Modern Protection of Three-Phase and Spare Transformer Banks

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***Abstract*—Three-phase-and-spare transformer banks are used for important transmission and generator applications. Given the importance of large transformer banks to the operation of the bulk electric system and the long lead time to repair or replace these critical assets, migrating to three-phase and spare designs is one way to improve the resiliency of the grid. Often, the spare transformer cannot easily be energized or periodically substituted into the bank and therefore may sit for decades until required, at which time it may not be fit for service. Differential protection circuits often require complicated modifications to accommodate substituting the spare transformer into the bank after a failure. This paper examines two example applications and describes the use of modern protection technology to precisely identify the faulted equipment, simplify wiring, and allow easy, automatic reconfiguration of protection zones to facilitate quickly returning an important transmission facility to service.**

I. Introduction

Three-single-phase-and-spare transformer banks are used for important transmission and generator applications. In some cases, three single-phase transformers are used to facilitate the construction and transport of very large-capacity transformers where a three-phase transformer may be too heavy. In other cases, three-single-phase-and-spare transformer banks are used to improve fault tolerance by providing a fourth single-phase transformer that can be substituted for a failed one to enable fast restoration of a critical path in the transmission grid.

Major equipment, such as transformer banks, are very expensive devices with long lead times. The size of the equipment required means that repair or replacement projects take a great deal of planning and time. For this reason, system planning engineers must often consider overbuilding facilities to deal with extended outages. If the expected outage times can be reduced to hours instead of weeks, months, or years, the cost of building new bulk power system facilities can be significantly reduced. Further, concern about sabotage [1] damaging transmission assets that can take months or years to repair or replace can be mitigated by using three-single-phase-and-spare transformer bank installations and single-phase rapid-response mobile resiliency transformers.

Normally, after a three-single-phase-and-spare transformer bank has been tripped by a protective relay operation, determining the failed transformer, isolating it, and substituting the spare to return the transformer bank to service can take many days. It is often necessary to unbus and perform extensive testing of each transformer to determine the cause of the trip. Once it has been determined that the spare should be inserted, many days of complex wiring, testing, and reconfiguration of the protection systems by personnel with specialized knowledge is required before the bank can be returned to service.

In most installations, the differential current transformer (CT) circuits have to be manually rewired and tested to insert the spare transformer [2]. Alternatively, very complex switching circuits can be designed and installed to allow fast reconfiguration of the CT circuits. The authors have seen one such installation that used empty draw-out relay cases with jumpers to switch the CT circuits between the three of four transformers and the three differential relays. To reconfigure the differential circuits, operators only had to insert and remove test paddles from the cases. The complexity of the wiring to achieve fast restoration is daunting to design and verify.

Because of the difficulty in inserting the spare transformer, often the spare remains de-energized and out of service for decades until called upon for service. At that point, it may not be fit for service. One of the motivations for writing this paper is to show how to make it so easy to substitute a spare that it can become standard practice to switch the bank configuration quarterly (i.e., the spare is idle for three months, substituted to Phase A for three months, and so on). With regular operational practice, restoration of a critical bank after a failure could be accomplished in hours instead of weeks.

Modern protection technology can be used to speed up restoration in these applications. The protection systems can be designed to provide positive identification of the precise location of any fault within the transformer zone of protection. By providing precise indication of whether the fault is located in one of the transformers or in the lead buswork, operators can immediately initiate switching procedures to substitute the spare transformer for the failed one without waiting for extensive and time-consuming transformer testing to assess the situation. Coupled with precise fault location indication, if the protection system design includes automatic reconfiguration for any transformer out-of-service (TOOS) configuration, the dilemma of whether to initiate reconfiguring the bank and returning it to service right away is significantly reduced. Modern protection technology enables this new way for planning and operations personnel to think.

Finally, modern multifunction transformer protection systems can provide enhanced sensitivity and speed of operation to minimize damage and possibly enable a simple repair instead of replacement of the failed transformer.

This paper analyzes and provides recommendations for two common applications on the bulk electric power system: the transmission substation autotransformer that interconnects the extra-high voltage grid to the transmission and subtransmission grid, and the generator-step-up (GSU) transformer.

II. Transformer Bank Configurations

There are three general configurations for three-single-phase-and-spare transformer banks. The first requires the failed transformer to be removed from the pad and the spare to be moved into its place. This paper does not discuss applications designed in this way. The second configuration has a designated spare transformer that can be substituted for any of the three normally in-service transformers. Fig. 1 shows this general configuration for a substation autotransformer application. The figure shows switches for reconfiguring the bank. In many applications, removable buswork links are used to reconfigure the primary connections. The switches are shown with T2 out of service and T4 (the spare) inserted into Phase B.

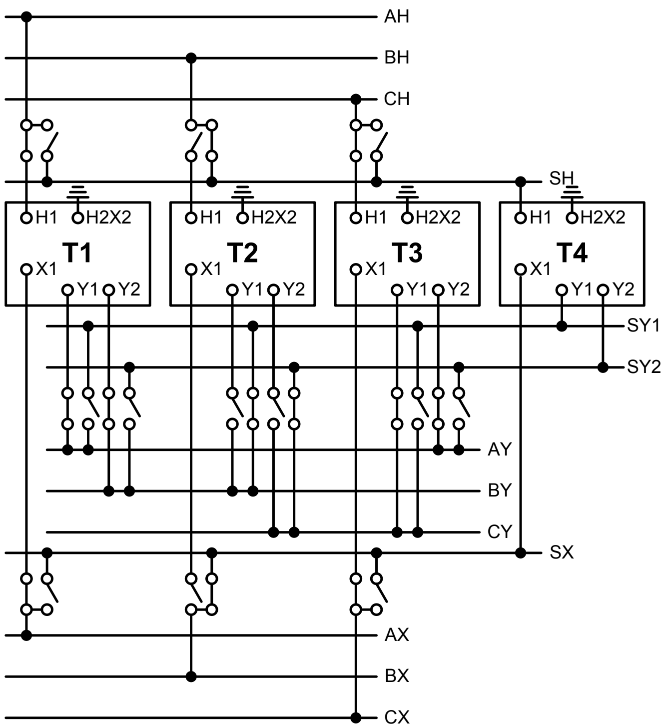

Fig. 1. Installation with a designated spare transformer

The third configuration does not have a designated spare transformer. Each of the high- and low-side phases can be landed on one of two transformers to reconfigure the bank. Fig. 2 shows this general configuration for a substation autotransformer application. The bank is shown with T2 out of service.

The examples in this paper use this third configuration. However, all of the concepts that are presented are easily adapted to the second configuration.

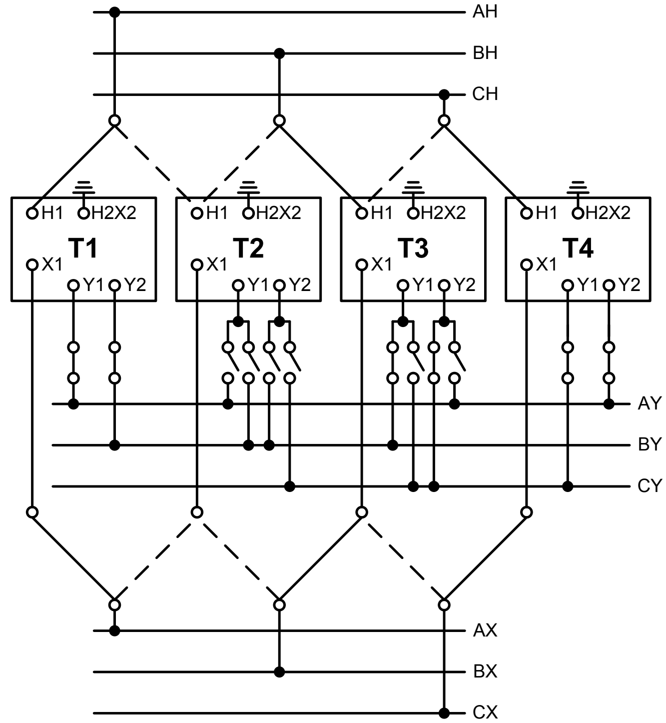

Fig. 2. Installation with two positions for each phase

III. Fundamentals of Transformer Protection

A. Protection Concepts for Single-Phase Transformers

Proper transformer protection requires matching ampere-turns (ATs) around the magnetic circuit of the transformer core [3]. Following this concept for common three-legged core transformers requires writing the AT balance (ATB) equations around all three loops in the magnetic circuit. By doing so, we accommodate zero-sequence flux that returns outside the core, given that there is no magnetic path in a three-legged core for this flux. By following this methodology, we accomplish both phase-shift and zero-sequence compensation, which usually includes delta-compensated currents being applied to the restraint inputs of the differential relay that are associated with grounded wye-connected windings.

Single-phase transformers have a closed magnetic circuit for each phase. This allows us to write the ATB equations for each phase independently as long as we can measure the current in each winding of the transformer. This means that it is necessary to have CTs inside the delta of any delta-connected set of windings. Because the CTs are typically on the bushings of the transformer and any delta connection has to use external cables or buswork to interconnect the three single-phase transformers, this is easily accomplished. Zero-sequence compensation using delta compensation is not necessary. Thus, it is possible to configure the differential elements to precisely identify the faulted transformer in a three-single-phase transformer bank. This significant advantage is used where possible in the recommended protection schemes presented in this paper.

Fig. 3 illustrates the ATB equation for a single-phase autotransformer with a tertiary winding. The ATB equation (21) from [3] is reproduced here as (1).

$$AT = (n_S + n_C) \bullet i_H + n_C \bullet i_X + n_Y \bullet i_Y \quad (1)$$

Note that in Fig. 3, the secondary windings of the CTs on each end of the delta winding are paralleled with additive polarity such that i_Y is measured twice. This connection allows fault current in the Y winding to be measured with equal sensitivity regardless of whether the internal fault is closer to the Y1 terminal or the Y2 terminal. When calculating tap compensation factors for this winding, the effective CT ratio (CTR) is the primary rating to 10 A secondary instead of the primary rating to 5 A secondary as shown on the CT nameplate (5 A nominal CTs are assumed to illustrate the point). The effective CTR in this configuration is half of the number of turns versus configurations in which only one CT is used to measure i_Y.

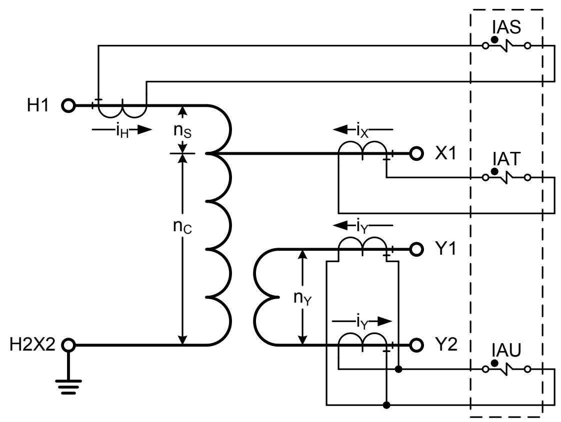

Fig. 3. ATB differential protection for Phase A of a three-single-phase autotransformer bank

To calculate the magnitude normalization tap factors for this configuration, the traditional tap equations are modified from a three-phase basis to a single-phase basis, as shown in (2).

$$TAPn = \frac{MVA_{T1\Phi} \bullet 1000}{KVn_{WINDING} \bullet CTRn} \quad (2)$$

where:

n is the current input designation.

TAP is the magnitude normalization factor.

$MVA_{T1\Phi}$ is the single-phase rating of the transformer in megavolt amperes (MVA).

$KV_{WINDING}$ is the voltage rating of the winding in kilovolts. For wye-connected windings, this is the line-to-neutral rating.

When the CTs feeding the scheme are connected to the bushing CTs of the single-phase transformers as shown in Fig. 3, positive faulted tank indication is provided. However, the buswork is excluded from the zones of protection, requiring a separate bus differential relay to cover this portion of the transformer zone.

B. Partial-Winding Fault Protection

Partial-winding faults can be difficult for the phase differential element to detect. Partial-winding faults include turn-to-turn faults and turn-to-ground faults. When a few turns are shorted on a transformer winding, the transformer acts as an autotransformer. There is high current in the shorted turns, but this high current is stepped down by the ratio of shorted turns to full-winding turns so that the differential current seen at the phase terminals of the transformer is small. A winding-to-ground fault is especially difficult for the phase differential elements to detect when it is near the neutral point of a grounded wye-connected winding.

The short-circuit current in a turn-to-turn or turn-to-ground fault can be very high and dissipate a great deal of energy at the location of the fault. Providing protective elements that are sensitive to these types of faults can allow these faults to be detected and isolated before they evolve to involve more turns, allowing the phase differential element to detect the larger fault current. Sensitive protection that detects these faults before they evolve can often mean the difference between repair and replacement of the transformer.

1) Sudden Pressure Protection (63 w/50P)

The sudden pressure relay is the classic device for detecting turn-to-turn faults inside the tank [4]. This protective relay detects the rapid pressure rise caused by the energy in the arc across the shorted turns. Because each transformer tank is isolated from the others, this protective function provides a positive indication of the faulted tank.

In very large transformers, this element can misoperate because of winding movement during high-current external faults. One solution to this problem is to use current supervision to improve the security of the element. The one-line diagrams illustrating the recommended schemes for the applications in this paper (Fig. 9, Fig. 16, Fig. 18, and Fig. 19) show the 63 function connected to a relay and the function code “63 w/50P” used to indicate this overcurrent supervision function. The 63 devices are wired to trip through the microprocessor-based relay for sequence-of-events recording and target reporting.

Another security issue with sudden pressure relays can be caused by moisture contamination across the microswitch tripping contact that can cause the switch to arc over. The device is mounted on the transformer tank, an environment where electrical surges can also cause this contact to arc over. In many cases, a sudden pressure auxiliary tripping relay is installed that uses the b side of the Form c contact to short the tripping coil. Thus, “63a and NOT 63b” logic is obtained by contact logic. A trip cannot occur unless the Form c contact actually changes state.

Fig. 4 shows two ways to implement this logic using microprocessor-based relays so that this electromechanical auxiliary relay can be eliminated to improve reliability for this function. The top diagram and logic uses two inputs to the relay. The bottom diagram and logic uses only one. The bottom diagram requires installing a loading resistor to prevent a dc short circuit if the 63a contact arcs over. The timer is set for about a one-cycle delay to ensure that the 50 element has time to assert. If the scheme does not require overcurrent supervision, the timer and 50P element can be eliminated.

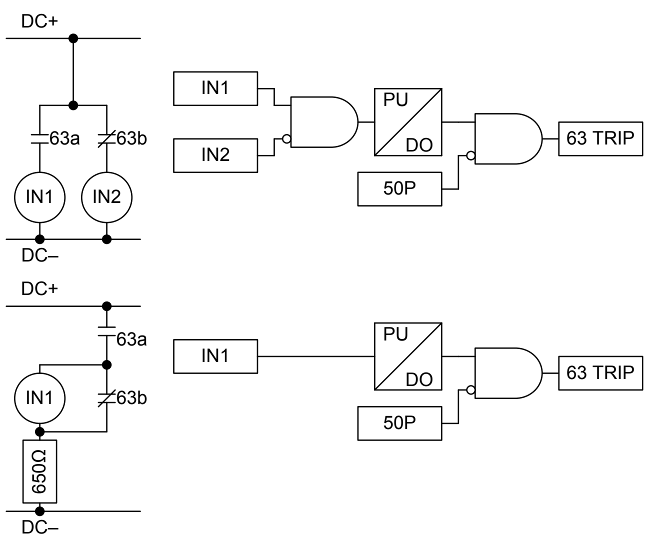

Fig. 4. Sudden pressure tripping via relay logic

2) Transformer Restricted Earth Fault (REF) Protection

REF protection is recommended to detect faults near the neutral terminal of any wye-connected winding [3]. For these faults, the phase currents measured at the terminals of the transformer can be quite low, while the current in the shorted turns can be very high, quickly damaging the transformer. REF schemes take advantage of the fact that the current in the fault loop can be measured directly by the neutral bushing CT. The following are the two main schemes used for REF protection [5]:

- Current-polarized directional ground element.
- High-impedance differential element.

REF schemes work on the principle of Kirchoff's current law (KCL), summing the zero-sequence currents around the transformer zone. They do not balance ATs and therefore do not detect turn-to-turn faults, only turn-to-ground faults.

A three-single-phase-and-spare bank includes four separate transformers with four separate neutral bushing CTs that must be summed to measure the neutral current. This presents problems for traditional schemes, but it also presents an opportunity to obtain positive faulted-transformer identification. So, a modified scheme (described later in this section) is recommended.

a) Current-polarized directional REF scheme

The directional schemes available in transformer relays use the current in the power transformer neutral as the operating signal and the current in the residual at the boundary of the zone as the reference signal, as shown in Fig. 5. A simple directional comparator can determine if the ground fault is internal or external to the transformer zone.

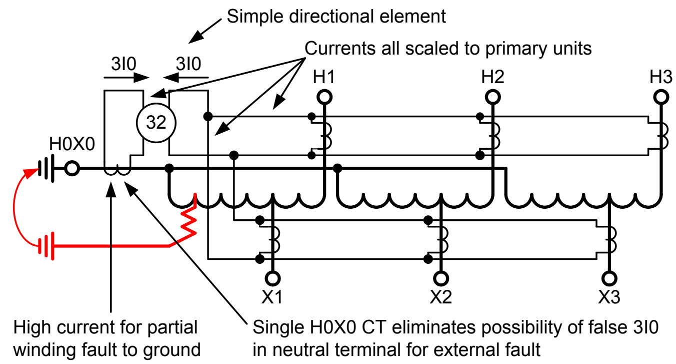

Fig. 5. Traditional current-polarized directional REF scheme for autotransformers

These schemes can be set with high sensitivity because they count on the fact that the neutral of a three-phase power transformer is made up inside the tank and the ground current can be measured using a single CT. There is no chance of false zero-sequence current in the operating signal because of CT performance issues for an external fault not involving ground.

This type of scheme is of limited usefulness for three-single-phase-and-spare applications for the following reasons:

- With single-phase transformers, current at the neutral is measured with a residual connection of the three neutral bushing CTs. Thus, the main characteristic that provides high sensitivity with high security, using a single CT to measure the 3I0 operating signal, is not possible without providing an insulated neutral bus to make the wye connection and running a single ground lead from the neutral bus through a CT to ground.
- These schemes typically do not provide positive faulted-transformer indication.

b) High-impedance differential REF scheme

A high-impedance differential REF scheme is connected so that the zero-sequence current sums to zero between the neutral CT and the residual of the phase CTs. Fig. 6 shows this implementation for an autotransformer. This scheme has inherently high security for false residual currents and, therefore, is suitable for this application, where a residual connection of three CTs is included at the neutral of the power transformer.

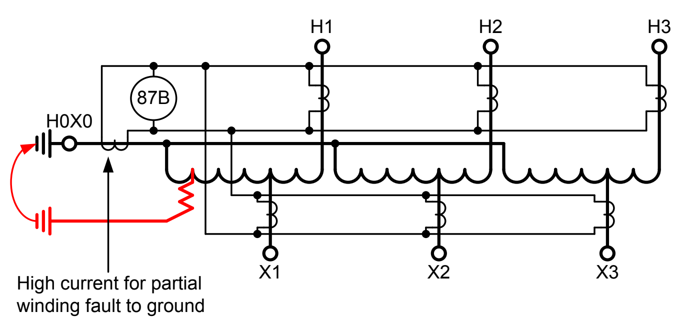

Fig. 6. Traditional high-impedance REF scheme for autotransformers

If a microprocessor-based, three-phase, high-impedance relay is applied, this scheme could be modified to use the three separate elements—one for each tank—as shown in Fig. 7. This would provide a faulted transformer identification [6]. However, this scheme requires dedicated equal-ratio CTs, which increase wiring, and it has no way of accommodating the spare transformer without using a separate relay or physically switching CT secondary circuits.

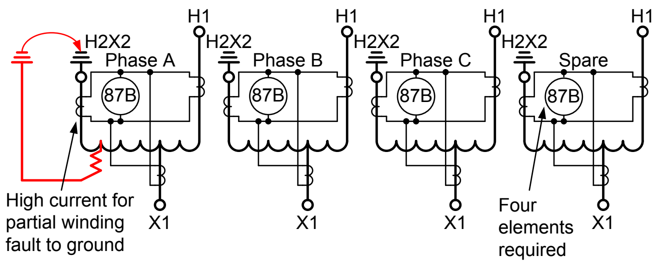

Fig. 7. Modified high-impedance REF scheme to provide positive phase identification for single-phase banks

c) Modified REF scheme

A low-impedance bus differential relay with advanced zone switching capability can be used as shown in Fig. 8 to cover the three in-service transformers. These advanced bus differential relays often include two sets of differential elements. Because the recommended schemes presented later in this paper have bus differential relays for covering the buswork external to the transformer tanks, the extra set of zones available in the low-impedance bus differential relays can be used to provide phase-segregated REF protection. The three zones can be switched inside the relay based on bank configuration to cover the spare. Also, a KCL differential relay does not have to contend with magnetic effects such as inrush because it sums the currents in an electrical node. Thus, a bus differential relay without harmonic restraint is suitable.

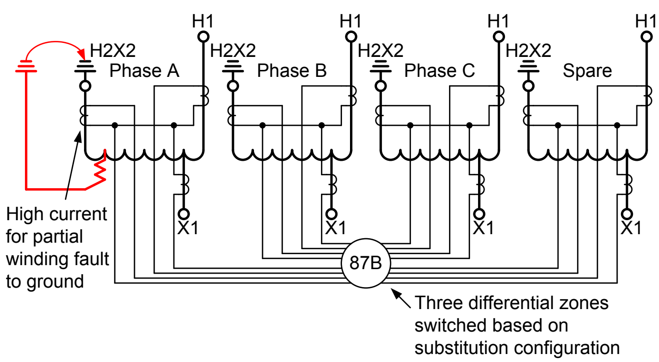

Fig. 8. Low-impedance REF scheme to provide positive phase indication and spare substitution

3) Negative-Sequence Differential Protection (87Q)

Negative-sequence differential protection can provide superior sensitivity to all faults in the zone, including turn-to-turn faults, because there is very little negative-sequence through current during normal load flow to restrain the relay [3] [7]. The highly sensitive 87Q element is disabled by an external fault detector during external faults where false negative-sequence current can occur because of CT performance issues.

Negative-sequence differential protection is very important in providing sensitive electrical detection of partial-winding faults to supplement the mechanical detection provided by the sudden pressure relay. Reference [8] reports a case where the negative-sequence differential element tripped for a turn-to-turn fault caused by the transient launched by a capacitor bank switching restrike event. The 87Q element tripped before enough energy was dissipated inside the transformer tank to trip the sudden pressure relay.

For three-single-phase-and-spare bank applications, providing negative-sequence differential protection can be difficult. Negative-sequence current is derived from the three-phase currents. If the method of inserting the currents from the spare transformer results in one set of three-phase current inputs having two phases and another set having one phase, even though the negative-sequence operate current would properly balance, the relay would measure a high negative-sequence load flow that would restrain the differential element.

In the proposed protection schemes shown later in this paper, an effort has been made to ensure that at least one of the Main A and Main B protection schemes is configured to provide 87Q protection. In cases where only one protection system has an 87Q element, the sudden pressure relaying is configured to trip through the other protection system.

One downside of the negative-sequence differential protection for this application is that these elements do not typically provide positive faulted-phase identification.

C. Low-Oil Tripping (71Q)

The recommended schemes in this paper all include tripping on low oil. Oil leaks tend to be a slow process, giving maintenance personnel plenty of time to respond. As such, only alarming on low oil is not uncommon. There are concerns today about sabotage, such as the shooting of radiators or the opening of oil valves to cause a transformer to fail. Tripping on low oil prior to a flashover can make it possible to simply patch the holes and refill the transformer with oil to restore it to service.

IV. Conventions

A. Diagram Conventions

For the one-line diagrams illustrating the recommended schemes (Fig. 9, Fig. 16, Fig. 18, and Fig. 19), Table I provides the legend of the various function codes. The one-line diagrams use the "list box method" described in IEEE Standard C37.2 [9] for representing which functions are being used and in which multifunction relay they reside. Relays with the letter *A* in the device identifier that are color-coded blue are part of the Main A system. Relays with the letter *B* in the device identifier that are color-coded red are part of the Main B system. The differential relay restraint inputs are arbitrarily designated as S, T, U, W, X, and Y to eliminate confusion with phase or winding designations. The standalone numbers (1, 3, 4) indicate the number of signals.

TABLE I
ONE-LINE DIAGRAM LEGEND

Element	Description	Suffixes
51P	Phase time-overcurrent protection	H = high-side terminals X = low-side terminals Y = tertiary terminals
51G	Ground time-overcurrent protection	
63 w/50P	Sudden pressure with 50P supervision	NA
71Q	Low oil level trip	NA
87P	Phase differential protection	O = overall BHT = high-side lead bus BXT = low-side lead bus BYT = tertiary bus T = transformer
87Q	Negative-sequence differential protection	
REF	REF protection	NA

B. Compensation Conventions

The examples in this paper use matrix representation to indicate the phase-shift and zero-sequence compensation settings in the relay, as defined in Annex E of IEEE Standard C37.91 [10]. Matrix representation is a convenient way to describe how the currents are combined to achieve the desired compensation. The rows of the three-by-three matrix represent the differential elements of a three-phase set (87A, 87B, and 87C). The columns represent the three phase currents measured by the relay (IA, IB, and IC). For example, in the identity matrix shown in (3), the first row (87A) has coefficients of 1 for the IA column, 0 for the IB column, and 0 for the IC column. This means that element 87A sees one times IA and zero times IB and IC.

$$\mathrm{M0} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The matrixes are identified as Mn, where n represents the row of Table E.1 in IEEE Standard C37.91 [10]. This number also represents the number of 30-degree increments of phase shift for the positive-sequence current in the clockwise direction that the matrix cancels.

V. AUTOTRANSFORMER PROTECTION

This section discusses the protection of a three-single-phase-and-spare autotransformer bank in a bulk electric power substation application. It is assumed that the high side of the transformer bank is a double-breaker arrangement, such as a ring bus, breaker-and-a-half bus, or double-bus double-breaker arrangement. The low side has a single breaker. In the example applications, the tertiary bus is assumed to be unloaded. However, in most cases, the schemes can easily be modified to accommodate tertiary bus loading, such as a station service transformer, shunt reactor, or shunt capacitor. Accommodation of tertiary loading is discussed as the schemes are described.

A. Option 1

Fig. 9 shows the first recommended configuration.

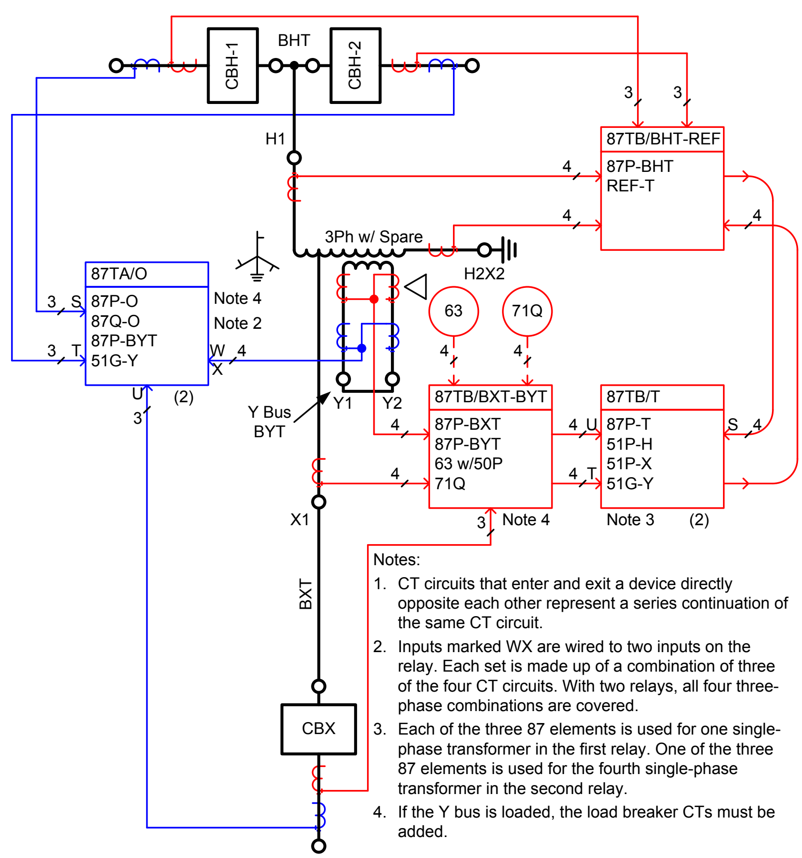

Fig. 9. Option 1: autotransformer protection one-line diagram

The Main A system consists of two multifunction relays configured as an overall differential zone. The Main B system consists of multiple multifunction bus and transformer relays to create subzones that provide precise indication of whether a fault is on the buswork or inside one of the transformers. This option can easily be revised to full functional redundancy by replicating the Main B system in place of the overall Main A system. Doing so involves a tradeoff: both systems provide precise fault location, but it may be necessary to sacrifice 87Q protection.

The following subsections discuss each scheme in detail.

1) Main A System, 87TA/O-1 and 87TA/O-2 Relays

The Main A system consists of two five-restraint transformer relays. Being an overall differential zone, the CT inputs S, T, and U are connected to the breakers at the boundary of the zone of protection. These CTs measure the three-phase currents and are not affected by the reconfiguration of the spare transformer. However, to obtain the ATB for each transformer, it is necessary to bring the CTs inside the delta tertiary into the differential elements, which requires reconfiguration of those currents to accommodate the four possible TOOS configurations. Further, for 87Q protection, if the tertiary bus is loaded, it is necessary that these currents be measured in three-phase sets. The use of two relays makes this possible, as described in the following paragraph.

To accommodate both of these requirements, the two relays are wired as shown in Fig. 10. Three of the four currents are wired to the W input of the first relay. A different combination of three of the four currents is wired to the X input of the first relay. Similarly, the remaining two combinations of three of the four currents are wired to the W and X inputs on the second relay.

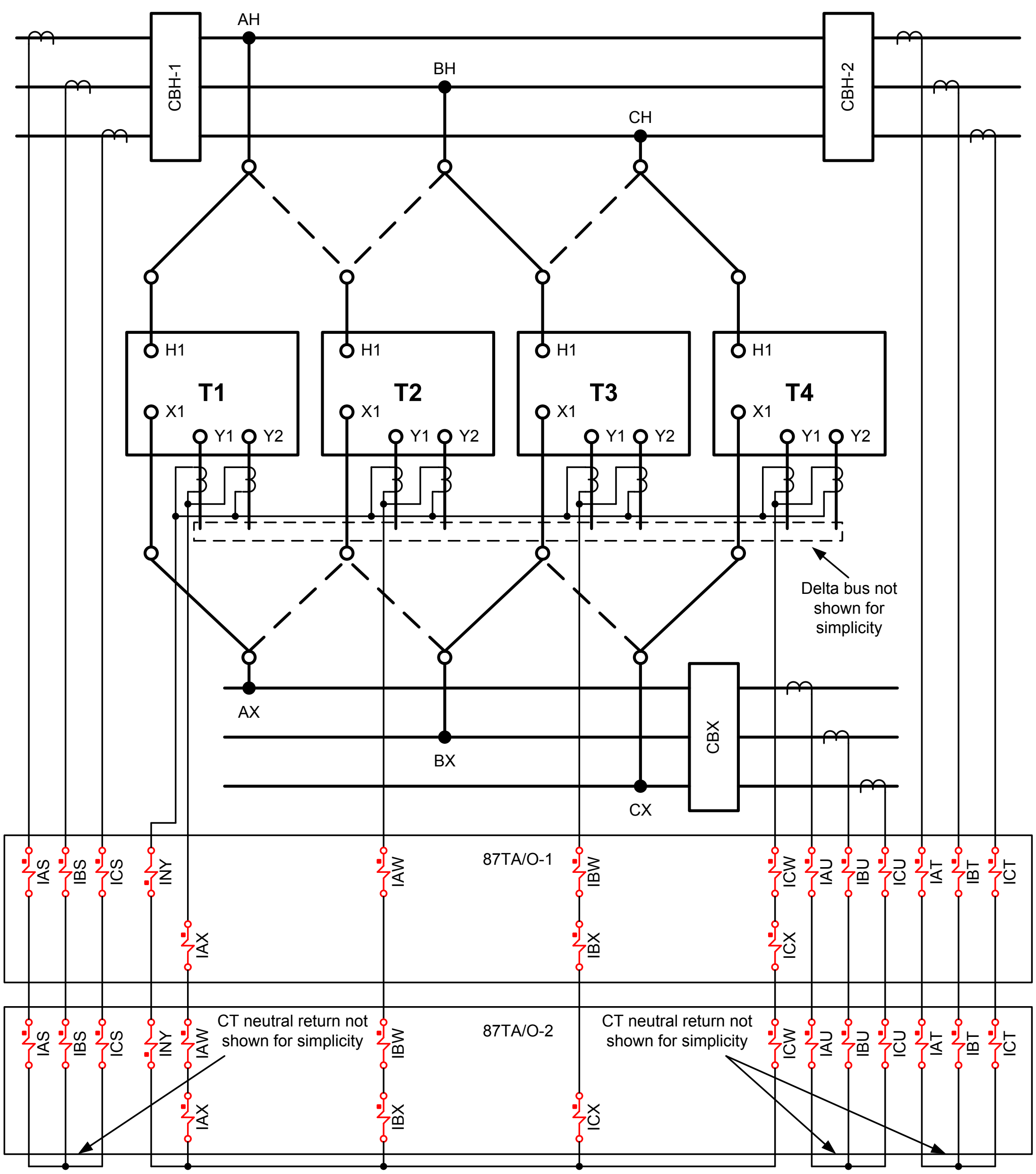

Fig. 10. 87TA/O relay connections

Because the Main A relays provide an overall zone, they cannot differentiate between faults on the buswork and faults in each single-phase transformer.

a) 87P-O and 87Q-O transformer differential elements

For the T1 TOOS configuration, the relays are configured with the compensation matrixes shown in Fig. 11. In this configuration, the 87TA/O-1 relay uses the currents measured in the W input and ignores the currents measured in the X input. This can be accomplished by changing setting groups or, if the relay is capable of dynamically turning current inputs on and off, by properly setting a logic equation that identifies the T1 TOOS configuration. Fig. 12, Fig. 13, and Fig. 14 show the compensation settings for the other TOOS configurations.

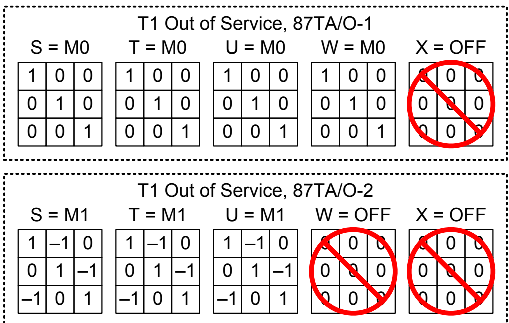

Fig. 11. T1 TOOS compensation settings

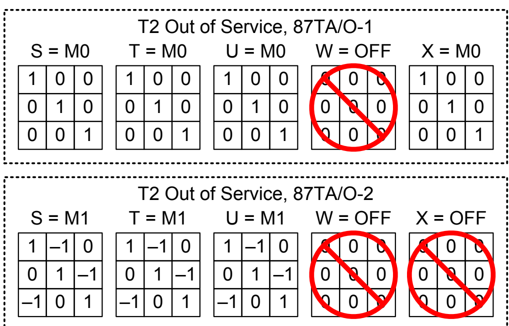

Fig. 12. T2 TOOS compensation settings

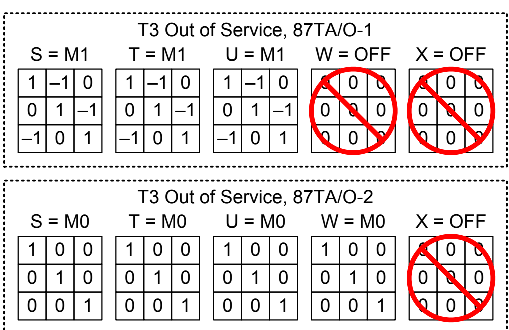

Fig. 13. T3 TOOS compensation settings

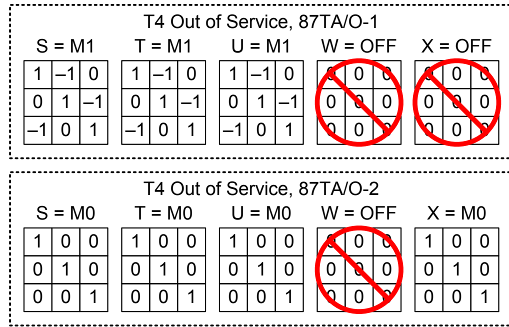

Fig. 14. T4 TOOS compensation settings

If the tertiary bus is unloaded, the 87TA/O-2 relay can still be enabled, even though it cannot measure the correct set of three-phase current signals from the Y bushings of the transformer to perform a per-transformer ATB differential protection. The W and X inputs are OFF for this configuration. Because this relay does not have access to the currents in the Y winding (current circulating in the delta), zero-sequence compensation is required. For this reason, a delta compensation matrix, M1, is selected for the S, T, and U current inputs to the relay. This relay provides conventional differential protection, but it is not able to provide precise faulted transformer identification. In this configuration, the differential elements are open to faults on the tertiary bus as well. If the tertiary is loaded, this relay will be disabled.

b) 87P-BYT tertiary bus differential element

Because the phase differential elements are configured for ATB on a per single-phase transformer basis and use the current from the Y bushing CTs, the tertiary bus (BYT) is outside the differential zone of protection. This must be addressed by a separate differential relay, which is not shown in Fig. 9. Instead, the example shows an element identified as 87P-BYT in the 87TA/O relays. Most transformer differential relays do not have a second set of differential elements that can be used for this purpose. However, if the relay is capable of doing mathematical calculations in programmable logic at protection speeds, it is relatively easy to sum the currents from the Y bushing CTs for each phase and create a differentially connected overcurrent bus differential scheme. The logic equations can dynamically change which currents are being summed depending on the TOOS configuration that is enabled at the time. The sum of the currents for each tertiary bus phase can then be used in a short inverse-time overcurrent element to provide differential protection for the tertiary bus, as described in Annex C of IEEE Standard C37.234 [11]. Reference [12] provides guidance on how to implement an inverse timing element in programmable logic.

c) 51G-Y ground backup element

It is usually desirable to have a ground relay that responds to the zero-sequence current circulating in the delta tertiary of the autotransformer to provide ground backup protection. To provide this protection, the residual of the four Y bushing CT circuits is wired to the Y input on the relays, as shown in Fig. 10. The connection in the residual ensures that the element only sees 3I0, even if the tertiary bus is loaded.

It is assumed that the current in the out-of-service transformer will always be zero such that, even though the CT from the transformer is always connected, it will not affect the measurement. To ensure this, the grounding practice of the out-of-service transformer is important. It is common to ground circuits with one safety ground. This practice is fine for the Y winding. However, grounding both Y bushings of the transformer should be avoided. This places an electrical short circuit on the primary of the Y bushing CTs. This electrical short circuit is reflected to the secondary of the CT. Thus, at the summing junction for the residual connection, current in the three in-service transformers can divide, with some current flowing toward the relay and some current flowing toward the CT with the shorted primary. If only one of the Y bushings is grounded, the primary of this CT is open-circuited. That open circuit is reflected to the secondary of the CT and presents a high impedance to the flow of current in that branch of the CT circuit.

2) Main B System, 87TB/T-1 and 87TB/T-2 Relays

The Main B system consists of a combination of bus and transformer relays. This subsection discusses the transformer relays, which consist of two three-restraint transformer relays. The 87TB/T-1 relay is wired to the T1, T2, and T3 bushing CTs. The 87TB/T-2 relay is wired to the T4 bushing CTs, with the Phase B and C inputs unused, as shown in Fig. 15. The connections are similar to those shown in Fig. 3. Each differential element protects one of the single-phase transformers. No dynamic switching of current circuits is required.

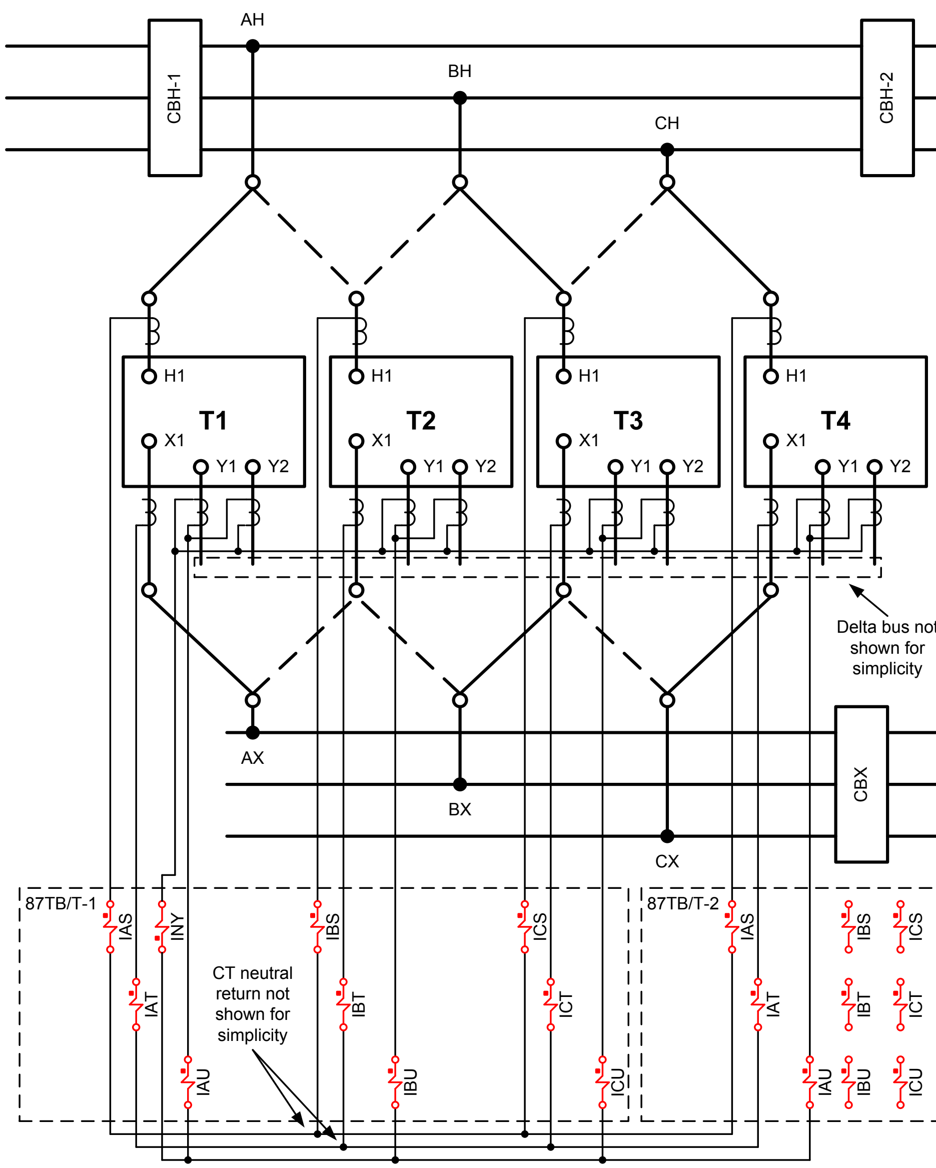

Fig. 15. 87TB/T relay connections

a) 87P-T transformer differential elements

Each differential element protects one single-phase transformer. The identity matrix, M0, is used such that each element only looks at currents from a specific transformer. This, coupled with the fact that the CTs that bound the differential zone are located on the bushings of each transformer, provides positive indication that the fault is located inside a particular transformer.

b) 51P-H and 51P-X winding damage curve elements

Backup for uncleared faults in adjacent zones is provided by phase time-overcurrent elements that are coordinated with the transformer through-fault withstand curve. These are shown implemented in the 87TB/T-1 and 87TB/T-2 relays. Because the CTs are not switched to these relays, in addition to protection these relays can also provide through-fault monitoring for each individual single-phase transformer [13].

c) 51G-Y ground backup element

Ground backup protection is implemented the same as was described for the Main A relay by wiring the residual of the Y winding CTs to a ground current input on the relays.

3) Main B System, 87TB/BHT-REF Relay

The 87TB/BHT-REF Relay is a low-impedance bus differential relay with advanced zone switching capability and six differential elements. This relay provides high-side lead bus differential and modified REF protection.

a) 87P-BHT high-side transformer bus differential element

In a dual-breaker application, the CTs on the breakers often have to be set to a high ratio to accommodate the bus rating, which may be considerably higher than the transformer rating. This often results in the sensitivity of the transformer differential element being compromised. As was discussed in Subsection III.B on partial-winding faults, high sensitivity is desirable for transformer protection. One recommended practice to mitigate this issue is to apply a bus differential relay on the lead bus and a transformer differential relay on the transformer. This allows the CTRs to be optimized for these two very different zones of protection.

For the three-single-phase-and-spare application, this configuration also meets the goal of providing precise identification of the location of any fault within the zone. If the lead bus differential trips, it is easy to narrow the search to a flashed insulator, failed arrester, or (if neither of these) a failed bushing.

With advanced zone-selection logic, it is easy to insert the correct CTs into each zone depending on which three of the four transformers are in service. Note that the polarity of the H bushing CTs is into the transformer. So, these CTs are set for negative polarity when brought into the bus differential elements.

b) REF-T transformer restricted earth fault element

Because the bus relay includes two sets of three differential elements, we can use the three unused elements to implement the modified REF scheme described in Subsection III.B.2.c. It is only necessary to wire in the X and neutral terminal CTs from the four transformers to the relay, because it already has the H terminal CTs for the BHT zone boundary.

4) Main B System, 87TB/BXT-BYT Relay

The 87TB/BXT-BYT relay is a low-impedance bus differential relay with advanced zone switching capability and six differential elements. This relay provides low-side lead bus and tertiary bus protection in addition to sudden pressure relay supervision and tripping.

a) 87P-BXT low-side transformer bus differential element

The 87P-BXT protection is implemented similarly to the 87P-BHT protection.

b) 87P-BYT tertiary bus differential element

The second set of three differential elements available in the 87TB/BXT-BYT relay can be used to cover the tertiary bus. The configuration of the tertiary buswork zones is not perfect because the actual bushing CTs required to bound the busbars are not directly available. We refer to Fig. 2 to illustrate the configuration of these zones. In Fig. 2, the bank is configured with T2 TOOS. Consider the AY bus differential element for example. It needs to sum the current flowing in the T1-Y1 bushing and the T4-Y2 bushing. However, these currents are not directly available because the Y1 and Y2 CTs on each transformer are summed in an additive fashion, as described in Subsection III.A. We can call this current T*n*-Y, where *n* is the transformer number. To balance the AY bus differential element, we can set it to monitor the T1-Y current and the negative of the T4-Y current. This allows it to balance KCL during normal conditions and to trip for any fault involving the AY busbar. However, it also may respond to faults inside the T4 transformer. This is not a particularly serious deficiency and is an acceptable compromise. If additional CTs are available on the Y bushings, dedicated CTs can be configured for use by the 87P-BYT elements. Note that this limitation also applies to the 87P-BYT element in the Main A relay discussed in Subsection V.A.1.b.

c) 63 w/50P sudden pressure with supervision

The 87TB/BXT-BYT relay is also configured to provide sudden pressure tripping supervision and targeting. As discussed in Subsection III.B.3, because the Main A system includes the 87Q element, we want the 63 protection to be part of Main B. The 63 protection is paired with the low-side bus relay instead of the Main B transformer relay because the 63 protection is complementary to the differential protection. So, tripping through the bus subzone relay adds a small degree of additional independence.

If overcurrent blocking supervision is desired, the bus relay directly measures the currents in the X1 bushings of all four transformers so that the overcurrent function can be directly paired with each set of 63 contact inputs. In a sudden pressure blocking scheme, the currents on the transformer terminals opposite the strongest source of through-fault current are usually used. That way, the 63 tripping is less likely to be blocked for an internal fault.

d) 71Q low-oil tripping

The 87TB/BXT-BYT relay is also configured to provide low-oil tripping and targeting, as discussed in Subsection III.C.

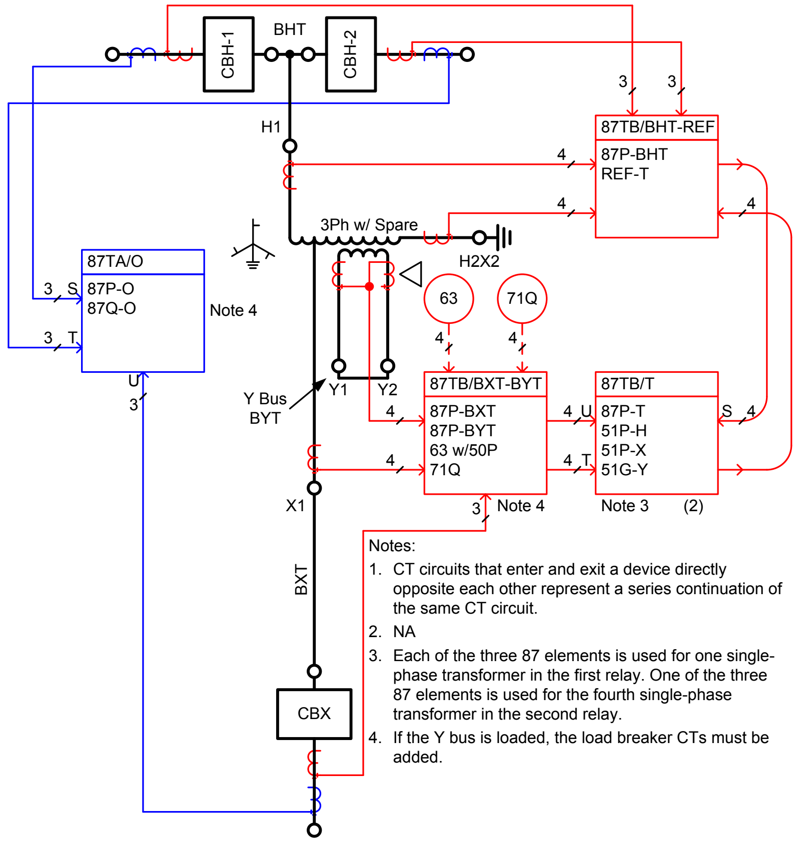

Fig. 16. Option 2: autotransformer protection one-line diagram

B. Option 2

Fig. 16 shows a configuration that requires only one relay in the overall differential protection provided by the Main A system. The Main B system is identical to what was described for Option 1.

In this implementation, the Main A system is greatly simplified but with the tradeoff of reduced functionality. In this system, the currents in the Y bushings of the four single-phase transformers are not wired into the differential protection. Thus, it is not necessary to reconfigure the CT inputs to the differential elements for the four TOOS configurations. However, not directly monitoring the current in the Y winding precludes this scheme from performing ATB on a per-transformer basis. The current inputs on the breakers must be configured for delta zero-sequence compensation, which makes positive phase identification impossible. This may be deemed an acceptable compromise given that the overall differential element cannot precisely identify whether the fault is on the buswork or inside the transformer anyway.

Another advantage of not monitoring the Y bushing CTs is that the tertiary bus is in the differential zone, so it is no longer necessary to provide a separate differential element for the tertiary bus by either using a separate relay or building a differential element in programmable logic as was necessary for Option 1.

VI. GSU Transformer Protection

This section discusses the protection of a three-single-phase-and-spare GSU transformer bank in a power generating station. It is assumed that the high side of the transformer bank is a double-breaker arrangement such as a ring bus, breaker-and-a-half bus, or double-bus-double-breaker arrangement. In this application, the transformer bank is a two-winding wye/delta with the delta bus made up using isophase bus. Fig. 17 shows the configuration with T2 TOOS. Removable links in the isophase bus are used to reconfigure the bank on the secondary side.

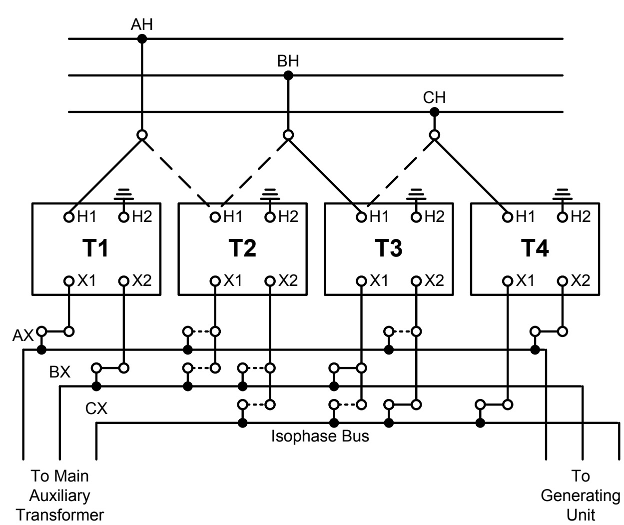

Fig. 17. GSU transformer application

A. Option 1

Fig. 18 shows the recommended configuration. The Main A system consists of a multifunction relay configured as an overall differential zone that covers the generator, GSU transformer, and isophase bus. The Main B system consists of separate multifunction bus and transformer relays to create subzones that provide precise indication of whether a fault is on the buswork or inside one of the transformer tanks.

The following subsections discuss each scheme in detail.

1) Main A System, 87TA/O Relay

The Main A system consists of a five-restraint transformer relay. As is common practice for unit-connected generators, this system provides an overall zone of protection that covers the generator, isophase bus, and GSU transformer. Bounding an overall differential zone, the CT inputs S, T, U, and W are connected to the breakers and CTs at the boundary of the zone of protection. These CTs measure the three-phase currents and are not affected by the reconfiguration of the spare transformer.

a) 87P-O and 87Q-O transformer differential elements

Because the zone of protection extends to the neutral terminals of the generator, it is not possible to incorporate the transformer secondary delta currents to perform per-transformer ATB differential protection. Because this relay does not have access to the currents in the Y winding (current circulating in the delta), zero-sequence compensation is required. For this reason, delta-compensation matrix M1 or M11 (depending on the phase shift) is selected for the S and T currents, and M0 is selected for the U and W current inputs to the relay. This relay provides conventional differential protection, but it is not able to provide precise faulted transformer identification.

This relay can also provide 87Q protection because all CTs properly measure their three-phase currents on all terminals, regardless of which of the four possible TOOS configurations is active.

b) 51G-H ground backup element

It is usually desirable to have a ground relay that responds to the zero-sequence current contributed by the transformer during system faults to provide ground backup protection. To provide this protection, the residual of the four H2 bushing CT circuits is wired to the Y input on the relay. The connection in the residual ensures that the element only sees 3I0.

As with the autotransformer application, the grounding practice of the out-of-service transformer is important. In this case, however, it is the H1 terminal that must not be grounded. It is recommended that the H2 terminal be grounded and that the H1 terminal only be connected to its surge arrester to prevent reflecting a short circuit into the summing junction of the residual connection.

2) Main B System, 87TB/T Relay

The Main B system consists of a combination of bus and transformer relays. This subsection discusses the transformer relays, which include two two-restraint transformer relays. Similar to the autotransformer application, the 87TB/T-1 relay is wired to the T1, T2, and T3 bushing CTs. The 87TB/T-2 relay is wired to the T4 bushing CTs with the Phase B and C inputs unused. Each differential element protects one single-phase transformer. No dynamic switching of current circuits is required.

a) 87P-T transformer differential elements

Each differential element protects one single-phase transformer. Identity matrix M0 is used so that each element only looks at currents from a specific transformer. This, coupled with the fact that the CTs that bound the differential zone are located on the bushings of each transformer, provides positive indication that the fault is located inside a particular transformer.

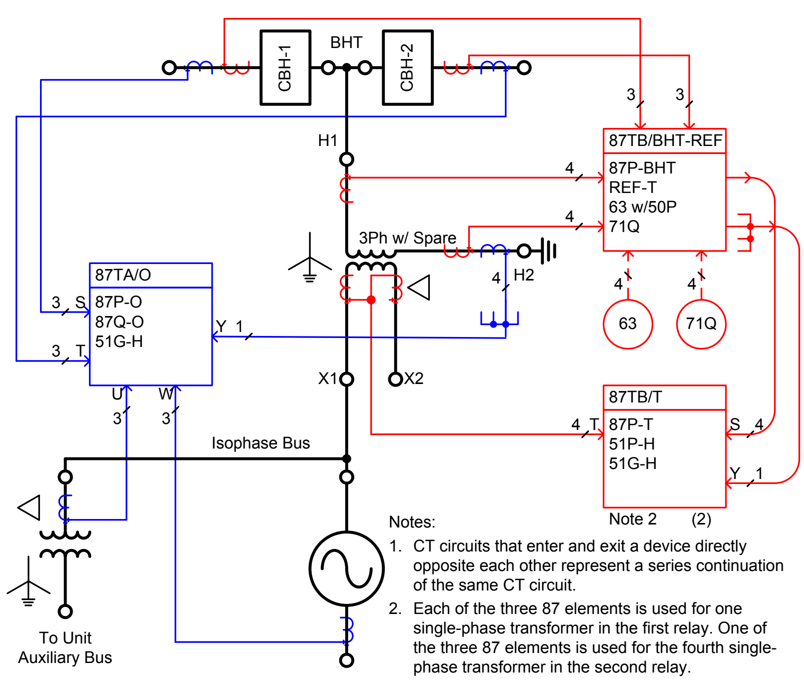

Fig. 18. GSU transformer bank Option 1: protection one-line diagram

b) 51P-H winding damage curve elements

Backup for uncleared faults in adjacent zones is provided by phase time-overcurrent elements that are coordinated with the transformer through-fault withstand curve. These are shown implemented in the 87TB/T-1 and 87TB/T-2 relays. Because the CTs are not switched to these relays, in addition to protection these relays can also provide through-fault monitoring for each individual single-phase transformer.

c) 51G-H ground backup element

Ground backup protection is implemented the same as was described for the Main A relay by wiring the residual of the H2 bushing CTs to a ground current input on the relays.

3) Main B System, 87TB/BHT-REF Relay

The 87TB/BHT-REF relay is a low-impedance bus differential relay with advanced zone switching capability and six differential elements. This relay provides high-side lead bus differential and modified REF protection.

a) 87P-BHT high-side transformer bus differential element

Similar to the autotransformer application, by applying a separate lead bus differential zone, we can optimize CTRs for the different sensitivity requirements of the bus and the transformer. We also obtain the goal of providing precise identification of the location of any fault within the zone. If the lead bus differential trips, it is easy to narrow the search to a flashed insulator, failed arrester, or (if neither of these) a failed bushing.

An additional advantage of this configuration comes from the fact that, in many cases, the generating facilities and the bulk electric system substation facilities belong to different entities. By separating the zones of protection at the high-side bushings of the transformer, the boundaries of the protection zones closely match the boundaries of ownership and responsibility.

b) REF-T transformer restricted earth fault element

Similar to the autotransformer application, we use the three extra zones in the bus relay to implement the modified REF scheme described in Subsection III.B.2.c.

c) 63 w/50P sudden pressure with supervision

The 87TB/BHT-REF relay is also configured to provide sudden pressure tripping and targeting. As discussed in Subsection III.B.3, because the Main A system has the 87Q element, we want the 63 protection to be part of the Main B system. Overcurrent blocking supervision is easily implemented, if required.

d) 71Q low-oil tripping

The 87TB/BHT-REF relay is also configured to provide low-oil tripping and targeting, as discussed in Subsection III.C.

B. Option 2

Option 2 is shown in Fig. 19. This option uses fewer relays. Both the Main A and Main B systems consist of a single five-restraint transformer relay. The Main B relay is configured to provide ATB on a per-phase basis for precise transformer phase identification. However, there is no separate bus zone, so it is not possible to indicate whether a fault is internal or external to the transformer tanks.

The following subsections discuss each scheme.

1) Main A System, 87TA/O Relay

The Main A system is nearly identical to the system in Option 1. In this case, REF protection has been added to the 87TA/O relay. Because we do not have a bus relay to provide per-phase REF protection, the standard current-polarized directional element REF protection described in Subsection III.B.2.a is turned on. This provides the desired additional sensitivity for winding-to-ground faults without providing positive phase identification.

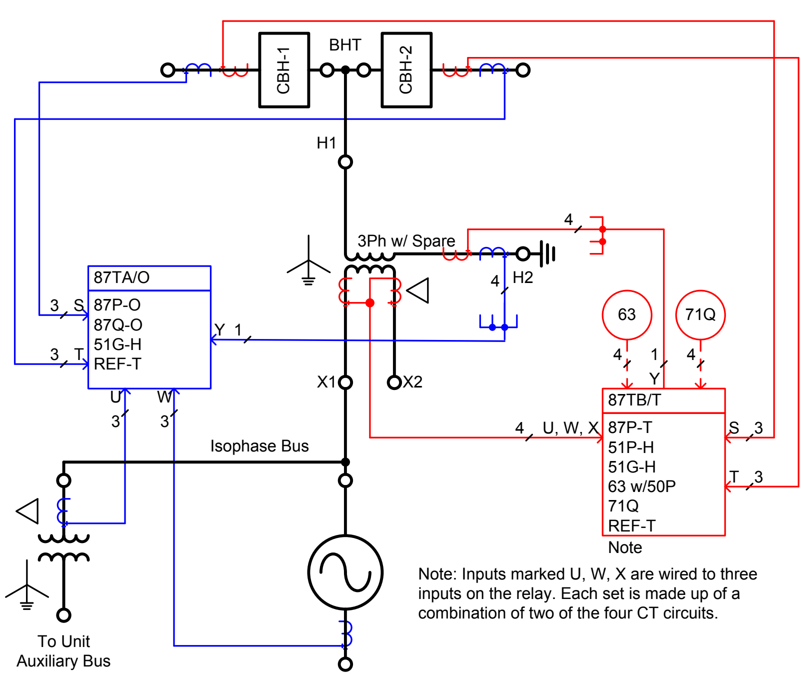

Fig. 19. GSU transformer bank Option 2: protection one-line diagram

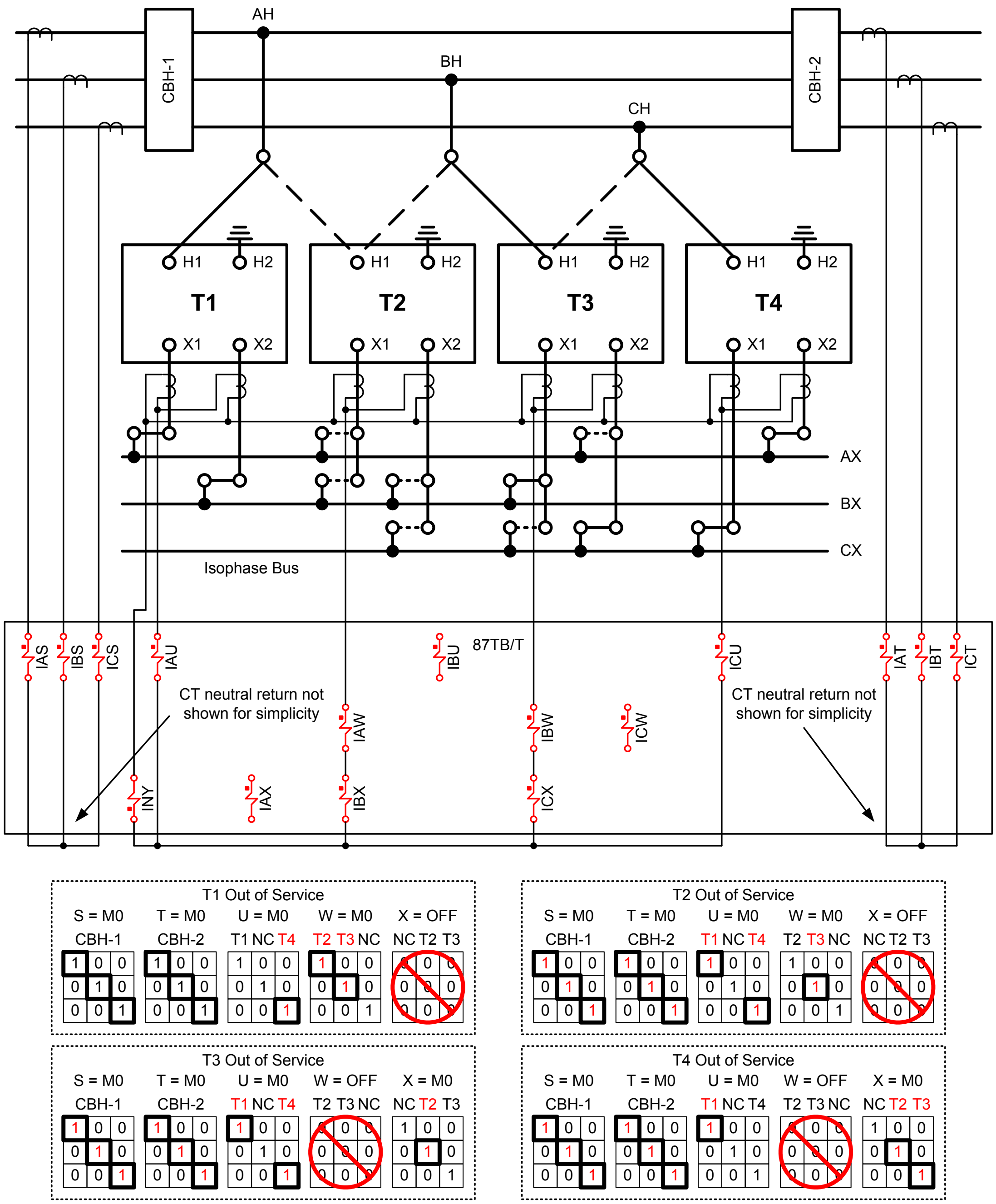

Fig. 20. GSU transformer bank Option 2: 87TB/T relay connections and compensation settings

2) Main B System, 87TB/T Relay

The 87TB/T relay is wired to the three-phase CTs on the two high-side breakers in a conventional fashion. The CTs from the X bushing CTs on the four transformers are connected to the relay in a novel way to cover all four of the TOOS configurations. Three sets of three-phase inputs are used. In Fig. 20, they are marked U, W, and X. Two phase inputs are used in each three-phase set.

a) 87P-T transformer differential elements

The compensation settings are also shown in Fig. 20. By turning off one of the three CT inputs that monitor the X bushing currents for each configuration, all combinations are covered. Examination of the compensation matrixes highlights which current signals are included in each differential element. Because all three phases of the low-side currents are never in a complete three-phase set, 87Q protection is not possible in this configuration. These inputs continually measure a negative-sequence unbalance under load.

In using this approach for compensation, the current input from the out-of-service transformer is still connected to the relay and is still actively monitored by the differential element. For this reason, we have to ensure that the current in the out-of-service transformer is always zero. Similar to the autotransformer application, it is important that the X winding of the out-of-service transformer is only grounded on one terminal. In this case, the primaries of the transformer CTs are open-circuited, and the open circuit is reflected to the secondary of the CT. Thus, any transient-induced currents are prevented from circulating in the CT secondary circuit and affecting the differential element.

b) 51P-H winding damage curve elements

Backup for uncleared faults in adjacent zones is provided by phase time-overcurrent elements that are coordinated with the transformer through-fault withstand curve. In this case, the CTs used for through faults are not specific to each transformer, so accumulated through-fault monitoring for each individual single-phase transformer is also not possible.

c) 51G-H ground backup element

Ground backup protection is implemented as described for the Main A relay in Subsection VI.A.1.b by wiring the residual of the H2 bushing CTs to a ground current input on the relays.

d) REF-T restricted earth fault element

Similar to the 87TA/O relay, REF protection is implemented in this relay as well. As discussed in Subsection III.B.2.a, because the operate signal in this REF scheme is the residual of three CTs instead of the desired single CT in the neutral ground path, it is not immune to false 3I0 current caused by CT performance issues. Thus, in this application, the output of the REF directional element is not directly used for tripping. Instead, it is used to torque control a 51REF element that is used for tripping. The short inverse-time overcurrent element provides some delay to ride through any transient false residual for a fault not involving ground. The sensitivity of the 51 element is also reduced relative to typical applications with a single ground CT.

VII. Configurable Compensation Matrix

Modern relays have a great deal of configurability for handling all sorts of transformer compensation challenges, such as round-the-clock compensation and accommodation of in-zone grounding banks. However, for specialized applications, such as the subject of this paper or for phase-shifting transformers, the fixed compensation matrixes available do not solve all of the problems. As evidenced by the scheme described in Fig. 19 and Fig. 20, sometimes it is necessary to think outside the box to come up with a solution.

A user-configurable compensation matrix can greatly simplify the accommodation of unconventional applications for advanced users of programmable transformer relays. This section gives two examples of how a user-programmable compensation matrix can be used to simplify and improve three-single-phase-and-spare transformer bank applications. We call this user-configurable compensation matrix Matrix 13. The substation autotransformer and the GSU transformer examples are used to illustrate how Matrix 13 can be used to simplify these applications.

A. Autotransformer 87TA/O Relay Application With Matrix 13

In the example in Fig. 9, the Main A protection system requires two 87TA/O relays to cover the application. If the relays allow the user to configure custom matrixes, only one relay is required. Fig. 21 shows how the relay would be connected and how the custom compensation would be configured for each of the four TOOS configurations.

In comparing Fig. 21 to Fig. 10, we see that the Y bushing CTs are wired to the W and X inputs on the relay differently. In the Matrix 13 application, we wire the Y bushing CTs from T1, T2, and T3 to the three-phase current W input. The Y bushing CTs from T4 are wired to the IA terminals of the X input.

The custom compensation matrixes are constructed by placing the coefficient 1 and coefficient 0 in the appropriate positions of the matrix. Each 1 is placed in the matrix to insert the correct currents into each differential element. Placing the coefficient 0 in the column for the out-of-service transformer has the advantage of totally excluding the current from the out-of-service transformer so that there is no concern about how the transformer is grounded or that an error while testing the transformer may inadvertently trip the in-service bank by injecting a spurious current into the live differential elements.

Consider the T1 TOOS configuration in Fig. 21. The configurable Matrix 13 for the W input for this configuration has zeros in every row of the first column (for IAW). Examination of the connections shows that IAW is connected to the CT for T1 (the out-of-service transformer). The second column (for IBW) has a 1 in the first row to insert the T2 current into the Phase A 87 element. The third column has a 1 in the second row to insert the T3 current into the Phase B 87 element. Finally, the first column of the X input has a 1 in the third row to insert the T4 current into the Phase C 87 element.

In this application, we can also use the 87Q element if the tertiary bus is unloaded because it is open-circuited in the positive- and negative-sequence networks. Only zero-sequence currents can flow in the Y terminals for an internal fault, even though the W and X inputs only have one or two of three currents in their three-phase set. If the tertiary bus is relatively lightly loaded compared with the overall capacity of the transformer, the 87Q element can still be used. The small additional negative-sequence restraint caused by the load flow only decreases the sensitivity slightly.

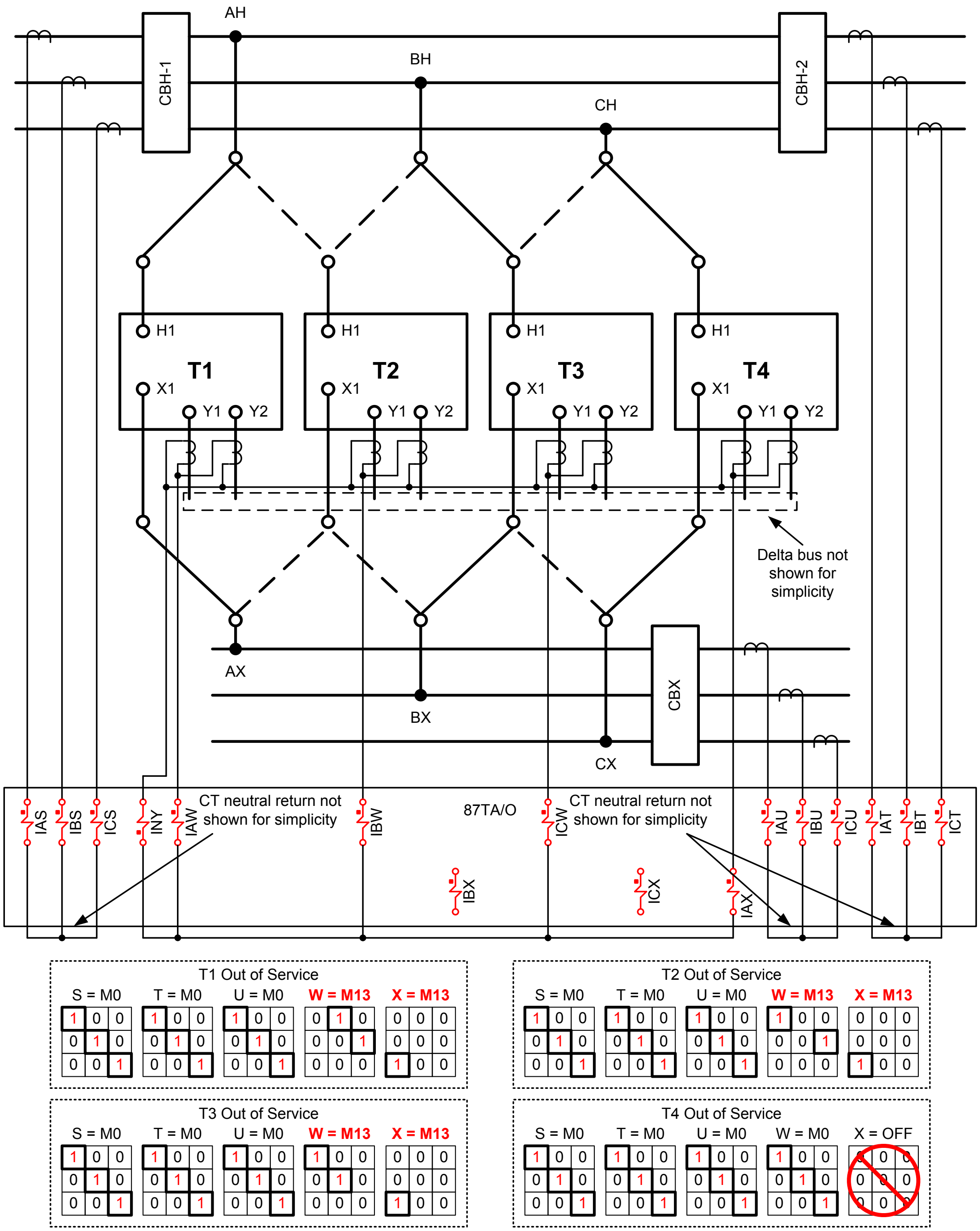

Fig. 21. Autotransformer 87TA/O relay connections and compensation using Matrix 13

B. GSU Transformer 87TB/T Relay Application With Matrix 13

In the example illustrated in Fig. 18, the Main B protection system requires two 87TB/T relays to cover the application. If the relays allow the user to configure custom matrixes, only one relay is required. Fig. 22 shows one way to connect the relay and configure Matrix 13 for each of the four TOOS configurations.

In this case, two three-phase restraint inputs are used to cover the four H bushing CTs, and two additional three-phase restraint inputs are used to cover the four X bushing CTs. The S input measures the T1 and T4 H bushing currents using the Phase A and C inputs, respectively. The T input measures the T2 and T3 H bushing currents using the Phase A and B inputs, respectively. The U and W inputs are configured similarly to measure the X bushing currents. S and T combined allow the measurement of the appropriate three of the four current signals for the high side, and U and W allow measurement of the appropriate three of the four current signals for the low side. Again, we place the coefficient 1 in the appropriate locations to inject the correct currents into each differential element and the coefficient 0 in the appropriate locations to exclude currents from the out-of-service transformer.

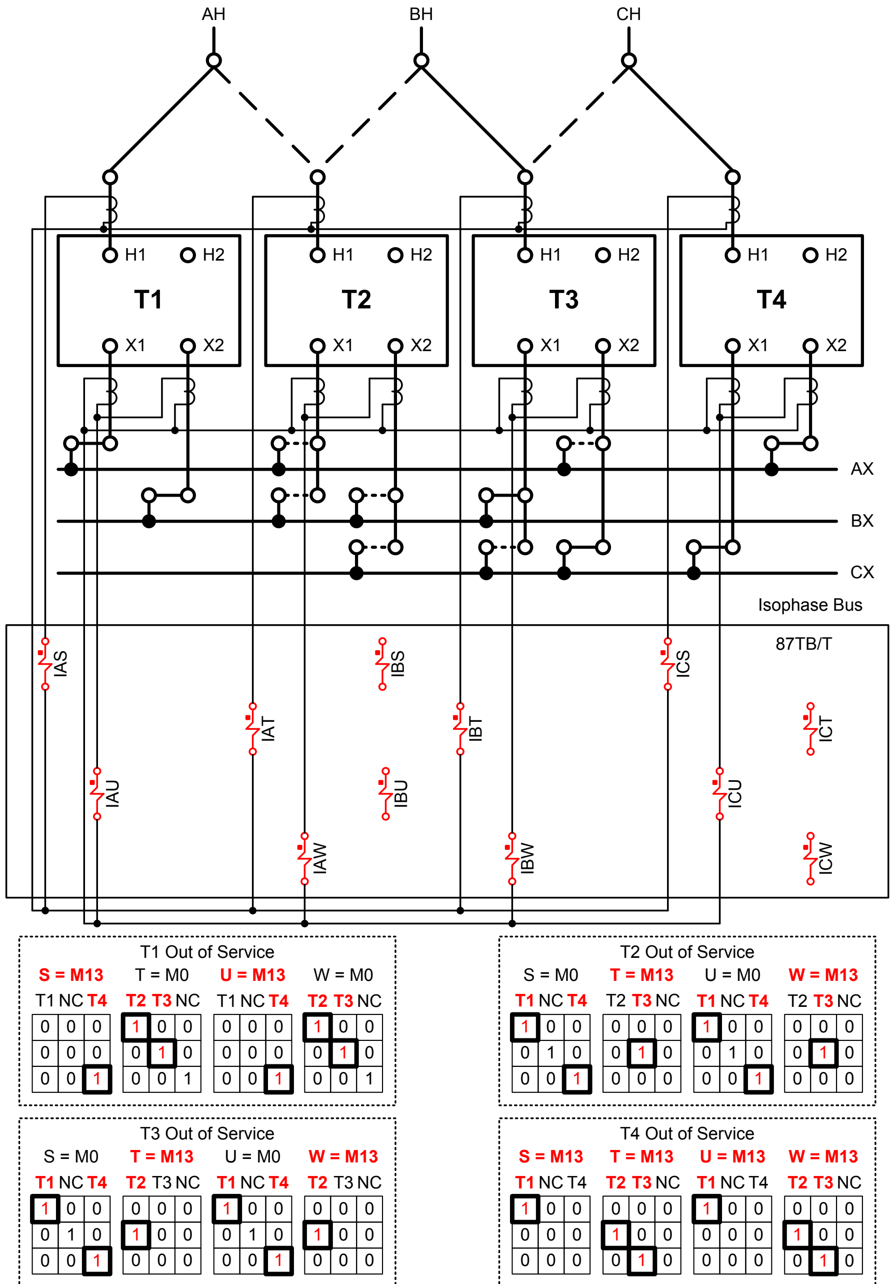

Fig. 22. GSU transformer 87TB/T relay connections and compensation using Matrix 13

Fig. 23 shows how it is possible to accomplish the correct substitution of currents using conventional compensation matrixes. In this case, because of how the relay is wired in Fig. 22, we use M0 for all compensation for the T1 TOOS and T2 TOOS configurations. For the T3 TOOS and T4 TOOS configurations, the wye matrix, M4, from Row 4 of Table E-1 in [10] (120-degree phase shift) is used to insert the currents into the proper phases for the T and W inputs. Examination of Table E-1 shows that there are two possible matrixes for each of the even-numbered rows of the table. If the transformer relay includes both selections, this is a possible solution that does not require the user-configurable matrix. The only drawback of this approach is that it is not possible to exclude the out-of-service transformer currents from the differential elements.

In this application and the application illustrated in Fig. 22, 87Q protection is not possible because of the fact that every three-phase input to the relay measures only one or two of three phases, resulting in the appearance of a large negative-sequence load flow.

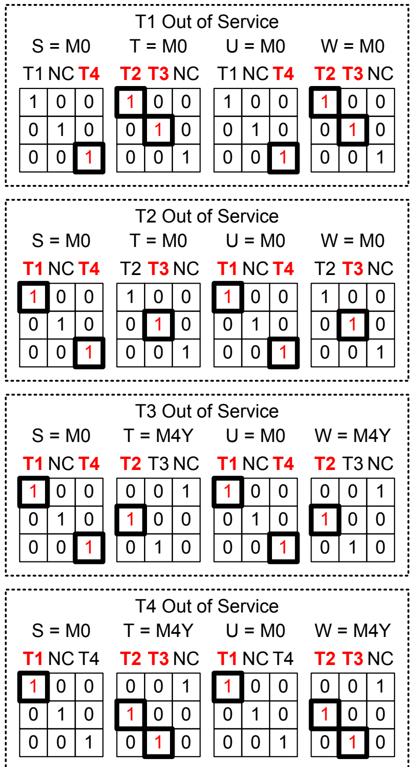

Fig. 23. Compensation using conventional matrixes

VIII. Conclusion

Transformer banks are critical to the operation of the bulk electric system. These are the most expensive assets in the substation and require significant time and logistics to repair and replace. It is prudent to provide the best possible protection. Planning substations using three-single-phase-and-spare construction can improve the resiliency of the grid and reduce the possibility of extended outages in the event of a failure or sabotage.

The fact that single-phase transformers have closed magnetic circuits allows us to design our differential protection schemes to indicate precisely the location of any fault within the overall transformer zone of protection. Easily knowing if the fault is on the buswork or inside a specific transformer can allow operations personnel to quickly assess the situation and know how to respond. This, coupled with a protection system that is designed to allow reconfiguration of the protection system for any of the four TOOS configurations at the push of a button, enables operations to restore first and test and assess later, speeding restoration of critical transmission paths.

Modern protection technology makes it possible to improve protection sensitivity to trip quickly for partial-winding faults before they can evolve and become more serious. The configurability of modern transformer and bus relays makes the design for automatic reconfiguration to any of the four TOOS configurations relatively simple and robust compared with the complexity required with traditional protection technology.

Reconfiguration can be implemented by the use of pushbuttons programmed on the front of each relay to switch the internal logic and settings to one of the four TOOS configurations. A simple panel selector switch can also be used to signal all of the relays as to which of the four TOOS configurations is active. Alternatively, if the reconfiguration of the primary bus work is done via switches with 89a and 89b status contacts, the schemes can be designed to automatically determine the topology and switch to the appropriate logic and settings. Signaling between relays can easily be designed to alarm for any configuration where all of the relays are not in the correct configuration.

The schemes described use multiple relays to meet the following goals of optimal protection for these important assets:

- Indication of the fault location within the zone.
- Automatic reconfiguration for any TOOS configuration.
- Sensitive protection, including 87Q and REF.
- Simple CT circuits that are easy to wire and test.

Given the low cost of modern multifunction relays compared with the cost of the facilities that are being protected and the cost of the unavailability of these facilities, the number of relays required to implement the recommended schemes is easily justified.

Further advances in the configurability of transformer protection schemes, such as user-configurable compensation matrixes, can someday be used by advanced users to simplify protection systems in these unusual applications.

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X. Biographies

Michael J. Thompson received his B.S., magna cum laude, from Bradley University in 1981 and an M.B.A. from Eastern Illinois University in 1991. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN), where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a Fellow Engineer in the Engineering Services Division of SEL. He is a senior member of the IEEE, main committee member of the IEEE PES Power System Relaying Committee, and a registered professional engineer. Michael has published numerous technical papers and holds a number of patents associated with power system protection and control.

Faridul Katha Basha received his B.E. in electrical engineering from Anna University, India, in 2008 and an M.S.E.E. from the State University of New York at Buffalo in 2011. Since graduation, he has been employed with Schweitzer Engineering Laboratories, Inc. as a protection engineer in the Engineering Services Division.

Craig Holt received his B.S. in electrical engineering from California State University of Fresno in 2006 and an M.E. from the University of Idaho in 2011. Upon graduating in 2006, he worked at Southern California Edison for over six years. He joined Schweitzer Engineering Laboratories, Inc. in 2013 as a protection engineer.