Differential Protection for Power Transformers With Non-Standard Phase Shifts

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***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, winding connections vary. Some common power system applications require installation of two- or three-winding conventional power transformers or autotransformers, while others require 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) installed in non-common locations adds even more to the complexity of applying the protection correctly. The later is associated with special CT – relay connections, correct computation of winding currents, phase angles, and selection of protective device supporting such applications.

The paper provides essential knowledge on the transformer differential protections 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, Converter Transformers, Phase and Magnitude compensations**

I. INTRODUCTION

The technological advancements in the design of relay hardware and the development of better algorithms for protection of power transformers enabled the power system engineers to apply differential protection not only to conventional power transformers, but also to transformers with non-standard phase shifts. We find those non-standard phase shifts between the winding currents from 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 either the distribution or the transmission power system 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 there is grounding within the zone of protection. More settings would be needed if the relay has provisions 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 the 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 operation or no operation.

A. Winding Currents Magnitude Compensation

Every transformer is characterized by its power capacity, voltage transformation ratio, winding, and mutual impedances. While the 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 the ratio between the winding currents need be the same, but in reverse proportion. The current from the 13.8kV winding will be 5 times higher than the current from the 69kV winding. The nominal currents for each winding is computed using the following equations:

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

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

To apply the protection correctly, the current transformers from both windings should measure and input the winding currents to the relay within the same reversed ratio. This however in most of the cases is not possible, as the primary ratings of the CTs used to replicate the winding currents within the range of secondary amps, are different than the winding nominal currents. The CTs are build with standard primary/secondary turns providing standard primary rated currents. The CTs are selected with primary current ratings of at least 1.2 – 1.5 times bigger 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 mismatch between the currents measured by the relay and the currents needed for providing the differential protection is evident. To make it simple, the user selects a magnitude reference winding with meaning of winding phase-phase voltage and winding CT primary, and the algorithm computes the magnitude compensation coefficients, by which the non-reference winding currents are scaled. If winding 1 is selected as a reference winding, the magnitude compensation coefficient for winding 2 would be:

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

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

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

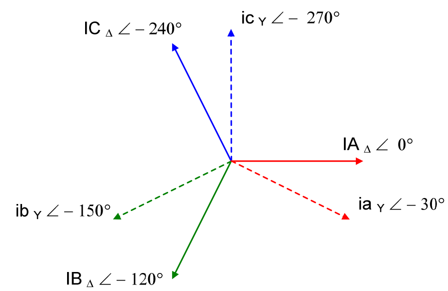
B. *Winding Currents Phase Shift Compensation*

The windings wound on each of the three single core legs from 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 arrangement 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 accounted. Phase shift is accounted between the primary and secondary winding, when the connection arrangement of the three secondary windings is different than the one of the three individual primary windings.

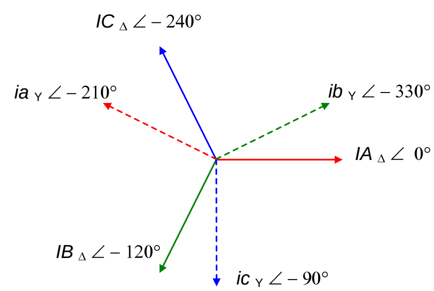
In the past, the phase shift compensation has been done externally, by connecting the CTs from the Wye winding in Delta, and the ones from the Delta winding in Wye. This way the phase shifting compensation is performed by the Delta CTs from the Wye winding. The impact of the Delta and the Wye connected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

- Perform external phase shift compensation introducing 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 zero sequence free currents measured from the Wye connected CTs on the Delta winding.

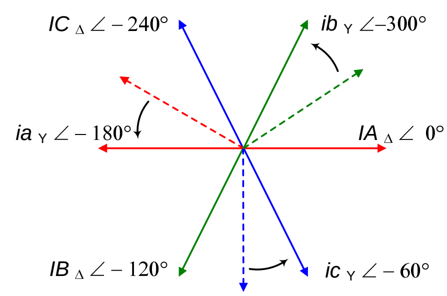
In the modern time, the external phase shift compensation is not so common, as the new digital relays can perform the phase shift compensation automatically. The CTs from both sides of the transformer are connected in Wye, meaning that the currents introduced to the relay terminals have the same transformer phase shift plus 180 degrees incurring 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 shifted by 30° degrees from the Delta currents looks like shown on figure 1-a,b,c,d:



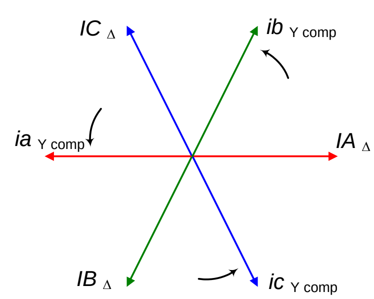
a) Wye currents lag Delta currents by 30° degrees



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



c) Phase shifting of the Wye currents



d) Phase compensated Wye and Delta currents

Fig. 1 Phase shift compensation stages

The applied set of equations depends on the type of transformer group selected on the relay. The standard phase shifts seen on conventional type power transformers is in multiples of 30° degrees, so that many transformer differential protection relays provide a pre-set table for selection of the desired transformer type. The table contains combinations of Wye, Delta and Zig-Zag windings for two and three winding transformers with standard phase shifts that are in multiples of 30° degrees angles. As 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 places 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 costly auxiliary CTs or 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 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 used to shift 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:

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

where,

P - real power flow per unit
V_S - per unit voltage of the Source side
V_L - per unit voltage of the Load side
Θ - phase angle difference between V_S and V_L
X - per unit reactance between the Source and Load sides

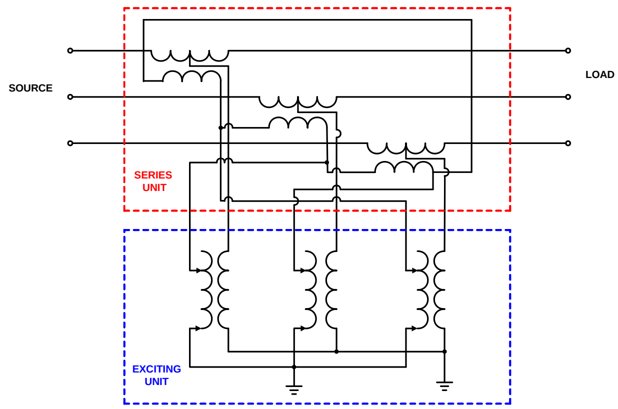


Fig.2 Typical PAR configuration

Normally two differential protections are employed to protect the Phase Shifter: 87P called primary differential protection with zone of protection that includes the series winding and the grounded Wye primary winding from the exciting unit, and 87S called secondary differential protection, including the Delta secondary winding from the series unit, and the 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.

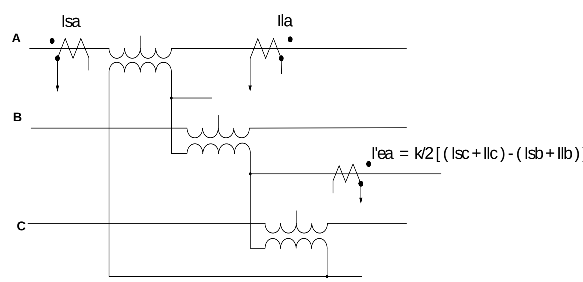


Fig.3 87S - the PST secondary differential protection

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,

$\vec{I}sa$ is the phase A primary current source side
$\vec{I}la$ is the 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, Load, and exciting unit current per phase, one can arrive to the conclusion that the angle (Fig. 4) between the current (summation of the source and load currents), and the exciting unit current is 90° degrees. This angle has to be reflected in the transformer setup to assure correct phase shift compensation.

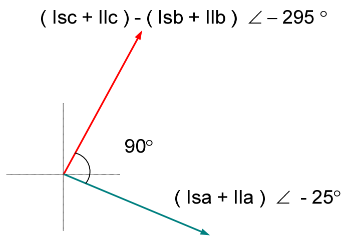


Fig.4 Angle difference between S+L current and the exciting current

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.

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 5 bellow shows a Scott transformer connection by the means of two single-phase transformers with 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.

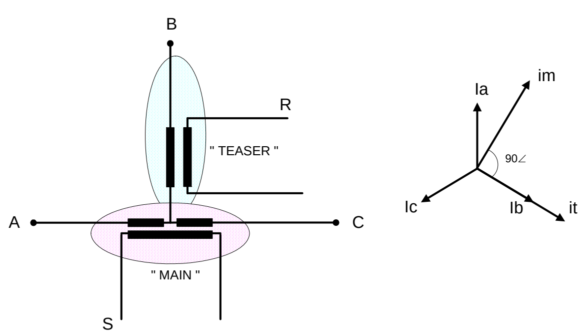


Fig. 5 Scott transformer construction and currents

Normally one current transformer (CT) is available on each phase from the three phases side (Fig.6), 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. The arrangement is dictated by the two individual transformers forming the Scott connections, accounting for the current $(\vec{ia} - \vec{ic})$ 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.7). Phase B terminal remains open.

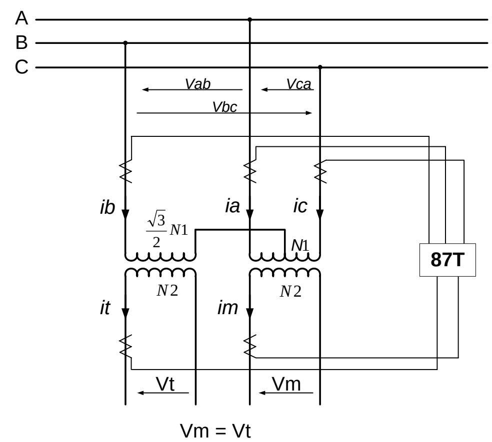


Fig. 6 Scott transformer connections for 87T protection

For example, a 100MVA Scott transformer with HV=154kV, and LV = 55kV can be set as follow:

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, need 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: $V_{W2} = \frac{154kV * \sqrt{3}}{2} = 133.4kV$. 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 $Ib = \frac{100MVA}{154kV * \sqrt{3}} = 375Amps$

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 the summation of "ia" and "ic" currents both connected to phase C terminals (Fig.7) 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:

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

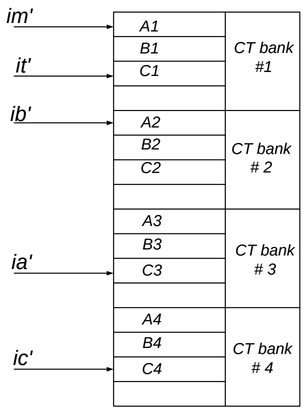


Fig. 7 Currents from Scott transformer CTs connected to relay terminals

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:

$$\begin{aligned} I_{DA} &= it + \frac{\sqrt{3}.N1}{2.N2}.ib = 0 \\ I_{DB} &= 0 \qquad\qquad\qquad\qquad (4) \\ I_{DC} &= im + \frac{N1}{2.N2}.(ia - ic) = 0 \end{aligned}$$

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 the Scott transformer 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 the Scott transformers used for the same purpose of converting three-phase to two-phase system, and vise versa. The difference here is that the *LeBlanc* transformer is build on three-limb core (Fig.8) , 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 on space compared to the Scott transformer

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

$$I_{DA} = ia + \frac{2.N2}{\sqrt{3}.N1}.it$$

$$I_{DB} = ib + \frac{N2}{N1}.(im - \frac{1}{\sqrt{3}}.it) \qquad (5)$$

$$I_{DC} = ic - \frac{N2}{N1}.(\frac{1}{\sqrt{3}}it + im)$$

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

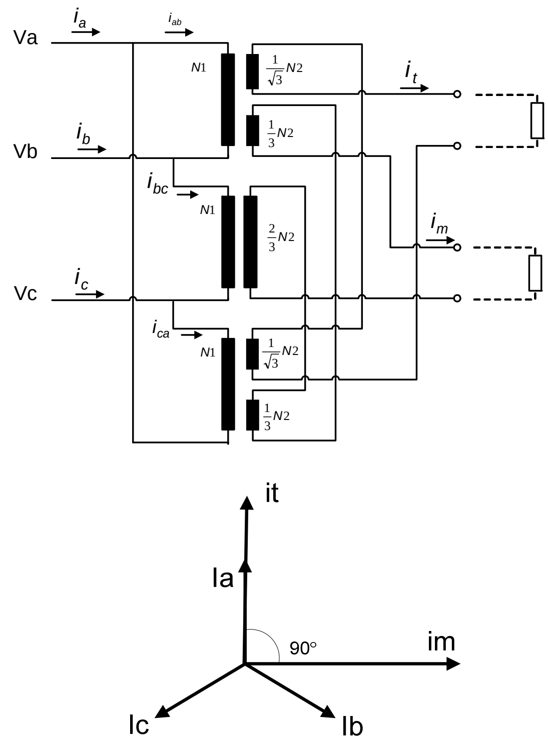


Fig. 8 LeBlanc winding arrangements and currents phase diagram

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

C. Converter Transformers

The converter transformers are transformers with special winding connections such that the output voltages are shifted from the input voltages, and from the other output voltages by a non-standard angle (standard being 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 used converter, i.e., 6-pulse, 12-pulse, 18-pulse, 24-pulse, or

48-pulse, the transformers are either 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 47^{th}, 49^{th}, 95^{th}, 97^{th}, harmonics in its output AC voltage waveform. The power system is affected mostly by the lower order harmonics of up to the 25^{th} 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. 9) 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.

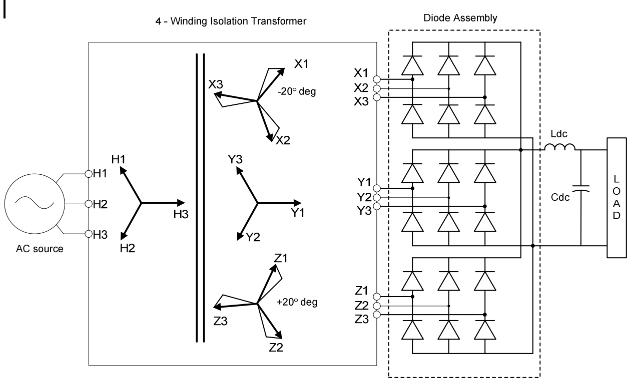


Fig. 9 Traditional 18-pulse converter

To provide differential protection, one may find, that 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°deg phase shift (Fig.10) 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° deg sector (Fig.11)

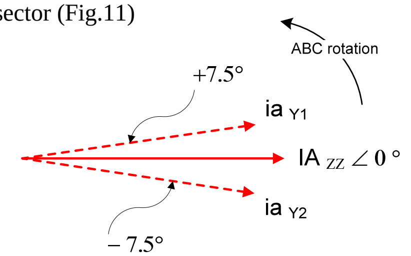


Fig. 10 Zig-Zag and Wye windings P~~Wye winding ~~hase A currents

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:

$$\Theta_{PCA} = \Theta_{W_R} - \Theta_{W_{NR}} \quad (6)$$

where,

Θ_{W_R} -reference winding angle

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

Θ_{PCA} -phase compensation angle

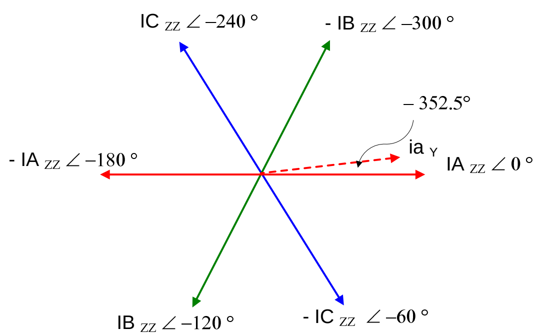


Fig. 11 Phase compensation angle within

-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.

$$ia_Y\angle\Theta = k_{AA}.Ia\angle 0^o + k_{AB}.Ib\angle -120^o + k_{AC}.Ic\angle -240^o$$
$$ib_Y\angle\Theta = k_{BA}.Ia\angle 0^o + k_{BB}.Ib\angle -120^o + k_{BC}.Ic\angle -240^o$$
$$ic_Y\angle\Theta = k_{CA}.Ia\angle 0^o + k_{CB}.Ib\angle -120^o + k_{CC}.Ic\angle -240^o$$

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

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

where,

$$\cos\Theta = k_{AA} - \frac{1}{2}k_{AB} - \frac{1}{2}k_{AC}$$
$$\sin\Theta = -\frac{\sqrt{3}}{2}k_{AB} + \frac{\sqrt{3}}{2}k_{AC} \qquad (7)$$

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:

$$k_{AA} = \cos\Theta - \frac{1}{\sqrt{3}}\sin\Theta$$
$$k_{AB} = -\frac{2}{\sqrt{3}}\sin\Theta \qquad (8a)$$
$$k_{AC} = 0$$

Correspondingly, the phase shift coefficients for Phase B will be:

$$k_{BA} = 0$$
$$k_{BB} = \cos\Theta - \frac{1}{\sqrt{3}}\sin\Theta \qquad (8b)$$
$$k_{BC} = -\frac{2}{\sqrt{3}}\sin\Theta$$

and the ones for phase C will be:

$$k_{CA} = -\frac{2}{\sqrt{3}}\sin\Theta$$
$$k_{CB} = 0 \qquad (8c)$$
$$k_{CC} = \cos\Theta - \frac{1}{\sqrt{3}}\sin\Theta$$

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:

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

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.

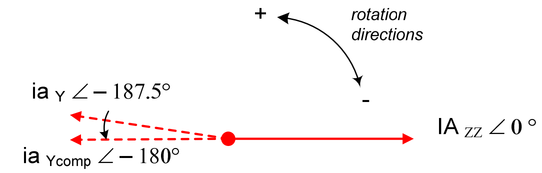


Fig. 12 Wye winding ph A rotation

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.14) 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. 13). The Delta windings were not used during the simulation.

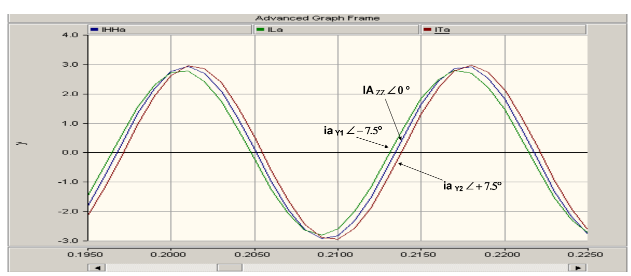


Fig.13 Ph A currents from Zig-Zag/Y-7.5/y+7.5 converter transformer

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.

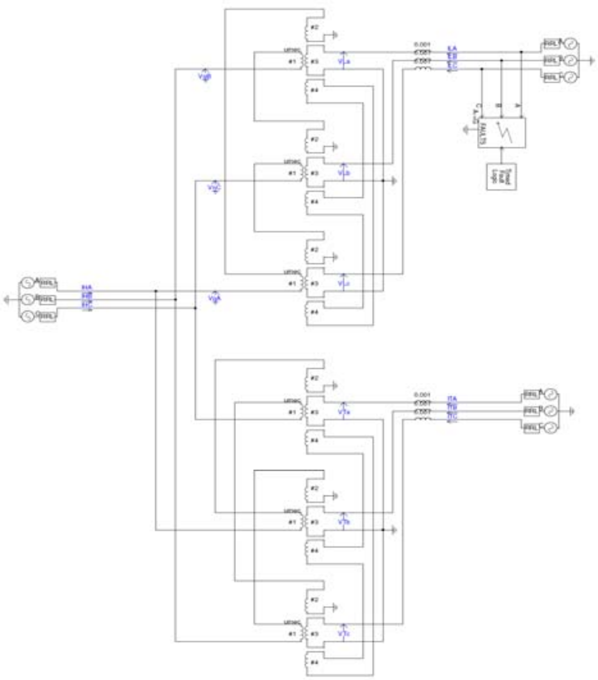
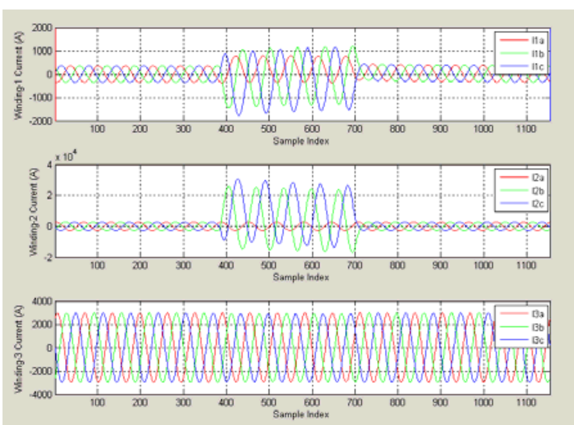


Fig.14 Zig-Zag/Y-7.5/y+7.5 converter transformer model



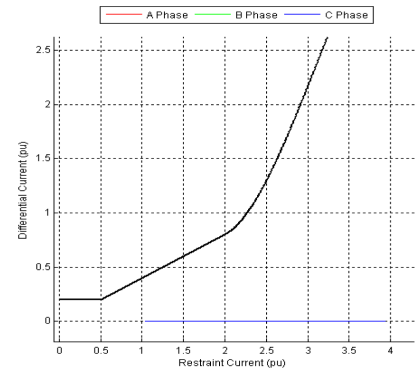


Fig. 15 External B-C-G fault at 13.8kV Wye1 winding

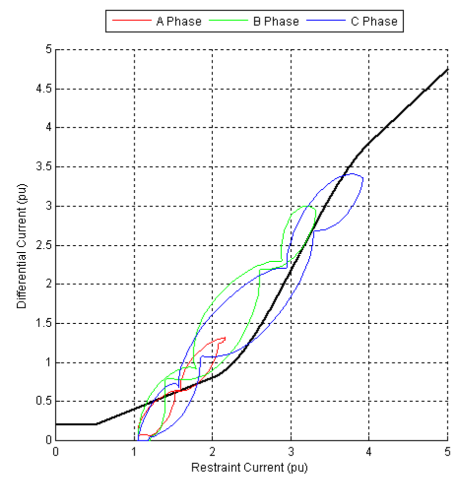


Fig. 16 Internal B-C-G fault at 13.8kV Wye1 winding

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.

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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 an application engineer with GE Multilin in Markham Ontario since 1999, 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.

Jorge Cardenas received his Engineering degree from the Universidad de Ingenieria (Peru) in 1977 and his MBA from the Universidad Politecnica de Madrid (Spain) in 1998. Jorge began his career with the Utility Electroperu (Peru) in 1979, as a Protection & Control Engineer, and in 1987 he moved to ABB (Spain) as a HV equipment Sales Engineer, and than promoted to a Control Design Engineer. In 1989 he joined GE, where he has held several positions. Currently Jorge works as EMEA-Application Manager with GE Digital Energy-Multilin. He authored and co-authored more than 30 papers presented on protective relay conferences around the world. He is a member of the CIGRÉ WG B5.31 and the WG B5.43 working groups.