Beyond the Nameplate: Transformer Compensation Revisited – New Applications, Greater Simplicity

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Abstract—**Transformer relay installations require phase angle compensation to properly balance the differential calculations and avoid misoperations during load and external faults. The proper selection of angle compensation settings is based on physics—specifically, by creating ampere-turn balance equations for the magnetic core loops of the transformer. Modern relays use three-by-three matrices for each terminal to create the ampere-turn balance equations required for the three phase differential elements. IEEE C37.91 describes a set of matrices that are used to compensate for phase shifts in increments of 30°. In an ideal world, selecting the correct matrices for a given transformer is a straightforward process and only a subset of these matrices are required (those that perform 0°, 30°, or 330° shifts). However, real-world installations often require the full set of matrices to achieve simple compensation settings. In addition, power electronic converter transformers often have phase shifts that are not increments of 30°, therefore requiring matrices not covered in IEEE C37.91 for proper compensation. The first "Beyond the Nameplate" paper laid out clear rules on how to select compensation settings to cover many common real world application variations when the relay being applied provides a subset of matrices available in IEEE C37.91. This paper revisits the subject and provides guidelines on using newly available compensation settings (all matrices in IEEE C37.91 and generalized matrices for non-standard phase shifts) to address new applications and achieve greater simplicity.**

I. Introduction

Transformer protection relays primarily use percent-restrained differential elements (87R) to detect internal faults in transformers. There are many factors to an 87R installation that must be correct to ensure the element will function properly. Current transformer (CT) taps, polarity, wiring and connections, and relay settings must all be installed and set properly for the 87R element to remain secure during external faults and avoid costly misoperations [1]. Out of all these factors, the authors have found that incorrect phase angle compensation settings are one of the most common mistakes that lead to 87R element misoperations.

A. Looking Beyond the Nameplate

The configuration of the windings internal to a transformer can result in a phase shift across the transformer; that is, the positive-sequence currents on one side of the transformer may lead or lag the positive-sequence currents on the other side. Before a settings engineer can select proper phase angle compensation settings for an installation, they must determine the phase shift observed by the relay; this is the phase shift that needs to be compensated. In an ideal world, this phase shift could be determined directly from the nameplate of the transformer. It is important to understand that using the nameplate of the transformer alone assumes a standard installation where all the following requirements must be true:

- The system has an ABC phase sequence.
- The phase-to-bushing connections are standard (i.e., A-phase on the system is connected to the H1 and X1 bushings of the transformer, B-phase on the system is connected to the H2 and X2 bushings of the transformer, and C-phase on the system is connected to the H3 and X3 bushings on the transformer).
- The CT connections are standard. This means all CTs are connected in wye and have differential polarity. In addition, all CT-to-relay connections follow proper labeling (i.e., the A-phase CT on the system is connected to the A-phase input on the relay, etc.).

However, in the real world, installations are often anything but standard. If any of the factors listed above are not true, the phase shift observed by the relay may be different from what an engineer would determine using the nameplate affixed to the transformer. Reference [2] explains how to derive the phase shift observed by the relay for any real-world installation and is required knowledge prior to reading this paper.

B. Methods of Compensating for the Phase Shift Across a Transformer

The fundamentals of selecting proper phase angle compensation settings are based on physics. To properly compensate for the phase shift across a transformer, we must create ampere-turn balance equations for the magnetic core loops of the transformer. Reference [3] describes how these equations are derived and should be reviewed prior to reading this paper.

In the days of electromechanical relaying, CT connections were used to compensate for the phase shift across the transformer. CTs on delta-connected transformer windings were connected in wye, and CTs on wye-connected transformer windings were connected in delta. These connections physically created the necessary ampere-turn balance equations required to balance the differential [3]. The downside to this solution was it required CTs on wye windings to be wired in delta. Delta-connected CTs are more complicated to wire and troubleshoot. They also increase the burden for certain fault types compared to wye-connected CTs and are therefore more likely to saturate [4]. In addition, currents measured by a relay connected to delta-connected CTs do not include zero-sequence quantities and have a magnitude $\sqrt{3}$ higher than what is flowing on the system. This makes it more difficult for engineers to coordinate backup overcurrent elements that use delta-connected CT measurements with other downstream devices that are using wye-connected CTs.

In modern installations, CTs are connected in wye and the phase angle compensation occurs inside the relay using mathematics. Relays use three-by-three matrices for each transformer winding (or terminal) to create the ampere-turn balance equations required for the three phase differential elements. The measured phase currents on each winding are multiplied by the corresponding winding compensation matrix to calculate compensated currents, as shown in (1). These compensated currents are then used to calculate restraint and operate quantities for the 87R element [2].

$$\begin{bmatrix} Ia_{compensated} \\ Ib_{compensated} \\ Ic_{compensated} \end{bmatrix} = \left[\text{Compensation Matrix}\right] \bullet \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \quad (1)$$

C. Compensating for Transformers With Standard Phase Shifts

Most transformers on the power system have phase shifts that are multiples of 30° (0°, 30°, 60°, etc.). This paper will call these "standard phase shifts." Reference [5] provides a table of matrices that can be used to balance the differential for transformers with standard phase shifts. These matrices are shown in Table VIII in Appendix A and will be referenced often throughout this paper.

The matrices in Table VIII are shown in three columns. The matrices in the "Wye" column mathematically simulate wye-connected CT connections. These matrices are used to balance delta-connected transformer windings. Like wye-connected CT connections, these matrices do not remove zero-sequence current. The matrices in the "Delta" column mathematically simulate delta-connected CT connections. These matrices are used to balance wye-connected transformer windings. Like delta-connected CT connections, these matrices remove zero-sequence current. The matrices in the "Double-Delta" column mathematically simulate double-delta connected CT connections. The designation of "Double-Delta" is explained in detail in [5]. These matrices are used to balance zigzag windings and delta-connected transformer windings when zero-sequence current removal is necessary (i.e., there is an in-zone grounding transformer on the delta side of the transformer).

Each row of Table VIII is labeled with a number 0–11. The row number represents the number of multiples of 30° that the matrices in that row shift the positive-sequence currents. The shift occurs in the counter-clockwise (ccw) direction for currents with an ABC phase sequence, and in the clockwise (cw) direction for currents with an ACB phase sequence. Because of this, system phase sequence alone does not affect the compensation settings for a given installation.

In an ideal world with all transformers having standard installations and 0° or 30° lead/lag phase shifts, we would only ever require four matrices from Table VIII to perform angle compensation (those that perform 0°, 30°, or 330° shifts). Therefore, some relay designs expect that installations will be connected in a "standard" way and only provide a subset of the matrices in Table VIII as selections for compensation settings. These relays can still be applied to nonstandard applications as long as the settings engineer follows manufacturer recommendations for selecting compensation settings to maintain security. Reference [2] provides rules for correctly selecting compensation settings when the relay being applied provides the matrices in cells with no fill in Table VIII [6] [7]. This includes all delta and double-delta compensation matrices, but only one wye matrix. Note that the rules in [2] are for relays that calculate restraint as the sum of the compensated currents multiplied by a k factor (usually 0.5 or 1) [6] [7].

Some relay designs give the settings engineer access to all the matrices in Table VIII, including the additional wye matrices that are highlighted with blue fill [8]. Having the complete set of matrices available in the relay provides several benefits. Installations that used to require wiring changes (rolling phases) can now be solved using compensation settings. Applications that used to require careful selection of the reference winding and resulted in unintuitive compensation settings can now be solved with intuitive settings. This paper will provide a four-step procedure for properly selecting compensation settings for various applications when all the matrices are available.

D. Compensating for Transformers With Nonstandard Phase Shifts

In addition, some relays may allow for generalized matrices that will support transformer installations with nonstandard phase shifts (phase shifts that are not multiples of 30°), such as power electronic converter transformers [8]. This paper will show how generalized matrices work and give an example of how they can be used.

II. Procedure for Selecting Angle Compensation Matrices

Reference [3] shows that proper compensation requires deriving the ampere-turn balance equations necessary to balance the differential currents. For transformers with standard phase shifts, the resulting equations are realized using either wye, delta, or double-delta matrices. For transformers with nonstandard phase shifts, the ampere-turn balance equations can be realized using generalized matrices. Follow the steps in this procedure to identify the proper compensation matrices for a given installation:

1. Select a reference winding of the transformer (usually the primary winding). Use the nameplate or vector group of the transformer to determine the number of degrees that each winding lags the reference winding assuming a standard installation.
2. Considering the system phase sequence, phase-to-bushing connections, and CT wiring, determine the phase relationship between each winding and the reference winding as seen by the relay. Refer to [2] if you are unfamiliar with how to do this.
3. Identify the compensation matrix type for appropriate zero-sequence removal for each winding.

a) For windings with standard phase shifts (multiples of 30°), identify the column of possible matrices in Table VIII that should be used for each winding:
   i) A delta transformer winding should use a wye matrix.
   ii) A wye transformer winding should use a delta matrix.
   iii) A zigzag transformer winding or a delta transformer winding with a ground source (such as a zigzag grounding transformer) within the differential zone should use a double-delta matrix.

b) For windings with nonstandard phase shifts, identify the equation in Appendix B that should be used for each winding:
   i) If the winding has a connection to ground, use (4).
   ii) If the winding does not have a connection to ground, use (5).

4. Select the compensation for the reference winding as the lowest-numbered compensation matrix that meets the criteria in Step 3a.
   For the remaining windings, determine the number of degrees each winding must be shifted for the currents to plot 180° out of phase with the reference winding after angle compensation:

a) For windings with standard phase shifts, divide the number of degrees by 30° to identify the row in Table VIII that should be used for each winding. Select the matrix on that row that matches the column identified in Step 3a.

b) For windings with nonstandard phase shifts, use the number of degrees directly in (4) or (5).

A. Dangers of Shortcuts

Some settings engineers may be tempted to bypass Steps 1–3 and go directly to Step 4, directly applying compensation so the winding currents are 180° out of phase with each other. The problems that can occur if the previous steps are bypassed have been well documented. Reference [2] gives a field example of how using a double-delta matrix on a wye transformer winding caused the relay to misoperate during an external phase-to-phase fault with CT saturation. Reference [9] shows how compensating an autotransformer with wye matrices without removing zero-sequence current will leave the installation vulnerable to misoperating on external ground faults. These examples prove it is important not to take shortcuts. Always complete all steps in the given procedure to ensure correct results.

B. Other Solutions for Zigzag Windings

Using a double-delta matrix to compensate for a zigzag transformer winding or a delta transformer winding with a ground source (such as a zigzag grounding transformer) is required when using compensation settings to balance the differential currents. However, it is possible for this solution to misoperate when CT saturation causes false ground current to flow during external faults. References [5] and [10] explain this problem in detail and show how wiring the ground current measurement to the relay and including it in the zone of protection is a better solution.

III. Examples of Selecting Compensation for Transformers With Standard Phase Shifts

The best way to become comfortable applying these recommendations is to practice. This section shows several different examples of applying the steps in Section II to identify the correct angle compensation settings for various transformer installations with standard phase shifts. The simplifications to the selection process that are gained when all wye matrices are available (compared to when only one is available, as in [2]) will be highlighted.

A. Example 1: Dyn1 (DABY) Transformer With Standard Connections

This example applies the steps in Section II to determine the correct angle compensation settings for the standard Dyn1 (DABY) transformer installation shown in Fig. 1. The installation has an ABC system phase sequence, standard phase-to-bushing connections, and standard CT connections.

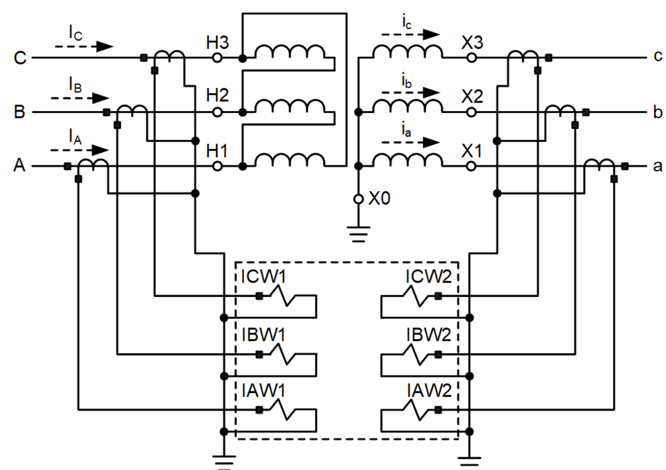

Fig. 1. Dyn1 transformer with standard connections

Step 1 is to select a reference winding and determine the number of degrees each winding lags the reference in an assumed standard installation. In this example, Winding 1 (the delta winding) will be our reference. Determining the number of degrees that Winding 2 lags the reference winding is easiest if the IEC vector group of the transformer is known. An IEC vector group is a notation that shows how each winding on a transformer is connected as well as how many multiples of 30° each winding lags the primary winding. In this Dyn1 transformer, the "D" tells us that the primary winding is connected in delta, and the "yn1" tells us that the secondary winding (Winding 2) is connected in wye-grounded and lags the primary winding by by 1 • 30 = 30°. This phase relationship is shown in Fig. 2a. If the IEC vector group for a transformer is not known, follow the process in Appendix C to derive the IEC vector group from the transformer nameplate.

Step 2 is to determine the phase relationship between each winding and the reference winding as observed by the relay. Using the procedure described in [2], we can determine the phase currents observed by the relay as shown in Fig. 2b. This takes into account the differential CT polarity of Winding 2 with respect to Winding 1. Note that for the purpose of this procedure, the magnitudes of Winding 1 and Winding 2 currents are shown as equal. In reality, there may be a difference in the magnitudes due to the ratios and connections of the transformer and CTs. Any magnitude differences between the two currents are equalized by CT ratios and tap settings in the relay and can be ignored when determining angle compensation settings.

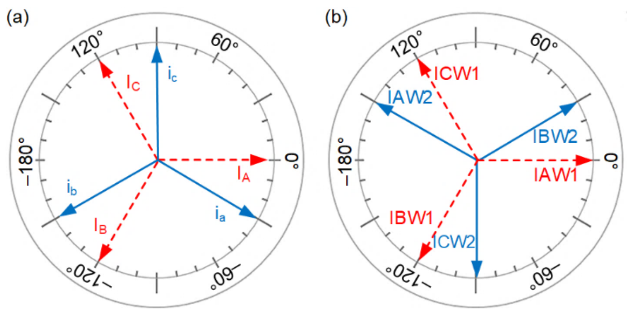

Fig. 2. Phase currents for a Dyn1 transformer with standard connections on the nameplate (a) and at the relay (b)

Step 3 is to select the column of possible matrices in Table VIII that should be used for each winding. In this case, Winding 1 is a delta winding so it should use a wye matrix (a matrix in the "Wye" column of Table VIII). Winding 2 is a wye winding, so it should use a delta matrix (a matrix in the "Delta" column of Table VIII).

Step 4 is to select the matrix for the reference winding as the lowest-numbered compensation matrix that meets the criteria in Step 3a. In this example, we determined in Step 3a that the reference winding (Winding 1, a delta winding) would need a wye matrix. The lowest-numbered wye matrix in Table VIII is in row 0. This matrix provides a phase shift of 0° in the ccw direction for systems with an ABC phase sequence. The resulting Winding 1 currents after compensation are shown in Fig. 3; notice there is no shift between the Winding 1 phasors in Fig. 2b and Fig. 3.

Step 4 also says we must determine the number of degrees the remaining winding (Winding 2) must be shifted for the currents to plot 180° out of phase with the reference winding after angle compensation. Winding 2 from Fig. 2b must be shifted 30° ccw for it to plot 180° out of phase with Winding 1 in Fig. 3. Dividing this angle by 30° tells us that row 1 in Table VIII should be used for compensating Winding 2. Combining this with the result of Step 3a (Winding 2 should use a delta matrix) results in Winding 2 using the delta matrix in row 1. The final compensation matrices are shown in Table I and the currents after compensation are shown in Fig. 3.

The engineer must consult the documentation for the relay being applied to determine how each matrix from Table VIII is selected in the relay. For the relay in this application, the proper matrices are selected by setting the Winding 1 compensation setting to 0 and the Winding 2 compensation setting to 1. Some of the matrices have an additional setting for "Zero-Sequence Removal" (ZSR) that can be set to Y or N to differentiate between a wye and double-delta matrix in the same row, but that does not apply in this example.

TABLE I
COMPENSATION MATRICES FOR DYN1 TRANSFORMER WITH STANDARD CONNECTIONS

Relay Input Terminal	Winding 1 (Reference)	Winding 2
Winding Type	Delta	Wye-ground
Compensation Matrix	Wye matrix, row 0	Delta matrix, row 1

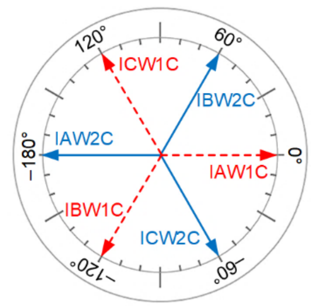

Fig. 3. Phasors after compensation for Dyn1 transformer with standard connections

B. *Example 2: Transformers With Inverted CT Connections*

There are several instances when an engineer may be forced to use CTs with inverted connections in transformer 87R protection. The most common examples are applications where a single CT is shared at a boundary between two differential zones. These situations are especially common at zone boundaries between transformers and buses, as well as between transformers and generators. Another example where an inverted CT connection may be encountered is when CTs connected to a differential relay have been wired incorrectly. This section explains the challenges of each of these situations and gives an example of how to determine correct compensation settings using the steps in Section II.

1) Transformer and Bus Zone Boundaries

In a transformer zone that has a dual breaker terminal, it is desirable to cover the bus and transformer portions of the zone with separate relays [11]. Often, the transformer may not have been originally specified with multiple CT cores on the bushings to support separating the bus zone and the transformer zone at the transformer bushings. To implement the protection upgrade, the available set of CTs may need to be applied as a zone boundary for both zones. In many cases, the bus differential zone must be wired with the correct polarity as shown in Fig. 4 because compensation may not be a feature of a simple bus Kirchhoff's current law (KCL) type differential relay. This leaves the transformer relay observing inverted polarity from the CT at the zone boundary.

There are several ways to account for the inverted polarity in the transformer relay. The first option is to use a CT polarity inversion setting that inverts the polarity of the current being measured before it enters the 87R algorithm. The second option is to use compensation settings. In this example, inverting the polarity on the delta winding can be done by selecting a wye matrix that also inverts the polarity (rotates the currents 6 • 30 = 180°). If the relay does not have this type of matrix available, the correction must be done in wiring. This would typically be accomplished by wiring the CTs to the non-polarity input of the transformer relay. In such an application, selecting the wye matrix in row 6 would allow the CT circuit to be wired conventionally as shown in Fig. 4.

2) Transformer and Generator Boundaries

Another common situation where protection is being upgraded and it becomes desirable to share a CT at a zone boundary is with unit-connected generators. Legacy generator protection installations often had less redundancy due to the number of relays required. In many cases, the generator had a stator differential relay and an overall stator and step-up transformer differential relay. When modernizing using multifunction generator relays, the practice is often to design the new protection for full redundancy. This includes fully redundant differential protection on both the stator and the step-up transformer. Again, the legacy installation may not have enough CTs at the generator terminals to separate the stator and transformer zones with dual differential protection. Fig. 5 shows a typical application. The redundant set of generator and transformer relays is not shown.

In this case, generator terminal CTs must be wired in differential polarity with respect to the generator (as shown in Fig. 5) because the simple KCL differential element used on the stator will typically not support polarity reversal. Inverting the polarity of the CT at the neutral end of the stator (so both terminals are connected with polarity opposite of that shown in Fig. 5) is not an option because the remaining generator protection elements (directional power, loss of field, backup distance, etc.) must be connected with polarity toward the power system.

The same compensation setting solution and wiring solutions as described in the previous case can be used to solve this problem. However, wiring the CTs to the non-polarity input of the transformer relay may not be possible when a single multifunction relay is being used for both stator and transformer differential protection (as is the case in some modern generator relays). For these installations, reversal of the polarity using compensation settings is the only solution.

3) Incorrect Wiring

In addition to inverted CT polarity being an intentional design choice, as shown in Fig. 4 and Fig. 5, it is also possible for it to be the result of incorrect wiring, as shown in Fig. 6. Here, the polarities of the CTs on Winding 1 were inadvertently connected to the non-polarity terminals of the relay inputs. This is the opposite of the two previous cases in that the CTs are in differential polarity with respect to the transformer, while the connections at the relay invert the polarity of the delta-side CTs. However, these connections result in the same current measurements observed by the relay as in the intentional cases discussed previously. We will use the example in Fig. 6 to illustrate obtaining the correct angle compensation settings using the steps in Section II for an installation with inverted CT polarity.

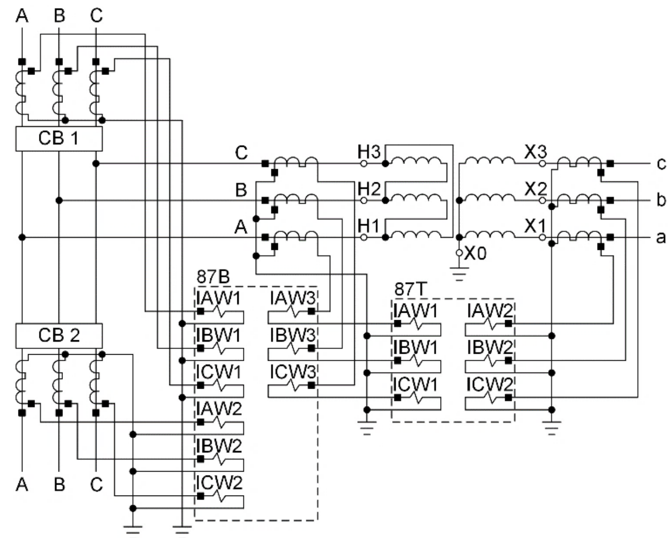

Fig. 4. Sharing a CT between a bus and transformer zone leads to inverted CT connections on the transformer relay

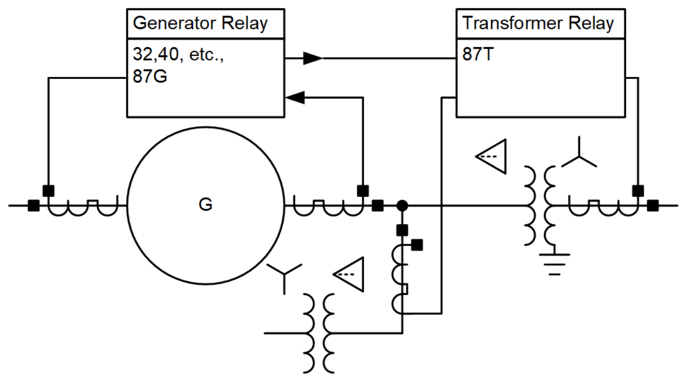

Fig. 5. Sharing a CT between a generator and transformer zone leads to inverted CT connections on the transformer relay

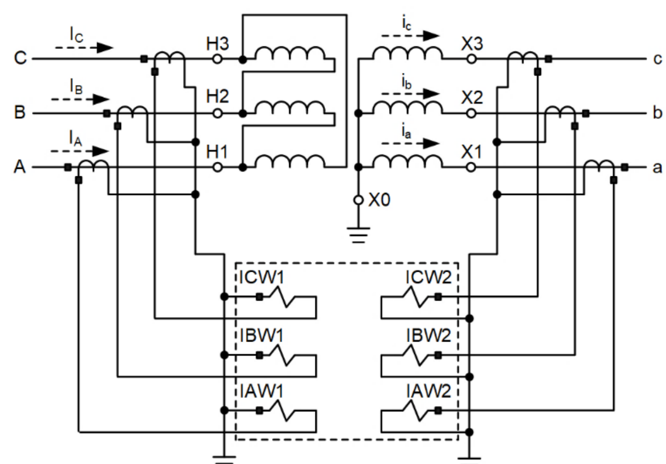

Fig. 6. Dyn1 transformer with incorrect CT-to-relay connections on Winding 1

For Step 1, we can select either winding as the reference. Because Winding 2 (the wye winding) is wired with correct polarity, it can be our reference. Winding 1 (the delta winding) lags the reference by 330°. This is shown in Fig. 7a.

For Step 2, we can determine the phase relationship observed by the relay as shown in Fig. 7b. Notice that the angles are the same as those in Fig. 7a due to the incorrect CT connections on Winding 1.

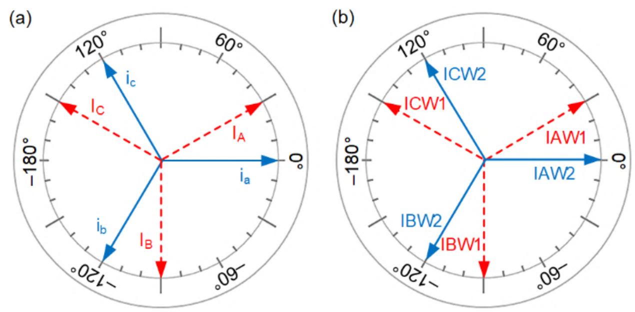

Fig. 7. Phase currents for Dyn1 transformer with incorrect CT connections on the nameplate (a) and at the relay (b)

For Step 3, Winding 1 requires a wye matrix and Winding 2 requiries a delta matrix.

For Step 4, we can select the matrix for the reference winding (Winding 2) as the lowest-numbered delta matrix in Table VIII (the delta matrix in row 1). The resulting Winding 2 currents after compensation are shown in Fig. 8. Next, we determine that Winding 1 in Fig. 7b must be shifted 180° ccw for it to plot 180° out of phase with Winding 2 in Fig. 8. Dividing this angle by 30° tells us that row 6 in Table VIII should be used for compensating Winding 1 (180° / 30° = row 6). Combining this with the result of Step 3a (Winding 1 should use a wye matrix) results in Winding 1 using the wye matrix in row 6. The final compensation matrices are shown in Table II and the currents after compensation are shown in Fig. 8.

Recall that this example is the same transformer in Example 1, but with incorrectly wired CTs on the Winding 1 side. If the compensation settings for Example 1 were already determined before the wiring error was discovered, an intuitive shortcut can be used to correct the compensation and account for the polarity inversion. Simply use the original compensation settings and add 6 multiples of 30° (6 • 30° = 180°) to the winding with inverted polarity (Winding 1). This results in the same compensation settings as following the four-step procedure with Winding 2 as the reference. Note that a relay with all wye matrices available is required to implement this solution. Without all the wye matrices available, the compensation for the terminal that is properly configured would need to be adjusted. This adds complexity when there are multiple properly configured terminals and one miswired terminal, as the compensation for all the properly configured terminals would need to be adjusted.

TABLE II
COMPENSATION MATRICES FOR DYN1 TRANSFORMER WITH INVERTED CT CONNECTIONS

Relay Input Terminal	Winding 1	Winding 2 (Reference)
Winding Type	Delta	Wye-ground
Compensation Matrix	Wye matrix, row 6	Delta matrix, row 1

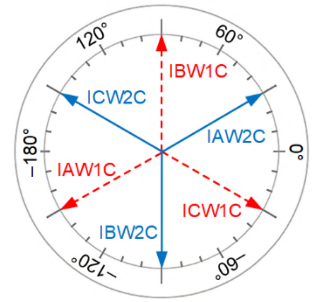

Fig. 8. Phasors after compensation for Dyn1 transformer with incorrect CT wiring

C. *Example 3: Dd2 Transformer With Standard Connections*

This example shows how a relay with all wye matrices available is properly set for a transformer with two delta windings that are not in phase. It also shows the challenges encountered when protecting the transformer with a relay that does not provide a full set of wye matrices. The example shown in Fig. 9 uses a Dd2 transformer and has an ABC system phase sequence, standard phase-to-bushing connections, and standard CT connections. On a standard Dd2 nameplate, the low-side delta lags the high-side delta by 2 • 30° = 60°.

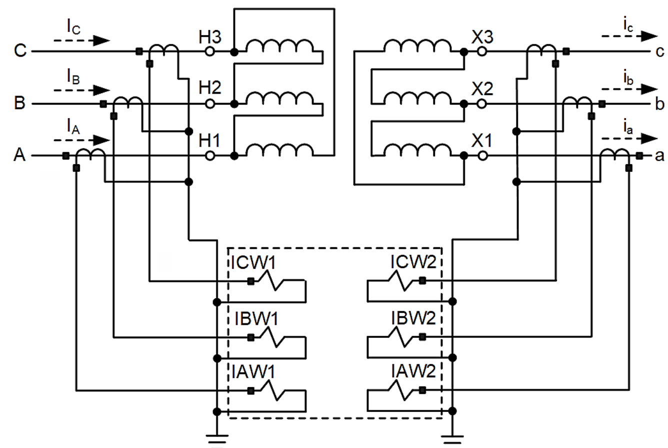

Fig. 9. Dd2 transformer with standard connections

For Step 1, we can select Winding 1 (the high-side delta winding) as our reference. Winding 2 (the low-side delta winding) lags the reference by 60° as shown in Fig. 10a.

For Step 2, we can determine the phase relationship observed by the relay as shown in Fig. 10b. This takes into account the differential CT polarity of Winding 2 with respect to Winding 1.

For Step 3, because this transformer has two delta connections, we should select wye matrices for both Winding 1 and Winding 2.

For Step 4, we can select the matrix for the reference winding (Winding 1) as the lowest-numbered wye matrix in Table VIII (the wye matrix in row 0). The resulting Winding 1 currents after compensation are shown in Fig. 11a. Next, we determine that Winding 2 in Fig. 10b must be shifted 60° ccw for it to plot 180° out of phase with Winding 1 in Fig. 11a. Dividing this angle by 30° tells us that row 2 in Table VIII should be used for compensating Winding 2 (60° / 30° = row 2). Combining this with the result of Step 3a (Winding 2 should use a wye matrix) results in Winding 2 using the wye matrix in row 2. The final compensation matrices are shown in Table III and the currents after compensation are shown in Fig. 11a.

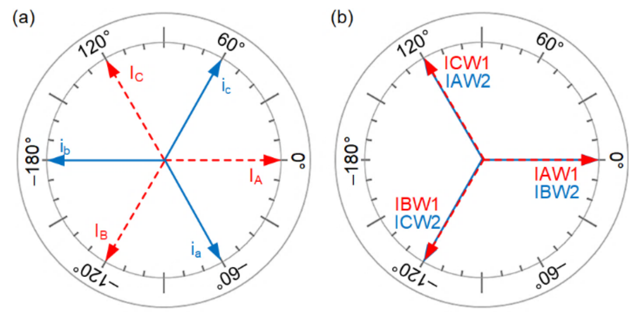

Fig. 10. Phase currents for Dd2 transformer with standard connections on the nameplate (a) and at the relay (b)

TABLE III
COMPENSATION MATRICES FOR DD2 TRANSFORMER WITH STANDARD CONNECTIONS

Relay Input Terminal	**Winding 1 (Reference)**	**Winding 2**
Winding Type	Delta	Delta
Compensation Matrix	Wye matrix, row 0	Wye matrix, row 2

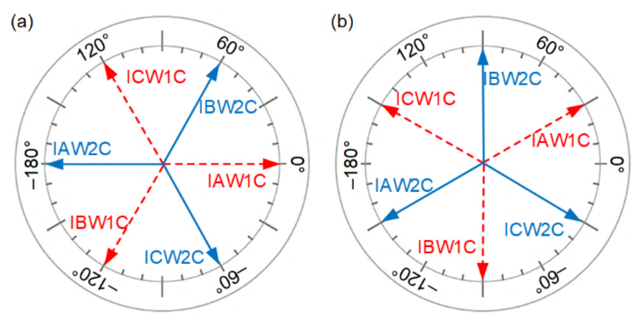

Fig. 11. Phasors after compensation for Dd2 transformer with standard connections using wye matrices (a) and delta matrices (b)

For relays that do not provide a full set of wye matrices, the wye matrix in row 2 may not be available. Following the rules in [2] proves to be a challenge because both windings are delta windings and they cannot both be assigned as the reference winding due to the 60° phase shift between them. There are two common workarounds to this problem. The first sets both windings to the wye matrix in row 0, effectively turning off angle compensation in the relay. The compensation is then performed externally by physically rolling or swapping the phases at the relay terminals to make them 180° out of phase when they arrive at the relay. Using the CT-to-relay connections shown in Fig. 12 will result in the compensated phasors in Fig. 11a.

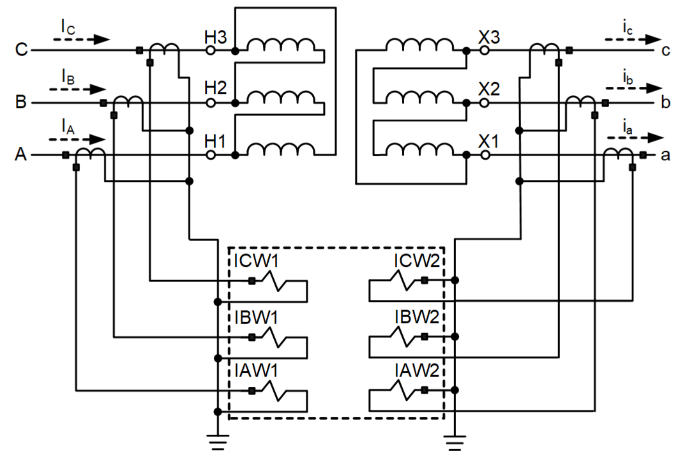

Fig. 12. Dd2 transformer with rolled Winding 2 phase compensation

The second workaround that can be used when a full set of wye matrices is not available is to select delta matrices instead of wye. Instead of selecting a reference winding, both windings are compensated using a delta winding. Selecting the delta matrix in row 1 for Winding 1 currents gives them a 1 • 30° = 30° ccw shift, and selecting the delta matrix in row 3 for Winding 2 gives them a 3 • 30° = 90° ccw shift. The difference between these two phase shifts is the desired 60° shift without having to use a double-delta matrix. Fig. 11b shows the compensated phasors using this method. While this method ensures proper compensation with standard CT-to-relay connections, it is an exception to the rules discussed in [2].

D. *Example 4: Dd4y7 Transformer With Standard Connections*

This example will show how a relay with all wye matrices available is properly set for the Dd4y7 transformer in Fig. 13. The same delta winding challenges exist in this example for relays that do not provide a full set of wye matrices as in the previous example, but with the added complexity of compensating a third wye winding. This installation has an ABC system phase sequence, standard phase-to-bushing connections, and standard CT connections.

For Step 1, we can select Winding 1 (the primary delta winding) as our reference. The phase relationship across the transformer taken from the nameplate data is shown in Fig. 14a. Winding 2 ($I_{a'}$) lags the reference by 4 • 30° = 120° and Winding 3 (I_a) lags the reference by 7 • 30° = 210°.

For Step 2, we can determine the phase relationship observed by the relay as shown in Fig. 14b. This takes into account the differential CT polarities of Windings 2 and 3 with respect to Winding 1.

For Step 3, we should select a wye matrix for Windings 1 and 2, and a delta matrix for Winding 3.

For Step 4, we can select the matrix for the reference winding (Winding 1) as the lowest-numbered wye matrix in Table VIII (the wye matrix in row 0). The resulting Winding 1 currents after compensation are shown in Fig. 15.

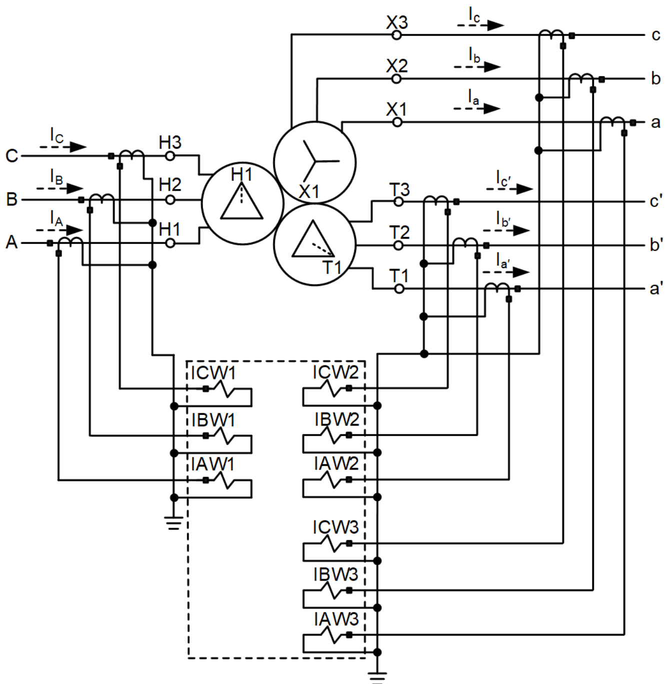

Fig. 13. Dd4y7 transformer with standard connections

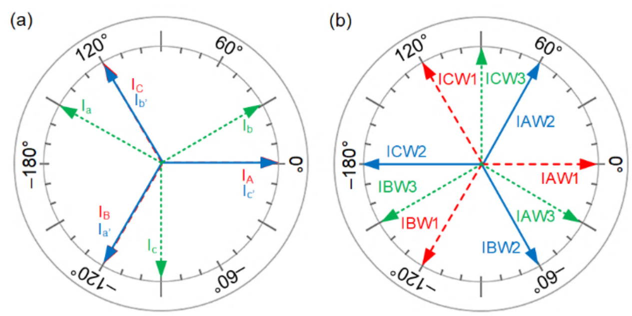

Fig. 14. Phase currents for Dd4y7 transformer with standard connections on the nameplate (a) and at the relay (b)

Next, we determine that Winding 2 in Fig. 14b must be shifted 120° ccw for it to plot 180° out of phase with Winding 1 in Fig. 15. Dividing this angle by 30° tells us that row 4 should be used for compensating Winding 2 (120° / 30° = row 4). Combining this with the result of Step 3a (Winding 2 should use a wye matrix) results in Winding 2 using the wye matrix in row 4.

Next, we determine that Winding 3 in Fig. 14b must be rotated 210° ccw for it to plot 180° out of phase with Winding 1 in Fig. 15. Dividing this angle by 30° tells us that row 7 should be used for compensating Winding 3 (210° / 30° = row 7). Combining this with the result of Step 3a (Winding 3 uses a delta matrix) results in Winding 3 using the delta matrix in row 7. The final compensation matrices are shown in Table IV and the currents after compensation are shown in Fig. 15. Notice the Winding 2 and Winding 3 currents are 180° out of phase with the reference (Winding 1).

TABLE IV
COMPENSATION MATRICES FOR DD4Y7 TRANSFORMER WITH STANDARD CONNECTIONS

Relay Input Terminal	Winding 1 (Reference)	Winding 2	Winding 3
Winding Type	Delta	Delta	Wye-ground
Compensation Matrix	Wye matrix, row 0	Wye matrix, row 4	Delta matrix, row 7

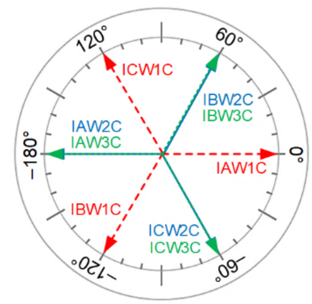

Fig. 15. Phasors after compensation for Dd4y7 transformer with standard connections

For relays that do not provide a full set of wye matrices, the wye matrix in row 4 may not be available. If we were to set Winding 1 as our reference using the wye matrix in row 0, we would need to use the double-delta matrix in row 4 to bring the Winding 2 currents 180° out of phase with Winding 1. As discussed in [2], using double-delta matrices for compensation leaves the relay vulnerable to misoperation during external phase-to-phase faults with CT saturation.

Alternatively, we could try using the delta matrix in row 1 for Winding 1, which allows us to select the delta matrix in row 5 for Winding 2. Although this balances the currents between Windings 1 and 2, Winding 3 now requires the double-delta matrix in row 8 to bring its currents 180° out of phase with Winding 1. This again introduces the undesired double-delta matrix.

The only solution, based on fundamentals, for proper compensation when the wye matrices are not fully supported, is to roll phases. Looking at Fig. 13, the CT on T1 would need to be wired to the IBW2 relay input, the CT on T2 would need to be wired to ICW2, and the CT on T3 would need to be wired to IAW2. Under these conditions, the Winding 1 and Winding 2 currents observed by the relay would be 180° out of phase with each other. Once Winding 1 and Winding 2 are balanced from the wiring changes, no additional angle compensation is required and both windings must be set to use the wye matrix in row 0. Winding 3 must then be set to the delta matrix in row 7. The compensated phasors for this configuration are the same as those in Fig. 15.

E. *Discussion*

The examples in this section showed how to apply the steps in Section II to select angle compensation settings for various transformer configurations when the relay being used supports a full set of wye matrices. The examples also showed several instances when having a limited set of wye matrices in the relay required special workarounds involving rolling phases to the relay. These workarounds are not the most intuitive and add complexity to wiring installations and commissioning procedures. They can also cause confusion for technicians and engineers reviewing event data after a fault, as phase targeting and signal names in the relay may not represent the expected phase in the field. To avoid having to solve compensation challenges with phase rolling, it is greatly beneficial to have a relay capable of compensating with all the matrices shown in Table VIII. This allows the engineer to apply proper compensation using the steps in Section II with settings alone, and no phase swaps are required.

Notice that when all compensation matrices are available, the final compensation matrix rows for each example in this section match the vector group designation on the nameplate of the transformer. For instance, in Example 4 (Dd4y7 transformer), the selected matrix rows were 0, 4, and 7. This shortcut makes selecting the correct compensation matrices incredibly simple, but will only work when the installation meets the "standard installation" requirements described in Section I. It also requires that the vector group designation is written in the standard notation with the primary winding as the reference (at 0°). If these requirements are not met, the engineer must follow the steps in Section II.

IV. Selecting Compensation for Transformers With Nonstandard Phase Shifts

87R protection can also be used to protect transformers with nonstandard phase shifts (i.e., not multiples of 30°). A common example of transformers with nonstandard phase shifts is converter transformers, which are typically used to feed medium-voltage drives or power electronics devices, static frequency converters, and other industrial applications. There are many types of converter transformer designs, three of which are shown in Table V [12].

Table V
Common Converter Transformer Designs

Number of Pulses in One Cycle	Phase Shift Between LV Windings	Number of Transformer LV Windings
18	360° / 18 pulses = 20°	18 pulses / 3 ph / 2 = 3
24	360° / 24 pulses = 15°	24 pulses / 3 ph / 2 = 4
36	360° / 36 pulses = 10°	36 pulses / 3 ph / 2 = 6

Eighteen- and 24-pulse converter transformers are very similar, with 18-pulse applications requiring four restraint inputs (one primary winding and three LV windings) on the relay and 24-pulse applications requiring five restraint inputs (one primary winding and four LV windings) on the relay. Thirty-six-pulse (and sometimes 24-pulse) converter transformers may consist of two transformer cores in the same tank. These installations should be protected as two independent transformers, with each core in its own 87R zone. It is important that these transformers be specified with CTs on both primary windings for this protection to be possible.

A. *Compensating With Standard Matrices*

Any attempt at using only the standard matrices in Table VIII to protect transformers with nonstandard phase shifts will result in the 87R element calculating false differential current for an external fault in one of the power electronics converters, resulting in the need to desensitize the relay with settings. To create compensation that provides the proper ampere-turn balance equations with a relay that only supports compensation for standard phase shifts, external interposing CTs must be used as shown in [12], thereby eliminating the need to perform angle compensation in the relay. It is also possible to use interposing CTs to bring the phase shift across the transformer to a multiple of 30°, at which point compensation can be performed using a relay with only standard matrices available [13].

B. *Compensating With Modern Relays*

If a relay capable of compensating for nonstandard phase shifts is available, there is no need to desensitize the relay or use interposing CTs. Performing the compensation inside the relay simplifies the installation, reduces wiring, and increases sensitivity. How nonstandard phase shift compensation is implemented in a relay can vary. One relay allows the user to specify that they would like to enter in the required phase shift for the winding by selecting a matrix number of 13, followed by the desired shift in degrees [8]. The user also selects whether zero-sequence current should be removed from that winding (ZSR = Y or N). The relay then uses the the selected generalized matrix shown in Appendix B to perform the compensation for the winding. These generalized matrix equations can be used to create a matrix that will shift the currents any number of degrees.

At first glance, it may be tempting to use generalized matrices to compensate for all phase shifts, including standard phase shifts. Inserting angles that are multiples of 30° into the equations in Appendix B should ideally yield all the matrices in Table VIII. Unfortunately, this does not occur for angles of 60°, 180°, and 30°. Therefore, generalized matrices should not be used for windings with standard phase shifts unless the relay firmware manually overrides the generalized matrices in these specific cases with the matrices from Table VIII.

The steps in Section II encourage using the matrices in Table VIII for windings with standard phase shifts and generalized matrices for windings with nonstandard phase shifts.

C. *Example of Determining Compensation Settings for a 24-Pulse Converter Transformer*

This example shows how to select compensation settings for the 24-pulse converter transformer in Fig. 16. The transformer is installed in a standard installation and protected by a relay with five restraint inputs (S, T, U, W, and X). The relay is connected with Terminal S on the primary delta winding and Terminals T, U, W, and X connected to secondary Windings 1, 2, 3, and 4, respectively. The vector group for the transformer is given as Dyn5zn5:30zn6zn6:30. Note that a 15° offset on a 12-hour clock would equate to 30 minutes. To understand the IEC nomenclature of this vector group, see Appendix C.

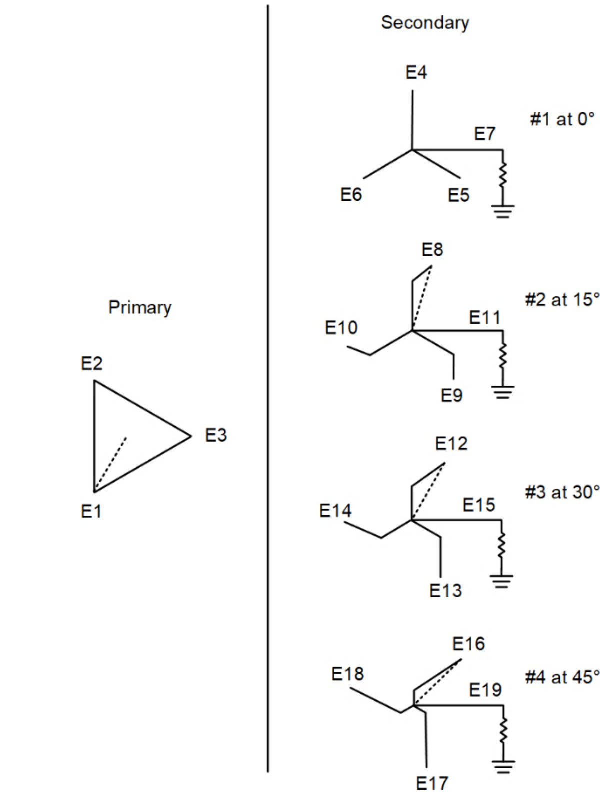

Fig. 16. Nameplate for 24-pulse converter transformer

Step 1 is to select a reference winding and determine the number of degrees that each winding lags the reference in an assumed standard installation. In this example, Terminal S (the primary delta winding) will be our reference. To determine the number of degrees that each winding lags the reference, the vector group of the transformer can be directly used to determine the "Degrees Winding Lags Reference" row in Table VI.

Step 2 is to determine the phase relationship between each winding and the reference winding as observed by the relay. This takes into account the differential CT polarity of Terminals T, U, W, and X with respect to Terminal S, and is shown in the last row of Table VI as well as in Fig. 17.

Step 3 is to identify the compensation matrix type for appropriate zero-sequence removal for each winding. For the terminals with standard phase shifts (S, T, and W), we can use the matrices in Appendix A and select columns in Table VIII. Terminal S will get a wye matrix, Terminal T will get a delta matrix, and Terminal W will get a double-delta matrix. For the terminals with nonstandard phase shifts (U and X), we must use generalized compensation matrices and identify the equation in Appendix B that should be used for each terminal. Because Terminals U and X both have connections to ground, they will use (4). Step 4 is to select the matrix for the reference winding as the lowest-numbered compensation matrix that meets the criteria in Step 3a. In this example, we determined in Step 3a that the reference winding (Terminal S, a delta winding) would need a wye matrix. The lowest-numbered wye matrix in Table VIII is in row 0. The resulting Terminal S currents after compensation are shown in Fig. 18.

Step 4 also says that we must determine the number of degrees the remaining windings must be shifted for them to plot 180° out of phase with the reference winding after angle compensation. Looking at the number of degrees the phasors in Fig. 17 must be shifted, we conclude: Terminal T must be shifted 150°, Terminal U must be shifted 165°, Terminal W must be shifted 180°, and Terminal X must be shifted 195°.

TABLE VI
DETERMINING THE PHASE SHIFT OBSERVED BY THE RELAY USING THE VECTOR GROUP

Relay Input Terminal	S	T	U	W	X
Winding	Primary	#1	#2	#3	#4
Winding Type	Delta	Wye-ground	Zigzag ground	Zigzag ground	Zigzag ground
Vector Group	D	yn5	zn5:30	zn6	zn6:30
Degrees Winding Lags Reference	0°	150°	165°	180°	195°
A-Phase Angle as Observed by Relay	0°	30°	15°	0°	–15°

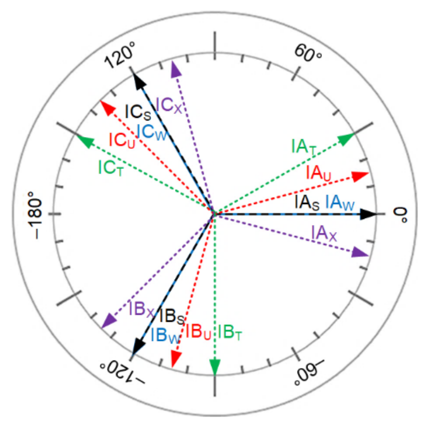

Fig. 17. Phase currents at the relay for 24-pulse converter transformer

For the windings with standard phase shifts (T and W), we can divide their angles by 30° to find that row 5 should be used for Terminal T (150° / 30° = row 5) and row 6 should be used for Terminal W (180° / 30° = row 6). Combining these results with the result of Step 3a (Terminal T should get a delta matrix and Terminal W should get a double-delta matrix) results in the compensation matrices for Terminals T and W in Table VII.

For the windings with nonstandard phase shifts (U and X), we can enter the number of degrees that each winding lags the reference directly in the generalized compensation matrix in (4). The final compensation matrices are shown in Table VII and the currents after compensation are shown in Fig. 18. Notice the Terminal T, U, W, and X currents are 180° out of phase with the reference (Terminal S).

The "relay implementation" row of Table VII shows how these compensation settings are implemented in a modern relay [8].

TABLE VII
ANGLE COMPENSATION SETTINGS FOR 24-PULSE CONVERTER TRANSFORMER

Relay Input Terminal	S (Reference)	T	U	W	X
Winding Type	Delta	Wye-ground	Zigzag ground	Zigzag ground	Zigzag ground
Compensation Matrix	Wye matrix, row 0	Delta matrix, row 5	Equation (4) with $\phi = 165°$	Double-delta matrix, row 6	Equation (4) with $\phi = 195°$
Relay Implementation	TSCTC=0	TTCTC=5	TUCTC=13 TUANG=165 TUZSR=Y	TWCTC=6 TWZSR=Y	TXCTC=13 TXANG=195 TXZSR=Y

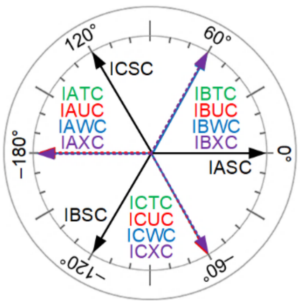

Fig. 18. Phasors after compensation for a 24-pulse converter transformer with standard connections

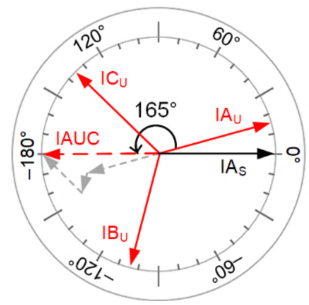

Fig. 19. Phasor example of a generalized compensation matrix

D. Obtaining Nonstandard Phase Shifts With Generalized Compensation Matrices

It is interesting to see how the generalized compensation matrices produce nonstandard phase shifts. In the previous example, Winding U required a zero-sequence current to be removed and a nonstandard phase shift of 165°. To do this, (4) is used with $\phi = 165°$. Equation (2) derives the matrix coefficients for the resulting compensation matrix.

$$\frac{2}{3}\begin{bmatrix} \cos(165°) & \cos(165°+120°) & \cos(165°-120°) \\ \cos(165°-120°) & \cos(165°) & \cos(165°+120°) \\ \cos(165°+120°) & \cos(165°-120°) & \cos(165°) \end{bmatrix} = \begin{bmatrix} -0.644 & 0.173 & 0.471 \\ 0.471 & -0.644 & 0.173 \\ 0.173 & 0.471 & -0.644 \end{bmatrix} \quad (2)$$

Equation (1) showed how compensation matrices are applied to a set of winding currents. Applying (2) to a balanced set of currents on Terminal U with an ABC phase sequence, we get:

$$\begin{bmatrix} IAUC \\ IBUC \\ ICUC \end{bmatrix} = \begin{bmatrix} -0.644 & 0.173 & 0.471 \\ 0.471 & -0.644 & 0.173 \\ 0.173 & 0.471 & -0.644 \end{bmatrix} \bullet \begin{bmatrix} IA_U \\ IB_U \\ IC_U \end{bmatrix} \quad (3)$$

The top row of (3) shows that the A-phase compensated current, IAUC, is calculated as:

$$IAUC = -0.644 \bullet IA_U + 0.173 \bullet IB_U + 0.471 \bullet IC_U$$

This is shown graphically in Fig. 19. Notice that IAUC is rotated 165° ccw with equal magnitude relative to IA_U. The compensated current IAUC is now 180° out of phase with the reference (IA_S).

V. CONCLUSION

Incorrect phase angle compensation settings continue to be a leading cause of transformer relay misoperations. Although selecting compensation settings should be straightforward, many field installations are not standard, leading to more involved processes in selecting compensation settings.

This paper showed that for relays that support all compensation matrices included in [5], the rules for selecting correct compensation matrices are greatly simplified. Section II showed the steps that can be used to correctly set angle compensation in these relays. These steps are based on the fundamentals of ampere-turn balance and lead to simple and direct settings that, in standard installations, can be read directly from the nameplate. For relays with a limited set of wye matrices available, selecting compensation settings becomes more complicated and may require rolling phases to accommodate for some installations. The rules that should be followed when selecting compensation matrices for relays with a limited set of wye matrices are documented in [2].

This paper also showed how the addition of generalized compensation matrices to transformer relays can be used to provide compensation for transformers with nonstandard phase shifts. The steps in Section II can also be used to determine compensation settings for these applications. The flexibility of generalized compensation matrices allows 87R protection to be easily applied to converter transformers and other applications with nonstandard phase shifts, without the complication of interposing CTs.

VI. Appendix A

Table VIII shows the matrices available in [5] to compensate for phase shifts in increments of 30°. In Table VIII, "cw" is clockwise and "ccw" is counterclockwise. The settings below each matrix show how the matrix can be selected in a microprocessor-based relay [8].

TABLE VIII
COMPENSATION MATRICES FOR STANDARD PHASE SHIFTS AVAILABLE IN IEEE C37.91

Row	System Phase Sequence	Degree Shift That Matrix Provides	Wye	Delta	Double-Delta
0	ABC	0 • 30° = 0° ccw	$\begin{bmatrix}1 & 0 & 0\\0 & 1 & 0\\0 & 0 & 1\end{bmatrix}$ Matrix number = 0		$\frac{1}{3}\begin{bmatrix}2 & -1 & -1\\-1 & 2 & -1\\-1 & -1 & 2\end{bmatrix}$ Matrix number = 12
	ACB	0 • 30° = 0° cw			
1	ABC	1 • 30° = 30° ccw		$\frac{1}{\sqrt{3}}\begin{bmatrix}1 & -1 & 0\\0 & 1 & -1\\-1 & 0 & 1\end{bmatrix}$ Matrix number = 1	
	ACB	1 • 30° = 30° cw			
2	ABC	2 • 30° = 60° ccw	$\begin{bmatrix}0 & -1 & 0\\0 & 0 & -1\\-1 & 0 & 0\end{bmatrix}$ Matrix number = 2 ZSR = N		$\frac{1}{3}\begin{bmatrix}1 & -2 & 1\\1 & 1 & -2\\-2 & 1 & 1\end{bmatrix}$ Matrix number = 2 ZSR = Y
	ACB	2 • 30° = 60° cw			
3	ABC	3 • 30° = 90° ccw		$\frac{1}{\sqrt{3}}\begin{bmatrix}0 & -1 & 1\\1 & 0 & -1\\-1 & 1 & 0\end{bmatrix}$ Matrix number = 3	
	ACB	3 • 30° = 90° cw			
4	ABC	4 • 30° = 120° ccw	$\begin{bmatrix}0 & 0 & 1\\1 & 0 & 0\\0 & 1 & 0\end{bmatrix}$ Matrix number = 4 ZSR = N		$\frac{1}{3}\begin{bmatrix}-1 & -1 & 2\\2 & -1 & -1\\-1 & 2 & -1\end{bmatrix}$ Matrix number = 4 ZSR = Y
	ACB	4 • 30° = 120° cw			
5	ABC	5 • 30° = 150° ccw		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1 & 0 & 1\\1 & -1 & 0\\0 & 1 & -1\end{bmatrix}$ Matrix number = 5	
	ACB	5 • 30° = 150° cw			
6	ABC	6 • 30° = 180° ccw	$\begin{bmatrix}-1 & 0 & 0\\0 & -1 & 0\\0 & 0 & -1\end{bmatrix}$ Matrix number = 6 ZSR = N		$\frac{1}{3}\begin{bmatrix}-2 & 1 & 1\\1 & -2 & 1\\1 & 1 & -2\end{bmatrix}$ Matrix number = 6 ZSR = Y
	ACB	6 • 30° = 180° cw			
7	ABC	7 • 30° = 210° ccw		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1 & 1 & 0\\0 & -1 & 1\\1 & 0 & -1\end{bmatrix}$ Matrix number = 7	
	ACB	7 • 30° = 210° cw			
8	ABC	8 • 30° = 240° ccw	$\begin{bmatrix}0 & 1 & 0\\0 & 0 & 1\\1 & 0 & 0\end{bmatrix}$ Matrix number = 8 ZSR = N		$\frac{1}{3}\begin{bmatrix}-1 & 2 & -1\\-1 & -1 & 2\\2 & -1 & -1\end{bmatrix}$ Matrix number = 8 ZSR = Y
	ACB	8 • 30° = 240° cw			
9	ABC	9 • 30° = 270° ccw		$\frac{1}{\sqrt{3}}\begin{bmatrix}0 & 1 & -1\\-1 & 0 & 1\\1 & -1 & 0\end{bmatrix}$ Matrix number = 9	
	ACB	9 • 30° = 270° cw			

10	ABC	10 • 30° = 300° ccw	$\begin{bmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \end{bmatrix}$ Matrix number = 10 ZSR = N		$\frac{1}{3}\begin{bmatrix} 1 & 1 & -2 \\ -2 & 1 & 1 \\ 1 & -2 & 1 \end{bmatrix}$ Matrix number = 10 ZSR = Y
	ACB	10 • 30° = 300° cw			
11	ABC	11 • 30° = 330° ccw		$\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$ Matrix number = 11	
	ACB	11 • 30° = 330° cw			

VII. Appendix B

This appendix shows generalized matrices that can be used to compensate for phase shifts of any angle [8] [14]. Equation (4) performs the compensation and removes zero-sequence current, while (5) performs the compensation without removing zero-sequence current. The variable ϕ is the angle that the matrix will shift the currents in the ccw direction for systems with an ABC phase sequence (or cw for systems with an ACB phase sequence).

$$\frac{2}{3}\begin{bmatrix} \cos(\phi) & \cos(\phi+120°) & \cos(\phi-120°) \\ \cos(\phi-120°) & \cos(\phi) & \cos(\phi+120°) \\ \cos(\phi+120°) & \cos(\phi-120°) & \cos(\phi) \end{bmatrix} \quad (4)$$

$$\frac{2}{3}\begin{bmatrix} 0.5+\cos(\phi) & 0.5+\cos(\phi+120°) & 0.5+\cos(\phi-120°) \\ 0.5+\cos(\phi-120°) & 0.5+\cos(\phi) & 0.5+\cos(\phi+120°) \\ 0.5+\cos(\phi+120°) & 0.5+\cos(\phi-120°) & 0.5+\cos(\phi) \end{bmatrix} \quad (5)$$

VIII. Appendix C

Step 1 in Section II is most easily performed when the IEC vector group of a transformer is known. An IEC vector group is a notation that shows how each winding on a transformer is connected as well as how many multiples of 30° each winding lags the primary winding. If the IEC vector group for a transformer is not known, use the process in the following example to derive the IEC vector group from the transformer nameplate.

This example derives the IEC vector group from the nameplate of the example in Section IV. It is reproduced in Fig. 20 for convenience.

The process to convert the nameplate to a vector group is shown in Table IX. The first two rows in the table describe how each winding is connected per the nameplate. Row 3 shows the absolute angle of A-phase based on the nameplate drawing. On a standard nameplate, A-phase is assumed to connect to the terminal with the lowest non-zero number. Because the primary winding is the reference and must be at 0° per IEC, row 4 adds 120° to all the angles to bring the reference to 0°. Row 5 converts the angles to the number of degrees each winding lags the primary winding. Row 6 converts the angles to a multiple of 30°. Angles that are not exact multiples of 30° can be written as a number of multipes of 30° plus a remainder. This remainder is then converted to minutes. A 15° offset on a 12-hour clock would equate to 30 minutes.

Finally, row 7 determines the vector group for each winding in IEC notation. IEC notation starts with the primary winding as the reference (D), followed by the winding type of each subsequent winding (“d” for delta, “yn” for wye-grounded, and “zn” for zigzag grounded) as well as how many hours (or multiples of 30°) and minutes that winding lags the reference. The vector group zn6:30 would lag the reference by 6 hours and 30 minutes, which equates to 195°. The final vector group for this transformer is Dyn5zn5:30zn6zn6:30.

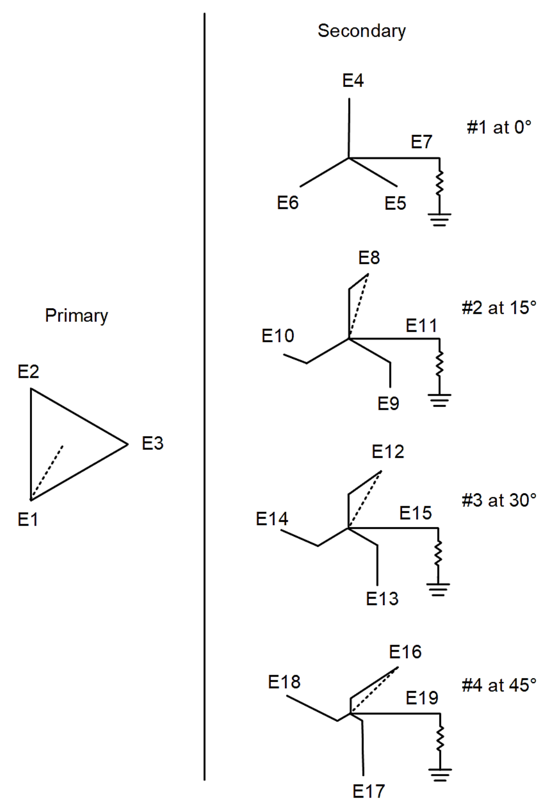

Fig. 20. Nameplate for 24-pulse converter transformer

TABLE IX
USING THE NAMEPLATE TO DETERMINE THE VECTOR GROUP

1	**Winding**	Primary	#1	#2	#3	#4
2	**Winding Type**	Delta	Wye-ground	Zigzag ground	Zigzag ground	Zigzag ground
3	**Absolute Angle of A-Phase (From Nameplate)**	–120°	90°	75°	60°	45°
4	**Relative Angle of A-Phase to Reference**	0°	210°	195°	180°	165°
5	**Degrees Winding Lags Reference**	0°	150°	165°	180°	195°
6	**Multiples of 30°**	0	5	5 + 15° = 5 + 30 minutes	6	6 + 15° = 6 + 30 minutes
7	**Vector Group**	D	yn5	zn5:30	zn6	zn6:30

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X. BIOGRAPHIES

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