-2016, IEEE Standard Requirements for Instrument Transformers, includes several clauses that describe the insulation requirements and testing for CTs [10]:

- Clause 4.5 Basic impulse insulation levels, dielectric tests, and outdoor instrument transformer creepage distance and wet test.
- Clause 4.8 Classification of tests.
- Clause 6.7 Secondary winding-induced voltages.
- Clause 8.1 Ratio and phase angle measurement and calculations.

- Clause 8.2 Impedance, excitation, and composite error measurements.
- Clause 12.3, Inter-turn overvoltage test.

Section 4.8 of [10] provides a table of routine and type tests with cross references to the appropriate clauses. Routine tests are typically run on all production units to ensure that they were manufactured properly. Type tests are only run on prototype units to verify the design.

The high-voltage tests described in Clause 4.5, Clause 6.7, and Clause 12.3 are briefly described in the following subsections. We also discuss how each test relates to the CT insulation stress resulting from using mismatched-ratio CTs.

1) Clause 4.5 Routine Applied Voltage Test

This applied voltage test is a routine test required to determine the condition of the insulation between the windings. In this test, the whole winding voltage is raised to a predefined value depending on the rated voltage of the CT with a minimum of 2.5 kV for 60 seconds. This test checks the insulation of the windings to ground but does not provide any information on the condition of the insulation between the turns.

2) Clause 6.7 Routine Secondary Winding-Induced Voltage Test

The induced voltage test is a routine test to check the condition of the insulation between the turns and layers. Protection CTs are tested with a voltage equal to twice the CT rated secondary terminal voltage with a minimum of 200 V. Clause 6.7.1 states that the CT secondary winding is capable of withstanding an open-circuit condition up to its rating factor, or 3,500 V_{Peak}, whichever occurs first, for one minute at rated frequency.

This clause emphasizes that CTs should never be operated open-circuited. For open-circuit voltages higher than 3,500 V_{Peak}, it is recommended that the user connect a voltage limiting device across the windings. It is expected that a 2000:5, C800 CT challenged with a primary current of 4,000 A (2,000 A times a thermal rating factor of 2) will generate a voltage higher than 3,500 V_{Peak} under open-circuit conditions. Because CT application in a high-impedance differential scheme closely resembles the conditions for this open-circuit test, this requirement is of particular interest. The routine induced voltage test value for the C800 class CT is 1,600 V rms. Converting this value to peak voltage results in 1,600 V (1.414) = 2,263 V_{Peak}. This value compares favorably to the 1,500 V_{Peak} MOV level with a margin of 1.5.

While this test appears to be adequate for validating the insulation under the expected fault conditions, the waveshape of the test voltage signals differ from the expected conditions during an internal fault. The secondary voltage during the open-circuit test may include a fundamental component and some harmonics, whereas the voltage clamped by the MOV during a high-current internal fault has a much faster rise time. The effect of a fast rise-time signal on the turn-to-turn voltage stress may be higher than that caused by the induced voltage sinusoidal test waveform. This difference in voltage waveform shape between routine and type tests versus actual application

conditions is a major factor in deciding to set up a test with realistic conditions in a high-current laboratory.

3) Clause 12.3 Inter-Turn Overvoltage Test

The inter-turn overvoltage test is a type test, not a routine test. This test is similar to the open-circuit test described in Clause 6.7.1. The voltage of this test is limited to 3,500 V_{Peak}. The standard cautions that this test is not to be used to verify the suitability of a CT to be operated with the secondary open-circuited. It again states that CTs should never be operated open-circuited because of the potentially dangerous overvoltage and overheating that can occur.

The test level of 3,500 V_{Peak} also compares favorably with the expected voltage of 2,500 V_{Peak} between the X1 and X5 terminals calculated in Section VI, Subsection B (neglecting voltage drops in the circuit between the CT and the MOV).

D. CT Lead Evaluation

Fully assessing the risk of lead-to-lead insulation failure requires additional information on the voltage withstand capability of the 600 V class insulation of the conductor used in the wiring. During the Green Street substation project, a conference call with the circuit breaker supplier and the CT supplier revealed that the circuit breaker manufacturer applies a 2,500 Vdc high-potential test to the CT and wiring to ground as a normal factory test. The Birchwood substation circuit breaker supplier performs a similar test. As previously discussed, the voltage to ground should be within the withstand capability of the insulation. The 2,500 Vdc high-potential test compares favorably to the 1,500 V_{Peak} expected. Because a lead-to-lead fault would have two layers of insulation between the leads, it can be safely assumed that the insulation should be able to withstand the expected 2,500 V_{Peak} between the X1 and X5 leads as well.

VII. MITIGATION OF INSULATION FAILURE RISKS

Options to mitigate insulation failure risks include:

- Apply a separate MOV or silicon carbide nonlinear resistor across the full winding of the tapped CT.
- Use the tapped CT as an autotransformer to match the ratios [12].
- Use an auxiliary CT as an autotransformer to match the ratios [12].
- Change the relay model to one that has an MOV voltage clamping specification of 1,500 V_{Peak} instead of 2,000 V_{Peak}, which may provide additional margin from failure.
- Change the relay to a percentage-restrained bus differential relay.

High voltage cannot be mitigated by grounding the X5 terminal because that would short-circuit the turns from X3 to X5. The induced circulating current would affect the CT functionality. The volts per turn of a transformer must be the same for the whole winding, so grounding two terminals of the CT results in impressing zero volts across every turn of the CT. The CT would not supply any current to the X1 to X3 turns. Another way of stating this is that the ampere-turns between the

primary and secondary windings of the transformer must balance as well. If you short-circuit two terminals of the secondary, most of the current will flow in the shorted turns to balance the single turn primary current and no current will flow in the turns connected to the burden loop.

The options listed at the beginning of this section are summarized in the following subsections. Because this paper focuses on assessing the risk of insulation failure for the simple option of tapping the CT with the higher ratio, more in depth discussion of these options is beyond the scope of this paper. However, it should be noted that the first three options require difficult analyses of current distributions and voltage drops in the CT circuit [11]. This setting calculation complexity detracts from one of the main reasons for choosing this type of protection scheme.

A. External Nonlinear Resistor

In this solution, an external MOV or silicon carbide nonlinear resistor located in the circuit breaker cabinet is connected across the full winding of the tapped CT. This device will limit the voltage across the full winding of the tapped CT and also limit the summing junction voltage by approximately the ratio of the tapped to full ratio of the tapped CT.

The relay MOV will likely not conduct, and the relay overcurrent elements will not be effective. The high current that flows through the external voltage limiting device before the CTs saturate and short-circuit the stabilizing resistor will flow from the summing junction to the circuit breaker cabinet with the tapped CT and external nonlinear resistor.

B. Using the Tapped CT as an Autotransformer

This method requires that all 240-turn CTs in the bus differential circuit be wired to the circuit breaker cabinet with the tapped CT. This application can complicate the wiring of the bus differential circuit. In addition, this CT must remain in service at all times for the bus protection scheme to operate—including when the circuit breaker is out of service. Alliant Energy deemed this issue a deal breaker.

C. Using an Auxiliary CT as an Autotransformer

This method requires an auxiliary CT to be installed in the bus differential summing junction cabinet. The auxiliary CT must be rated equivalent to at least a C200 CT. It is difficult to find auxiliary CTs with an adequate rating to allow the relay to receive pulses of adequate width to operate for an internal fault.

Further, it is recommended to use only toroidal CTs with fully distributed windings for a high-impedance differential application [13]. Most standard auxiliary CTs are T class. It is possible to use a toroidal bushing type CT of adequate C class as an auxiliary CT to meet this requirement. The fact that the primary winding is open-circuited (no conductor passes through the window of the CT core) is of no consequence. The main drawback of this option is the difficulty of accommodating the large size of three such CTs in the summing junction box.

D. Change the High-Impedance Differential Relay Model

Selecting a high-impedance differential relay with a lower rated MOV can provide additional insulation margin, for example, using a relay with a clamping voltage rating of 1,500 V_{Peak} instead of 2,000 V_{Peak}. The actual clamping voltage of this optional MOV is around 1,000 V_{Peak} as observed in the testing described in Section VIII.

E. Apply Percentage-Restrained Differential Relays

This option was discussed and discarded in Section II and Section III.

VIII. CT TESTING AND ANALYSIS

Given the alternative options listed in Section VII, Alliant Energy wanted to pursue assessing the risk of insulation damage, flashover, and possible failure to trip for the option of simply tapping the higher-ratio CT at the matching tap as shown in Fig. 7. This option has the following benefits:

- Avoids the need to purchase circuit breakers with nonstandard CTs on projects with existing circuit breakers with lower-ratio CTs.
- Avoids the more complex wiring and operational flexibility issues associated with using the higher-ratio circuit breaker CT as an autotransformer.
- Avoids the more complex wiring and costs associated with using an auxiliary CT as an autotransformer.
- Avoids complex setting calculations associated with the special CT connections.

To this end, they consulted the CT manufacturers for the two projects. Neither manufacturer would certify that their CTs could withstand the voltages expected in the application without performing tests under realistic conditions. One of the CT manufacturers provided a proposal to test CTs in their high-current laboratory to help assess the risk of this simpler option.

A. Test Setup

A test procedure was developed in a collaborative effort between individuals from the utility, the relay manufacturer, and the CT manufacturer. Alliant Energy had three new CTs manufactured in the same configuration as specified in the Alliant Energy distribution circuit breaker standards for testing. They purchased a new high-impedance differential relay to use during the tests. The relay selected included the optional MOVs with 1,500 V_{Peak} clamping rating to reduce the overvoltage stress and make a successful test more likely.

Fig. 9 shows the test setup. The following list highlights significant details of the configuration:

- The CT on the left was used to monitor the current in the primary bus. The CT was connected to a harmonic power analyzer (labeled S-703 in the figure) to meter the current. It was also connected to the otherwise unused IC input on the high-impedance differential relay to record primary current oscillography.
- The CT on the right is the unit under test (UUT).

- Precision capacitor dividers with 100:1 ratio were connected to the X3 and X5 terminals of the CT to measure the voltages using a high-speed digital recording oscilloscope.
- Fifteen feet of 600 V conductor was wired from each terminal of the CT to a terminal block of the same type as used by the circuit breaker manufacturer to simulate the CT-to-circuit-breaker terminal cabinet wiring.
- Fifty feet of 600 V insulation wiring was connected between the terminal block and the relay to simulate the cable between the circuit breaker and the relay.
- The A-phase inputs to the relay were wired to the UUT CT circuit as they would be in a real installation, including a lockout relay (labeled 86 in the figure) to short-circuit the high-impedance input to the high-impedance differential relay.
- The relay was configured to trip the lockout relay with a 12-cycle delay. The 12-cycle delay ensured that the CT and wiring insulation was stressed for a minimum period of time during each high-current shot while limiting the heat buildup in the relay burden resistors and MOVs due to repeated test shots.
- The X1 terminal of the test circuit was grounded as opposed to the X3 terminal, as would be the case in the actual application. This configuration was necessary to use the precision capacitor divider devices. Thus, the secondary winding and lead insulation to ground was more highly stressed than would be the case in the actual application.

B. Test Procedure

The test procedure used for each of the three UUT CTs was as follows:

1. The UUT CTs were tested according to normal production tests.
2. The secondary winding of the UUT CT was short-circuited via an ammeter, and the secondary current was verified relative to the primary current using the standard CT.
3. The secondary circuit of the UUT CT was open-circuited with only the precision capacitor dividers connected to monitor the UUT CT terminal voltages, and primary current was applied.
4. The secondary circuit of each UUT CT in turn was connected to the high-impedance differential relay as shown in Fig. 9, and primary current was applied.
5. The high-current shots were repeated a minimum of five times on each UUT CT.
6. Normal production tests were repeated on each UUT CT to determine if any damage had occurred.

Fig. 10 shows the voltages recorded for Step 3, the open-circuit test. The primary current for this test was 4,159 A, which is slightly higher than the specified current (2,000 A times a thermal rating factor of 2) in Clause 12.3 of [10]. It can be seen that the voltage across the full winding of the UUT CT is around 3,800 V_{Peak}, which is greater than the 3,500 V_{Peak} limit specified for this test.
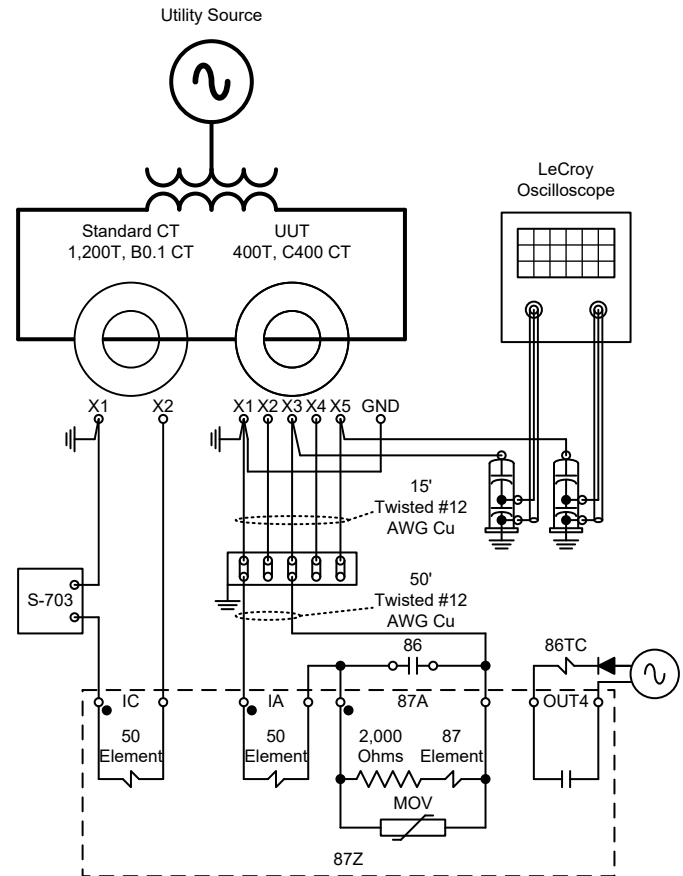

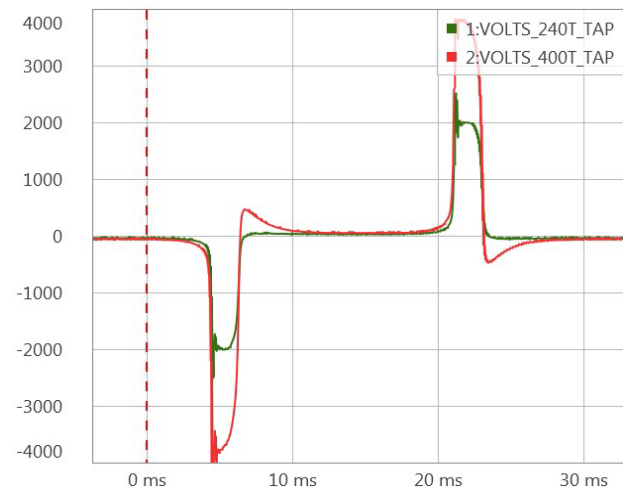Fig. 9.   High-current laboratory test circuit

Fig. 10.   CT voltage waveforms for the open-circuit test

We observed that the open-circuit impedance reflected into the primary circuit by the CT reduced the magnitude of the primary current for a given tap setting on the source transformers. The nonlinear nature of the impedance, as reflected through the CT core, distorted the primary current waveform.

C. Analysis of High-Current Tests With the High-Impedance Differential Relay Connected

Fig. 11 shows a one-cycle recording for one of the high-current shots with the high-impedance differential relay connected to the CT. We offer the following observations:

- The MOV clamping rating is 1,500 V_{Peak}, but the observed clamping voltage at the X3 terminal is actually 1,000 V_{Peak}. This result is like the result shown in Fig. 4, in which the MOVs with a specification of 2,000 V_{peak} actually clamp at 1,500 V_{peak}.

- Given the 240:400 ratio of the X3 to X5 terminals, we would expect that, with the X3 terminal at 1,000 V_{Peak}, the X5 terminal voltage would be 1,667 V_{Peak}. However, we observed that this voltage reached a much higher value of around 2,000 V_{Peak}.

- The voltage at the floating X5 tap displays transients and, during the pulse when the MOV is conducting, it displays an exponential discharge waveform.
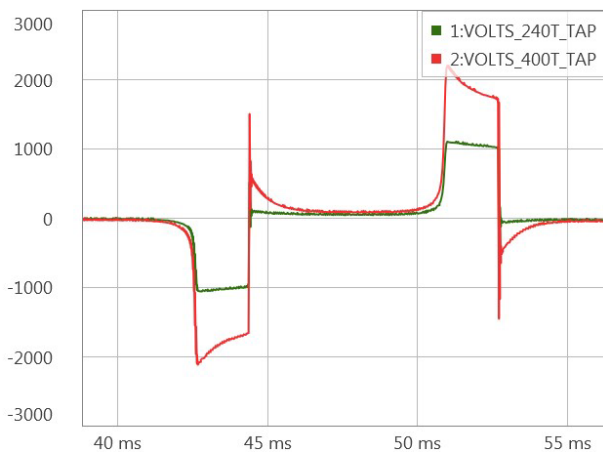

Fig. 11.   CT voltage waveforms for one of the high-current test shots

The top half of Fig. 12 zooms in on the first negative pulse of the Fig. 11 voltage waveforms. The bottom half of Fig. 12 shows the actual ratio of X5 to X3 voltages compared to the expected ratio of X5 to X3 voltages. We notice that at the start of the pulse the ratio is greater than 2 compared to the expected value of 1.67. By the end of the pulse, the ratio has returned to nearly the expected 1.67. The following subsections provide explanations of these differences.
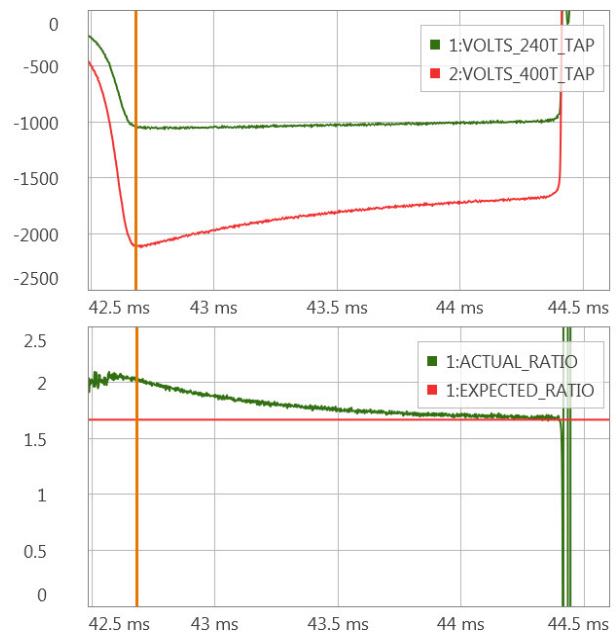

Fig. 12.   Zoom in of one negative pulse of the Fig. 11 voltage waveforms (top) and actual and expected ratios of X5 to X3 voltages (bottom)

1) Difference in Actual MOV Clamping Voltage Versus Specification

We consulted with the manufacturer of the MOVs and discovered that the specifications sheet provides for a worst-case value under specific, very high-current laboratory conditions. The observed clamping voltage during the test is more realistic of the conditions that would be encountered in this application. Thus, the MOVs provide greater protection from overvoltage than the specifications would lead you to believe.

2) Difference in Observed Ratio of Voltages

The primary current in the CT generates the voltage to drive the ratio current in the burden loop. The MOV clamps the voltage at the X3 terminal of the CT. However, the voltage induced in the turns between X1 and X3 behind the impedance must overcome the voltage drop caused by the resistance of the turns between X1 and X3 and the secondary ratio current. Fig. 13 illustrates the equivalent circuit representing the stage when the MOV is not conducting. The highest voltage measured at X5 at the beginning of the pulse in Fig. 12 is 2016 V. The voltage at X3 at that instance is 1,052 V. Assuming that the current in the X5 terminal is near zero, the voltage drop across R_{X3-X5} is near zero. Thus, $V_{X3-X5} = 964$ V. From that, we conclude:

$$V_{X1\text{-}X3} = \left(\frac{964\,\text{V}}{(400-240)\,\text{turns}} \right) \cdot 240\,\text{turns} = 1,446\,\text{V}$$

The voltage drop across R_{X1-X3} is 1,446 – 1,052 = 394 V. Thus, the actual voltage across the unconnected turns caused by the autotransformer effect is higher than what we would have predicted by repeating the simple analysis discussed in Section VI, Subsection B, using a clamping voltage of 1,000 V instead of 1,500 V.
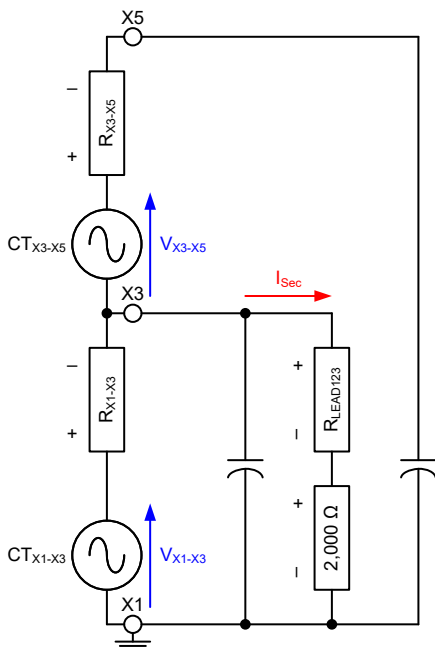

Fig. 13.   Equivalent circuit for the stage when the MOV is not conducting

3)   Exponential Decay of X5 Voltage

To understand this observation, it is necessary to understand the three stages that this circuit goes through during each half cycle. Fig. 14 depicts the CT secondary current and breaks each half cycle into Time A, Time B, and Time C. For Time A, the current flows through the 2,000-ohm burden resistor. The MOV is not conducting. (The Time A section is exaggerated for illustrative purposes.) For Time B, the MOV is conducting and current will divide between the 2,000-ohm burden and the MOV. The secondary current is still being driven by the internal voltage developed by induction, but the magnitude of the voltage is no longer changing. Once the volt-time area limit of the CT is exceeded, the CT saturates and the current drops to zero for Time C until the current crosses zero and the CT pulls out of saturation.
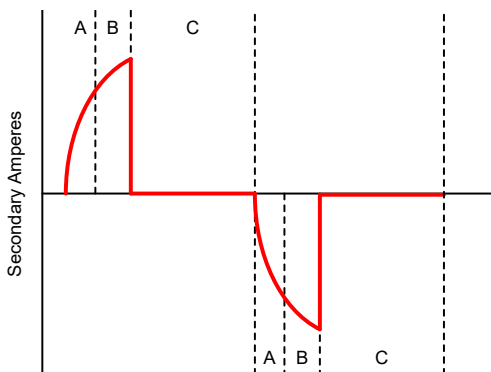

Fig. 14.   CT secondary current illustrating the three stages the CT circuit goes through during each half cycle

During Time A, the circuit looks like that illustrated in Fig. 13. Whereas, during Time B, the circuit looks like that illustrated in Fig. 15. The MOV holds the voltage at X3 at a dc level. The ac sources now appear as dc sources because there is no longer a change in voltage due to the clamping action of the MOV. The X5 voltage now follows an exponential decay as the capacitive voltage divider device discharges through R_{X3-X5}.
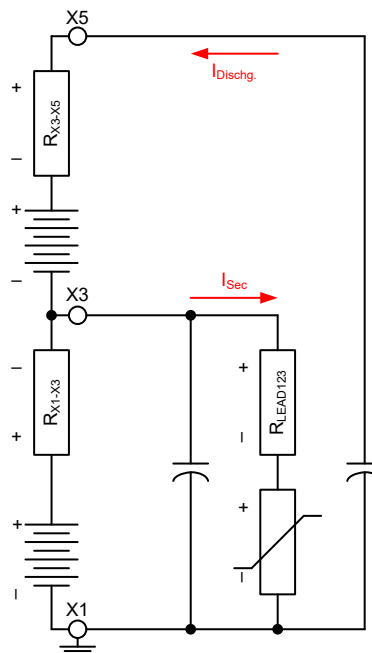

Fig. 15.   Equivalent circuit for the stage when the MOV is clamping the voltage at a dc level

In an actual application without a capacitor connected between X1 and X5, we would expect the observed overvoltage to peak on the leading edge of the voltage pulse and to end sooner, because the distributed capacitance of the circuit would be much lower than that of the capacitive voltage divider device used to measure the voltage in the high-current test.

D.   Final Results

After subjecting all three CTs to at least five overvoltage events, the CTs were subjected to normal production tests and were found to be in an "as manufactured" condition. No change from pretest parameters was observed. The 600 V wiring and terminal blocks were also high-potential tested with no indication of damage. The test confirmed the theory that the turn-to-turn and turn-to-ground insulation of the CTs and wiring are adequate for the voltages that can be expected during an internal fault when the 400-turn tap is left floating with a high-impedance differential relay with 1,500 V_{Peak} rated MOVs connected across the 240-turn tap.

IX.   CONCLUSION

High-impedance differential protection has many attributes that make it a popular choice for protecting buses. This principle provides very high security, dependability, and sensitivity. One desirable attribute is that it is extremely easy to set because the protection engineer can make the simplifying assumption that one CT saturates completely and provides no

voltage to the circuit. The setting is obtained using a simple voltage drop calculation in a simple resistive circuit.

The greatest limitation of this protection scheme is that, because the CTs are paralleled at a summing junction, all the CT ratios must be equal. Reference [1] does not recommend applying this scheme when you have CTs of mismatched ratios at each zone boundary. It states that other protection schemes can more easily deal with this issue. However, additional considerations beyond protection guidance, such as standards and practices, must be considered.

A number of methods are available to use CTs with mismatched ratios in high-impedance differential schemes, including the use of external voltage limiting devices and the use of the higher-ratio CT as an autotransformer to interconnect the CTs. However, these methods require complex analysis to calculate current distributions and voltage drops in the circuit.

The simplest method is to connect the higher-ratio CT to the summing junction at a matching tap. This option requires the protection engineer to evaluate the high-voltage levels caused by the autotransformer effect on the end terminals of the CT winding. The problem with this requirement is that the protection engineer does not have access to detailed information on CT construction and insulation design practices. Failure to properly assess insulation margins could result in damage to CTs and wiring. An even worse consequence is the possibility of a failure to trip for a bus fault if the insulation fails and short-circuits the high-impedance differential relay.

To close this knowledge gap, we tested CTs under realistic conditions to determine the risk of failure. We learned about how CTs are constructed and about the standards followed to build and test them. We also learned about the highly unusual behavior of the high-impedance differential scheme during internal and external faults. We concluded that a simple analysis of voltage levels in the circuit does not adequately predict the high voltages that we observed.

The successful results of the high-current laboratory tests allow concluding that a high-impedance differential scheme can be safely applied with 1200:5 and 2000:5 CTs with the C class required to achieve an equivalent accuracy class of C200 or higher. In this application, we simply connect the higher-ratio CT into the circuit on the matching taps and let the terminals float without danger of insulation failure, equipment damage, or failure to trip. However, the reader should be aware that our tests were performed on a limited number of CTs from one manufacturer, which limits the generality of our conclusion.

In this type of mismatched CT application, lead insulation can be assessed by comparing the expected peak voltage levels with the results of the dc high-potential tests normally performed on the wiring.

Additional work may be warranted to assess the risk for using this same method to mix 600 A and 1,200 A CTs in the same scheme. The conditions for this application appear to be more severe than the application that was tested. Further, testing a larger and more varied sample of CTs could provide greater confidence to draw more general conclusions than those of the research reported in this paper.

X. APPENDIX

This Appendix examines a second common example. Let us consider a 240-turn multiratio CT tapped at 120 turns (1,200 A circuit breakers mixed with 600 A circuit breakers) as shown in Fig. 16. During an internal fault, the MOV clamping voltage will be impressed between the X2 and X4 terminals of the CT. The volts per turn will be 1,500 V/120 turns = 12.5 V/turn.
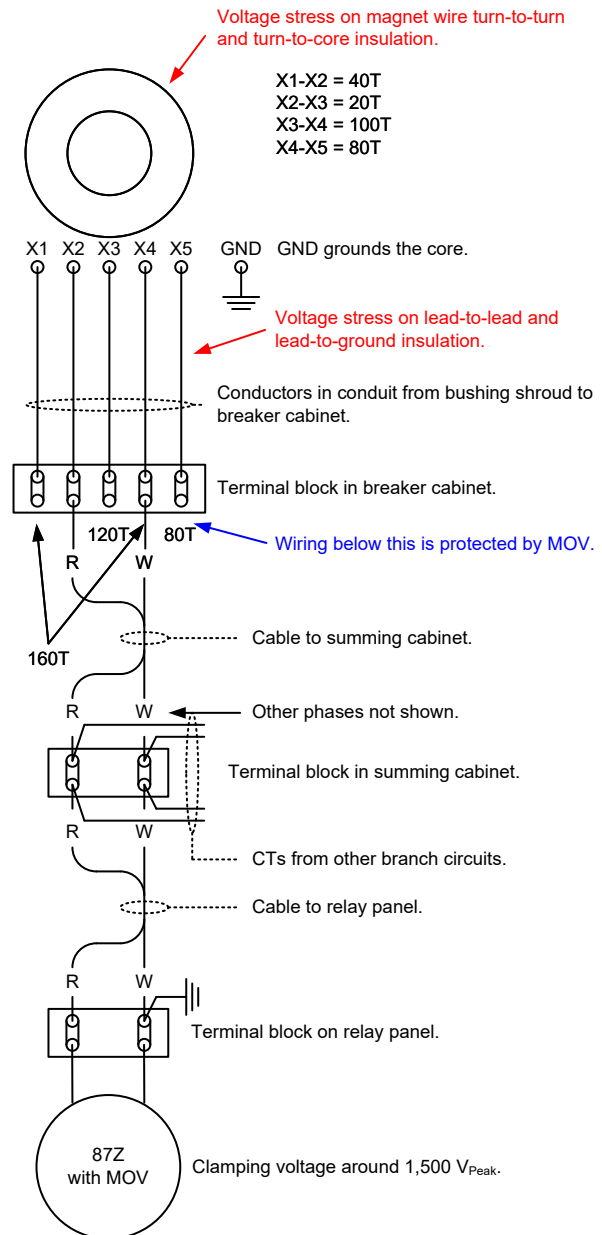

Fig. 16. Wiring diagram of a 240-turn CT, tapped at 120 turns

In this case, the voltage between X1 and X5 will be approximately:

$$240 \text{ turns} \cdot 12.5 \text{ V/turn} = 3{,}000 \text{ V}_{\text{Peak}}$$

For this application, the X4 terminal is grounded. In this case, the voltage from X1 to ground will be:

$$160 \text{ turns} \cdot 12.5 \text{ V/turn} = 2{,}000 \text{ V}_{\text{Peak}}$$

The voltage from X5 to ground will be:

$$80 \text{ turns} \cdot 12.5 \text{ V/turn} = 1,000 \text{ V}_{Peak}$$

Notice that the turn-to-turn insulation now has more stress because the volts/turn value is twice the value of the previous application. The voltage between X1 and X5 is now 3,000 V_{Peak} instead of 2,500 V_{Peak}. It is likely that the magnet wire used in the 2000:5, 400-turn CT secondary is exactly the same magnet wire used in the 1200:5, 240-turn CT secondary. Similarly, the voltage from X1 to ground is now 2,000 V_{Peak} instead of 1,500 V_{Peak}. We can conclude that the case tested in the laboratory did not necessarily represent the worst case. The authors caution the reader to evaluate the specifics of their application before drawing conclusions.

XI. REFERENCES

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XII. BIOGRAPHIES

Russell Franklin received his B.S. degree in electrical engineering from Iowa State University in 1990. Since then, he has worked in the utility industry for Alliant Energy Corporation, Madison, WI. During this time, he worked in various positions supporting engineering design, construction, and operations support of transmission, distribution, and generation facilities. Currently, he is the manager of the System Protection Department. His research interests include power system protection.

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Héctor J. Altuve received his B.S.E.E. degree in 1969 from the Central University of Las Villas in Santa Clara, Cuba, and his Ph.D. degree in 1981 from Kiev Polytechnic Institute in Kiev, Ukraine. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School at the Central University of Las Villas. From 1993 to 2000, he served as professor of the Graduate Doctoral Program in the Mechanical and Electrical Engineering School at the Autonomous University of Nuevo León in Monterrey, Mexico. In 1999 through 2000, he was the Schweitzer Visiting Professor in the Department of Electrical and Computer Engineering at Washington State University. Dr. Altuve joined Schweitzer Engineering Laboratories, Inc. (SEL) in January 2001, where he is currently a distinguished engineer and dean of SEL University. He has authored and coauthored more than 100 technical papers and several books and holds four patents. His main research interests are in power system protection, control, and monitoring. Dr. Altuve is an IEEE fellow.