Lessons Learned in Vector Matching: A Comprehensive Review of the Fundamentals

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Abstract—**This paper is a tutorial intended to give protection engineers a better understanding of how vector matching fundamentals are applied to transformer differential schemes. The need for a concise, methodical approach to vector matching has become evident through numerous lessons learned during substation commissioning. Particular examples of lessons learned from autotransformer standardization projects have created an ideal opportunity for a discussion covering all the essentials and complexities of vector matching fundamentals. The highlights of the tutorial include superimposing the phasor and connection diagrams from the transformer nameplate to illustrate how current flows through distribution power banks and autotransformers when the order of the phase connection sequence is changed. The tutorial also addresses intelligent electronic device (IED) and legacy relaying, grounding sources, and zero-sequence filtering in-depth. A complete understanding of vector matching principles allows engineers to arrive confidently at vector matching solutions for even the most complex transformer topologies. The concepts presented in this paper clearly demonstrate the fundamentals for engineers beginning their career and provide a review for more experienced engineers.**

I. INTRODUCTION

Historical evidence shows that simplified methods and shortcuts do not always prevail when determining how to compensate for the transformer phase shift in differential protection schemes. Numerous false trips have resulted from overlooking the details or applying them incorrectly. For these methods to work reliably, a detailed systematic approach emphasizing the fundamentals is essential.

The key to vector matching depends on rigorously following the well-defined rules of transformer, current transformer (CT), and relay polarity. It is very important to separate what the protected equipment is doing from the relay scheme protecting it. This is especially true in modern intelligent electronic device (IED) relays. Delta-connected CTs, formerly used to compensate for the transformer phase shift, are now emulated in the relay, and the equations used to emulate those deltas are now based on the way the transformer phase shift is defined in the relay.

Relay settings commonly defined by clock hour positions represent the transformer phase shift in multiples of 30-degree lagging increments. The clock hour positions are used in International Electrotechnical Commission (IEC) vector group notation to indicate the transformer phase shift when referenced to the high-voltage winding [1].

Transformers built to American National Standards Institute (ANSI) standards, however, do not use vector groups. Instead, a vector diagram is provided on the transformer nameplate that shows the relationship between the primary and other windings [2]. For delta-wye or wye-delta transformers, the standard states that the low-voltage side always lags the high-voltage side by 30 degrees [3]. It is important to note that the ANSI standard assumes that the system phase rotation follows the transformer phase connection sequence.

II. DEFINING THE VECTOR GROUP

Vector groups identify the transformer based on its windings and phase shift. Vector group notation begins with the high-voltage winding (designated with a capital letter), followed by the other windings (designated with lowercase letters). The windings with the lowercase letters are in descending order of their voltage magnitudes. The letters are followed by a clock hour position that represents the transformer phase shift with respect to the high-voltage winding. For example, a Dy1 vector group, representing a typical distribution power bank, indicates that the secondary low-voltage wye side of the transformer lags the primary high-voltage delta side by 30 degrees (1 • 30°). A Yyd1 vector group, representing a typical autotransformer, indicates that the tertiary delta side of the transformer lags the primary and secondary wye sides by 30 degrees. Although the vector group system has not been adopted in the United States, it is often provided on the transformer nameplate in conjunction with the vector diagram.

III. INTERPRETING THE VECTOR DIAGRAM

The vector (or phasor) diagram from the transformer nameplate is a convenient way of determining the transformer phase shift. Fig. 1 shows typical nameplate vector diagrams for power banks and autotransformers. Before the phase shift is known, however, the system phase rotation and external transformer connections must be verified to determine if they conform to the assumptions of the ANSI standard. If the assumptions are not followed, the system phase rotation must be compared to the transformer phase connection sequence before the phase shift is known. Initially, these ideas will be discussed separately, even though they need to be taken into account together to determine the transformer phase shift.

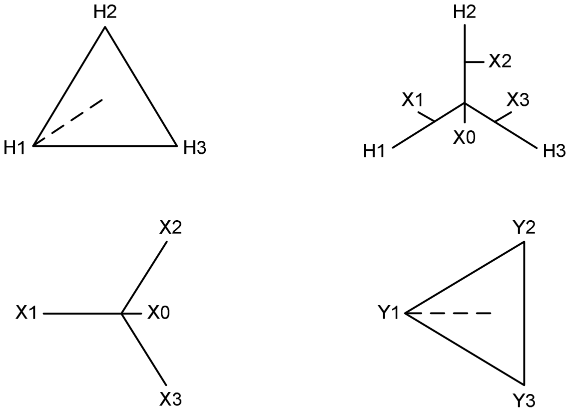


Fig. 1. Typical vector diagrams from the nameplates of power banks (left) and autotransformers (right).

A. System Phase Rotation

The commonly used term “system phase rotation” can be misleading because the phasors by definition always rotate counterclockwise. The system phase rotation, as shown in Fig. 2, actually refers to the order in which a three-phase set of phasors pass a fixed point as they rotate in this counterclockwise direction [3]. Although ABC rotation is common today, several utilities use ACB. Changing the system phase rotation affects the transformer phase shift by switching the B- and C-phase current angles in the nodal equations at each corner of the transformer delta.

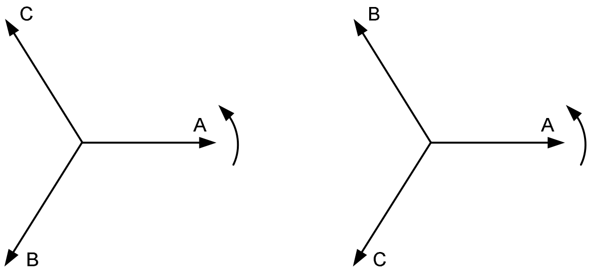
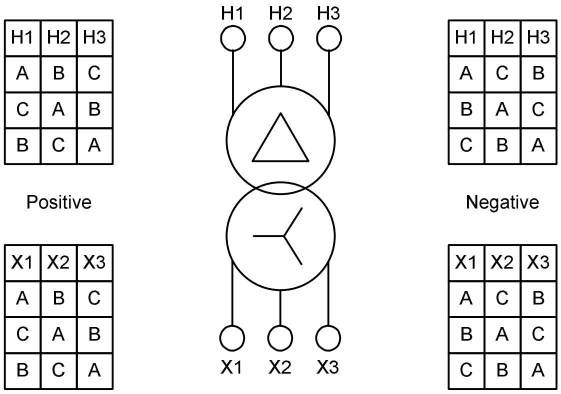


Fig. 2. Positive-sequence ABC system phase rotation (left) and negative-sequence ACB system phase rotation (right).

Defining the system phase rotation is also critical because this parameter is required for all symmetrical component-based protection and metering elements. It is important to note that the phase rotation setting in the relay is completely independent from the way the relay compensates for the transformer phase shift.

B. External Transformer Connections

The phase connections to the transformer terminals, as shown in Fig. 3, also affect the phase shift. Changing the order in which the phases are sequentially connected to the terminals on the transformer redefines the nodal equations by changing the way currents combine in the main winding delta. It is important to note that changing the transformer connections does not alter system phase rotation.



H1	H2	H3
A	B	C
C	A	B
B	C	A

X1	X2	X3
A	B	C
C	A	B
B	C	A

H1	H2	H3
A	C	B
B	A	C
C	B	A

X1	X2	X3
A	C	B
B	A	C
C	B	A

Fig. 3. Positive ABC phase connection sequence (left) and negative ACB phase connection sequence (right) for a two-winding transformer.

When the transformer phase connection sequence follows the order of the system phase rotation, the vector diagram on the transformer nameplate can be used to determine the phase shift by comparing the phasors of the delta winding terminals (shown by the direction of the dotted line in Fig. 1) to the phasors of the wye winding terminals. If the order of the transformer phase connection sequence opposes the system phase rotation, the mirror image of the vector diagram must be used to determine the phase shift. Using the mirror image changes the vantage point of the vector diagram by rotating it 180 degrees on a vertical axis to realign its phasors in the direction of the system phase rotation. Fig. 4 shows the mirror image of the typical nameplates shown in Fig. 1.

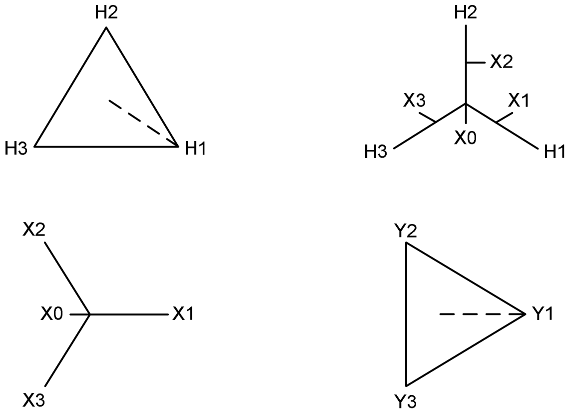


Fig. 4. Mirror image of the power bank (left) and autotransformer (right) vector diagrams.

The system phase rotation and phase connection sequence can be thought of as signed integers whose product sign can be used to determine if the nameplate vector diagram or its mirror image should be used when determining the transformer phase shift. If the product sign is positive, the nameplate vector diagram determines the phase shift. If the product sign is negative, its mirror image determines the transformer phase shift. Table I is a truth table that illustrates this corollary.

TABLE I
NAMEPLATE VECTOR DIAGRAM TRUTH TABLE

System Phase Rotation	**Phase Connection Sequence**	**Nameplate (+) or Mirror Image of Nameplate (–) Vector Diagram**
+	+	+
–	+	–
+	–	–
–	–	+

IV. PHASE SHIFT FUNDAMENTALS OF DISTRIBUTION POWER BANKS AND AUTOTRANSFORMERS

The phase shift of power banks and autotransformers can be determined simply by applying Kirchhoff's current law at each corner of the main winding delta. The nodal equations for the deltas shown in Fig. 5 through Fig. 8 define whether they are leading or lagging. Assuming ABC system phase rotation, the nodal equations that produce a leading delta are:

$$I_{A(TERMINAL)} = I_A - I_B \quad (1)$$

$$I_{B(TERMINAL)} = I_B - I_C \quad (2)$$

$$I_{C(TERMINAL)} = I_C - I_A \quad (3)$$

The nodal equations that produce a lagging delta are:

$$I_{A(TERMINAL)} = I_A - I_C \quad (4)$$

$$I_{B(TERMINAL)} = I_B - I_A \quad (5)$$

$$I_{C(TERMINAL)} = I_C - I_B \quad (6)$$

These leading and lagging equations are with respect to the wye winding reference. It is important to note that the transformer phase shift can be referenced to the wye or delta winding when defining the clock hour position settings.

For the diagrams shown in Fig. 5 through Fig. 8, currents are assumed to flow into the primary high-voltage terminals (H1, H2, and H3) and out of the secondary low-voltage and tertiary terminals (X1/Y1, X2/Y2, X3/Y3, and X0/Y0). The current phasors at the transformer terminals are in per unit to neglect magnitudes and are shown positive in the direction of assumed current flow. The direction current is flowing in the delta is governed by the rule of subtractive polarity, as shown in Fig. 5 [3].

Reference [3] states that the two fundamental rules of polarity are the following:

- Current flowing in at the polarity mark of one winding flows out of the polarity mark of the other winding. Both currents are substantially in phase.
- The voltage drop from polarity to nonpolarity across one winding is essentially in phase with the voltage drop from polarity to nonpolarity across the other winding(s).

The rules of transformer polarity also allow the vector diagram to be superimposed on the connection diagram because the currents for the wye-delta windings sharing the same core leg are substantially in phase. Superimposing the vector and connection diagrams aligns the delta windings and their respective currents in the direction of the phasors, whose current combinations, governed by the nodal equations, produce a phase shift as seen from the vector diagram. The examples in Fig. 5 through Fig. 8 show both positive and negative phase connection sequences for distribution power banks and autotransformers. The system phase rotation is ABC.

V. DETERMINING THE CLOCK HOUR POSITION SETTINGS

The clock hour position settings for the IED can readily be determined from the vector diagrams shown in Fig. 5 through Fig. 8, once a reference has been chosen. The H2 terminal was selected as the 12 o'clock reference because it and all other phasors on the X2 and Y2 terminals align with the clock face. The high-voltage H2 reference also allows the clock hour positions to match the IEC vector groups when the system phase rotation follows the order of the transformer phase connection sequence.

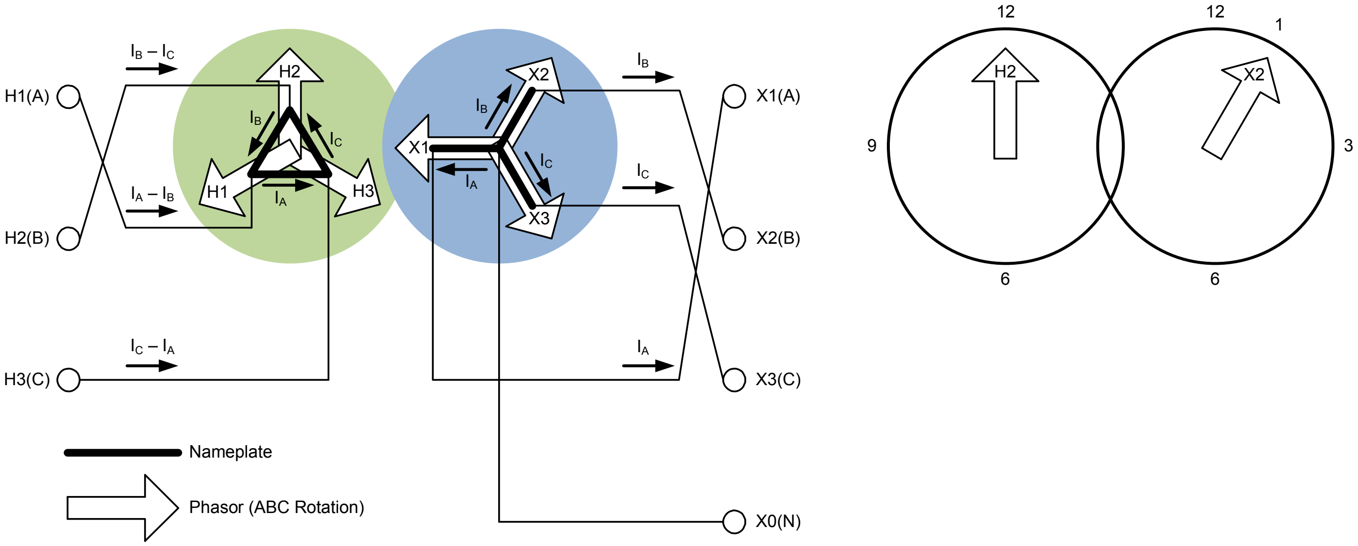


Fig. 5. Positive phase connection sequence for a distribution power bank (left) and clock hour position settings (right). Vector diagram aligns with nameplate.

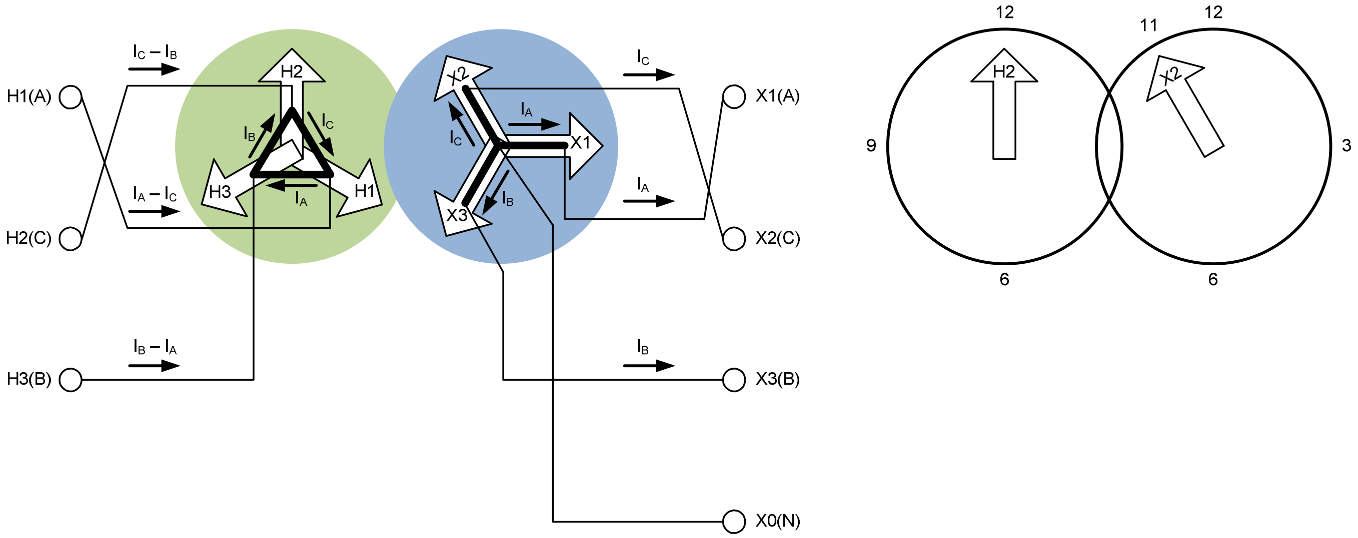


Fig. 6. Negative phase connection sequence for a distribution power bank (left) and clock hour position settings (right). Vector diagram aligns with the mirror image of the nameplate.

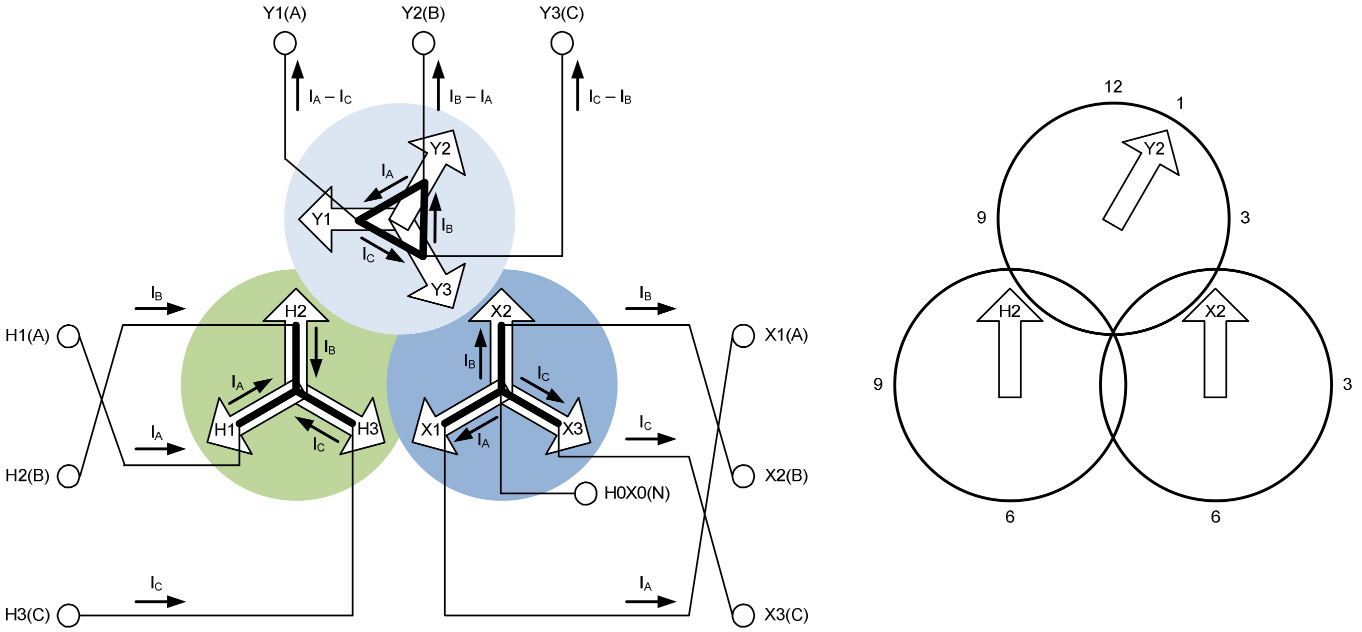


Fig. 7. Positive phase connection sequence for an autotransformer (left) and clock hour position settings (right). Vector diagram aligns with nameplate.

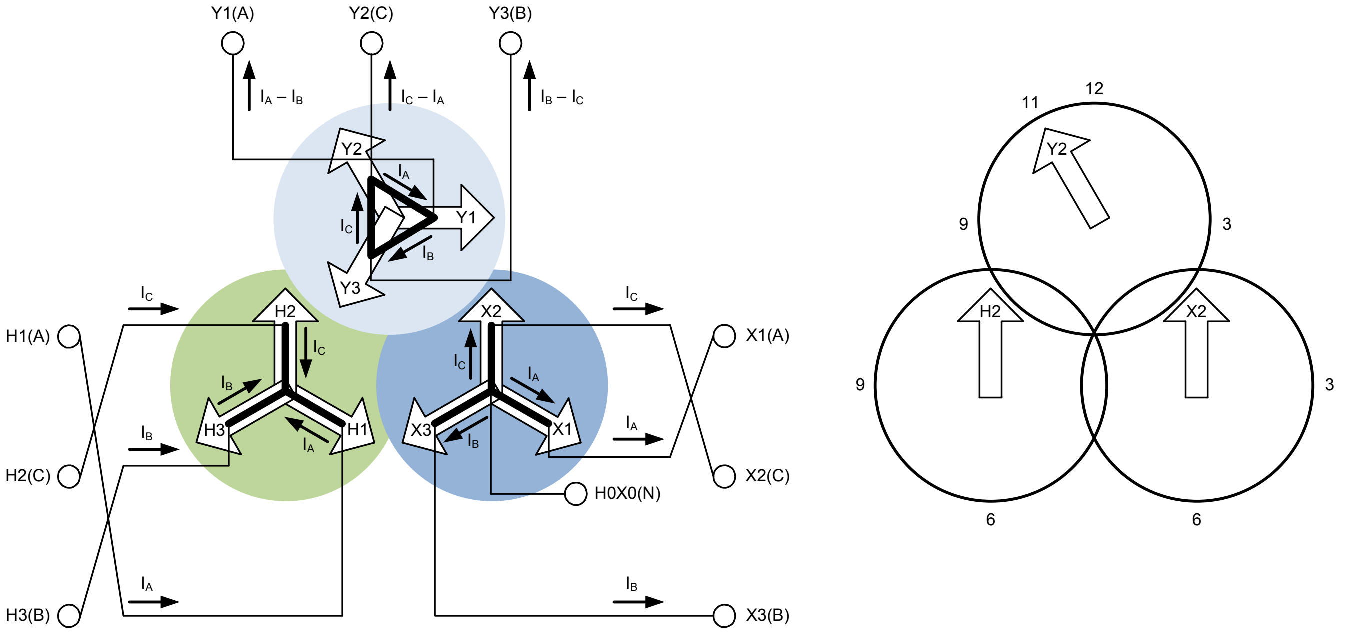


Fig. 8. Negative phase connection sequence for an autotransformer (left) and clock hour position settings (right). Vector diagram aligns with the mirror image of the nameplate.

VI. CONNECTIONS TO THE RELAY

Once the current directions and phasors have been defined at the transformer terminals, the direction of CT secondary currents entering the relay can also be determined by the rules of transformer polarity, as shown in Fig. 9 [3]. For IEDs, the common standard is to connect all CTs in wye.

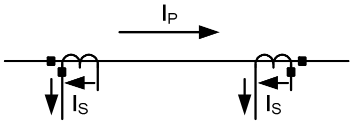


Fig. 9. Polarity markings for CTs.

Fig. 10 shows a typical single-phase connection diagram for a transformer differential IED. The diagram indicates how the fundamentals of CT polarity are applied in determining the direction of CT secondary current flow at the relay terminals.

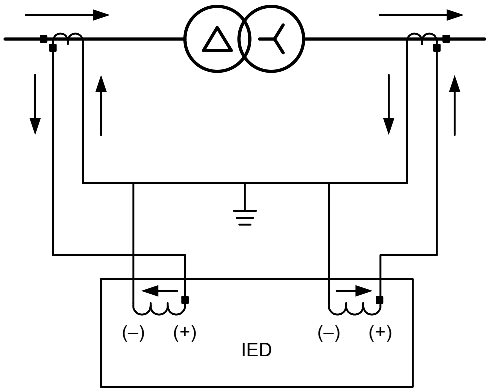


Fig. 10. Typical single-phase, two-winding transformer IED connection diagram.

This connection diagram can vary, however, because the CT polarities are sometimes on the transformer side, as shown in Fig. 11. It is important to observe that the direction of secondary current is the same independent of whether the polarity marks are together on one side or on the other [3]. The secondary currents entering the relay are the same as in Fig. 10.

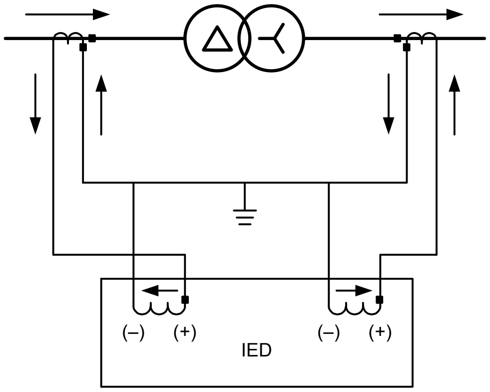


Fig. 11. Typical single-phase, two-winding transformer IED connection diagram. The delta-side CT polarity is on the transformer side.

Therefore, the important thing to remember is that the direction of CT secondary currents measured by the relay from the primary side of the transformer must oppose the direction of the CT secondary currents measured by the relay from the other side(s) of the transformer. It is a common convention to show the CT secondary currents flowing into the polarity terminal of the relay from the primary side of the transformer and out of the polarity terminal(s) from the other side(s) of the transformer.

The per-unit restraint currents in the IED are modeled exactly the same way as their electromechanical counterparts. Under balanced conditions, CT secondary currents entering electromechanical relays are magnitude and phase compensated as they pass through the restraint elements. According to Kirchhoff's current law, no current flows through the operating element because the restraint currents entering and leaving the node connected to the operating element are equal. The currents bypass the operating element as they circulate through the CTs, as shown in Fig. 12.

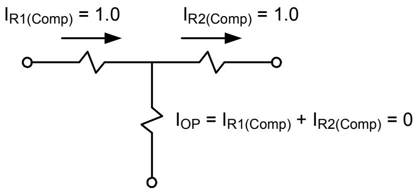


Fig. 12. Restraint current flow in electromechanical relays for a two-winding transformer.

For IED relays, the CT secondary currents entering the nonpolarity terminal of the relay from the wye side of power banks and the delta side of autotransformers will now be 150 degrees (30-degree lagging phase shift) or 210 degrees (30-degree leading phase shift) out of phase from CT secondary currents from the primary side. After magnitude and phase compensation, those currents will be 180 degrees out of phase. Therefore, because the restraint currents cancel each other out, the vector sum for the operating element is zero, as shown in Fig. 13. The secondary currents entering the relay effectively pass through the restraint elements as they do in electromechanical relays.

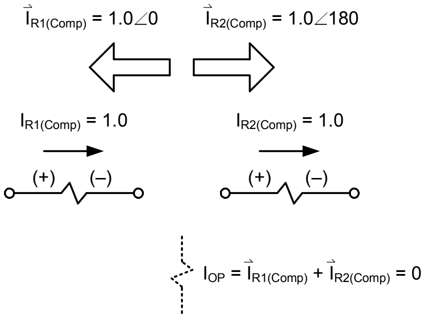


Fig. 13. Restraint current phasors in IED relays for a two-winding transformer.

VII. LESSONS LEARNED AT THE WELEETKA SUBSTATION

Weleetka is a Public Service Company of Oklahoma substation that has two 138-69-13.2 kV autotransformers sharing a common tertiary bus, as shown in Fig. 14. A grounding bank is connected to the tertiary bus, which supplies loads to customers. The tertiary CTs on the load breakers can be connected to either autotransformer differential relay using a differential selector switch. One autotransformer uses a modern IED for its differential protection, and the other uses electromechanical relays. The vector diagrams from the autotransformer nameplates follow the example shown in Fig. 7. The reference for the IED clock hour position settings was chosen to be on the high-voltage side.

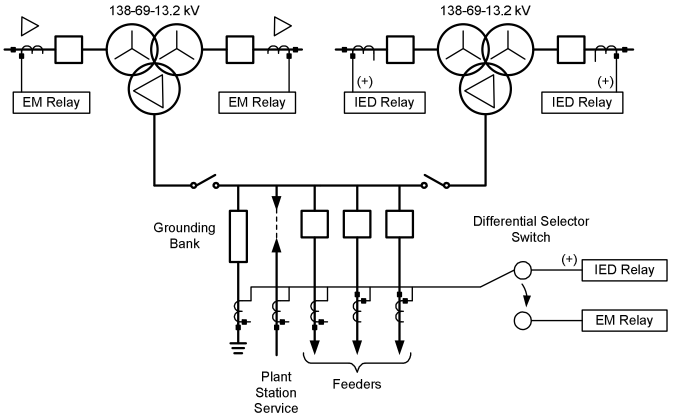


Fig. 14. Weleetka Substation.

The tertiary CT connections to the relay, however, did not conform to the standard. The CT secondary currents from the 13.2 kV tertiary side of the transformer entered the polarity terminal of the relay instead of leaving, as shown in the single-phase connection diagrams in Fig. 15 (IED relay) and in Fig. 16 (electromechanical relays).

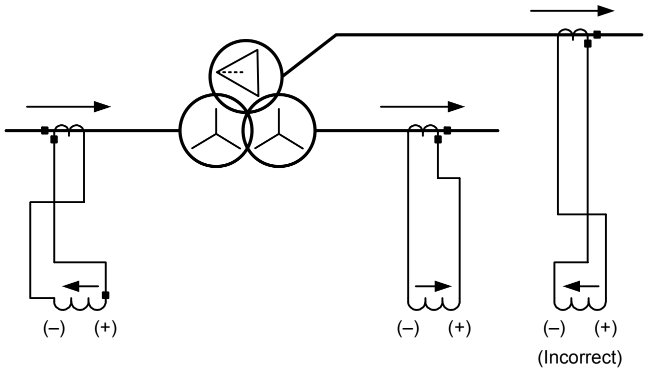


Fig. 15. Single-phase IED connection diagram for a three-winding autotransformer at the Weleetka Substation.

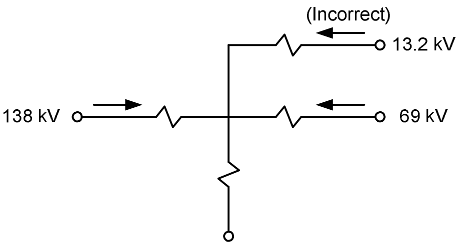


Fig. 16. Restraint currents for single-phase electromechanical relays at the Weleetka Substation.

Therefore, in order to indicate the correct current direction, the sign of the CT secondary tertiary terminal currents leaving the delta of Fig. 7 had to be changed. The tertiary currents leaving the polarity terminal of the relay then became:

$$I_{A(TERMINAL)} = -(I_A - I_C) \tag{7}$$

$$I_{B(TERMINAL)} = -(I_B - I_A) \tag{8}$$

$$I_{C(TERMINAL)} = -(I_C - I_B) \tag{9}$$

or

$$I_{A(TERMINAL)} = I_C - I_A \tag{10}$$

$$I_{B(TERMINAL)} = I_A - I_B \tag{11}$$

$$I_{C(TERMINAL)} = I_B - I_C \tag{12}$$

This misaligned the phases between the tertiary and the rest of the relay phase connections. The tertiary currents were also shifted in the lead with respect to the wye sides of the transformer. By following standard setting procedures based on incorrect CT wiring, the IED clock hour position setting on the tertiary side was still set at 1 o'clock to represent the lagging transformer phase shift shown in Fig. 7. This resulted in numerous false trips issued by the IED for the autotransformer supplying the tertiary load.

The problem was corrected by rolling all three phases from the tertiary CTs at the relay and changing the clock hour position setting to 11 o'clock. The tertiary currents leaving the polarity side of the relay then became:

$$I_{A(TERMINAL)} = I_A - I_B \tag{13}$$

$$I_{B(TERMINAL)} = I_B - I_C \tag{14}$$

$$I_{C(TERMINAL)} = I_C - I_A \tag{15}$$

The phases now aligned with the rest of the relay connections. The clock hour position setting was changed accordingly to 11 o'clock, representing a leading delta. The connection shown in Fig. 17 shows the leading delta terminal currents flowing away from the polarity terminal of the relay and into the 13.2 kV tertiary wye-connected CTs.

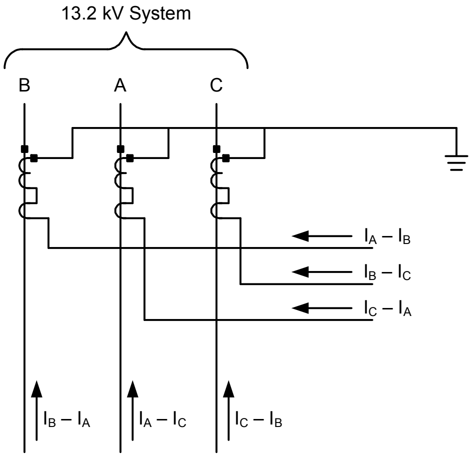


Fig. 17. 13.2 kV tertiary wye-connected CTs at Weleetka.

To correct the problem on the autotransformer with the electromechanical relays, the wye-side delta CTs were connected to balance the leading currents flowing out of the restraint windings on the 13.2 kV tertiary side. Fig. 18 shows the leading currents flowing away from the delta-connected CTs on the 138 kV side and into the polarity terminal of the relay.

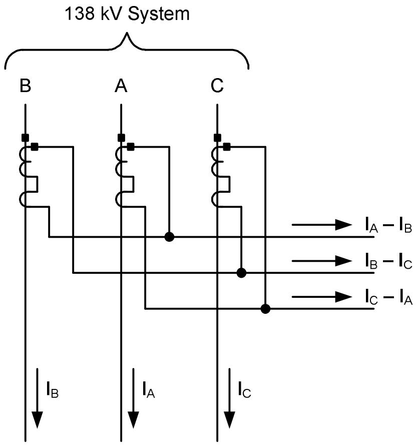


Fig. 18. 138 kV leading delta-connected CTs at Weleetka.

Fig. 19 shows the leading currents flowing into the delta-connected CTs on the 69 kV side and away from the polarity terminal of the relay.

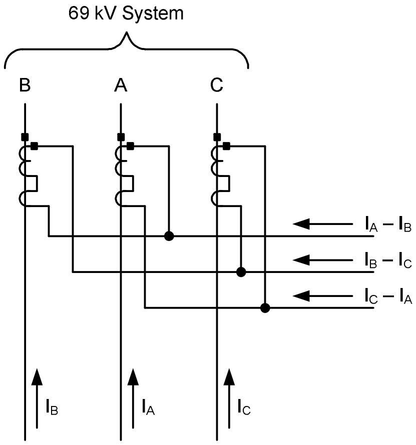


Fig. 19. 69 kV leading delta-connected CTs at Weleetka.

Determining exactly what went wrong at Weleetka was necessary before standardizing the transformer differential protection. Minimizing delays investigating false trips limits the time the transformer is taken out of service.

To correct this unorthodox solution, primarily developed through trial and error, a package was issued using standard settings and design. Several rolls and color codes were corrected. Standardizing the protection at Weleetka will serve engineers and technicians well when these relays are scheduled to be replaced.

VIII. DETERMINING THE RELAY CURRENT COMPENSATION EQUATIONS

The table in the relay manual that shows the current compensation equations for each clock hour position setting can serve as a second check to verify the relay is correctly compensating for the transformer phase shift [5]. The current compensation equations produce leading or lagging phase shifts to restore the phase shift indicated by the clock hour position settings back to the 12 o'clock reference. Assuming ABC system phase rotation, the relay magnitude-compensated equations that define a 30-degree leading phase shift to compensate for a 1 o'clock lagging phase shift, as shown in Fig. 5 and Fig. 7, are:

$$I_{A(COMP)} = \frac{1}{\sqrt{3}} \bullet \left[I_{A(TERMINAL)} - I_{B(TERMINAL)} \right] \quad (16)$$

$$I_{B(COMP)} = \frac{1}{\sqrt{3}} \bullet \left[I_{B(TERMINAL)} - I_{C(TERMINAL)} \right] \quad (17)$$

$$I_{C(COMP)} = \frac{1}{\sqrt{3}} \bullet \left[I_{C(TERMINAL)} - I_{A(TERMINAL)} \right] \quad (18)$$

The magnitude-compensated equations that define a 30-degree lagging phase shift to compensate for an 11 o'clock leading phase shift, as shown in Fig. 6 and Fig. 8, are:

$$I_{A(COMP)} = \frac{1}{\sqrt{3}} \bullet \left[I_{A(TERMINAL)} - I_{C(TERMINAL)} \right] \tag{19}$$

$$I_{B(COMP)} = \frac{1}{\sqrt{3}} \bullet \left[I_{B(TERMINAL)} - I_{A(TERMINAL)} \right] \tag{20}$$

$$I_{C(COMP)} = \frac{1}{\sqrt{3}} \bullet \left[I_{C(TERMINAL)} - I_{B(TERMINAL)} \right] \tag{21}$$

IX. GROUND SOURCES AND ZERO-SEQUENCE CURRENT FILTERING

Once the clock hour positions are selected, it is important to check that zero-sequence currents are filtered out on all sides of the transformer whose CT measuring locations are in the path of ground current. Star point grounded-wye windings and grounding transformers within the zone of protection provide a ground source for zero-sequence currents to flow [4]. Filtering out zero-sequence currents is necessary in order to prevent false trips due to relay restraint current unbalances caused by external ground faults.

Zero-sequence current filtering is accomplished inherently in delta-connected CTs (or emulated delta-connected CTs) and by algorithms in the relay that remove the zero-sequence current component when no phase shift and, consequently, no deltas CTs are required. The algorithm may be built into the relay or selectable through the settings. For sides of transformers protected by electromechanical relays that require zero-sequence current filtering using wye-connected CTs, a zero-sequence trap or a set of auxiliary CTs is needed. This occurs when a grounding transformer is connected to the delta side of the transformer and is within the main transformer protected zone [3].

A. Zero-Sequence Current Filtering in Deltas

Because zero-sequence currents by definition are of equal magnitude and direction, they are cancelled out at each corner of the delta (Kirchhoff's current law). The currents are trapped and remain circulating in the delta, as shown in Fig. 20.

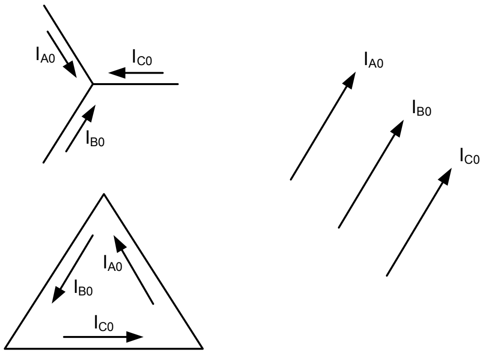


Fig. 20. Zero-sequence current flow in a delta.

B. Deriving the Zero-Sequence Current Filtering Equation

Algorithms in modern IED relays have the capability to remove the zero-sequence current for the 12 o'clock settings not emulating a delta. The zero-sequence current filtering equation can easily be derived from the general symmetrical component equation sets by subtracting the zero-sequence component from each phase current [3]. The general symmetrical component equation sets are:

$$I_1 = \frac{1}{3}\left(I_A + aI_B + a^2 I_C\right) \tag{22}$$

$$I_2 = \frac{1}{3}\left(I_A + a^2 I_B + aI_C\right) \tag{23}$$

$$I_0 = \frac{1}{3}\left(I_A + I_B + I_C\right) \tag{24}$$

and

$$I_a = I_1 + I_2 + I_0 \tag{25}$$

$$I_b = a^2 I_1 + aI_2 + I_0 \tag{26}$$

$$I_c = aI_1 + a^2 I_2 + I_0 \tag{27}$$

Rearranging (25), (26), and (27) to subtract the zero-sequence component of each phase, the equations become:

$$I_A - I_0 = I_1 + I_2 \tag{28}$$

$$I_B - I_0 = a^2 I_1 + aI_2 \tag{29}$$

$$I_C - I_0 = aI_1 + a^2 I_2 \tag{30}$$

Substituting (22), (23), and (24) into (28), (29), and (30), the magnitude-matching zero-sequence filter equations are:

$$I_A - I_0 = \frac{2}{3} I_A - \frac{1}{3} I_B - \frac{1}{3} I_C \tag{31}$$

$$I_B - I_0 = \frac{2}{3} I_B - \frac{1}{3} I_A - \frac{1}{3} I_C \tag{32}$$

$$I_C - I_0 = \frac{2}{3} I_C - \frac{1}{3} I_A - \frac{1}{3} I_B \tag{33}$$

The relay current compensation equations for each phase of the 12 o'clock setting requiring zero-sequence current filtering become:

$$I_{A(COMP)} = \frac{2}{3} I_{A(TERMINAL)} - \frac{1}{3} I_{B(TERMINAL)} - \frac{1}{3} I_{C(TERMINAL)} \tag{34}$$

$$I_{B(COMP)} = \frac{2}{3} I_{B(TERMINAL)} - \frac{1}{3} I_{A(TERMINAL)} - \frac{1}{3} I_{C(TERMINAL)} \tag{35}$$

$$I_{C(COMP)} = \frac{2}{3} I_{C(TERMINAL)} - \frac{1}{3} I_{A(TERMINAL)} - \frac{1}{3} I_{B(TERMINAL)} \tag{36}$$

Table II shows clock hour position settings and their corresponding current compensation equations for typical phase shifts of power banks and autotransformers.

TABLE II
TRANSFORMER PHASE SHIFT COMPENSATION EQUATIONS

Transformer Phase Shift With Respect to Reference (Lagging)	Clock Hour Position Settings	Current Compensation Equations
0°	12	$I_{A(Comp)} = \frac{2}{3} I_{A(Terminal)} - \frac{1}{3} I_{B(Terminal)} - \frac{1}{3} I_{C(Terminal)}$ $I_{B(Comp)} = \frac{2}{3} I_{B(Terminal)} - \frac{1}{3} I_{A(Terminal)} - \frac{1}{3} I_{C(Terminal)}$ $I_{C(Comp)} = \frac{2}{3} I_{C(Terminal)} - \frac{1}{3} I_{A(Terminal)} - \frac{1}{3} I_{B(Terminal)}$
30°	1	$I_{A(Comp)} = \frac{1}{\sqrt{3}} I_{A(Terminal)} - \frac{1}{\sqrt{3}} I_{C(Terminal)}$ $I_{B(Comp)} = \frac{1}{\sqrt{3}} I_{B(Terminal)} - \frac{1}{\sqrt{3}} I_{A(Terminal)}$ $I_{C(Comp)} = \frac{1}{\sqrt{3}} I_{C(Terminal)} - \frac{1}{\sqrt{3}} I_{B(Terminal)}$
• • •		
330°	11	$I_{A(Comp)} = \frac{1}{\sqrt{3}} I_{A(Terminal)} - \frac{1}{\sqrt{3}} I_{B(Terminal)}$ $I_{B(Comp)} = \frac{1}{\sqrt{3}} I_{B(Terminal)} - \frac{1}{\sqrt{3}} I_{C(Terminal)}$ $I_{C(Comp)} = \frac{1}{\sqrt{3}} I_{C(Terminal)} - \frac{1}{\sqrt{3}} I_{A(Terminal)}$

X. CONCLUSION

Applying the fundamentals of transformer polarity and Kirchhoff's current law is essential when developing standard setting and wiring practices for transformer differential relays. Vector matching procedures can be simplified considerably by following a consistent approach. Understanding the fundamentals can also be invaluable when trying to unravel problems that do not follow a consistent approach, such as at the Weleetka Substation.

IEDs have elements that measure the internal restraint and operate quantities as well as the currents at the relay terminals. Understanding these measurement principles can be particularly beneficial in discriminating between settings errors and wiring errors during load tests. The importance of testing can never be overemphasized because transformer differential schemes in general lend themselves to being error prone.

The information in Table II is based on lessons learned from the examples presented in this paper. The concepts can be applied to solve a wide variety of vector matching problems. Tables similar to this are always included in the sections of relay manuals that address transformer phase shift compensation.

XI. REFERENCES

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XII. BIOGRAPHIES

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Previously presented at the 2010 Texas A&M
Conference for Protective Relay Engineers.

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20100201 • TP6405-01