Solutions for Unconventional CT Connections

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Abstract - This paper describes current transformer connections that are not physically conventionally connected as portrayed in ANSI Standards and Guides or relay manufacturers' literature. A three-line diagram of a basic conventional current transformer connection for a two winding delta wye power transformer differential relaying is presented. Then, scenarios of one set of CT's having reverse polarity, then the other set reversed and, finally, both sets with reversed or rolled out polarity from the conventional connection. This shows the three phase current phasors for the proper connection of the unconventional connected CTs. Also, the effect of ACB phase rotation connection to a delta wye transformer is illustrated with phasors, and a solution for proper connection of the differential relay CTs is shown. This paper is a primer on how to analyze unconventional current transformer polarity connections or reversed phase connections to a transformer and how to solve for the right current transformer connections to achieve the desired direction of operation or polarity as indicated in protective relay manufacturers' literature.

Keywords - Current Transformer, Differential Relay, Phase Rotation, Polarity

Introduction

During my ten years as an Application Engineer for a protective relay manufacturer two questions that have frequently been asked are:

1. How can I determine the proper connection of a current transformer (CT) whose polarity mark location does not match the way a relay manufacturer's instruction manual shows them?
2. What affect does ACB power system phase rotation have on a transformer differential current circuit connections?

The most frequent problem is the transformer differential relays operating incorrectly, usually only during increasing load conditions or for faults outside the differential zone, due to incorrect polarity of the CT connections to the differential relay. In most instances, the differential relays were connected to polarity of the CTs as indicated in the relay Instruction Manual, but no consideration was given by the engineer, designer, or in-service commissioning crew to the physical mounting of the CTs and the effect of their polarity marks on the differential zone of protection. The second question is answered by analyzing power system phase rotation as it passes through power transformer winding connections. Phasor analysis is used to answer both of these questions, but most of the time the commissioning crew didn't have phase angle and current metering to tell them if the current going into a differential zone is cancelled by the current leaving the differential zone.

One advantage of most of today's numeric or digital differential relays is their ability to provide the magnitude and angle of each phase current connected to the relay. If an unbalance is detected in the differential element, an alarm contact output can alert personnel of unbalance conditions. Also, a diagnostic report can be triggered through a remote communication link and retrieved from the differential relay. It is not essential, yet still recommended by ANSI standards, that "check out" or commissioning crews have phase angle meters as part of their tool kit even if the differential relay is numeric and has reports containing the input current information. Phase angle meters are a <u>must</u> when commissioning older solid state and electromechanical relays that are not designed with reporting capabilities.

Polarity

Polarity of current transformers is defined [1] as "The designation of the relative instantaneous directions of the currents entering the primary terminals and leaving the secondary terminals during most of each half cycle. Primary and secondary terminals are said to have the same polarity when, at a given instant during most of the half cycle, the current enters the identified, similarly marked primary lead and leaves the identified, similarly marked secondary terminal in the same direction, as though the two terminals formed a continuous circuit."

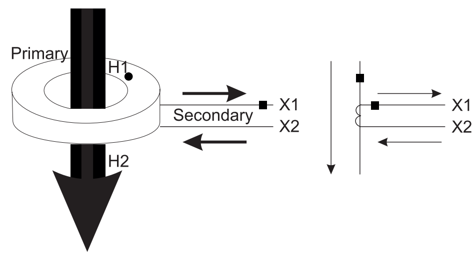

Figure 1a: Bushing CT

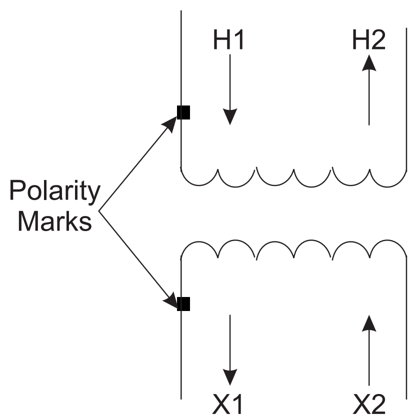

Figure 1b: Wound CT

Figure 1a shows the primary lead passing through the annular opening of a bushing current transformer with polarity mark H1 on the side of the CT where normal current flow enters the device on which the CT is mounted. Secondary polarity mark X1 is the exit point of the transformed current when the transformed current flow is as stated in the definition above. Figure 1b shows a wound-type CT that has both primary and secondary windings wound on a core. The primary and secondary polarity marks physically are on the same side of the CT. This indicates the CT has subtractive polarity. When the X1 secondary polarity mark is physically on the opposite side of the secondary where X2 is shown in Figure 1b, then the transformer would be considered additive polarity. Current transformers are nearly always subtractive polarity.

Why Switchgear CTs are not installed to Match Relay Instruction Manual Diagrams

ANSI and NEMA Standards specify bushing current transformers to be physically mounted in power equipment with their H1 primary polarity mark pointing away from the device rather than toward its internal components. When mounted in a power circuit breaker, conventional polarity is pointing away from the contacts, as shown in Figure 2. The transformer of both Figures 2 and 3 has its CTs conventionally mounted such that the polarity marks point away from the internal windings of the transformer.

Occasionally when purchasing a transformer, one set of CTs will be specified by the purchaser to have the polarity of one set of CTs turned toward the winding so they will have conventional polarity for a bus differential zone of protection. Physical locations of the polarity marks for the CTs in the switchgear of Figure 3 are physically reversed or unconventionally mounted. In switchgear where the current transformers are typically located as a part of the switchgear, rather than the drawout circuit breaker, the ANSI conventions for CT location in circuit breakers is not always followed.

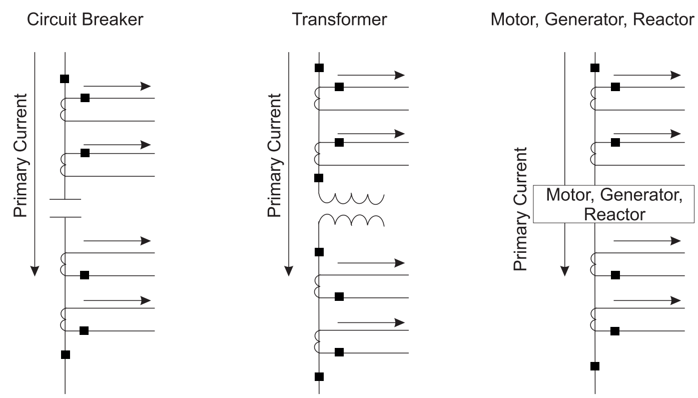

Figure 2: Standard CT Polarity

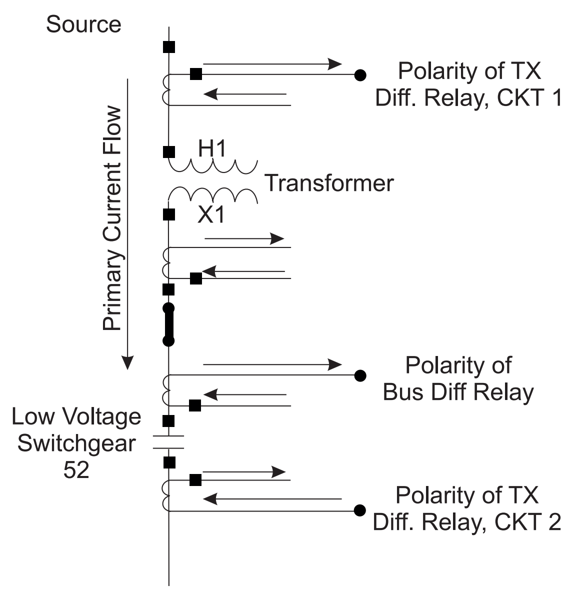

Figure 3: Reversed CT Polarity

Baldy Bridger states [2] a valid point for installing switchgear CTs unconventionally as follows:

> "In metal-enclosed switchgear with drawout circuit breakers,…the CTs are part of the equipment, not the circuit breaker. In many cases it is more convenient to mount the CT's with the polarity mark pointing toward the breaker. In the typical drawout switchgear enclosure, mounting the CT with polarity mark toward the breaker also means that the CT nameplate is visible, which is desirable.
>
> "From time to time, some users have expressed concerns that reversing the polarity marks from the arrangement shown in the relay or meter instructions would lead to improper operation of the device. This is not true. Relays or meters will work properly regardless of the direction of the polarity marks on the CTs if the connections are made properly. Great care must be taken in making these connections, especially for such things as differential relays on delta-wye transformers, but proper operation is not a function of which way the polarity marks point."

What is not stated is that proper operation of protective relays is a function of being able to relate the physical position of the CT and current flow through it to relay manufacturer's polarity designations for their relay.

At times, insufficient communications between the switchgear manufacturer and the project engineer results in the switchgear builder not knowing the use of all current transformers mounted in the switchgear so they can be polarized to agree with protective relay manufacturer's polarization diagrams. In Figure 4, the transformer differential CTs are mounted with the same polarity as the feeder protection CTs, thus they are unconventional or "rolled out", as sometimes referred to with regard to polarity markings, for a transformer differential protection zone.

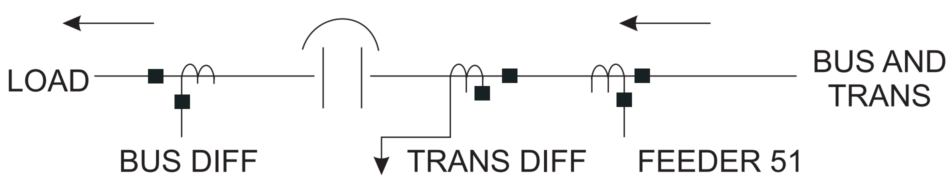

Figure 4: Multiple CTs on Switchgear Pole

Dealing with Transformer Winding Connections

In delta-wye or wye-delta power transformers, the delta winding connection can be classified as one of two delta connections: Delta IA-IB (DAB) or Delta IA-IC (DAC). The wye windings are used as the point of reference to determine the delta winding connection, because the current that flows in the wye winding is the same as the current in the delta side primary phase windings of the transformer before the delta is formed. Figure 5 shows an example of a transformer with a DAB connection with phasor data for balanced system conditions and an ABC phase rotation. Phase current IA is the sum of the winding current coming out of polarity of the A winding and current going into non-polarity of the B winding or minus B current. For ABC phase rotation, the phase IA current on the delta side will lead the phase Ia current of the wye side by thirty degrees. Figure 6 shows an example of the same transformer with the phases reconnected to the delta side terminals to provide a DAC connection. Now, the phase IA current is made up of current coming out polarity of the A winding and current going into the non-polarity of the C winding or minus C current to provide the DAC connection. The phase IA current will lag the phase Ia current by thirty degrees.. Figure 6 is still the same transformer as in Figure 5, but the direction of shift between the delta and wye windings has changed from 30 degree lead by the phasor sum of Ia-Ib, to 30 degree lag from the phasor sum of Ia-Ic. Notice that Figures 5 and 6 do not have designations of High, H, or Low, X, voltage windings. When winding designations are added to the Figures, then the delta must be physically constructed to conform to ANSI Standard C57.12.00 that states “the angular displacement between high voltage and low voltage phase voltage of three phase transformers with wye-delta or delta-wye connections shall be thirty degrees with the low voltage lagging the high voltage.”

The secondary of the phase current transformers located on the wye side of the transformer must be connected in a delta that is a mirror image of the delta power transformer winding. This mirror image delta connection will provide the correct phase shift of phase current to the relay differential element so that the current in the differential element will have the same angular relationships and current component as the current in the phases entering and leaving the power transformer delta winding bushings.

The CT delta can be made by externally connecting the CT secondary leads in delta as described above or by using the internal compensation available in most numeric differential relays. Also, if the transformer is a source of ground fault current such as when the wye side neutral is solidly or impedance grounded, the CT delta connection filters out the zero sequence component of current that does not appear in the incoming current on the delta side of the power transformer. In numeric relays the zero sequence ground current can be filtered inside the relay with the external CT’s connected in wye.

The transformer wye side CT delta current to the differential relay will lead or lag the transformer delta side current by ±30 degrees. If the wrong choice of DAB or DAC delta connection is made, then the balance of the differential may be off by sixty degrees. For a delta high voltage side-wye low voltage side transformer, Figure 7 shows a DAC delta compensation to shift IA2 thirty degrees from 210 to 240 degrees which is in the wrong direction. DAB compensation provides the correct thirty-degree shift, so that IA2 current is at 180 degrees from the incoming IA1 current at zero degrees, thus opposing or canceling phasor angles are present in the differential element. When the current magnitude matching taps for each input have been selected as precisely as they can be, considering tap changer action when present, there will be a minimum of unbalance current in the differential operate element.

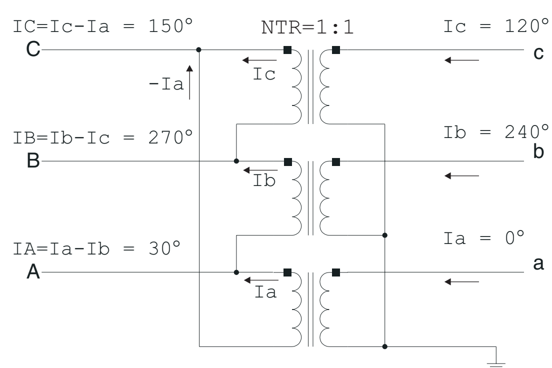

Figure 5: DAB Delta with assumed current phasors

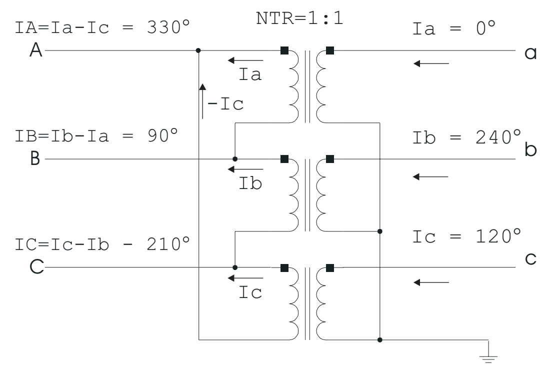

Fig 6: DAC Delta with assumed current phasors

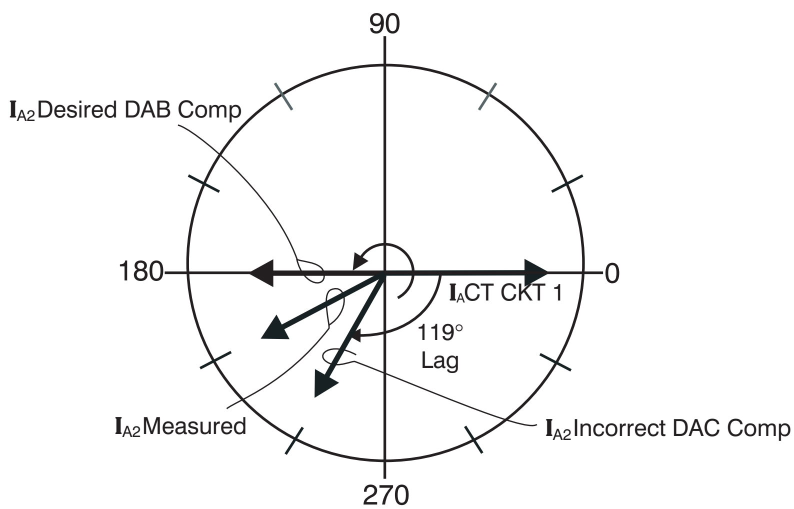

Figure 7: Delta Phase Shift Compensation

Phase Sequence and Transformer Connections

Figure 8 has transformer terminal designations assigned to the transformer of Figure 5, so now the transformer design must agree with ANSI Standard C57.12.00 design which is the high voltage side phase currents lead the low voltage side phase currents by 30 degrees. Power system phase rotation is ABC with the ABC incoming phase leads connected to terminals H1, H2 and H3. If the power system phase sequence is ACB and the incoming leads are connected to the transformer so that IA=H1, IB=H2 and IC=H3, the transformer is still transforming the currents the same way, IA=Ia-Ib etc, but the phasor addition is now such that the high side currents are now lagging the low voltage side instead of leading as indicated in Figure 9 [3]. The magnitude of the delta phase current from the phasor addition is square root of three larger than the individual winding current components. By phasor addition analysis of how the transformer delta connected windings combine the wye side phasors, the correct connection of the differential relay current circuits can be determined.

Figure 10 shows an ACB power system phase sequence applied to a delta high voltage – wye low voltage transformer. The low voltage side currents are shown reversed, as they would be for load flowing from the high to low voltage side of the transformer and will be discussed in detail in the next section of this paper. The low side currents are flowing out of the secondary non-polarity terminal of the current transformers to the differential relay. Performing the phasor addition based on the high voltage delta connections, which is winding 1 – winding 2 from the transformer nameplate diagram, an externally formed Ia-Ib delta connection to the relay will provide Ia current that is 180 degrees from the corresponding IA current. When external CTs are connected in delta and the system phase sequence is ACB, the CTs still should be connected to match the nameplate connection of the transformer delta winding. If the power system leads are connected to the transformer high voltage side bushing in other than H1, H2, and H3 sequence, similar analysis will determine the correct phase shift required to provide high and low side current phasors that are 180 degrees apart. The beauty of using a numeric differential relay is it has internal compensation for phase sequence and internal CT delta compensation. But, a downside of the numeric relay is the command for selection of the delta compensation shift is not standardized among relay manufacturers, so the art of analyzing CT connections is still necessary to be sure the selected delta compensation shifts the transformer wye or delta side current in the right direction for a particular design of relay.

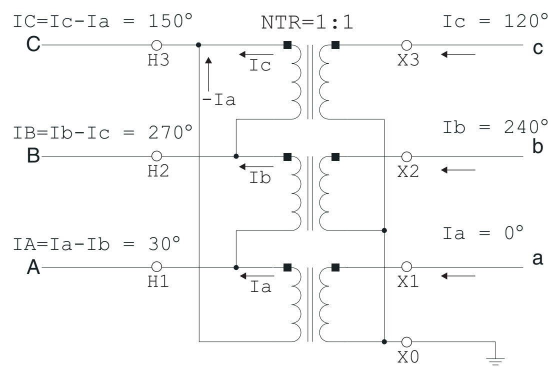

Figure 8: DAB Delta, ABC Sequence

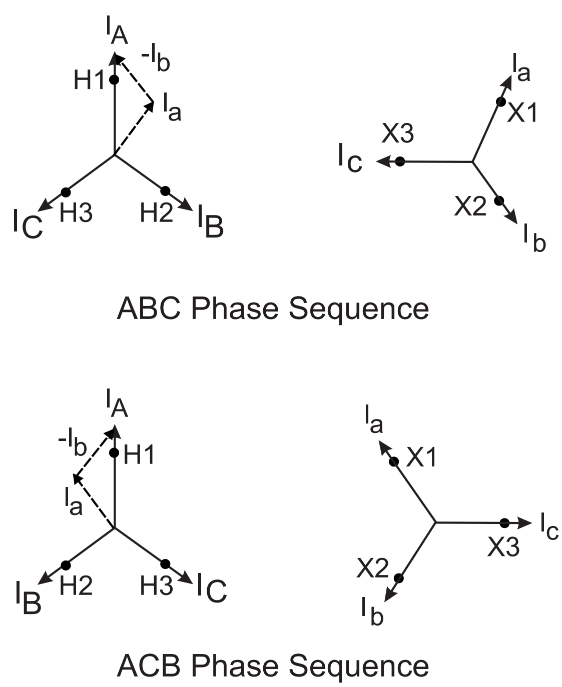

Figure 9: Phase Sequence Phasors through a Delta HV Wye LV Transformer

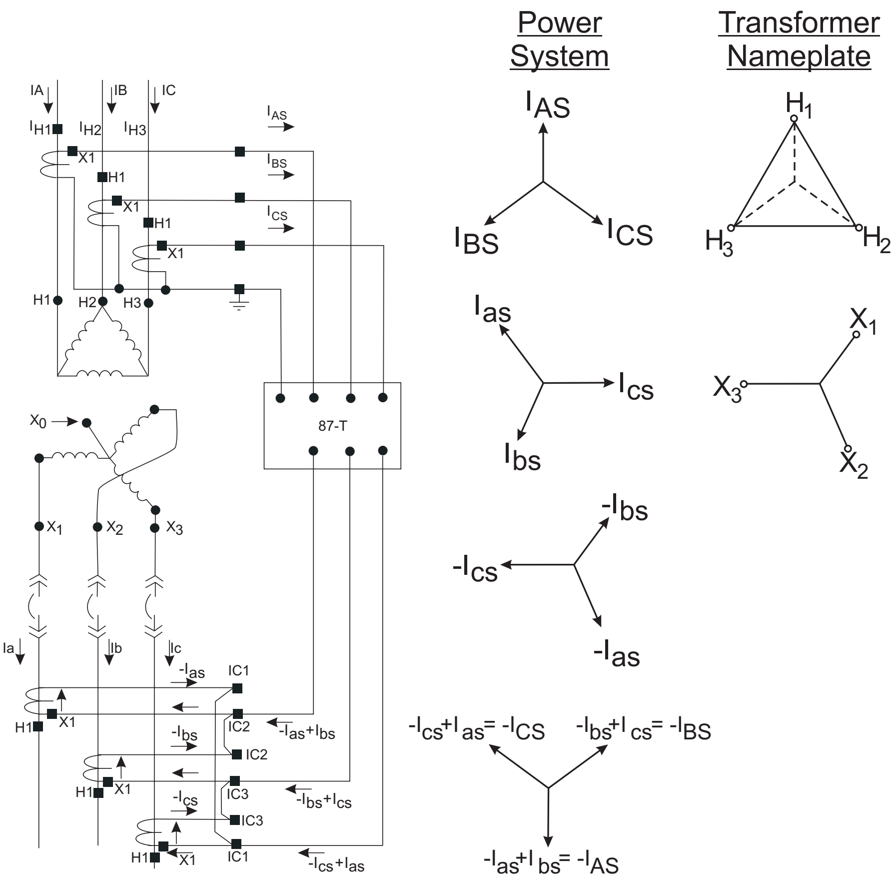

Figure 10: Transformer Differential Connections for ACB Phase Sequence

How do you compensate for Unconventional CT Polarity Connections?

Figure 11 is a three-line diagram of the correct CT wiring of a typical two winding delta primary wye secondary power transformer. The currents coming into the transformer from each side define the differential relay zone of protection. If there is a source connected to each winding of the transformer, the differential relay will operate on the sum of both the CT secondary currents. For through-load flow or external fault conditions, the sum of these two currents should be close to zero, because current coming into the differential zone will be opposite in polarity to that leaving the zone, thus canceling each other. Slight differential current will occur depending on the exciting current and the accuracy used in selecting and setting the differential relay current input matching taps. These taps are to account for current magnitude and CT ratios being different on the two voltage levels of the transformer.

The phasor diagrams in the following Figures 11 through 13 are for 1, 2, 3 or ABC counterclockwise phase rotation without regard to actual current magnitude. If rotation is 1, 3, 2 or ACB, connections to the relay will be determined as stated in the previous section. In Figure 11, the top phasor diagram shows phase currents labeled I_{H1}, I_{H2} and I_{H3} that are leading the current phasors from the wye low voltage side labeled I_{X1}, I_{X2} and I_{X3} in the phasor diagram immediately below it by 30 degrees. This shift is in accordance with ANSI standards for transformer manufacturers. For normal load current flow from transformer high side to low side, the current going to the 87T relay on the secondary side of the power transformer will be entering the low voltage side CT terminals on their primary non-polarity H2 terminal and will be transformed and exit on their X2 terminal, thus going to the relay in the opposite direction as designated in the third set of phasors labeled I_{-x1s}, I_{-x2s} and I_{-x3s}. They will be out of phase with the secondary currents from the high side CTs by 150 degrees instead of 180 degrees.

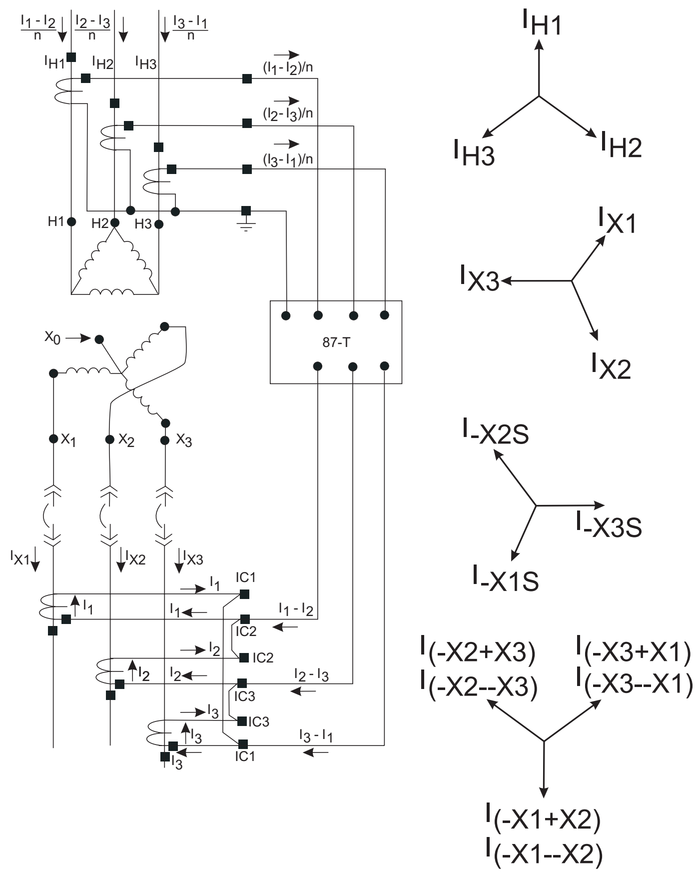

Figure 11: Three-line Diagram – Correct CT, Correct Wiring

Compensation must be made for this current phase shift. The secondary of the X side current transformers must be connected in the same physical delta configuration as the transformer H windings to compensate for this phase shift. By doing this, the currents labeled I (-x2+x3) or I(-x2--x3), I(-x3+x1) or I(-x3- -x1), and I(-x1+x2) or I(-x1- -x2), (Note: -- is the same as + so - - x3 = +x3 etc.) as shown in the bottom phasor diagram, exiting the differential zone will be 180 degrees out of phase and will cancel out phase angle wise in the differential element.

Reversed, “rolled out” [4] or unconventional polarity of the CTs on the low voltage side in Figure 12 are correctly connected to the 87T relay as indicated in the phasor diagrams. The low voltage CTs are connected in a delta configuration matching that of the transformer high voltage windings. The phasors in the bottom phasor diagram in Figure 12 are 180 degrees from the top set of phasors. If the polarity marks of the top set of CTs shown in Figure 12 also are physically reversed, the result will still be the same. Connections to the relay do not change because the polarity is different than shown in Figure 11, which is what is typically found in a relay manufacturer’s instruction manual.

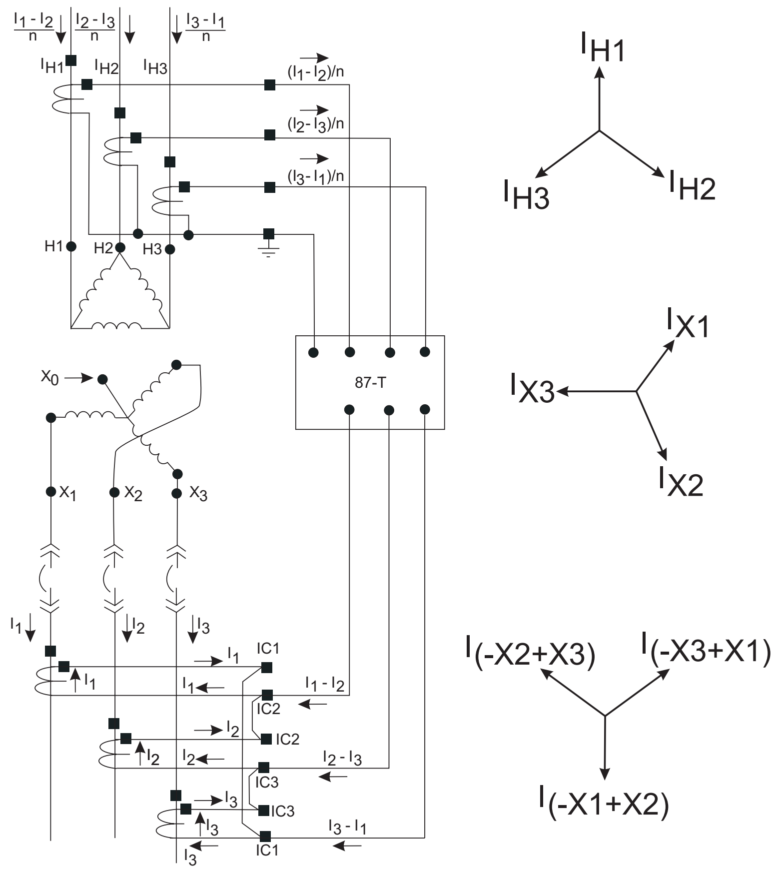

Figure 12: Roll-out CT, Correct Wiring

Figure 13 shows the delta connections made properly to get the correct phase shift, but the leads from the delta junction points were taken to the incorrect terminals of the transformer differential relay.

The A phase differential element inside the relay is seeing the sum of IH1 and IAR resulting in phasor addition, as illustrated by the dashed lines, instead of phasor cancellation. The operate current in the differential element will increase by a factor of two because of this addition, thus leading to a quick operation of the relay for increases in external load. Figure 12 shows the correct way the relay should have been connected.

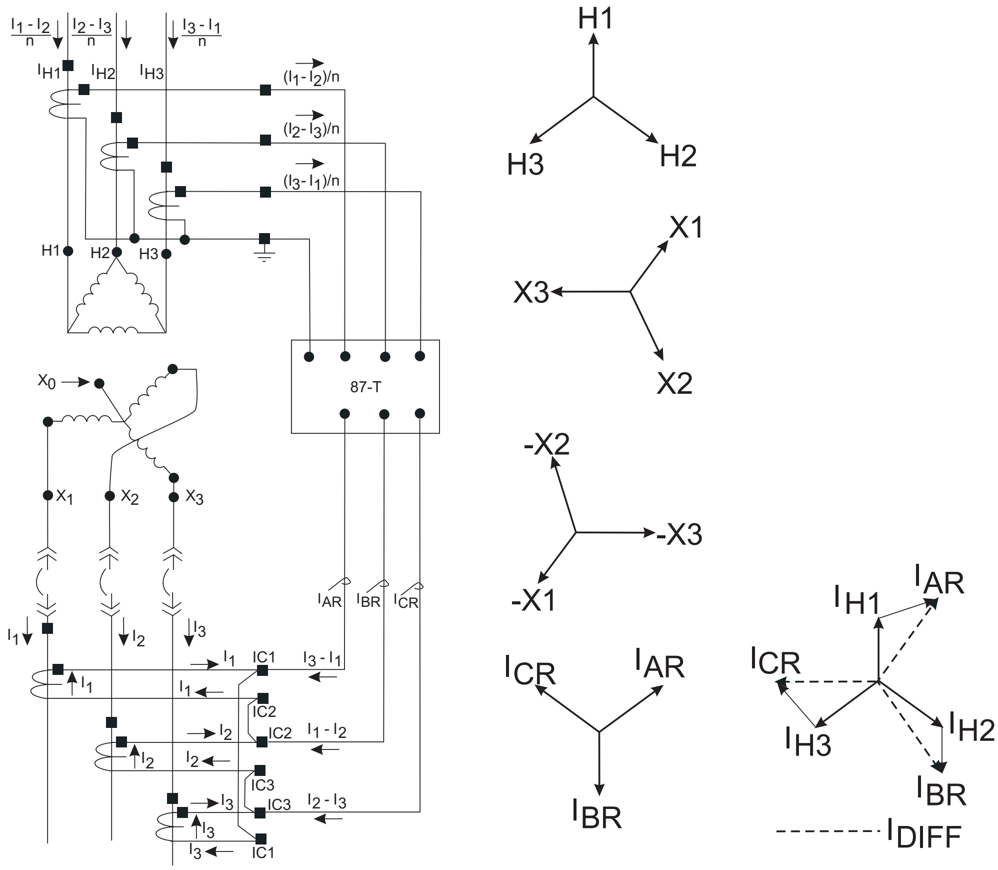

Figure 13: Three-line Diagram – Rolled-out CT, Wrong Wiring

The transformer differential relays applied in Figures 11, 12 and 13 were solid-state relays that have internal compensation for the delta connection. An advantage of using the relay's internal delta connection is that it reduces the burden of the CT secondary circuit, resulting in less chance of saturating the CTs. For a CT secondary connected in delta, the secondary burden from the delta formation point to the connected protective device is three times higher during fault conditions. Relay internal delta connections also allow other devices such as indicating ammeters and overcurrent relay elements, provided they also are low burden devices, to be inserted in series with the differential element current circuit. Modern numeric or digital differential relays also have internal delta CT compensation.

Be sure to verify your current connections!

When a transformer is first loaded readings must be taken to verify the current circuits are connected correctly and will not operate under load or external fault conditions. A very useful feature of most numeric relays is that they can provide a Differential Check Record [5] similar to that shown in Figure 14. This report can be triggered by a command to the relay or by an unbalance alarm point inside the relay. When triggered by the differential element unbalance alarm, the report lists areas that may be causing the unbalance such as: incorrect CT polarity, incorrect angle compensation or incorrectly selected taps causing current mismatch. The circled numbers in Figure 14 show that incorrect DAC or D1-3 delta compensation was selected inside the relay for a transformer with TX CON of DAB or D1-2 like the transformer delta connection as shown in Figures 11, 12 and 13. Instead of shifting the CKT 2 phasor from 211 degrees back to 181 degrees where it would cancel out the CKT 1 current at zero degrees, the phasor was incorrectly shifted 30 degrees ahead to make the relay see CKT 2 current at 241 degrees as previously shown in Figure 7. Besides being a troubleshooting tool, the report also can be used as a commissioning record of what the relay is seeing when loaded thus reducing the need for a phase angle meter and ammeter for “in service” readings. If the relays are not numeric then connections must be verified the old fashioned way with a phase angle meter, ammeter and polar graph paper to read and plot the magnitude and angle of the currents going into and out of the differential zone to verify that they are balanced in the differential element.

CDS220 Differential Check Record

REPORT DATE	: 11/10/98
REPORT TIME	: 10:12:42.701
STATION ID	: SIMULATED SUBST
RELAY ID	: BANK-T1
USER1 ID	: TEST1
USER2 ID	: TEST1
RELAY ADDRESS	: 0
ACTIVE GROUP	: 0

PHASE 87T Settings	CTR	CT CON	TX CON	GROUNDED
CT CKT1	240	WYE	DAB	NO
CT CKT2	400	WYE	WYE	YES
MINPU	0.20 *TAP			
SLOPE	25 %			
ALARM	50 %			
URO	6 *TAP			

Compensation	Angle	Tap
CT CKT1	WYE	3.12
CT CKT2	DAC	4.68

ALARMS	PHASE A	PHASE B	PHASE C
DIFFERENTIAL:	ALARM	ALARM	ALARM
POLARITY:	OK	OK	OK
ANGLE COMP:	ALARM	ALARM	ALARM
MISMATCH:	OK	OK	OK

MEASUREMENTS	PHASE A	PHASE B	PHASE C
MEASURED I PRI			
CT CKT1:	206 @ 0	202 @ 240	204 @ 121
CT CKT2:	516 @ 211	508 @ 91	516 @ 332
MEASURED I SEC			
CT CKT1:	0.86 @ 0	0.84 @ 240	0.85 @ 121
CT CKT2:	1.29 @ 211	1.27 @ 91	1.29 @ 332
ANGLE COMPENSATED I			
CT CKT1:	0.86 @ 0	0.84 @ 240	0.85 @ 121
CT CKT2:	1.329 @ 241	1.27 @ 122	1.29 @ 2
TAP COMP I			
CT CKT1:	0.27 @ 0	0.27 @ 240	0.27 @ 121
CT CKT2:	0.27 @ 241	0.27 @ 122	0.27 @ 2
IOP:	0.28 *TAP	0.28 *TAP	0.28 *TAP
SLOPE RATIO	104 %	104 %	104 %

Figure 14: Differential Check Record with Incorrect Delta CT Compensation

Conclusion

The key to determining proper connection of current transformers whose physical mounting is different than conventional connections is to be able to analyze the current flow through the current transformer and to be able to associate the fact that current going into a high side terminal of the CT will exit on the associated low side terminal. Unconventional or reversed current transformer connections need to be analyzed by the engineer or designer, focusing on the relation of the actual available CT terminations which define the zone of protection when compared to the relay manufacturers’ instructions without regard to the polarity marks of the CT. An IEEE Fellow summed it up well when he stated: “Relays or meters will work properly regardless of the direction of the polarity marks on the CT if the connections are made properly”. Phasor analysis techniques should also be used to determine proper phase shift of secondary current connections to differential relays when the power system leads to a transformer are ACB instead of ABC phase rotation. If the power system's lead connections to the transformer terminals can still be made in the sequence of ABC which is A to H1, B to H2, and C to H3, then the ACB analysis may be easier to comprehend. Make no exceptions and follow the practice of validating the differential current circuit connections by creating a record of the currents going into and out of the differential zone. By following these actions the number of incorrect transformer differential relay operations will be greatly reduced.

References

[1] "IEEE Guide for the Application of Current Transformers" IEEE STD C37.110-1996.

[2] B. Bridger, "Polarity markings on instrument transformers" Powell Electric Technical Brief PTB #34, December 17, 1992.

[3] Walter Elmore "Ways to Assure Improper Operation of Transformer Differential Relays" 45th Annual Conference for Protective Relaying, Georgia Tech University, Atlanta Georgia, May 1-3, 1991

[4] D. Paul, "Rolled Out CT connections of transformer differential relay caused 230/13.8 kV substation tripping", Industry Applications Society Annual Meeting, October 2002.

[5] Basler Electric BE1-CDS220 Instruction Manual Rev. A.

Author Biography

Gerald Dalke received the A.D. in Electrical Technology from Oklahoma State University in 1960. He served more than 33 years with Oklahoma Gas and Electric Company in system protection areas until retirement in July of 1994. He is a Registered Professional Engineer in the State of Oklahoma. Gerald joined Basler Electric in June 1995 and is a Senior Regional Application Engineer, specializing in system protection. He is a Senior Member of the IEEE and active in the Protection Subcommittee and Working Groups of the Industrial Application Society. Gerald has presented papers at various industry conferences and has taught at Basler's Relay Application School and seminars. He is based in Edmond, Oklahoma, and is a member of the Texas A&M Protective Relay Conference Planning Committee.

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