Differential Protection for Power Transformers With Non-Standard Phase Shifts

Astried Schneider, *AltaLink*
Lubomir Sevov, Zhiying Zhang, Ilia Voloh, *GE Digital Energy - Multilin*

Abstract - **The current differential protection is the most popular protection for transformers, providing good fault sensitivity, selectivity and security.**

Depending on the application, the transformer size, shape and winding connections may vary. Some common power system applications require installation of two- or three-winding conventional power transformers or autotransformers, while others require non-standard applications such as phase shifting transformers (PST), Scott transformers, LeBlanc transformers, Zig-Zag grounding transformers or converter transformers. Applying differential protection to conventional type power transformers with "standard" phase shifts of 30 degrees, or multiples of 30 degrees is trivial. However, applying this protection to transformers with non-standard phase shifts is challenging for the protection engineer. Current Transformers (CTs) placed in unusual locations add even more to the complexity of applying the protection correctly. The later is associated with a special CT to therelay connections, correct computation of winding currents, phase angles, and selection of protective devices, able to support such applications.

This paper provides essential knowledge on the transformer differential protection throughout theory and application examples. Current transformers and relay connections, as well as computation of transformer setup settings with standard and non-standard phase shift are covered.

Index Terms – **Scott transformer, LeBlanc transformer, Phase shifting transformers, Stray Flux and CT saturation, Converter Transformers, Phase and Magnitude compensation.**

I. INTRODUCTION

The technological advancements in the design of the relay hardware and development of better algorithms for protection of power transformers, gave ability to system engineers to apply differential protection not only to conventional power transformers, but also to transformers with a non-standard phase shifts. We find those non-standard phase shifts between the winding currents in Phase Shifting Transformers (PSTs), Converter transformers, Scott and LeBlanc transformers.

II. REVIEW OF DIFFERENTIAL PROTECTION FOR TRANSFORMERS WITH STANDARD PHASE SHIFT

Almost all of the medium and big size conventional transformers from distribution to transmission power systems are protected by current differential protection. The minimum data that one provides to the transformer differential relay requires entering information on the transformer capacity (kVA or MVA), winding phase-phase voltages, current transformer ratings, selection of transformer winding connections, phase shifts, and whether or not there is grounding within the zone of protection. More settings would be needed if relay has provision for on-load tap changer (OLTC) monitoring, which could impact the normal operation of the main differential protection. Further, the entered data is used by the relay to perform winding currents compensation, and compute correct differential and restraint currents. The final step is associated with fetching the calculated differential and restraint currents into a set of differential/restraint criteria (characteristic) for defining differential protection "operate" or "not operate" conditions.

A. Winding Currents Magnitude Compensation

Each transformer is characterized by its power capacity, voltage transformation ratio, windings arrangement and mutual impedances. While power capacity is mostly dependent on the size of the iron magnetic core, the transformer voltage ratio is solely dependent on the amper-turns of the windings wound around the same core leg. For example a two winding 37.5MVA D/Y1 transformer with winding voltages of 69kV and 13.8kV has a voltage ratio of 5:1. Neglecting the power consumed by the transformer, both windings are rated to transfer the same 37.5MVA power. This means that ratio between the winding currents need to be the same, but in reverse proportion. Currents from 13.8kV winding will be 5 times higher than currents from the 69kV winding. The nominal currents for each winding are computed using the following equations:

$$I_{N(w1)} = \frac{MVA}{kV(w1)\cdot\sqrt{3}} \qquad (1)$$

$$I_{N(w2)} = \frac{MVA}{kV(w2)\cdot\sqrt{3}}$$

where $kV(w*)$ denotes phase-to-phase voltage of the specific winding.

To apply protection correctly, current transformers from both windings should measure and supply the winding currents to the relay with the same reversed ratio. This, however, in most cases is not possible, because primary ratings of the CTs used to replicate the winding currents are different from the winding nominal currents. The CTs are manufactured with the standard primary/secondary turns, providing standard primary rated currents. Also, CTs are selected with primary current ratings of at least 1.2 – 1.5 times higher than the winding nominal current. For example, if the nominal current for the 69kV side equals 313.7 Amps, the selected CT primary should not be less than 400 A. Another factor for CT selection is the capability of the CT to replicate high fault currents without significant saturation. Hence the difference between currents measured by the relay and currents needed for providing the differential protection is evident. To make it simple, the user selects a magnitude reference winding by means of winding phase-phase voltage and winding CT primary, and the algorithm automatically computes the magnitude compensation factors used for scaling the currents from the non-reference winding. If winding 1 is selected as a reference winding, the magnitude compensation coefficient for winding 2 would be:

$$M_{1(w1)} = 1 \text{ - magnitude reference winding}$$

$$M_{2(w2)} = \frac{kV(w2)\cdot CT_{prim}(w2)}{kV(w1)\cdot CT_{prim}(w1)} \qquad (2)$$

For the example above, with a winding #1 CT (500:5), and winding #2 CT (2000:5), currents from the winding #2 CTs would be multiplied by a magnitude compensation factor of 0.8.

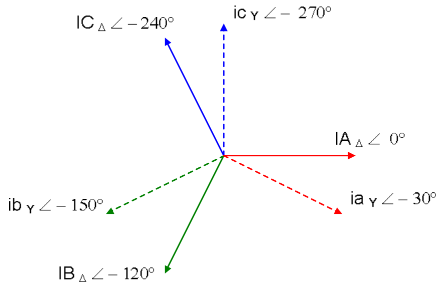
B. Winding Currents Phase Shift Compensation

The windings wound on each iron core leg in a three-phase transformer can be connected in a number of ways to satisfy the application of the transformer in the power system. Some windings are connected in “Star” (Wye connection), with the start point either grounded or ungrounded. Others are connected in Delta to provide ground isolation. When the three individual primary windings are connected in the exact same way as the three individual secondary windings, no phase shift is happening. Phase shift happens between the primary and secondary winding currents, when the connection arrangement of the three secondary windings is different than the one of the three individual primary windings.

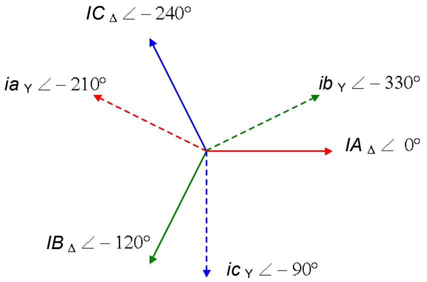
In the past, the phase shift compensation has been done externally, by connecting the CTs from the Wye winding in Delta, and the ones from the Delta winding in Wye. This way the phase shifting compensation is performed by the Delta CTs from the Wye winding. The impact of the Delta and the Wye connected CTs placed respectively on both Wye and a Delta side of the transformer is as follows:

- Perform external phase shift compensation and adjust currents with 180° degrees phase shift to the relay ready for magnitude matching and differential summation.
- Eliminate zero sequence currents (Delta connected CTs) from the grounded Wye winding and match the currents measured from the Wye connected CTs on the Delta winding.

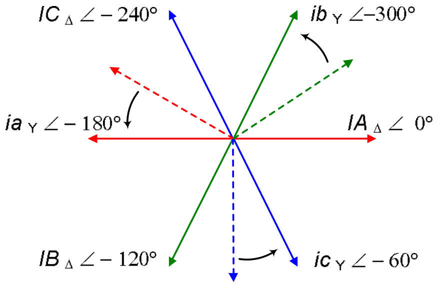
In the modern time, the external phase shift compensation is not so common, as new digital relays internally perform the phase shift compensation. The CTs from both sides of the transformer are connected in Wye, meaning that currents flowing into relay terminals have the same transformer phase shift plus 180 degrees resulting from the mirrored polarity of both winding CTs. These relays measure the shifted winding currents, and apply a set of equations to do the phase shifting correction. For example, the set of equations (3) used to phase compensate the currents measured from the Wye winding that is shifted by 30° degrees from the Delta currents like shown on figure 1-a,b,c,d:



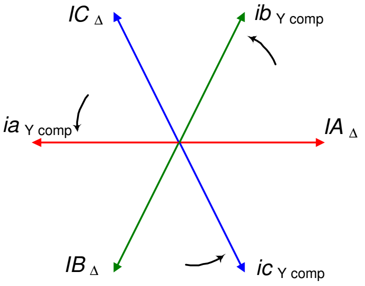
a) Wye currents lag Delta currents by 30° degrees (primary)



b) Wye and Delta currents from Wye connected CTs measured by the relay (secondary)



c) Phase shifting of the Wye currents



d) Phase compensated Wye and Delta currents for differential protection

Fig. 1. Phase shift compensation stages

Set of equations applied depends on the type of the transformer group, programmed in the relay. Standard phase shifts, seen in the conventional type power transformers is in multiples of 30° degrees, therefore many transformer differential protection relays provide a pre-set table for selection of the desired transformer type. Such table contains combinations of Wye, Delta and Zig-Zag windings for two and three winding transformers with a standard phase shifts that are in multiples of 30° degrees angles. As it will be seen further, this approach of defining the transformer phase shift to the transformer protective relay is not very sufficient for some transformers with non-standard phase shifts.

$$\overrightarrow{ia_{Y\,comp}} = \frac{\overrightarrow{ia_Y} - \overrightarrow{ib_Y}}{\sqrt{3}}$$

$$\overrightarrow{ib_{Y\,comp}} = \frac{\overrightarrow{ib_Y} - \overrightarrow{ic_Y}}{\sqrt{3}} \qquad (3)$$

$$\overrightarrow{ic_{Y\,comp}} = \frac{\overrightarrow{ic_Y} - \overrightarrow{ia_Y}}{\sqrt{3}}$$

III. TRANSFORMERS WITH NON-STANDARD PHASE SHIFTS

Depending on the core-winding construction, some power transformers do not introduce a standard phase shift of 30°, or multiples of 30° degrees. Employing differential protection for such transformers is not straight forward, and requires more analysis. The main concerns would be to define the following:

- zone of protection and locations of current transformers
- winding currents and phase shifts
- special CTs - relay terminals connections
- selection of protective relay that can be successfully applied without the need of connecting any auxiliary CTs or other equipment in general

A. *Phase Shifting Transformers*

The Phase Shifting Transformers (PSTs) are used to control the active and reactive power flow through a line by varying the phase angle between its source and load voltages. The PST controls the power by inserting regulated quadrature voltage in series with the line to neutral voltage of the series winding (Fig. 2). There are different types of PSTs, depending on their application and construction: with or without Load Tap Changer (LTC), PSTs with Delta/Wye or Wye/Wye exciting unit configuration, with or without voltage regulating winding, or hexagonal designed. They also differ by power and voltage ratings, and provide different ranges of phase angle regulation.

A conventional type PST (Fig. 2) consists of two units: Series Unit with secondary winding connected in Delta, and an exciting Unit of Wye-connected primary and secondary windings with grounded neutrals. The Load Tap Changer is located on the secondary Wye winding from the Exciting unit, and is used to control the quadrature voltage magnitude induced into the series winding. This results into shifting the angle of the Load side voltage with respect to the Source side voltage. The power flow between the Source and Load sides of the PST can be approximated by the following equation:

$$P = \frac{V_S \cdot V_L \cdot \sin\Theta}{X} \qquad (4)$$

where,

P - real power flow

V_S - voltage of the Source side

V_L - voltage of the Load side

Θ - phase angle difference between V_S and V_L

X - reactance between the Source and Load sides

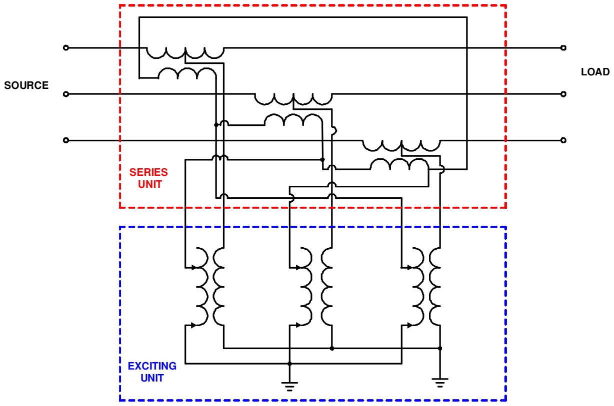


Fig. 2. Typical PST configuration

Normally two differential protections are employed to protect the Phase Shifter: a) 87P called primary differential protection with a zone of protection that includes series winding and the grounded Wye primary winding from the exciting unit, and b) 87S called secondary differential protection, including the Delta secondary winding from the series unit and a tapped secondary winding from the exciting unit. Figure 3 shows the distribution of phase A currents through the Source and Load sides, as well as the excitation winding used as inputs for the 87S phase A differential protection.

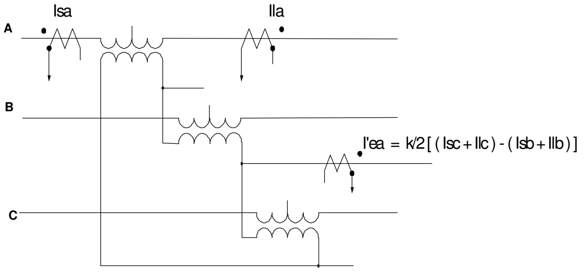


Fig. 3. 87S - PST secondary differential protection

The differential current for each phase is expressed as a summation of the currents from the corresponding Source, Load and excitation sides:

$$\vec{I}da = \vec{I}sa + \vec{I}la + \frac{k}{2}[(\vec{I}sc + \vec{I}lc) - (\vec{I}sb + \vec{I}lb)]$$

$$\vec{I}db = \vec{I}sb + \vec{I}lb + \frac{k}{2}[(\vec{I}sa + \vec{I}la) - (\vec{I}sc + \vec{I}lc)] \qquad (5)$$

$$\vec{I}dc = \vec{I}sc + \vec{I}lc + \frac{k}{2}[(\vec{I}sb + \vec{I}lb) - (\vec{I}sa + \vec{I}la)]$$

where,

$\vec{I}sa$ - phase A primary current source side

$\vec{I}la$ - phase A primary current load side

$\vec{I}'ea = \frac{k}{2}[(\vec{I}sc + \vec{I}lc) - (\vec{I}sb + \vec{I}lb)]$ is the phase A exciting current

k is the series unit turns ratio

Working out with the Source and Load currents, and the per-phase current from the exciting unit, one can arrive to the conclusion that the angle (Fig. 4) between current (summation of the source and load currents) and the exciting unit current is actually equal 90° degrees at all time. In other words, the applied quadrature voltage from the exciting unit into the series winding leads to the same relationship between the Source and Load summed current, and the exciting current. This angle has to be reflected in the transformer setup to assure correct phase shift compensation.

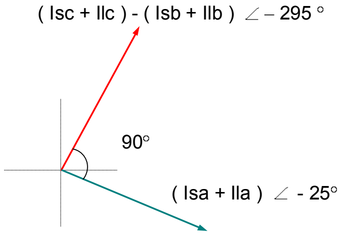


Fig. 4. Angle difference between S+L current and the exciting current

Issue #1: The PST setup in the transformer protection relay need to reflect Y0/Y0/D9 transformer, which is not a standard type transformer, hence not in the list of selection for many relays providing transformer differential protection.

The differential protection of PSTs represents another challenge that it is not commonly known or understood. Only few papers have been written to document the phenomenon of the stray flux on the CTs buried into the PST bank.

Figure 5 shows the distribution of the phase A currents through the Source, Load and Excitation windings used as inputs for the 87P phase differential protection.

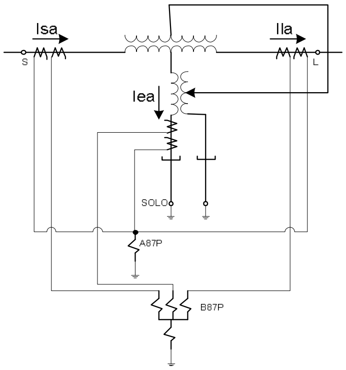


Fig. 5. A87P- Primary differential protection, high impedance, and B87P-Primary differential protection-low impedance

Both 87P relays utilize the Kirchhoff's current law principle in a similar manner as the relays used for bus protection.

Therefore, if applied with matching CT ratios no angle or magnitude compensations are required. Special attention should be given to the current transformers utilized by the primary differential scheme. In most PSTs designs, the current transformers located in the exciting unit are typically buried in the transformer tank in a close proximity to the core and windings. Unless otherwise specified by the user, most PSTs manufacturer will not provide shielding for these CTs.

A Transmission Facility Owner in Alberta, "AltaLink Management Ltd", experienced several false operations during the energization of a 600MVA, 260kV symmetrical Phase Shifting Transformer. The PST was energized from the source side with the load terminal open and at a tap angle of 0 degrees.

At this installation, the CTs are located in a close proximity to the excitation core and windings as shown in Figure 6.

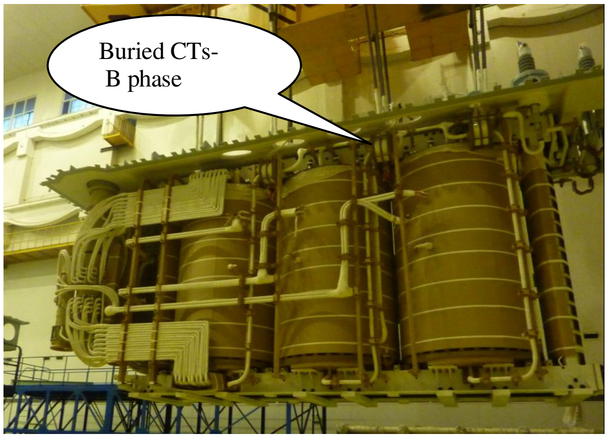


Fig. 6. Buried CTs in excitation unit

During several misoperations, a mismatch of the source current and excitation current was observed in the 87P protections. In the second event, The B phase excitation current (Ieb) recorded by the differential relay was found to be significantly larger than the corresponding source current (Isb) with a similar trace to the A phase current.

Figure 7 shows the waveforms recorded by the low impedance primary differential protection.

All of the CT connections, protection readings under the load and CT excitation characteristics were tested and confirmed to be satisfactory. Therefore, the utility concluded that excitation CTs were influenced by the external flux.

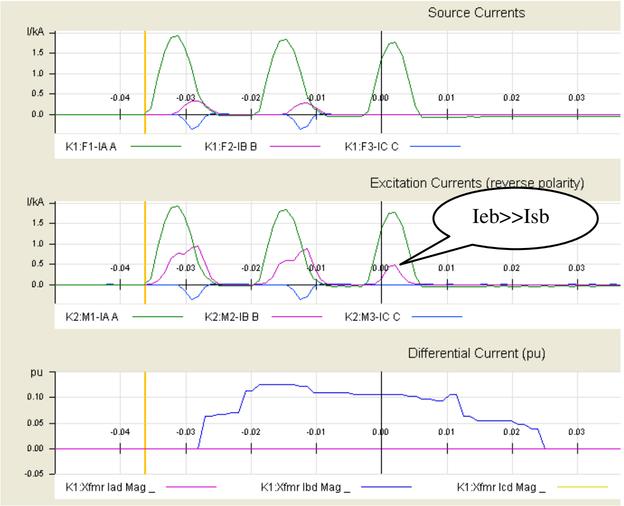


Fig. 7. Source and Excitation currents during PST energization.

The PST manufacturer conducted further investigation through detailed modeling of the electromagnetic field. The study confirmed the influence of the core flux on the buried CTs during PST energization. The maximum deviation error of the excitation currents was estimated to be approximately 48% under extreme PST core saturation.

Figure 8 shows the distribution of magnetic flux during PST energization.

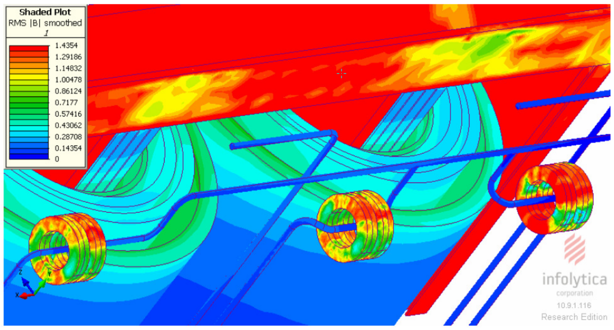


Fig. 8. Magnetic flux in excitation unit during energization.

Due to design clearance limitations and to avoid additional expenses, the utility decided to secure relays by adjusting the protection settings instead of installing electromagnetic shielding on the CTs. The addition of CT shielding is preferred but not always feasible at the existing installations.

In order to secure the primary relays, the event records captured by the primary protections were analyzed. For the low impedance primary differential relay, the content of second harmonic during energization was estimated from the raw data using a fault analysis tool with Discrete Fourier Transform. In all events, the ratio of second harmonic to fundamental was found to exceed the traditional threshold of 15% for the affected phase. Therefore, a per-phase harmonic blocking was applied to the low impedance differential protection. A conventional test set was used to play back the energization records and the relay was confirmed to be stable.

The pickup of the high impedance primary differential protection was also increased by a multiplier of five (5) based on the data obtained from the built–in event recording and to provide a safety margin. The new setting was calculated to be just below half of the CT knee point voltage in order to maintain relay dependability for internal faults.

For all subsequent PST energizations both relays were found to be stable after settings adjustments.

B. Scott and LeBlanc Transformers

Scott transformers are economical converters between three- and two-phase systems and mostly used to supply power for two-phase furnaces or two-phase motors from a three-phase system. Figure 9 below shows a Scott transformer connection by the means of two single-phase transformers with a three-phase inputs and two-phase outputs. The primary winding of the "teaser" transformer is center tapped and is connected to the three-phase system, where its secondary winding is connected to a two-phase circuit. The other transformer called "main" has one end of its primary winding connected to the third phase from the three-phase system, and the other end connected to the center tap of the "teaser" primary winding.

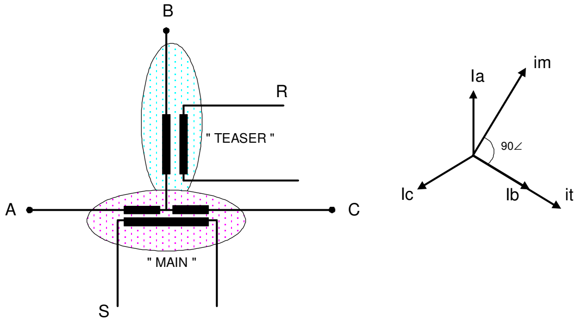


Fig. 9. Scott transformer construction and currents

Normally one current transformer (CT) is available on each phase from the three phases side (Fig. 10), and on each phase from the two-phase side. All those CTs are used as inputs for the transformer percent differential protection, under special connection arrangement. This arrangement is dictated by the two individual transformers forming the Scott connections, accounting for the current $(i\vec{a} - i\vec{c})$ transformed into *im* current, and current *ib* transformed into *it* current.

The Scott transformer setup performed on the relay requires three windings configuration, and entering data for winding power, voltages, connections, as well as the phase shifts. Inputs for winding #1 is the "*it*" current with CT secondary connected to phase A relay terminal, and current "*im*" with CT secondary connected to phase C terminal (Fig. 10). Phase B terminal remains open.

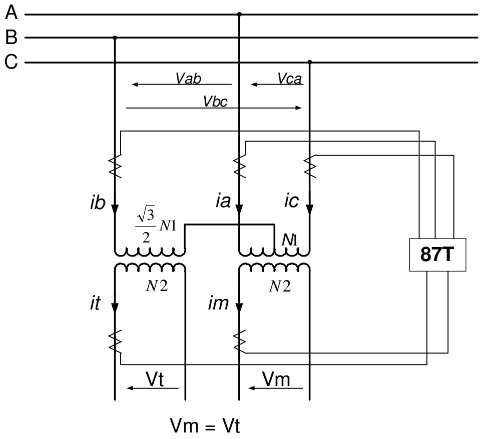


Fig. 10. Scott transformer connections for 87T protection

For example, a 100MVA Scott transformer with HV=154kV, and LV = 55kV can be set as follows: each LV winding gets 50% of the total power, meaning that winding #1 will have setting of 50MVA for the power and 55kV as phase voltage. The current is then calculated as:

$$im = it = \frac{50MVA}{55kV} = 909Amps$$

To balance "*im*" current from winding #1 - phase A, the current "*Ib*" connected to phase A/CT bank #2, needs to be calculated.

The turns ratio of the two windings from the "main" transformer is 86.6%N1: N2 primary/secondary, so that the corresponding voltage of the primary winding on phase B is calculated as:

$$V_{W2} = \frac{154kV \cdot \sqrt{3}}{2} = 133.4kV$$

Therefore the voltage setting of winding #2 is set to 133.4kV. The current flowing through the main transformer primary winding - phase B is calculated as:

$$Ib = \frac{100MVA}{154kV \cdot \sqrt{3}} = 375Amps$$

The current "it" flowing through the secondary winding from the teaser transformer is balanced against the sum of the teaser transformer primary currents "ia" and "ic" accounting for the teaser turns ratio. The winding #3 current is therefore a summation of "ia" and "ic" currents, both connected to phase C terminals (Fig. 11) from banks #3 and #4. Since both currents are equal and in opposite direction, the relay connected to their respective CTs with standard polarity will perform currents subtraction (4). The currents ia and ic have the same magnitudes as the current ib from the three phase system, so that the voltage on the primary winding of the teaser transformer has to be configured as half of the phase-to-phase voltage:

$$V_{W3} = \frac{154kV}{2} = 77kV$$

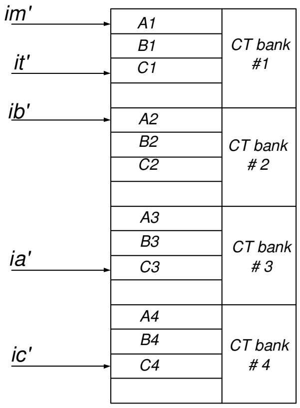


Fig. 11. Currents from Scott transformer CTs connected to relay terminals

Only phase A and phase C differential protections are used from the relay. Phase B terminals are not connected. The differential equations for all three phases can be written as follow:

$$\begin{aligned} I_{DA} &= it + \frac{\sqrt{3}\cdot N1}{2\cdot N2}\cdot ib = 0 \\ I_{DB} &= 0 \qquad (6) \\ I_{DC} &= im + \frac{N1}{2\cdot N2}\cdot (ia - ic) = 0 \end{aligned}$$

For Scott transformers, a non-standard phase shift of 90° degrees exists between its two output currents *im* and *it*. Normally, the transformer type selected in the relay is D/D0/D0/D0.

Issue #2: Protecting Scott transformer by applying differential protection requires selection of four winding delta transformer, which is not normally available in the list of standard transformer types. The setup requires special wiring between CTs and relay terminals as outlined above.

LeBlanc transformers are alternative to Scott transformers used for the same purpose of converting three-phase to two-phase system and vice versa. The difference here is that the *LeBlanc* transformer is build on three-limb core (Fig. 12), three-phase design as compared to two single cores of the Scott transformer. In addition to the simpler standard core arrangement, the LeBlanc transformer is less costly to manufacture due to the fact that for a given rating, less active materials are required for its construction. The LeBlanc unit is more economical relative to space, compared to the Scott transformer

Similarly, we can write the differential equations for each phase of the LeBlanc transformer:

$$\begin{aligned} I_{DA} &= ia + \frac{2.N2}{\sqrt{3}.N1}\cdot it \\ I_{DB} &= ib + \frac{N2}{N1}\cdot (im - \frac{1}{\sqrt{3}}\cdot it) \qquad (7) \\ I_{DC} &= ic - \frac{N2}{N1}\cdot (\frac{1}{\sqrt{3}} it + im) \end{aligned}$$

One can easily figure out the connections of each individual current to the relay terminals, and calculate winding voltages for correct ratio matching.

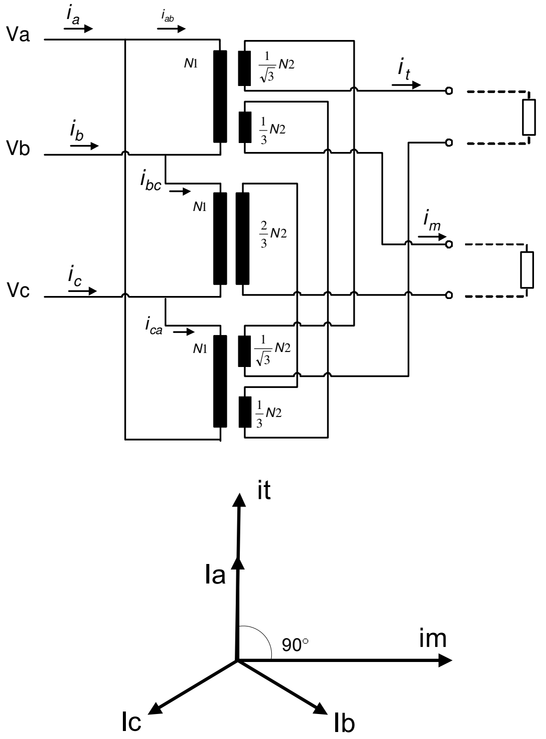


Fig. 12. LeBlanc winding arrangements and currents phase diagram

Applying differential protection for LeBlanc transformer is associated with the similar challenges as seen from the Scott transformer, where one needs to make special CTs - relay terminals connections, and enter special transformer configuration.

C. Converter Transformers

The converter transformers are transformers with a special winding connections, that the output voltages are shifted from the input voltages, and from the other output voltages by a non-standard angle (standard again being considered 30° or multiple of 30° degree). Normally these transformers are connected to electronic converters used to supply quality power to electronic equipment such as motor drives, Flexible AC Transmission System (FACTS) devices, or Static Synchronous Compensators (STATCOMS). At the same time these transformers and converters reduce up to 95% the current harmonics that may be injected by the power electronic equipment into the utility power system. Depending on the converter used, i.e., 6-pulse, 12-pulse, 18-pulse, 24-pulse, or 48-pulse, the transformers are equipped with 1, 2, 3, 4, or even 5 secondary windings, where the three phases from each of them are connected to a 6-pulse DC converter.

The standard 6-pulse voltage source converter (VSC) produces a quasi-square wave voltage at fundamental frequency gate switching, and can contain current harmonics in the order of $6n \pm 1$, where $n = 1,2,3......$ etc. In multi-pulse configuration, multiple 6-pulse VSCs are connected to produce waveforms with higher order harmonics. For example, a 48-pulse converter transformer constituted of 8x6-pulse standard voltage source converters will have 47th, 49th, 95th, 97th, harmonics in its output AC voltage waveform. The power system is affected mostly by the lower order harmonics of up to the 25th harmonic, so the higher the pulsed VSC system, the better power quality is guarantied in the power system. The permissible levels of harmonics are outlined in the IEEE 519 standard.

As mentioned, these converter transformers (Fig. 13) have more than one secondary winding with output voltages shifted by an angle different than 30° or multiple of 30° degrees. For example the 18-pulse converter transformer supplies a 3x6 pulse DC converters, with winding voltages shifted by +20°, 0° and -20° angles.

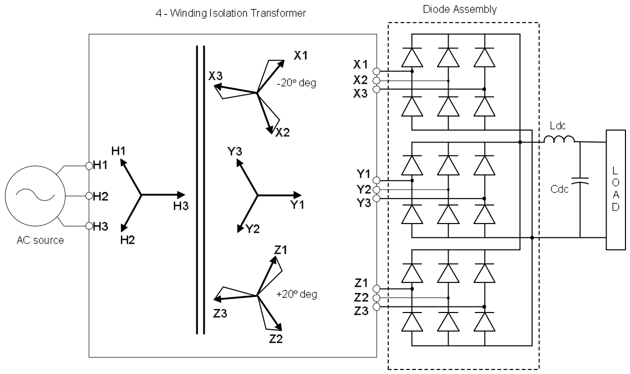


Fig. 13. Traditional 18-pulse converter

To provide differential protection, one may find that the most of the differential protective relays today do not provide the option to select phase shift compensation for winding currents with +20°, 0° and -20° angles. They only provide a list for selection for standard shift of 30° or multiple of 30°deg. transformer types.

Another example is the 24-pulse transformer, which introduces phase angle of ± 7.5° deg. on its secondary windings. This later one consists of two mirrored primary zig-zag windings with total of four secondary windings: one Wye and one Delta winding per each zig-zag winding. For this 24-pulse transformer, the transformer differential relay has to be able to compensate currents shifted by ± 7.5° degrees from the primary winding currents.

IV. UNIVERSAL PHASE SHIFT COMPENSATION METHOD

This method is employed in some advanced transformer protective relays, which perform universal phase shift compensation and practically provide differential protection for any transformer type, with any phase shift.

The method makes use of the fact that each current from the non-reference transformer winding can be represented as a sum of the currents from the phase reference winding. The following example is based on performing phase compensation for -7.5° degrees phase shift (Fig. 14) seen from the Wye winding secondary currents with respect to the primary zig-zag winding currents per a 24-pulse converter transformer. The example shows clearly the new phase compensation method:

First, to express the shifted current, the currents from the reference winding are projected with their negative values in the polar plane, where each two neighboring currents make a 60° degrees sector (Fig.15)

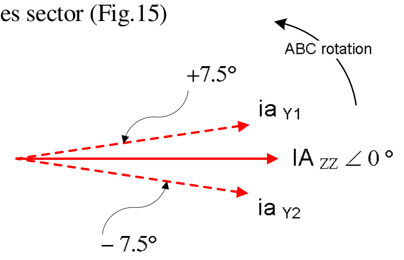


Fig. 14. Zig-Zag and Wye windings: Phase A currents

To define the phase reference winding, the algorithm looks for the first Delta, or Zig-Zag winding entered into the relay. If no Delta or Zig-Zag winding is entered, the algorithm selects the first Wye winding as the reference winding. In our example we use two paralleled converter transformers (Fig. 14) Zig-Zag/Wye(-7.5°), and Zig-Zag/Wye(+7.5°) where the Zig-Zag primary windings are phase reference windings. The phase A current ia_Y from the Wye winding is shifted by -7.5° degrees from the Zig-Zag winding phase A current IA_{ZZ}.

Further the algorithm calculates phase compensation angle (PCA), and defines the equations that need be applied to perform phase shift. The PCA for ABC power system rotation is computed as follow:

$$\Theta_{PCA} = \Theta_{W_R} - \Theta_{W_{NR}} \qquad (8)$$

where,

Θ_{W_R} -reference winding angle

$\Theta_{W_{NR}}$ -non-reference winding angle

Θ_{PCA} -phase compensation angle

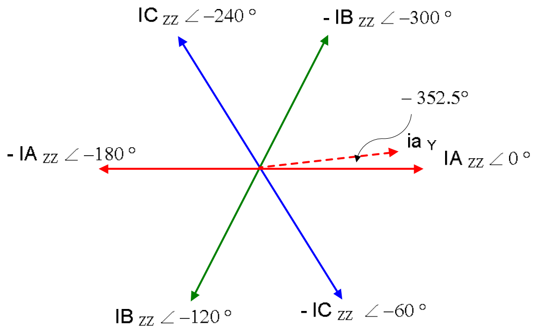


Fig. 15. Phase compensation angle within -300° and -360° deg sector

Applying the formula (6), the compensation angle equals -352.5 degrees.

The Wye currents ia_Y, ib_Y, and ic_Y are expressed using the reference winding currents.

$$ia_Y\angle\Theta = k_{AA}\cdot Ia\angle 0^o + k_{AB}\cdot Ib\angle -120^o + k_{AC}\cdot Ic\angle -240^o$$

$$ib_Y\angle\Theta = k_{BA}\cdot Ia\angle 0^o + k_{BB}\cdot Ib\angle -120^o + k_{BC}\cdot Ic\angle -240^o$$

$$ic_Y\angle\Theta = k_{CA}\cdot Ia\angle 0^o + k_{CB}\cdot Ib\angle -120^o + k_{CC}\cdot Ic\angle -240^o$$

Working for ia_Y current, the coefficients corresponding to PCA of -352.5° degrees angle will be as follow:

$$\cos\Theta + j\sin\Theta = k_{AA} + k_{AB}.(-\frac{1}{2} - j\cdot\frac{\sqrt{3}}{2}) + k_{AC}.(-\frac{1}{2} + j\cdot\frac{\sqrt{3}}{2})$$

where,

$$\begin{aligned} \cos\Theta &= k_{AA} - \frac{1}{2}k_{AB} - \frac{1}{2}k_{AC} \\ \sin\Theta &= -\frac{\sqrt{3}}{2}k_{AB} + \frac{\sqrt{3}}{2}k_{AC} \end{aligned} \qquad (9)$$

Solving (6) for k_{AA}, k_{AB}, and k_{AC}, and compensation angle falling into the (-300° ÷ -360°) sector, the phase shift coefficients for Phase A current will be:

$$\begin{aligned} k_{AA} &= \cos\Theta - \frac{1}{\sqrt{3}}\sin\Theta \\ k_{AB} &= -\frac{2}{\sqrt{3}}\sin\Theta \\ k_{AC} &= 0 \end{aligned} \qquad (10a)$$

Correspondingly, the phase shift coefficients for Phase B are:

$$\begin{aligned} k_{BA} &= 0 \\ k_{BB} &= \cos\Theta - \frac{1}{\sqrt{3}}\sin\Theta \\ k_{BC} &= -\frac{2}{\sqrt{3}}\sin\Theta \end{aligned} \qquad (10b)$$

and the ones for phase C will be:

$$\begin{aligned} k_{CA} &= -\frac{2}{\sqrt{3}}\sin\Theta \\ k_{CB} &= 0 \\ k_{CC} &= \cos\Theta - \frac{1}{\sqrt{3}}\sin\Theta \end{aligned} \qquad (10c)$$

Applying the equations for phase A current ($ia_Y\angle$-352.5°), we have the coefficients:

$k_{AA} = 0.916$

$k_{AB} = -0.15$

$k_{AC} = 0$

and phase A current shifted by:

$$ia_{Y\,COMP} = 0.916\cdot Ia\angle 0^o - 0.15\cdot Ic\angle -240^o =$$
$$= 0.9915 + j0.1305$$

Working back to polar quantities yields phase rotation angle for ia_Y of +7.5° degrees, meaning that all Wye currents that were lagging by 7.5 degrees will be rotated by positive 7.5° degrees, hence making the currents from each phase for both windings 180° degrees out of phase, and ready for differential current summation.

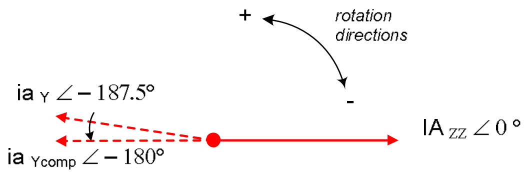


Fig. 16. Wye winding ph. A rotation

To prove the algorithm, we can do the same calculation for standard phase shift from a Y/d-30° transformer type for which the standard equations (3) apply. Now, applying equation (6), the PCA will be to -30° - 0° = -30° degrees (Delta winding is the reference), and coefficients applied for winding Wye phase A current from sector 0° and -60° degrees will be:

$$k_{AA} = -\frac{2}{\sqrt{3}} \sin \Theta$$

$$k_{AB} = 0$$

$$k_{AC} = \cos \Theta - \frac{1}{\sqrt{3}} \sin \Theta$$

The compensated phase A current from the Wye winding is shifted by -30 degrees and becomes 180° degrees out of phase compared to the Delta winding phase A current and accounting for the mirrored polarity of both winding CTs.

V. CONVERTER TRANSFORMER SIMULATION TESTS

To prove the algorithm, a 24-pulse converter transformer was modeled by connecting (Fig.18) two 12-pulse Zig-Zag/Y-7.5°/d+7.5° transformers.

Phase A currents from all three windings were scaled to the same units to show the -7.5°lagging angle for the first Wye winding, and the +7.5° leading angle of the second Wye winding to be compared with Zig-Zag currents (Fig. 17). The Delta windings were not used during the simulation.

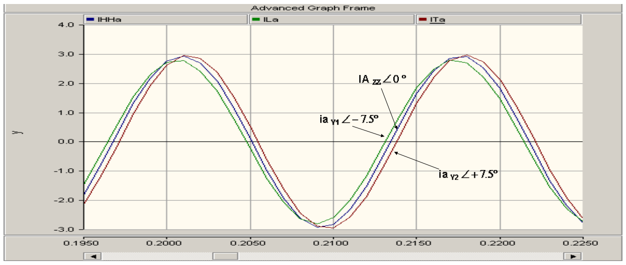


Fig. 17. Ph A currents from Zig-Zag/Y-7.5/y+7.5 converter transformer

Further, the tests included applying internal and external faults, and monitoring the relay for operation/no operation. The graphs from the following figures show captured response of the differential protection on applied internal B-C-G fault at the first Wye winding side, and an external B-C-G fault from the same side. The tests proved the new algorithm compensates the non-standard phase shift correctly.

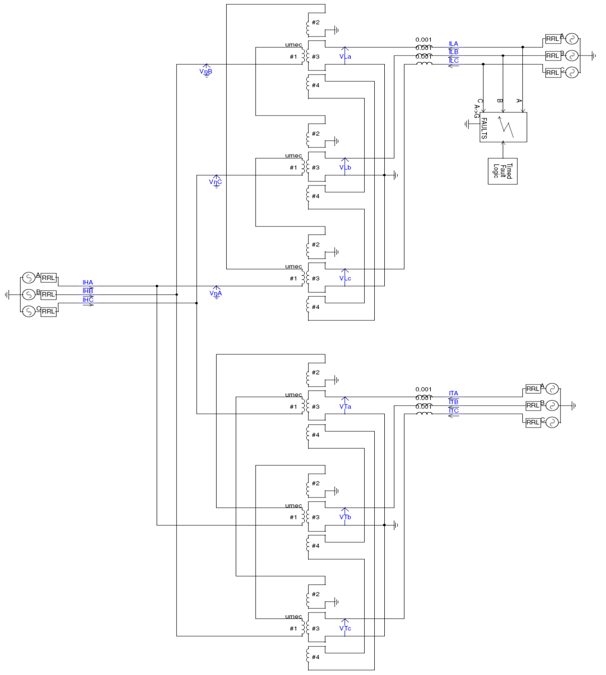
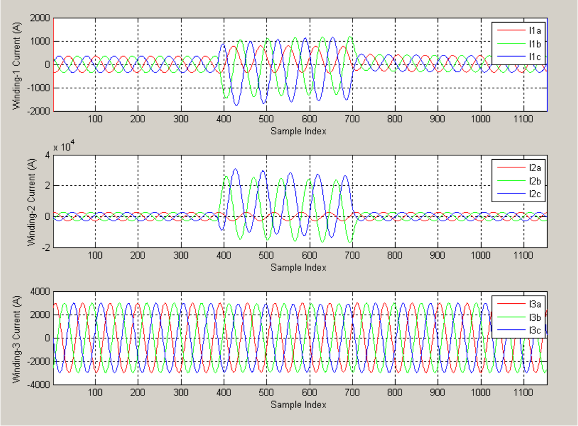


Fig. 18. Zig-Zag/Y-7.5/y+7.5 converter transformer model



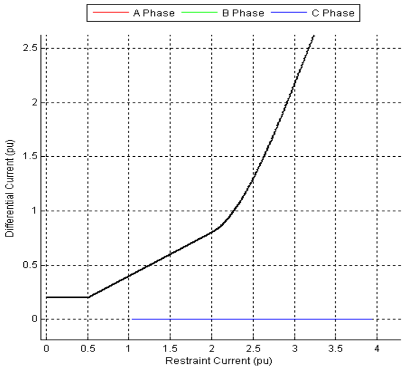


Fig. 19. External B-C-G fault at 13.8kV Wye1 winding

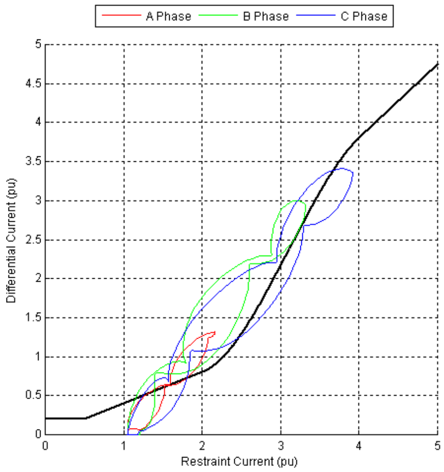


Fig. 20. Internal B-C-G fault at 13.8kV Wye1 winding

VI. CONCLUSIONS

- Modern microprocessor relays offer automatic phase shift compensation for any phase angle. This makes them universal in providing transformer differential protection.
- Protecting transformers with non-standard phase shifts does not require additional expenses for buying and installing auxiliary CTs for external phase shift compensation
- The information on CT locations, relay connections, as well as computation and entering of correct winding voltages is essential.

VII. REFERENCES

[1] Narain G. Hingorani, Laszlo Gyugyi "Understanding FACTS", The Institute of Electrical and Electronics Engineers, New York, 2000

[2] Martin J. Heathcote, "J&P Transformer Book", Thirteenth Edition, 2007 Elsiever Ltd.

[3] Yao-Hung Chan, Chi-Jui Wu "Power Quality Assessment of Specially Connected Transformers" Proceedings of the 9th WSEAS Int. Conference on Instrumentation, Measurement, Circuits and Systems

[4] GE DE Multilin, "T60 Transformer Management Relay", UR Series Instruction Manual, Revision 5.8, 2010

[5] Jin-Maun Ho, Tsung-Ling Tsou "The effect and Simulation Test of Harmonics on Differential Protection of Scott Transformers", 2001 IEEE Porto Power Tech Conference

[6] T.H. Chen, "Comparison of Scott and LeBlanc Transformers for Supplying Unbalanced Electric Railway Demands" EPRI, Vol. 28

VIII. VITA

Lubomir Sevov received his M.Sc. degree from Technical University of Sofia, Bulgaria in 1990. After graduation, he worked as a protection and control engineer for National Electric Company (NEC) Bulgaria. Mr. Sevov joined GE Multilin in 1998, where he currently works as a senior application engineer in the research and development team. Mr. Sevov specializes in the design and application of industrial protective relays and controls. In 2004 he became a member of the association of professional engineers Ontario, Canada. He is a senior member of IEEE.

Zhiying Zhang received his B.Sc. and M.Sc. degrees from the North China Institute of Electric Power (now North China Electric Power University-NCEPU) and a Ph.D. degree from the University of Manitoba, Canada, all in Electrical Engineering. He has 24 years of experience in power system engineering, including 6 years with electric utilities and 18 years with relay manufactures in various technical positions. In 2007, he joined GE Multilin as an application engineer, and currently he is a senior designer with the same company. Zhiying is a registered professional engineer in the province of Ontario and a senior member of IEEE.

Ilia Voloh received his Electrical Engineering degree from Ivanovo State Power University, Russia. After graduation he worked for Moldova Power Company for many years in various progressive roles in Protection and Control field. He is currently an applications manager with GE Multilin in Markham Ontario, and he has been heavily involved in the development of UR-series of relays. His areas of interest are current differential relaying, phase comparison, distance relaying and advanced communications for protective relaying. Ilia authored and co-authored more than 20 papers presented at major North America Protective Relaying conferences. He is an active member of the PSRC, and a senior member of the IEEE.