Analysis of Fundamental Differences in Transformer 87T Differential Protection

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1. Introduction

When protection requirements dictate the use of multivendor equipment to avoid common mode of failures, utility protection engineers may believe for the transformer differential protection function (87T) that the same best practice application rules and guidelines will apply equally to all.

Faced with two 87T protection functions to set, one from vendor A and the other from vendor B, the utility protection engineer may believe that both need to be set the same way, as by doing so both would comply to a common set of rules. For instance, applying a perceived common rule that dictates which winding should be used by the 87T function as the phase reference winding.

This paper explains that there is not just one set of rules that apply to all. In modern numerical Intelligent Electronic Devices (IEDs) the calculation of the differential currents can be done with any winding chosen as the phase reference winding. However, this doesn't hold true when it comes to the restraint currents as, depending on the method of restraint current calculation, the choice of the phase reference winding plays a significant role in the actual restraint currents calculated. Whereas the calculation of the differential currents imposes no firm requirement on the choice of the phase reference winding, the method of calculation of the restraint currents does.

The choice of phase reference winding also impacts how the 87T function operates. For example, in accordance with utility policy, a utility has installed two numerical transformer protection IEDs from two different vendors, as system A and system B, to protect a Dy transformer. The 87T function in each IED was set in accordance with the vendor recommendations (one with the D-winding as the phase reference, the other with the y-winding as the phase reference). While in service, the transformer experiences an internal single-phase fault. The 87T function in each IEDs operates, but the IED with the D-winding phase reference indicates operation of the 87T function in two phases, whereas the other IED with the y-winding phase reference indicates 87T operation in all three phases. This paper explains that both 87T functions operated correctly, and that the difference was due to the winding that was selected as the phase reference.

2. Overview of transformer differential protection (87T)

Differential protection is based on summing the currents, per phase, from all sides of the protected object. The primary currents are fed to the relays via CTs, and it is these CTs that form the zone boundaries of the differential protection zone. For no internal fault, the sum of the currents is zero, i.e. the currents entering and leaving the zone of protection are equal, whereas for an internal fault, the sum is non-zero, i.e. the currents entering and leaving are no longer equal. This non-zero sum represents the zone differential current.

When a transformer is the protected object, it is true to say that the differential measurement principle is based on the sum of power from all sides being zero, as the sum of currents will only be zero after all compensations have been performed. Differential protection of transformers therefore presents additional challenges, including:

- mismatch in magnitude between winding currents due to the voltage transformation
- phase angle shift between winding currents due to different types of winding connections
- zero-sequence currents that cannot be transformed to other windings, and so only flow on one side.

Due to the current magnitude mismatch, the primary currents entering and leaving the transformer are not equal, even under normal balanced load conditions. The traditional way to overcome this was with the selection of CT ratios and relay tap. The phase shift across the transformer was compensated for by the way in which the CT secondaries were connected. Take for example, Yd and Dy type transformers, where the standard practice was to select the delta-connected winding as the phase reference for the 87T protection by wye-connecting the CT secondaries on the delta-connected side of the transformer. The CT secondaries on the transformer wye-connected side were then connected in the same delta connection, DAB or DAC, as the transformer delta-winding connection. This delta connection of the wye-side CT secondaries served two purposes, one of these being to align the phase of the wye-side currents with the phase of the delta-side currents, allowing the currents to then be compared phase-wise. The second was to form a trap for zero sequence currents which could flow on the wye-side, but not on the delta-side of the transformer.

Modern numerical microprocessor-based relays perform this compensation mathematically within the 87T function. All CT secondaries can therefore be wye-connected to the protection IED, as the delta-connection on the wye-side of Yd/Dy transformers is no longer necessary. The mathematical compensation takes care of the magnitude mismatch, the phase angle shift, and the subtraction of zero-sequence currents as required. For the phase angle shift compensation, a reference winding must be assigned. The reference winding is the winding to which the currents from all other windings are aligned, whilst its own currents undergo no shift in phase, i.e. are not rotated.

To make the 87T function as sensitive and stable as possible, a restrained differential characteristic is used. To get operation with such a characteristic requires that the differential current be greater than a certain percentage of the current through the transformer. This stabilizes the 87T function under through fault conditions while still permitting good basic sensitivity.

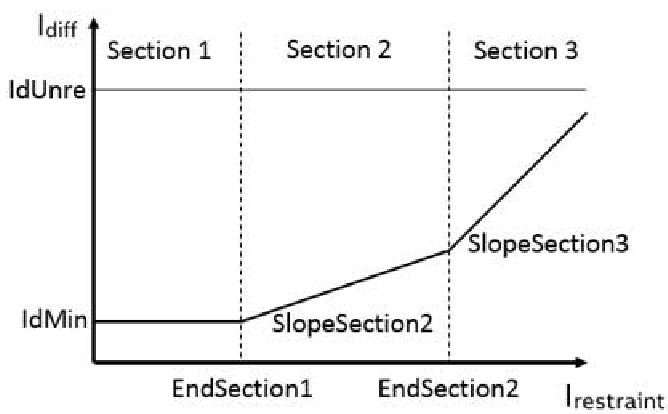

Figure 1: Typical characteristic for transformer 87T protection

Figure 1 shows a typical two-slope 87T characteristic for a standard two- or three-winding transformer.

The differential and restraint quantities are calculated from the measured currents. The way these values are calculated can vary depending on the design of the 87T function. The restraint quantity is a measure of through current level. It is an indicator of how high the currents are, i.e. an indicator of how difficult the conditions are under which the CTs are operating, as the higher the currents, the more difficult the conditions, and the higher the probability that the calculated differential currents may have a false component, primarily due to CT saturation.

If the calculated values of differential and restraint currents, which are calculated for each phase, plot above the characteristic, the 87T function operates, whereas if the point plots below the characteristic, the 87T function restrains.

3. Pre numerical relaying technology

The belief that the same best practice application rules and guidelines always apply appear justified for the older generations of relaying technology (pre numerical relaying technology). Take again, for example, Dy and Yd type power transformers, where the standard practice was to select the delta-connected winding as the phase reference for the 87T protection (delta-winding CT secondaries wye-connected to the 87T relay).

<u>Example 1:</u>

Dyn1 (=DABY) transformer; 100MVA; W1/W2 = 230kV/115kV
W1 I_{rated} = 251.0A; W2 I_{rated} = 502.0A
W1 CT ratio: 300/5; W2 CT ratio: 1000/5

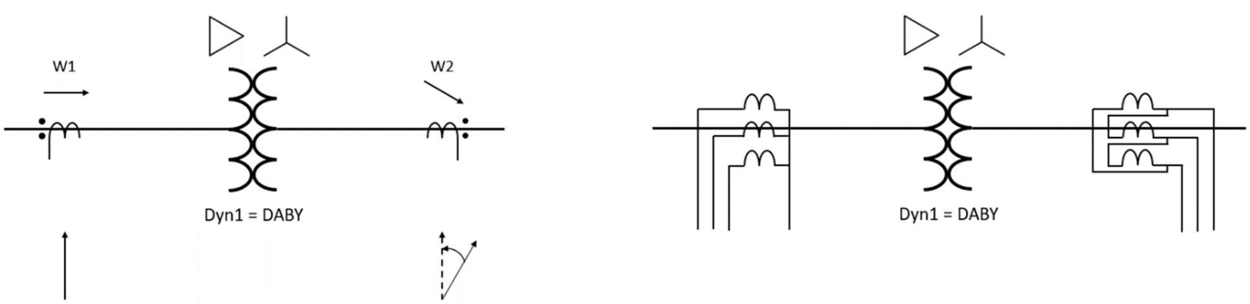

Figure 2: Dyn1 transformer showing W1 to W2 phase shift and CT secondary connections

The W1 delta-side is the phase reference. The W2 wye-side currents are rotated anti-clockwise +30° to align with the delta-side phase reference currents. This is achieved using the same delta-connection (DAB) of the W2 wye-side CT secondaries as the transformer delta-winding.

Example 2:

YNd11 (=YDAB) transformer; 100MVA; W1/W2 = 230kV/115kV
W1 I_{rated} = 251.0A; W2 I_{rated} = 502.0A
W1 CT ratio: 500/5; W2 CT ratio: 600/5

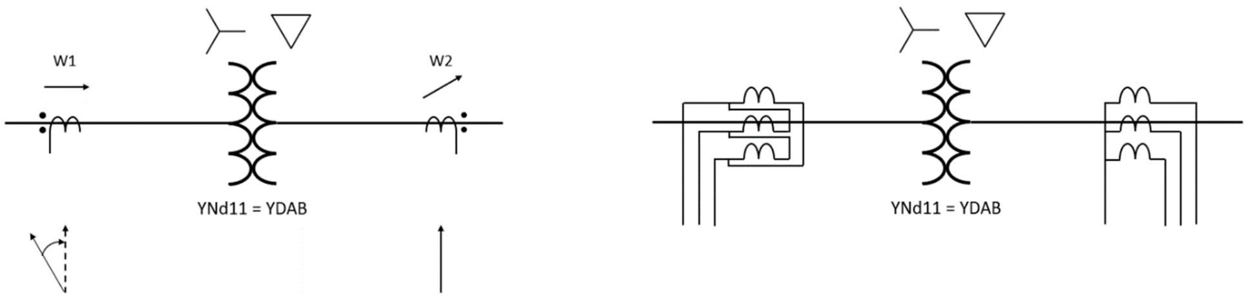

Figure 3: YNd11 transformer showing W1 to W2 phase shift and CT secondary connections

The W2 delta-side is the phase reference. The W1 wye-side currents are rotated clockwise -30° to align with the delta-side phase reference currents. This is achieved using the same delta-connection (DAB) of the W1 wye-side CT secondaries as the transformer delta-winding.

For both Examples 1 and 2, the differential currents are calculated for balanced load as well as different external fault types on the W2-side. See Appendix A for details. The delta-side of the transformer is always the phase reference, as the delta-side CT secondaries are wye-connected to the 87T relay.

For all cases studied, the differential currents are zero. Also, it can be clearly seen that the delta-side is the phase reference, as the CT secondary currents on this side connected to the 87T relay have the same phase angle as the primary currents. As all differential currents are zero for all cases, this demonstrates that having the delta-side as the phase reference for the 87T protection function provides a correctly operating solution.

4. Numerical relaying technology

Based on settings entered by the protection engineer, the 87T differential function will determine the matrix equations to be used on-line to calculate the differential and restraint currents. The entered settings therefore determine what the elements within each matrix will be, and in so doing define the phase reference winding for the calculation of the differential currents. With the phase reference winding defined this, in turn, impacts the restraint currents that will be calculated in accordance with the adopted method.

4.1 Matrix equations for the calculation of the differential currents

Two-winding power transformer

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = A * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{Ur\_W2}{Ur\_W1} * B * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

Three-winding power transformer

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = A * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{Ur\_W2}{Ur\_W1} * B * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix} + \frac{Ur\_W3}{Ur\_W1} * C * \begin{bmatrix} IA\_W3 \\ IB\_W3 \\ IC\_W3 \end{bmatrix}$$

where:
- ID_A, ID_B, ID_C are the calculated differential currents in, respectively, phase A, B, C
- IA, IB, IC are the actual primary phase currents in each winding
- A, B, C are 3x3 matrices for, respectively, winding-1 (W1), winding-2 (W2), and winding-3 (W3)

The actual A, B, and C matrix elements depend on:
- winding connection type, i.e. wye or delta
- transformer vector group, i.e. Dyn1 (D = DAB), YNd1 (d = DAC), etc., which introduces a phase shift between winding currents in multiples of 30°
- zero sequence current elimination set On or Off

Considering a two-winding power transformer:

$$A * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} = \begin{bmatrix} DCCA\_W1 \\ DCCB\_W1 \\ DCCC\_W1 \end{bmatrix}$$

and

$$\frac{Ur\_W2}{Ur\_W1} * B * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix} = \begin{bmatrix} DCCA\_W2 \\ DCCB\_W2 \\ DCCC\_W2 \end{bmatrix}$$

where:
- DCCA_W1 represents the Differential Current Contribution from W1 to the phase A differential current calculation, etc. These differential current contributions are also commonly termed the compensated currents in the differential current calculation.

$$|ID\_A| = |DCCA\_W1 + DCCA\_W2|$$

$$|ID\_B| = |DCCB\_W1 + DCCB\_W2|$$

$$|ID\_C| = |DCCC\_W1 + DCCC\_W2|$$

4.2 Calculation of the restraint currents

Looking at several 87T functions from various vendors, the restraint currents are calculated in different ways. Here are three methods commonly found:

Method 1

$$|I_{restraint}\_A| = |I_{restraint}\_B| = |I_{restraint}\_C| = MAX(|DCCA\_W1|, |DCCB\_W1|, |DCCC\_W1|, |DCCA\_W2|, |DCCB\_W2|, |DCCC\_W2|)$$

Method 2

$$|I_{restraint}\_A| = |DCCA\_W1| + |DCCA\_W2|$$

$$|I_{restraint}\_B| = |DCCB\_W1| + |DCCB\_W2|$$

$$|I_{restraint}\_C| = |DCCC\_W1| + |DCCC\_W2|$$

Method 3

$$|I_{restraint}\_A| = ½(|DCCA\_W1| + |DCCA\_W2|)$$

$$|I_{restraint}\_B| = ½(|DCCB\_W1| + |DCCB\_W2|)$$

$$|I_{restraint}\_C| = ½(|DCCC\_W1| + |DCCC\_W2|)$$

4.3 Principles behind the 87T function

The common characteristic for all types of three-phase power transformers is that they introduce a phase angle shift Θ between the W1- and W2-side no-load voltages. Furthermore, strict rules only exist for the phase angle shift between the sequence components of the no-load voltage on the two sides of the transformer, and not for individual phase voltages on the two sides of the transformer.

The following holds true for the positive, negative and zero sequence no-load voltage components:
- if the positive sequence no-load voltage component on W1 (UPS_W1) leads the positive sequence no-load voltage component on W2 (UPS_W2) by angle Θ; then
- the negative sequence no-load voltage component on W1 (UNS_W1) lags the negative sequence no-load voltage component on W2 (UNS_W2) by angle Θ; and
- the zero sequence no-load voltage component on W1 (UZS_W1) will be exactly in phase with the zero sequence no-load voltage component on W2 (UZS_W2), when the zero sequence no-load voltage component can be transferred across the transformer.

As soon as the power transformer is loaded, this voltage relationship will no longer be valid, due to the voltage drop across the power transformer's impedance. However, the same phase angle relationship will be valid for the sequence components of the current, which flow into W1 and out from W2.

Therefore, the following holds true for the sequence current components:

- if the positive sequence current component in W1 (IPS_W1) leads the positive sequence current component in W2 (IPS_W2) by angle Θ (the same relationship as for the positive sequence no-load voltage component); then
- the negative sequence current component in W1 (INS_W1) lags the negative sequence current component in W2 (INS_W2) by angle Θ; and
- the zero sequence current component in W1 (IZS_W1) will be exactly in phase with the zero sequence current component in W2 (IZS_W2), when the zero sequence current components can be transferred across the transformer.

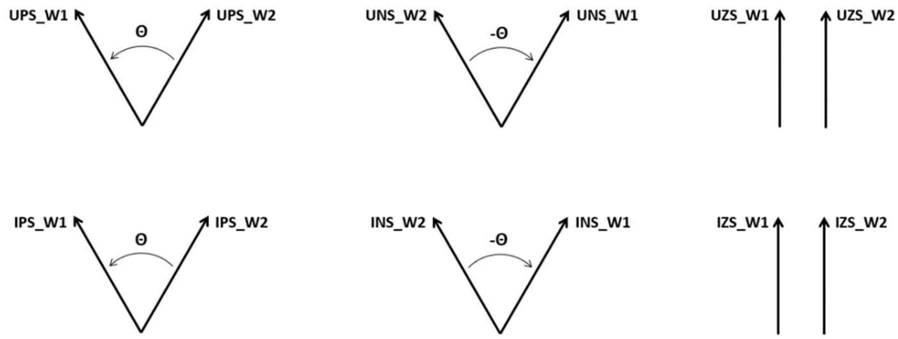

Figure 4: The phasor diagrams for positive, negative and zero sequence no-load voltage components and current components from the two sides of the power transformer

For the analysis to follow, it can be taken that the current magnitude compensation of individual phase currents from the two power transformer sides has been performed. Hence, only the procedure for phase angle shift compensation will be presented.

The sequence differential currents can be calculated with the following equations:

$$ID\_PS = IPS\_W1 + e^{j\Theta} * IPS\_W2$$

$$ID\_NS = INS\_W1 + e^{-j\Theta} * INS\_W2$$

$$ID\_ZS = IZS\_W1 + IZS\_W2$$

By using the basic relationship between sequence and phase quantities the following matrix relationship can be written for the phase differential currents:

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = A * \begin{bmatrix} ID\_ZS \\ ID\_PS \\ ID\_NS \end{bmatrix}$$

where

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

and where

$$a \;= {}^{j120}$$
$$a^2 = e^{-j120}$$

From the above, the following equation can be obtained:

$$\begin{bmatrix} \text{ID\_A} \\ \text{ID\_B} \\ \text{ID\_C} \end{bmatrix} = A * \begin{bmatrix} \text{IZS\_W1} \\ \text{IPS\_W1} \\ \text{INS\_W1} \end{bmatrix} + A * \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{j\Theta} & 0 \\ 0 & 0 & e^{-j\Theta} \end{bmatrix} * \begin{bmatrix} \text{IZS\_W2} \\ \text{IPS\_W2} \\ \text{INS\_W2} \end{bmatrix}$$

Again, by using the basic relationship between phase and sequence quantities the following equation can be obtained:

$$\begin{bmatrix} \text{ID\_A} \\ \text{ID\_B} \\ \text{ID\_C} \end{bmatrix} = \begin{bmatrix} \text{IA\_W1} \\ \text{IB\_W1} \\ \text{IC\_W1} \end{bmatrix} + A * \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{j\Theta} & 0 \\ 0 & 0 & e^{-j\Theta} \end{bmatrix} * A^{-1} * \begin{bmatrix} \text{IA\_W2} \\ \text{IB\_W2} \\ \text{IC\_W2} \end{bmatrix}$$

where

$$A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

The matrix transformation M(Θ) can then be defined as:

$$M(\Theta) = A * \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{j\Theta} & 0 \\ 0 & 0 & e^{-j\Theta} \end{bmatrix} * A^{-1}$$

which gives

$$\begin{bmatrix} \text{ID\_A} \\ \text{ID\_B} \\ \text{ID\_C} \end{bmatrix} = \begin{bmatrix} \text{IA\_W1} \\ \text{IB\_W1} \\ \text{IC\_W1} \end{bmatrix} + M(\Theta) * \begin{bmatrix} \text{IA\_W2} \\ \text{IB\_W2} \\ \text{IC\_W2} \end{bmatrix}$$

M(Θ) as function of Θ can be written as:

$$M(\Theta) = \frac{1}{3} \begin{bmatrix} 1+2*\cos(\Theta) & 1+2*\cos(\Theta+120°) & 1+2*\cos(\Theta-120°) \\ 1+2*\cos(\Theta-120°) & 1+2*\cos(\Theta) & 1+2*\cos(\Theta+120°) \\ 1+2*\cos(\Theta+120°) & 1+2*\cos(\Theta-120°) & 1+2*\cos(\Theta) \end{bmatrix}$$

Defining M(0°) as the unit matrix,

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

it can be assigned to the power transformer winding which is taken as the reference winding for phase angle compensation. The above equation can then be re-written as:

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M(0°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + M(\Theta) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

Θ is the angle by which the W2 positive sequence, no-load voltage component must be rotated to align with the positive sequence, no-load voltage component on W1. Angle Θ has a positive value when rotation is in the anticlockwise direction.

Note that it is equally possible to select W2 as the reference winding for the phase angle compensation. In this case a negative value for angle Θ is applied to W1.

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M(-\Theta) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + M(0°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

The M(Θ) matrix transform doesn’t subtract the zero sequence current. Therefore, it’s possible to define a new matrix transform M0(Θ), which simultaneously performs the phase angle shift compensation and the required zero sequence current subtraction.

$$M0(\Theta) = M(\Theta) - \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

M0(Θ) as function of Θ can be written as:

$$M0(\Theta) = \frac{2}{3}\begin{bmatrix} \cos(\Theta) & \cos(\Theta+120°) & \cos(\Theta-120°) \\ \cos(\Theta-120°) & \cos(\Theta) & \cos(\Theta+120°) \\ \cos(\Theta+120°) & \cos(\Theta-120°) & \cos(\Theta) \end{bmatrix}$$

Thus, it’s possible to select matrix transform M(Θ) to perform the phase angle shift compensation only or, when required, to select the matrix transform M0(Θ) to perform the phase angle shift compensation and also to remove the zero sequence currents.

5. Comparison of underlying calculation methods and their effect on the operation of the 87T functions

This section contains a discussion and comparative analysis of the different methods applied for the calculation of the differential and restraint currents and shows their impact on the operation of the 87T functions.

Three examples are used. Examples 3 and 4 are, respectively, for the same types of transformer as in Examples 1 and 2. Example 5 is for an autotransformer. For each example the differential and restraint currents are calculated for different external fault types on the W2-side.

For the purposes of this paper, in the examples that follow, only standard phase-to-bushing connections are considered. Good to note here is that a power transformer's rating plate is only valid for positive sequence quantities applied in the same sequence as the bushing markings.

Example 3

Dyn1 (=DABY) transformer; 100MVA; W1/W2 = 230kV/115kV
W1 I_{rated} = 251.0A; W2 I_{rated} = 502.0A

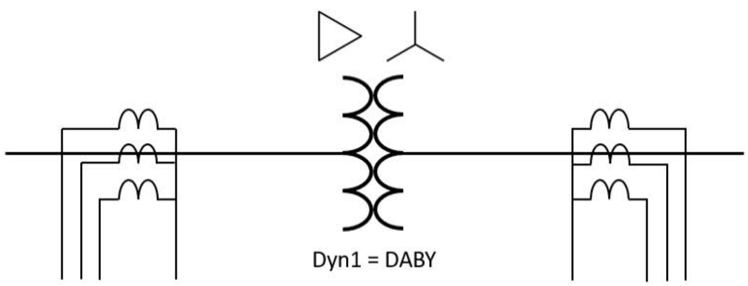

Figure 5: Dyn1 transformer with wye-connected CTs on both delta- and wye-sides

W1 D-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M(0°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{115}{230} * M0(30°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

$$M(0°) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$M0(30°) = \begin{bmatrix} 0.577 & -0.577 & 0.000 \\ 0.000 & 0.577 & -0.577 \\ -0.577 & 0.000 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

The M0(30°) matrix does the same as the old method of delta-connecting the CT secondaries on the transformer wye-winding side.

The W2 wye-side currents must be rotated anti-clockwise +30° to align with the W1 delta-side phase reference currents.

<u>W2 y-winding as the phase reference</u>

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M(-30°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{115}{230} * M0(0°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

$$M(-30°) = \begin{bmatrix} 0.911 & 0.333 & -0.244 \\ -0.244 & 0.911 & 0.333 \\ 0.333 & -0.244 & 0.911 \end{bmatrix}$$

$$M0(0°) = \begin{bmatrix} 0.667 & -0.333 & -0.333 \\ -0.333 & 0.667 & -0.333 \\ -0.333 & 0.667 & -0.333 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

The W1 delta-side currents must be rotated clockwise -30° to align with the W2 wye-side phase reference currents.

As the phase currents IA_W1, IB_W1 and IC_W1 have no zero sequence component (transformer D-side), applying M0(-30°) would yield the same result as applying M(-30°).

$$M0(-30°) = \begin{bmatrix} 0.577 & 0.000 & -0.577 \\ -0.577 & 0.577 & 0.000 \\ 0.000 & -0.577 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$

<u>Example 4:</u>

YNd11 (=YDAB) transformer; 100MVA; W1/W2 = 230kV/115kV
W1 I_{rated} = 251.0A; W2 I_{rated} = 502.0A

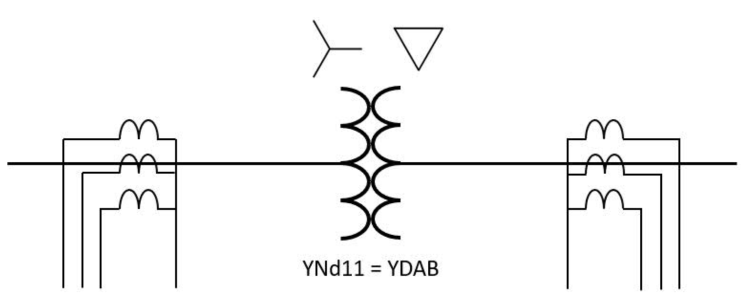

Figure 6: YNd11 transformer with wye-connected CTs on both delta- and wye-sides

W2 d-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M0(30°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{115}{230} * M(0°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

$$M0(30°) = \begin{bmatrix} 0.577 & -0.577 & 0.000 \\ 0.000 & 0.577 & -0.577 \\ -0.577 & 0.000 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

$$M(0°) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

As in the previous Example 3, the M0(30°) matrix does the same as the old method of delta-connecting the CT secondaries on the transformer wye-winding side.

The W1 wye-side currents must be rotated anti-clockwise +30° to align with the W2 delta-side phase reference currents.

W1 Y-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M0(0°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{115}{230} * M(-30°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

$$M0(0°) = \begin{bmatrix} 0.667 & -0.333 & -0.333 \\ -0.333 & 0.667 & -0.333 \\ -0.333 & 0.667 & -0.333 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

$$M(-30°) = \begin{bmatrix} 0.911 & 0.333 & -0.244 \\ -0.244 & 0.911 & 0.333 \\ 0.333 & -0.244 & 0.911 \end{bmatrix}$$

The W2 delta-side currents must be rotated clockwise -30° to align with the W1 wye-side phase reference currents.

Again, as the phase currents IA_W2, IB_W2 and IC_W2 have no zero sequence component (transformer d-side), applying M0(-30°) would yield the same result as applying M(-30°).

$$M0(-30°) = \begin{bmatrix} 0.577 & 0.000 & -0.577 \\ -0.577 & 0.577 & 0.000 \\ 0.000 & -0.577 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$

Example 5:

Autotransformer, no delta tertiary (YNyn0 transformer); 100MVA; W1/W2 = 230kV/115kV
W1 I_{rated} = 251.0A; W2 I_{rated} = 502.0A

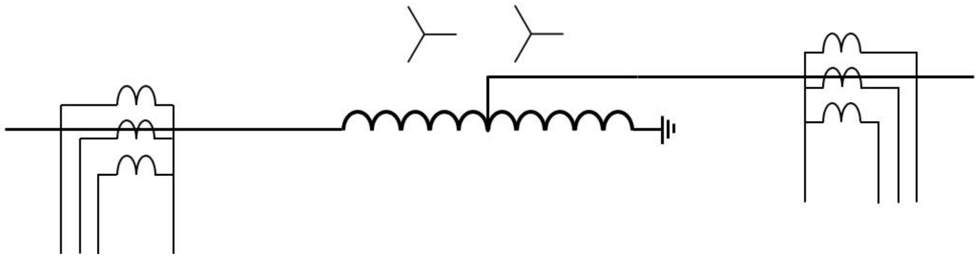

Figure 7: Autotransformer with wye-connected CTs on both sides

Using the M0(0°) transformation matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M0(0°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{115}{230} * M0(0°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

$$M0(0°) = \begin{bmatrix} 0.667 & -0.333 & -0.333 \\ -0.333 & 0.667 & -0.333 \\ -0.333 & 0.667 & -0.333 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$$

Using the M0(-30°) transformation matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = M0(-30°) * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{115}{230} * M0(-30°) * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$

$$M0(-30°) = \begin{bmatrix} 0.577 & 0.000 & -0.577 \\ -0.577 & 0.577 & 0.000 \\ 0.000 & -0.577 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$

5.1 Discussion and analysis of the different methods for calculation of the differential currents

There are, in reality, an infinite number of ways to calculate the differential currents for a three-phase power transformer, as any arbitrary angle can be defined as the phase reference, with the currents from all windings then being rotated to the selected phase reference. This can be explained further by looking at Example 3 for the W2-side external three-phase fault. The D-winding IA_W1 current has $\angle$-60° and the y-winding IA_W2 current has $\angle$-90°. Choosing the D-winding as the phase reference, the D-winding currents would have no phase angle rotation, whereas the y-winding currents must be rotated +30° anti-clockwise. Therefore, the chosen matrices would be M(0°) for the D-winding, and M0(30°) for the y-winding (M0 for the y-winding as zero sequence subtraction must be applied). However, it would be equally possible to select the matrix M(1°) for the D-winding, and M0(31°) for the y-winding, or M(10°) and M0(40°), or M(11°) and M0(41°), etc. This of course is mathematically possible but has no real practical meaning. In practice, typically, for an n-winding transformer, n approaches are used where any one of the n windings can be selected as the phase reference. Take for example a two-winding transformer (n = 2):

- one approach is to take the W1-side as the phase reference side (with 0° phase angle shift).
- the second approach is to take the W2-side as the phase reference side (with 0° phase angle shift).

For Examples 3, 4 and 5, the differential currents are calculated for different external fault types on the W2-side, using one winding as the phase reference for the calculation, then the other. See Appendix B for details.

For all cases, the differential currents for all phases, for all external fault types, are zero, irrespective of whether the delta- or wye-winding was taken as the phase reference. For any through-fault or load condition, so long as the 87T function is properly set and there is no CT saturation, the assigned phase reference side (and thus matrix selection) makes no difference, and the differential currents will be zero for all cases.

Matrix selection comes into play more for internal faults because most of them are single-phase faults and the calculated differential currents will be different for different matrix selections. Therefore, the differences in the calculated differential currents resulting from matrix selection will only be seen for internal faults or for external faults followed by CT saturation.

For D/y or Y/d transformers, taking the delta-winding as the phase reference mimics how the traditional (pre microprocessor-based numerical relaying technology) 87T differential protection schemes were engineered. For an internal single-phase winding fault in limb A of the magnetic core, equally large differential currents would be calculated in two phases (phase A and also phase B or C, depending on the delta connection), when assigning the delta-winding as the phase reference, and the 87T function would operate in both phases. The calculated differential currents would not correspond to one physical limb of the protected transformer. A clear indication of the faulted limb is therefore lost. However, in practice, this might not be of great importance as the tank anyway needs to be opened to inspect the transformer.

Taking the wye-winding as the phase reference (only available in numerical technology) correlates better with the physical winding layout around the limbs of the magnetic core within the transformer. The phase indication of the 87T operation correlates better to the actual faulted limb of the transformer, as the calculated differential currents correspond to a higher degree to one magnetic limb of the transformer. This is even true when zero sequence current subtraction is enabled. Enabling the zero sequence subtraction is often required, and is always required on the wye-winding for all types of Dy and Yd transformers. When the subtraction of zero sequence current is enabled, more phases can operate due to the applied matrix that mixes all three phases on the wye-side. Even so, by taking the wye-winding as the phase reference, the biggest differential current would appear in phase A for an internal single-phase winding fault in limb A of the magnetic core, clearly indicating the actual faulted limb.

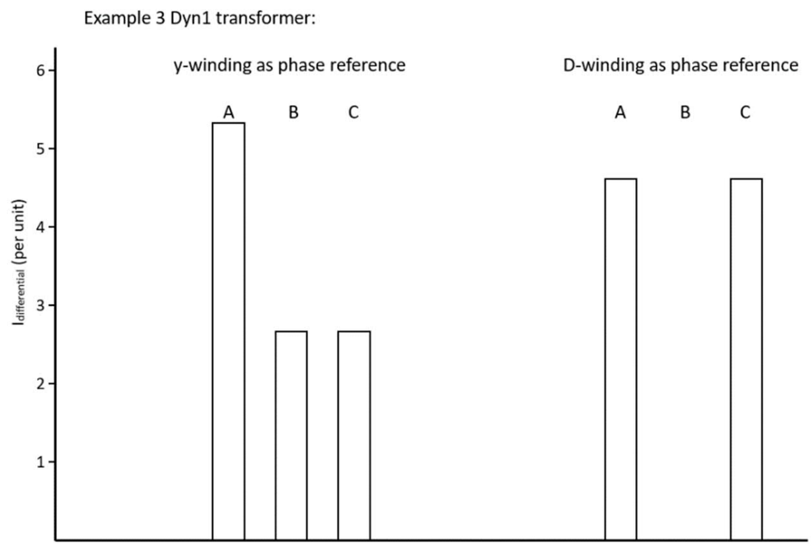

Figure 8: Differential currents for internal single-phase winding fault in limb A

It can also be seen in Figure 8 that a slightly larger magnitude of the differential current would be calculated for an internal single-phase fault by using the wye-winding as the phase reference. The ratio of the differential currents is:

$$\text{wye-reference : delta-reference} = \frac{2}{3} : \frac{1}{\sqrt{3}} = 0.667 : 0.577$$

i.e. when the wye-winding is selected as the phase reference, the differential current calculated for the phase of the faulted limb is 1.155 times larger than the differential currents calculated for the same fault when the delta-winding is selected as the phase reference.

From Figure 8 it can also be seen why the differential protection would operate in all three phases when the wye-winding is selected as the phase reference, but in only two phases for the same internal fault when the delta-winding is selected as the phase reference.

Therefore, for numerical differential protection with all CT secondaries wye-connected, and when considering the magnitude of the calculated differential currents, some benefits can be realized when selecting the wye-winding as the phase reference. A typical guideline to follow would be:
- select the first wye-connected winding as the phase reference winding (with 0° phase angle shift)
- select the first delta-connected winding as the phase reference winding only for transformers without any wye-connected windings.

However, the above recommendation doesn't consider how the restraint currents are calculated, and how this may govern the selection of the phase reference side.

A point to note is that applying the M0(Θ) matrix transformation (i.e. enabling zero sequence subtraction) reduces the sensitivity of the differential protection. The sole reason for subtracting the zero sequence is to ensure stability for external faults. Consider again an external phase-ground (A) fault on the W2-side of the Dyn1 transformer of Example 3. With zero sequence subtraction enabled for the wye-winding, the calculated differential current in all phases is zero (with either the D-winding or the y-winding selected as the phase reference). With zero sequence subtraction disabled for the wye-winding, the calculated differential current in all phases would be 334.7A (with either the D-winding or the y-winding selected as the phase reference), which would definitely cause unwanted operation of the differential function for the external fault.

Were it not necessary to enable zero sequence subtraction to ensure external fault stability, electing to not enable it would have benefits for internal single-phase faults. Such benefits would include increased magnitude in the calculated differential current for the same fault (i.e. increased sensitivity), and no need for the mixing of the measured phase currents, giving a much clearer indication of the limb with the fault, as the differential function would operate in just the phase of the limb with the fault.

Appendix C illustrates the above using the recording from an actual event.

5.2 Discussion and analysis of the different methods for calculation of restraint currents

For the same Examples 3, 4 and 5 from before, the restraint currents are calculated using Methods 1 and 2 for different external fault types on the W2-side, using first one winding as the phase reference for the calculation, then the other.

Method 1 for calculation of restraint currents

$$|I_{restraint\_A}| = |I_{restraint\_B}| = |I_{restraint\_C}| = MAX(|DCCA\_W1|, |DCCB\_W1|, |DCCC\_W1|, |DCCA\_W2|, |DCCB\_W2|, |DCCC\_W2|)$$

Method 2 for calculation of restraint currents

$$|I_{restraint\_A}| = |DCCA\_W1| + |DCCA\_W2|$$

$$|I_{restraint\_B}| = |DCCB\_W1| + |DCCB\_W2|$$

$$|I_{restraint\_C}| = |DCCC\_W1| + |DCCC\_W2|$$

Example 3:

Dyn1 (=DABY) transformer

External phase-phase (BC) 115kV-side fault – W1 D-winding as the phase reference

Method 1

$|I_{restraint\_A}|$ = 1,004.1A = 4.00 per unit

$|I_{restraint\_B}|$ = 1,004.1A = 4.00 per unit

$|I_{restraint\_C}|$ = 1,004.1A = 4.00 per unit

Method 2

$|I_{restraint\_A}|$ = 1,004.1A = 4.00 per unit

$|I_{restraint\_B}|$ = 2,008.2A = 8.00 per unit

$|I_{restraint\_C}|$ = 1,004.1A = 4.00 per unit

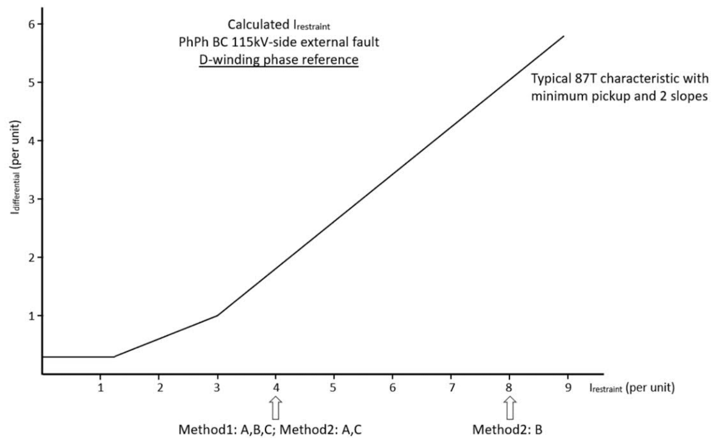

Figure 9: Method 1 versus Method 2 restraint current calculation for an external phase-phase (BC) fault with the D-winding as the phase reference

External phase-phase (BC) 115kV-side fault – W2 y-winding as the phase reference

Method 1

$|I_{restraint\_}A|$ = 869.6A = 3.46 per unit

$|I_{restraint\_}B|$ = 869.6A = 3.46 per unit

$|I_{restraint\_}C|$ = 869.6A = 3.46 per unit

Method 2

$|I_{restraint\_}A|$ = 0.0A = 0.00 per unit

$|I_{restraint\_}B|$ = 1,739.1A = 6.93 per unit

$|I_{restraint\_}C|$ = 1,739.1A = 6.93 per unit

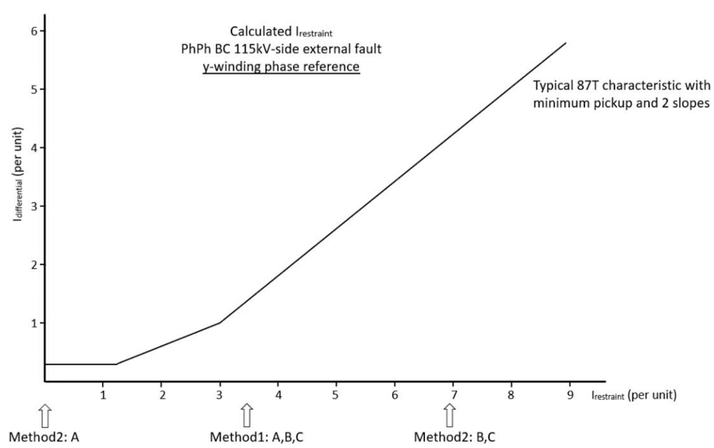

Figure 10: Method 1 versus Method 2 restraint current calculation for an external phase-phase (BC) fault with the y-winding as the phase reference

With the D-winding as the phase reference:

$$\text{ID\_A} = \text{IA} + \frac{115}{230} * \frac{1}{\sqrt{3}} * (\text{IA} - \text{IB})$$

$$= \text{DCCA\_W1} + \text{DCCA\_W2}$$

With the y-winding as the phase reference:

$$ID\_A = \frac{1}{\sqrt{3}} * (IA - IC) + \frac{115}{230} * \frac{1}{3} * (2IA - IB - IC)$$

$$= DCCA\_W1 + DCCA\_W2$$

Method 2 calculates the phase A restraint current as follows:

$$|I_{restraint}\_A| = |DCCA\_W1| + |DCCA\_W2|$$

y-winding as the phase reference:
The W1 A phase compensated current contains W1 A and C phase currents. Both are fault currents that are exactly equal in magnitude and phase angle when calculated theoretically. The W2 A phase compensated current contains W2 A, B and C phase currents. The W2 B and C phase currents are fault currents that are exactly equal in magnitude and have exactly opposite phase angle when calculated theoretically. The W2 A phase current is not a fault current, and is equal to zero when calculated theoretically, ignoring load current. See Appendix B.

When calculating the W1 A phase compensated current, the W1 A and C phase currents cancel each other out. Likewise, when calculating the W2 A phase compensated current, the W2 B and C phase currents cancel each other out. However, due to some CT error, a differential current could be calculated for phase A, which would also have a very small calculated restraint current when using Method 2.

Therefore, using the y-winding as the phase reference when using Method 2 for calculating the restraint currents introduces a possibility for misoperation for external phase-phase faults. To overcome this, when using Method 2 for calculating the restraint currents, the D-winding should be selected as the phase reference. This guarantees adequate restraint against misoperation due to some CT error, thereby ensuring stability for such external phase-phase faults.

Using Method 1 for calculating the restraint currents allows either the wye- or delta-winding to be selected as the phase reference as adequate restraint current to ensure through phase-phase fault stability is calculated for both selections.

<u>External phase-ground (A) 115kV-side fault – W1 D-winding as the phase reference</u>

Method 1	Method 2
$\lvert I_{restraint}\_A \rvert$ = 579.7A = 2.31 per unit	$\lvert I_{restraint}\_A \rvert$ = 1,159.4A = 4.62 per unit
$\lvert I_{restraint}\_B \rvert$ = 579.7A = 2.31 per unit	$\lvert I_{restraint}\_B \rvert$ = 0.0A = 0.00 per unit
$\lvert I_{restraint}\_C \rvert$ = 579.7A = 2.31 per unit	$\lvert I_{restraint}\_C \rvert$ = 1,159.4A = 4.62 per unit

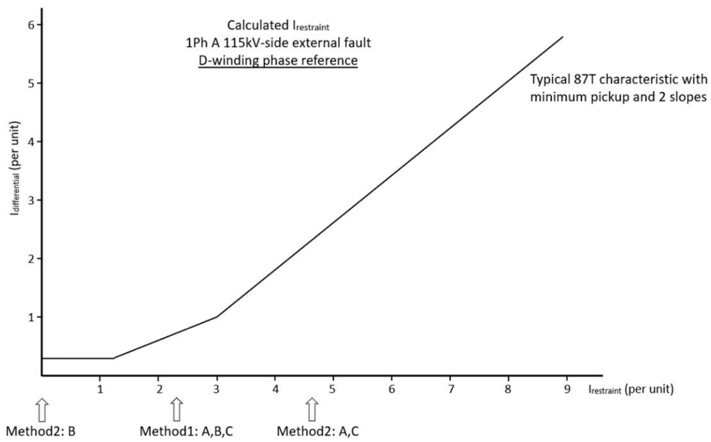

Figure 11: Method 1 versus Method 2 restraint current calculation for an external phase-ground (A) fault with the D-winding as the phase reference

External phase-ground (A) 115kV-side fault – W2 y-winding as the phase reference

Method 1

$|I_{restraint\_}A|$ = 669.4A = 2.67 per unit

$|I_{restraint\_}B|$ = 669.4A = 2.67 per unit

$|I_{restraint\_}C|$ = 669.4A = 2.67 per unit

Method 2

$|I_{restraint\_}A|$ = 1,338.8A = 5.33 per unit

$|I_{restraint\_}B|$ = 669.4A = 2.67 per unit

$|I_{restraint\_}C|$ = 669.4A = 2.67 per unit

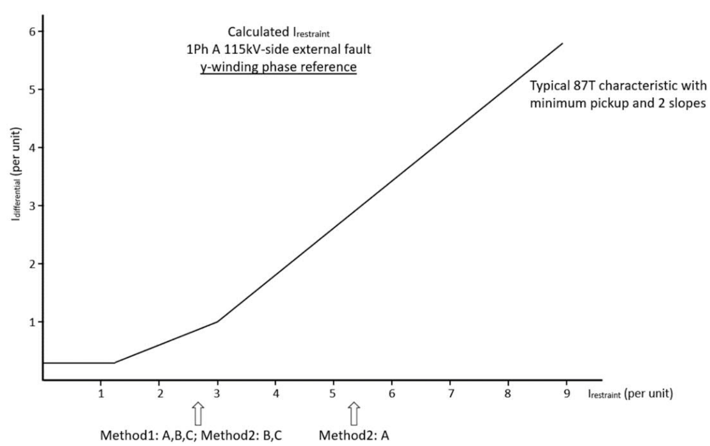

Figure 12: Method 1 versus Method 2 restraint current calculation for an external phase-ground (A) fault with the y-winding as the phase reference

With the D-winding as the phase reference

$$ID\_B = IB + \frac{115}{230} * \frac{1}{\sqrt{3}} * (IB - IC)$$

$$= DCCB\_W1 + DCCB\_W2$$

With the y-winding as the phase reference

$$ID\_B = \frac{1}{\sqrt{3}} * (IB - IA) + \frac{115}{230} * \frac{1}{3} * (2IB - IA - IC)$$
$$= DCCB\_W1 + DCCB\_W2$$

Method 2 calculates the phase B restraint current as follows:

$$|I_{restraint}\_B| = |DCCB\_W1| + |DCCB\_W2|$$

D-winding as the phase reference:
The W1 B phase compensated current contains only W1 B phase current, which is not a fault current, and is equal to zero when calculated theoretically, ignoring load current. The W2 B phase compensated current contains W2 B and C phase currents, which are also not fault currents, and so are equal to zero when calculated theoretically, ignoring load current. See Appendix B.

Although the calculated restraint current for phase B is very small, theoretically zero, the likelihood that some differential current, small but enough to cause a misoperation, would be calculated for phase B due to some CT error is small as no fault currents are included in the phase B compensated currents for the differential calculation.

Therefore, for restraint currents calculated using Method 2, it could be argued that the delta-winding could still be selected as the phase reference winding without a high probability of introducing a possibility for misoperation for external phase-ground faults.

Using Method 1 for calculating the restraint currents allows either the wye- or delta-winding to be selected as the phase reference as adequate restraint current to ensure through phase-ground fault stability is calculated for both selections. In fact, by selecting the wye-winding as the phase reference, a slightly higher stability is ensured.

Consider again the internal single-phase winding fault in limb A of the transformer's magnetic core with differential currents as shown in Figure 8. Figure 13(a) and Figure 13(b) show these differential currents plotted against the restraint currents calculated using both Methods 1 and 2.

In the figures, M1A means Method 1, phase A, and is shown next to the plotted point of the calculated phase A differential current versus the calculated phase A restraint current using Method 1. Similarly for the other points.

Figure 13(a) shows the plotted values when the D-winding is selected as the phase reference.

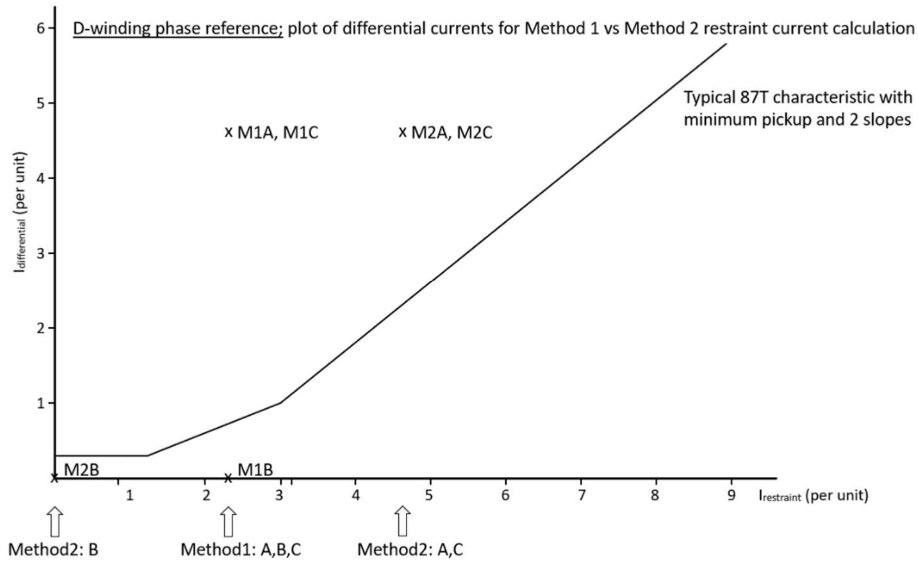

Figure 13(a): Typical differential-restraint current plot for internal single-phase fault in limb A showing Method 1 versus Method 2 of restraint current calculation with the D-winding as the phase reference

Figure 13(b) shows the plotted values when the y-winding is selected as the phase reference.

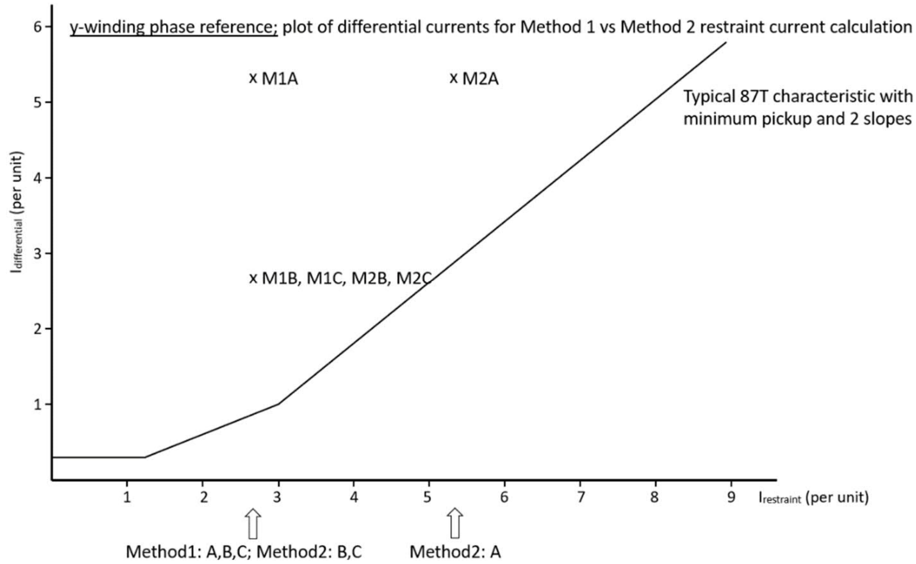

Figure 13(b): Typical differential-restraint current plot for internal single-phase fault in limb A showing Method 1 versus Method 2 of restraint current calculation with the y-winding as the phase reference

Example 4

YNd11 (=YDAB) transformer

External phase-phase (BC) 115kV-side fault – W2 d-winding as the phase reference

Method 1

$|I_{restraint}\_A|$ = 869.6A = 3.46 per unit

$|I_{restraint}\_B|$ = 869.6A = 3.46 per unit

$|I_{restraint}\_C|$ = 869.6A = 3.46 per unit

Method 2

$|I_{restraint}\_A|$ = 0.0A = 0.00 per unit

$|I_{restraint}\_B|$ = 1,739.1A = 6.93 per unit

$|I_{restraint}\_C|$ = 1,739.1A = 6.93 per unit

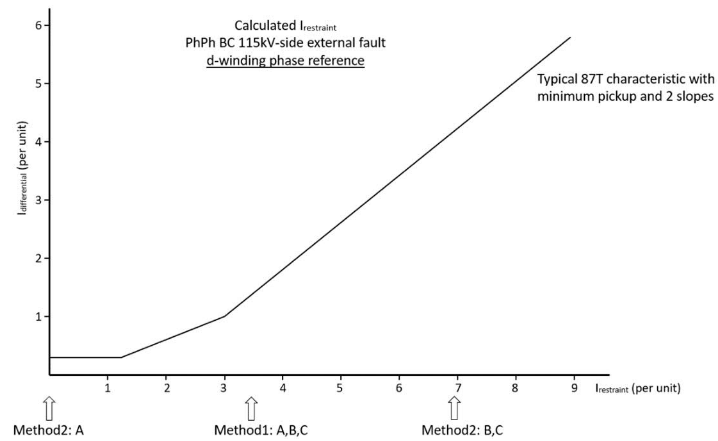

Figure 14: Method 1 versus Method 2 restraint current calculation for an external phase-phase (BC) fault with the d-winding as the phase reference

With the d-winding as the phase reference

$$ID\_A = \frac{1}{\sqrt{3}} * (IA - IB) + \frac{115}{230} * IA$$
$$= DCCA\_W1 + DCCA\_W2$$

External phase-phase (BC) 115kV-side fault – W1 Y-winding as the phase reference

Method 1

$|I_{restraint}\_A|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_B|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_C|$ = 1,004.1A = 4.00 per unit

Method 2

$|I_{restraint}\_A|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_B|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_C|$ = 2,008.2A = 8.00 per unit

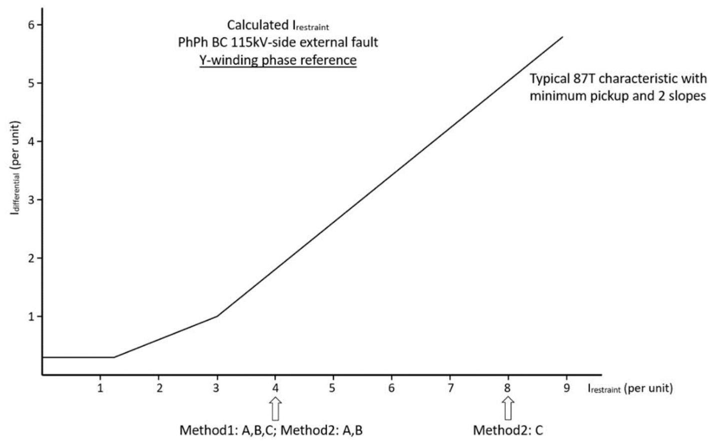

Figure 15: Method 1 versus Method 2 restraint current calculation for an external phase-phase (BC) fault with the Y-winding as the phase reference

With the Y-winding as the phase reference

$$ID\_A = \frac{1}{3} * (2IA - IB - IC) + \frac{115}{230} * \frac{1}{\sqrt{3}} * (IA - IC)$$

$$= DCCA\_W1 + DCCA\_W2$$

Method 2 calculates the phase A restraint current as follows:

$$|I_{restraint}\_A| = |DCCA\_W1| + |DCCA\_W2|$$

d-winding as the phase reference:
The W1 A phase compensated current contains W1 A and B phase currents. Both are fault currents that are exactly equal in magnitude and phase angle when calculated theoretically. The W2 A phase compensated current contains only W2 A phase current, which is not a fault current, and is equal to zero when calculated theoretically, ignoring load current. See Appendix B.

When calculating the W1 A phase compensated current, the W1 A and B phase currents cancel each other out. However, due to some CT error a differential current could be calculated for phase A, which would also have a very small calculated restraint current when using Method B.

Therefore, using the d-winding as the phase reference when using Method 2 for calculating the restraint currents introduces a possibility for misoperation for external phase-phase faults. To overcome this, when using Method 2 for calculating the restraint currents, it appears that the Y-winding should rather be selected as the phase reference. This would guarantee adequate restraint against misoperation due to some CT error, thereby ensuring stability for such external phase-phase faults.

Using Method 1 for calculating the restraint currents allows either the wye- or delta-winding to be selected as the phase reference as adequate restraint current to ensure through phase-phase fault stability is calculated for both selections.

Example 5:

Autotransformer, no delta tertiary (YNyn0 transformer)

External phase-phase (BC) 115kV-side fault – M0(-30°) transformation matrix (i.e. as if a delta-winding were being used as the phase reference)

Method 1

$|I_{restraint}\_A|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_B|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_C|$ = 1,004.1A = 4.00 per unit

Method 2

$|I_{restraint}\_A|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_B|$ = 1,004.1A = 4.00 per unit

$|I_{restraint}\_C|$ = 2,008.2A = 8.00 per unit

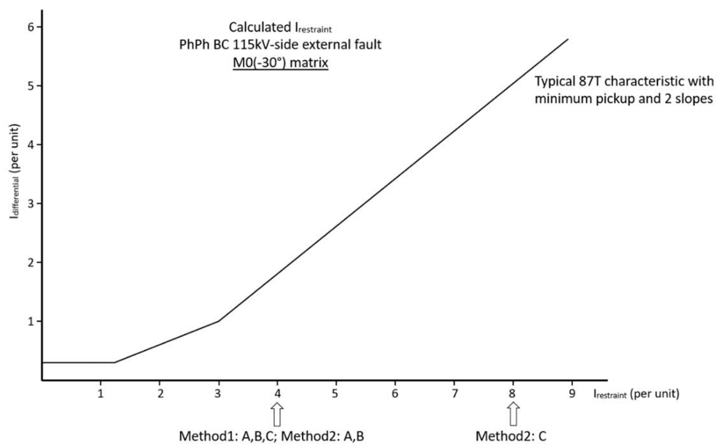

Figure 16: Method 1 versus Method 2 restraint current calculation for an external phase-phase (BC) fault using the M0(-30°) matrix

With the M0(-30°) transformation matrix

$$ID\_A = \frac{1}{\sqrt{3}} * (IA - IC) + \frac{115}{230} * \frac{1}{\sqrt{3}} * (IA - IC)$$

$$= DCCA\_W1 + DCCA\_W2$$

External phase-phase (BC) 115kV-side fault – M0(0°) transformation matrix (i.e. making the (first) wye-winding the phase reference)

Method 1

$|I_{restraint}\_A|$ = 869.6A = 3.46 per unit

$|I_{restraint}\_B|$ = 869.6A = 3.46 per unit

$|I_{restraint}\_C|$ = 869.6A = 3.46 per unit

Method 2

$|I_{restraint}\_A|$ = 0.0A = 0.00 per unit

$|I_{restraint}\_B|$ = 1,739.1A = 6.93 per unit

$|I_{restraint}\_C|$ = 1,739.1A = 6.93 per unit

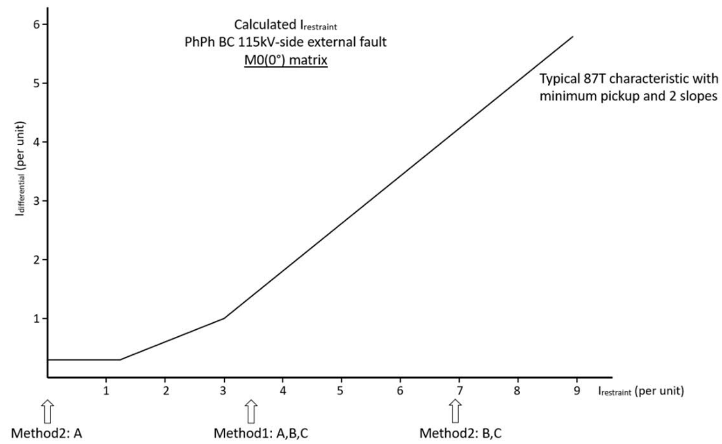

Figure 17: Method 1 versus Method 2 restraint current calculation for an external phase-phase (BC) fault using the M0(0°) matrix

With the M0(0°) transformation matrix

$$ID\_A = \frac{1}{3} * (2IA - IB - IC) + \frac{115}{230} * \frac{1}{3} * (2IA - IB - IC)$$

$$= DCCA\_W1 + DCCA\_W2$$

Method 2 calculates the phase A restraint current as follows:

$$|I_{restraint}\_A| = |DCCA\_W1| + |DCCA\_W2|$$

M0(0°) as the used transformation matrix:
The W1 A phase compensated current contains W1 A, B and C phase currents. The W1 B and C phase currents are fault currents that are exactly equal in magnitude and have exactly opposite phase angle when calculated theoretically. The W1 A phase current is not a fault current, and is equal to zero when calculated theoretically, ignoring load current. Likewise, the W2 A phase compensated current contains W2 A, B and C phase currents. The W2 B and C phase currents are fault currents that are exactly equal in magnitude and have exactly opposite phase angle when calculated theoretically. The W2 A phase current is not a fault current, and is equal to zero when calculated theoretically, ignoring load current. See Appendix B.

When calculating the W1 A phase compensated current, the W1 B and C phase currents cancel each other out. Likewise, when calculating the W2 A phase compensated current, the W2 B and C phase currents cancel each other out. However, due to some CT error a differential current could be calculated for phase A, which would also have a very small calculated restraint current when using Method 2.

Therefore, using the M0(0°) transformation matrix when using Method 2 for calculating the restraint currents introduces a possibility for misoperation for external phase-phase faults. To overcome this, when using Method 2 for calculating the restraint currents, the M0(-30°) transformation matrix should be selected. Note that it would also be okay to select the M0(30°) transformation matrix (see Appendix C).

Selection of one of these two matrices would guarantee adequate restraint against misoperation due to some CT error, thereby ensuring stability for such external phase-phase faults.

Using Method 1 for calculating the restraint currents allows either the M0(0°) or M0(-30°) transformation matrices to be selected as adequate restraint current to ensure through phase-phase fault stability is calculated for both selections. Selecting the M0(0°) transformation matrix is the same as selecting the first (W1) wye-winding as the phase reference. As the transformer is YNyn, the same matrix as for W1 applies also to W2.

<u>External phase-ground (A) 115kV-side fault – M0(-30°) transformation matrix</u>

Method 1

$|I_{restraint}\_A|$ = 579.7A = 2.31 per unit

$|I_{restraint}\_B|$ = 579.7A = 2.31 per unit

$|I_{restraint}\_C|$ = 579.7A = 2.31 per unit

Method 2

$|I_{restraint}\_A|$ = 1,159.4A = 4.62 per unit

$|I_{restraint}\_B|$ = 1,159.4A = 4.62 per unit

$|I_{restraint}\_C|$ = 0.0A = 0.00 per unit

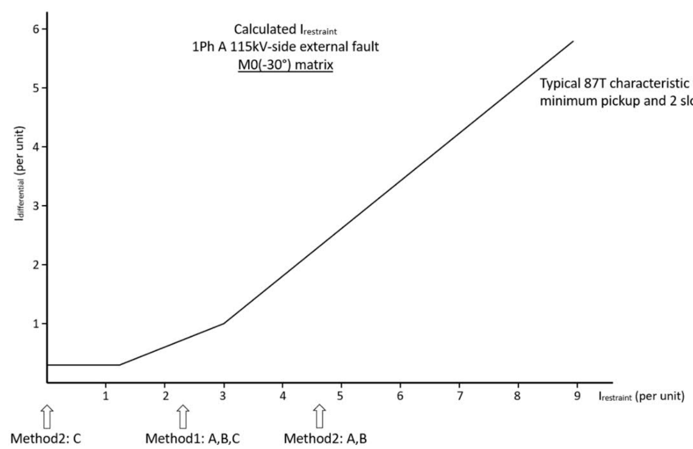

Figure 18: Method 1 versus Method 2 restraint current calculation for an external phase-ground (A) fault using the M0(-30°) matrix

<u>External phase-ground (A) 115kV-side fault – M0(0°) transformation matrix</u>

Method 1

$|I_{restraint}\_A|$ = 669.4A = 2.67 per unit

$|I_{restraint}\_B|$ = 669.4A = 2.67 per unit

$|I_{restraint}\_C|$ = 669.4A = 2.67 per unit

Method 2

$|I_{restraint}\_A|$ = 1,338.8A = 5.33 per unit

$|I_{restraint}\_B|$ = 669.4A = 2.67 per unit

$|I_{restraint}\_C|$ = 669.4A = 2.67 per unit

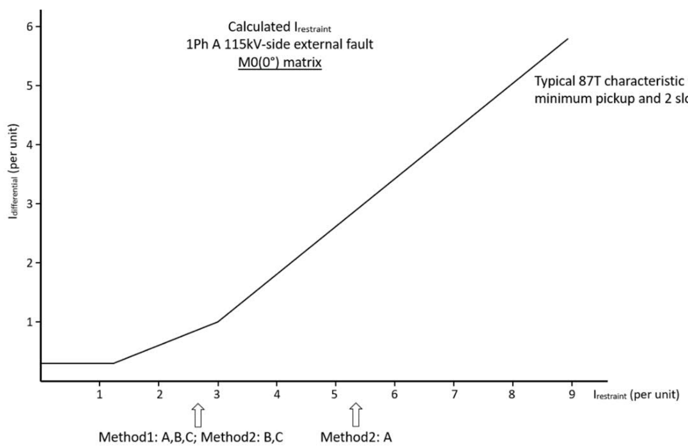

Figure 19: Method 1 versus Method 2 restraint current calculation for an external phase-ground (A) fault using the M0(0°) matrix

With the M0(-30°) transformation matrix

$$ID\_C = \frac{1}{\sqrt{3}} * (IC - IB) + \frac{115}{230} * \frac{1}{\sqrt{3}} * (IC - IB)$$
$$= DCCC\_W1 + DCCC\_W2$$

With the M0(0°) transformation matrix

$$ID\_C = \frac{1}{3} * (2IC - IA - IB) + \frac{115}{230} * \frac{1}{3} * (2IC - IA - IB)$$
$$= DCCC\_W1 + DCCC\_W2$$

Method 2 calculates the phase C restraint current as follows:

$$|I_{restraint}\_C| = |DCCC\_W1| + |DCCC\_W2|$$

M0(-30°) as the used transformation matrix:
The W1 C phase compensated current contains W1 B and C phase currents, neither of which are fault currents, with both equal to zero when calculated theoretically, ignoring load current. Similarly, the W2 C phase compensated current contains W2 B and C phase currents, neither of which are fault currents, with both equal to zero when calculated theoretically, ignoring load current. See Appendix B.

Although the calculated restraint current for phase C is very small, theoretically zero, the likelihood that some differential current, small but enough to cause a misoperation, would be calculated for phase C due to some CT error is small as no fault currents are included in the phase C compensated currents for the differential calculation.

Therefore, for restraint currents calculated using Method 2, it could be argued that the M0(-30°) transformation matrix could still be selected without a high probability of introducing a possibility for misoperation for external phase-ground faults.

Using Method 1 for calculating the restraint currents allows either the M0(0°) or M0(-30°) transformation matrices to be selected as adequate restraint current to ensure through phase-ground fault stability is calculated for both selections. In fact, by selecting the M0(0°) transformation matrix, a slightly higher stability is ensured.

6. Conclusions

It has been shown in this paper that it is not best practice to apply common setting rules to all numerical 87T transformer differential functions. However, each 87T function may well have its own setting rules that should be followed to provide optimum restraint for external faults. Each 87T function's setting rules align with how it has been designed, and in particular how the restraint currents are calculated. Therefore these rules are not common, and so are not applicable equally in all instances. Knowing and understanding these underlying rules is the first step towards developing optimum 87T function settings.

When it comes to calculating the differential currents, it has also been shown in this paper that there is benefit in selecting a wye-connected winding as the phase reference for Dy and Yd transformers. However, when calculating the differential currents for Dy and Yd transformers, it is acceptable for either the wye- or the delta-winding to be the phase reference. Matrix selection (phase reference selection) comes into play more for internal faults. Most of them are single-phase faults and the calculated differential currents will be different for different matrix selections. Selecting the wye-winding as phase reference gives a slight improvement in sensitivity, as well as a clearer indication of the actual limb of the magnetic core in which the fault occurred.

The issue to be aware of is how the restraint currents are calculated, as this does impact the winding that can be selected as the phase reference, to a greater or lesser extent depending on the method used to calculate the restraint currents. It is imperative to ensure with the selected phase reference that adequate restraint will always exist so that a small amount of false differential current (for example due to CT saturation) will not cause the 87T function to unwantedly operate for an external fault.

The method of restraint current calculation is also important when it comes to comparing operating characteristics, if this is to be done on a fair basis. It is simply not the same if the calculated restraint currents are 100% or 200% for the same through-load conditions. For this reason, it may not be best practice to adopt and apply standard slope settings to different 87T functions. Again, these should be based on the guidelines from the manufacturer of each 87T function.

Appendix A – Calculation of differential currents for pre numerical relaying technology

For all fault calculations, the following conditions apply:

- 1pu voltage
- no pre-fault load
- source impedance = 0
- transformer positive, negative and zero sequence reactances, as applicable, = 0.25pu

Note: as the through load flow is W1 to W2, and the faults are external on the W2 115kV-side, the direction for the W1 currents is "to object" (the transformer), whereas the direction for the W2 currents is "from object". For this reason, the W2 currents are phase shifted by 180°.

Example 1

Dyn1 (=DABY) transformer

Balanced rated load current

W1 tap scaling factor: 4.18
W2 tap scaling factor: 4.35

IA_W1 = 251.0$\angle$0°A_{pri} = 4.18$\angle$0°A_{sec} = 1.00$\angle$0°A_{pu}
IB_W1 = 251.0$\angle$-120°A_{pri} = 4.18$\angle$-120°A_{sec} = 1.00$\angle$-120°A_{pu}
IC_W1 = 251.0$\angle$120°A_{pri} = 4.18$\angle$120°A_{sec} = 1.00$\angle$120°A_{pu}

IA_W2 = 502.0$\angle$150°A_{pri} = 4.35$\angle$180°A_{sec} = 1.00$\angle$180°A_{pu}
IB_W2 = 502.0 $\angle$30°A_{pri} = 4.35$\angle$60°A_{sec} = 1.00$\angle$60°A_{pu}
IC_W2 = 502.0 $\angle$-90°A_{pri} = 4.35$\angle$-60°A_{sec} = 1.00$\angle$-60°A_{pu}

External phase-phase (BC) 115kV-side fault

W1 tap scaling factor: 4.18
W2 tap scaling factor: 4.35

IA_W1 = 502.0$\angle$0°A_{pri} = 8.37$\angle$0°A_{sec} = 2.00$\angle$0°A_{pu}
IB_W1 = 1,004.1$\angle$180°A_{pri} = 16.73$\angle$180°A_{sec} = 4.00$\angle$180°A_{pu}
IC_W1 = 502.0$\angle$0°A_{pri} = 8.37$\angle$0°A_{sec} = 2.00$\angle$0°A_{pu}

IA_W2 = 0.0A_{pri} = 8.70$\angle$180°A_{sec} = 2.00$\angle$180°A_{pu}
IB_W2 = 1,739.1$\angle$0°A_{pri} = 17.39$\angle$0°A_{sec} = 4.00$\angle$0°A_{pu}
IC_W2 = 1,739.1$\angle$180°A_{pri} = 8.70$\angle$180°A_{sec} = 2.00$\angle$180°A_{pu}

External phase-ground (A) 115kV-side fault

W1 tap scaling factor: 4.18
W2 tap scaling factor: 4.35

IA_W1 = 579.7∠-90°A_{pri}	= 9.66∠-90°A_{sec}	= 2.31∠-90°A_{pu}
IB_W1 = 0.0A_{pri}	= 0.00A_{sec}	= 0.00A_{pu}
IC_W1 = 579.7∠90°A_{pri}	= 9.66∠90°A_{sec}	= 2.31∠90°A_{pu}

IA_W2 = 2,008.2∠ 90°A_{pri}	= 10.04∠90°A_{sec}	= 2.31∠90°A_{pu}
IB_W2 = 0.0A_{pri}	= 0.00A_{sec}	= 0.00A_{pu}
IC_W2 = 0.0A_{pri}	= 10.04∠-90°A_{sec}	= 2.31∠-90°A_{pu}

Example 2:

YNd11 (=YDAB) transformer

Balanced rated load current

W1 tap scaling factor: 4.35
W2 tap scaling factor: 4.18

IA_W1 = 251.0∠0°A_{pri}	= 4.35∠30°A_{sec}	= 1.00∠30°A_{pu}
IB_W1 = 251.0∠-120°A_{pri}	= 4.35∠-90°A_{sec}	= 1.00∠-90°A_{pu}
IC_W1 = 251.0∠120°A_{pri}	= 4.35∠150°A_{sec}	= 1.00∠150°A_{pu}

IA_W2 = 502.0∠-150°A_{pri}	= 4.18∠-150°A_{sec}	= 1.00∠-150°A_{pu}
IB_W2 = 502.0 ∠90°A_{pri}	= 4.18∠90°A_{sec}	= 1.00∠90°A_{pu}
IC_W2 = 502.0 ∠-30°A_{pri}	= 4.18∠-30°A_{sec}	= 1.00∠-30°A_{pu}

External phase-phase (BC) 115kV side fault

W1 tap scaling factor: 4.35
W2 tap scaling factor: 4.18

IA_W1 = 502.0∠180°A_{pri}	= 0.0A_{sec}	= 0.00A_{pu}
IB_W1 = 502.0∠180°A_{pri}	= 15.06∠180°A_{sec}	= 3.46∠180°A_{pu}
IC_W1 = 1,004.1∠0°A_{pri}	= 15.06∠0°A_{sec}	= 3.46∠0°A_{pu}

IA_W2 = 0.0A_{pri}	= 0.0A_{sec}	= 0.00A_{pu}
IB_W2 = 1,739.1∠0°A_{pri}	= 14.49∠0°A_{sec}	= 3.46∠0°A_{pu}
IC_W2 = 1,739.1∠180°A_{pri}	= 14.49∠180°A_{sec}	= 3.46∠180°A_{pu}

Appendix B – Calculation of differential currents for numerical relaying technology

For all fault calculations, the following conditions apply:
- 1pu voltage
- no pre-fault load
- source impedance = 0
- transformer positive, negative and zero sequence reactances, as applicable, = 0.25pu

Example 3

Dyn1 (=DABY) transformer

External three-phase fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$IA\_W1 = 1{,}004.1\angle{-60°}A_{pri}$	$IA\_W2 = 2{,}008.2\angle{-90°}A_{pri}$
$IB\_W1 = 1{,}004.1\angle 180°A_{pri}$	$IB\_W2 = 2{,}008.2\angle 150°A_{pri}$
$IC\_W1 = 1{,}004.1\angle 60°A_{pri}$	$IC\_W2 = 2{,}008.2\angle 30°A_{pri}$

External phase-phase (BC) fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$IA\_W1 = 502.0\angle 0°A_{pri}$	$IA\_W2 = 0.0$
$IB\_W1 = 1{,}004.1\angle 180°A_{pri}$	$IB\_W2 = 1{,}739.1\angle 180°A_{pri}$
$IC\_W1 = 502.0\angle 0°A_{pri}$	$IC\_W2 = 1{,}739.1\angle 0°A_{pri}$

External phase-ground (A) fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$IA\_W1 = 579.7\angle{-90°}A_{pri}$	$IA\_W2 = 2{,}008.2\angle{-90°}A_{pri}$
$IB\_W1 = 0.0$	$IB\_W2 = 0.0$
$IC\_W1 = 579.7\angle 90°A_{pri}$	$IC\_W2 = 0.0$

Note: as the faults are external on the W2 115kV-side, the direction for the W1 currents is “to object” (the transformer), whereas the direction for the W2 currents is “from object”. For this reason, the W2 currents in the matrix equations following are phase shifted by 180°.

External three-phase fault – W1 D-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle{-60^\circ} \\ 1{,}004.1\angle{180^\circ} \\ 1{,}004.1\angle{60^\circ} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{-60^\circ} \\ 1{,}004.1\angle{180^\circ} \\ 1{,}004.1\angle{60^\circ} \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle{90^\circ} \\ 2{,}008.2\angle{-30^\circ} \\ 2{,}008.2\angle{-150^\circ} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{120^\circ} \\ 1{,}004.1\angle{0^\circ} \\ 1{,}004.1\angle{-120^\circ} \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External three-phase fault – W2 y-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle{-60^\circ} \\ 1{,}004.1\angle{180^\circ} \\ 1{,}004.1\angle{60^\circ} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{-90^\circ} \\ 1{,}004.1\angle{150^\circ} \\ 1{,}004.1\angle{30^\circ} \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle{90^\circ} \\ 2{,}008.2\angle{-30^\circ} \\ 2{,}008.2\angle{-150^\circ} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{90^\circ} \\ 1{,}004.1\angle{-30^\circ} \\ 1{,}004.1\angle{-150^\circ} \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-phase (BC) fault – W1 D-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 502.0\angle{0^\circ} \\ 1{,}004.1\angle{180^\circ} \\ 502.0\angle{0^\circ} \end{bmatrix}}_{\begin{bmatrix} 502.0\angle{0^\circ} \\ 1{,}004.1\angle{180^\circ} \\ 502.0\angle{0^\circ} \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1{,}739.1\angle{0^\circ} \\ 1{,}739.1\angle{180^\circ} \end{bmatrix}}_{\begin{bmatrix} 502.0\angle{180^\circ} \\ 1{,}004.1\angle{0^\circ} \\ 502.0\angle{180^\circ} \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-phase (BC) fault – W2 y-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 502.0\angle 0^\circ \\ 1{,}004.1\angle 180^\circ \\ 502.0\angle 0^\circ \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 180^\circ \\ 869.6\angle 0^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1{,}739.1\angle 0^\circ \\ 1{,}739.1\angle 180^\circ \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 0^\circ \\ 869.6\angle 180^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-ground (A) fault – W1 D-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 579.7\angle -90^\circ \\ 0.0 \\ 579.7\angle 90^\circ \end{bmatrix}}_{\begin{bmatrix} 579.7\angle -90^\circ \\ 0.0 \\ 579.7\angle 90^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle 90^\circ \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 579.7\angle 90^\circ \\ 0.0 \\ 579.7\angle -90^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-ground (A) fault – W2 y-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 579.7\angle -90^\circ \\ 0.0 \\ 579.7\angle 90^\circ \end{bmatrix}}_{\begin{bmatrix} 669.4\angle -90^\circ \\ 334.7\angle 90^\circ \\ 334.7\angle 90^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle 90^\circ \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 669.4\angle 90^\circ \\ 334.7\angle -90^\circ \\ 334.7\angle -90^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

Example 4:

YNd11 (=YDAB) transformer

External three-phase fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$$IA\_W1 = 1{,}004.1\angle{-120°}A_{pri} \qquad IA\_W2 = 2{,}008.2\angle{-90°}A_{pri}$$

$$IB\_W1 = 1{,}004.1\angle{120°}A_{pri} \qquad IB\_W2 = 2{,}008.2\angle{150°}A_{pri}$$

$$IC\_W1 = 1{,}004.1\angle{0°}A_{pri} \qquad IC\_W2 = 2{,}008.2\angle{30°}A_{pri}$$

External phase-phase (BC) fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$$IA\_W1 = 502.0\angle{180°}A_{pri} \qquad IA\_W2 = 0.0$$

$$IB\_W1 = 502.0\angle{180°}A_{pri} \qquad IB\_W2 = 1{,}739.1\angle{180°}A_{pri}$$

$$IC\_W1 = 1{,}004.1\angle{0°}A_{pri} \qquad IC\_W2 = 1{,}739.1\angle{0°}A_{pri}$$

Note: as the faults are external on the W2 115kV-side, the direction for the W1 currents is "to object" (the transformer), whereas the direction for the W2 currents is "from object". For this reason, the W2 currents in the matrix equations following are phase shifted by 180°.

External three-phase fault – W2 d-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle{-120°} \\ 1{,}004.1\angle{120°} \\ 1{,}004.1\angle{0°} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{-90°} \\ 1{,}004.1\angle{150°} \\ 1{,}004.1\angle{30°} \end{bmatrix}} + \underbrace{\frac{115}{230} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle{90°} \\ 2{,}008.2\angle{-30°} \\ 2{,}008.2\angle{-150°} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{90°} \\ 1{,}004.1\angle{-30°} \\ 1{,}004.1\angle{-150°} \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External three-phase fault – W1 Y-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle -120^\circ \\ 1{,}004.1\angle 120^\circ \\ 1{,}004.1\angle 0^\circ \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle -60^\circ \\ 1{,}004.1\angle 180^\circ \\ 1{,}004.1\angle 60^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle 90^\circ \\ 2{,}008.2\angle -30^\circ \\ 2{,}008.2\angle -150^\circ \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle 120^\circ \\ 1{,}004.1\angle 0^\circ \\ 1{,}004.1\angle -120^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-phase (BC) fault – W2 d-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 502.0\angle 180^\circ \\ 502.0\angle 180^\circ \\ 1{,}004.1\angle 0^\circ \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 180^\circ \\ 869.6\angle 0^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1{,}739.1\angle 0^\circ \\ 1{,}739.1\angle 180^\circ \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 0^\circ \\ 869.6\angle 180^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-phase (BC) fault – W1 Y-winding as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 502.0\angle 180^\circ \\ 502.0\angle 180^\circ \\ 1{,}004.1\angle 0^\circ \end{bmatrix}}_{\begin{bmatrix} 502.0\angle 180^\circ \\ 502.0\angle 180^\circ \\ 1{,}004.1\angle 0^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1{,}739.1\angle 0^\circ \\ 1{,}739.1\angle 180^\circ \end{bmatrix}}_{\begin{bmatrix} 502.0\angle 0^\circ \\ 502.0\angle 0^\circ \\ 1{,}004.1\angle 180^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

Example 5:

Autotransformer, no delta tertiary (YNyn0 transformer)

External three-phase fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$IA\_W1 = 1{,}004.1\angle{-90°}A_{pri}$ $\quad$ $IA\_W2 = 2{,}008.2\angle{-90°}A_{pri}$

$IB\_W1 = 1{,}004.1\angle{150°}A_{pri}$ $\quad$ $IB\_W2 = 2{,}008.2\angle{150°}A_{pri}$

$IC\_W1 = 1{,}004.1\angle{30°}A_{pri}$ $\quad$ $IC\_W2 = 2{,}008.2\angle{30°}A_{pri}$

External phase-phase (BC) fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$IA\_W1 = 0.0$ $\quad$ $IA\_W2 = 0.0$

$IB\_W1 = 869.6\angle{180°}A_{pri}$ $\quad$ $IB\_W2 = 1{,}739.1\angle{180°}A_{pri}$

$IC\_W1 = 869.6\angle{0°}A_{pri}$ $\quad$ $IC\_W2 = 1{,}739.1\angle{0°}A_{pri}$

External phase-ground (A) fault on the W2 115kV-side: the calculated W1 and W2 fault currents are as follows:

$IA\_W1 = 1{,}004.1\angle{-90°}A_{pri}$ $\quad$ $IA\_W2 = 2{,}008.2\angle{-90°}A_{pri}$

$IB\_W1 = 0.0$ $\quad$ $IB\_W2 = 0.0$

$IC\_W1 = 0.0$ $\quad$ $IC\_W2 = 0.0$

Note: as the faults are external on the W2 115kV-side, the direction for the W1 currents is "to object" (the transformer), whereas the direction for the W2 currents is "from object". For this reason, the W2 currents in the matrix equations following are phase shifted by 180°.

External three-phase fault – M0(-30°) matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle{-90°} \\ 1{,}004.1\angle{150°} \\ 1{,}004.1\angle{30°} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{-120°} \\ 1{,}004.1\angle{120°} \\ 1{,}004.1\angle{0°} \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle{90°} \\ 2{,}008.2\angle{-30°} \\ 2{,}008.2\angle{-150°} \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle{60°} \\ 1{,}004.1\angle{-60°} \\ 1{,}004.1\angle{180°} \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External three-phase fault – M0(0°) matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle -90^\circ \\ 1{,}004.1\angle 150^\circ \\ 1{,}004.1\angle 30^\circ \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle -90^\circ \\ 1{,}004.1\angle 150^\circ \\ 1{,}004.1\angle 30^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle 90^\circ \\ 2{,}008.2\angle -30^\circ \\ 2{,}008.2\angle -150^\circ \end{bmatrix}}_{\begin{bmatrix} 1{,}004.1\angle 90^\circ \\ 1{,}004.1\angle -30^\circ \\ 1{,}004.1\angle -150^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-phase (BC) fault – M0(-30°) matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 869.6\angle 180^\circ \\ 869.6\angle 0^\circ \end{bmatrix}}_{\begin{bmatrix} 502.0\angle 180^\circ \\ 502.0\angle 180^\circ \\ 1{,}004.1\angle 0^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1739.1\angle 0^\circ \\ 1739.1\angle 180^\circ \end{bmatrix}}_{\begin{bmatrix} 502.0\angle 0^\circ \\ 502.0\angle 0^\circ \\ 1{,}004.1\angle 180^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-phase (BC) fault – M0(0°) matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 869.6\angle 180^\circ \\ 869.6\angle 0^\circ \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 180^\circ \\ 869.6\angle 0^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1739.1\angle 0^\circ \\ 1739.1\angle 180^\circ \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 0^\circ \\ 869.6\angle 180^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-ground (A) fault – M0(-30°) matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle -90^\circ \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 579.7\angle -90^\circ \\ 579.7\angle 90^\circ \\ 0.0 \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle 90^\circ \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 579.7\angle 90^\circ \\ 579.7\angle -90^\circ \\ 0.0 \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

External phase-ground (A) fault – M0(0°) matrix

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \underbrace{\frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 1{,}004.1\angle -90^\circ \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 669.4\angle -90^\circ \\ 334.7\angle 90^\circ \\ 334.7\angle 90^\circ \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 2{,}008.2\angle 90^\circ \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 669.4\angle 90^\circ \\ 334.7\angle -90^\circ \\ 334.7\angle -90^\circ \end{bmatrix}}$$

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

Appendix C – Calculated differential currents using an actual recorded event

Autotransformer YNyn0(d) – d-winding is not used; 150MVA; W1/W2/W3 = 220kV/115kV/(10.5kV)
W1 I_{rated} = 394A; W2 I_{rated} = 753A
W1 CT ratio: 600/1; W2 CT ratio: 750/1
W1 secondary base current = 0.656A; W2 secondary base current = 1.004A

This transformer is protected with a 2-winidng 87T function. It has an OLTC, which is ignored for this analysis.

The event comprised an external W2-side three-phase fault that evolved to an internal C phase fault when the external fault was cleared.

Figure C.1 shows the W1 220kV-side currents. Figure C.1(a) the current waveforms, and Figure C.1(b) the RMS currents. Notice the transition point where the external three-phase fault cleared, and the internal C phase fault started.

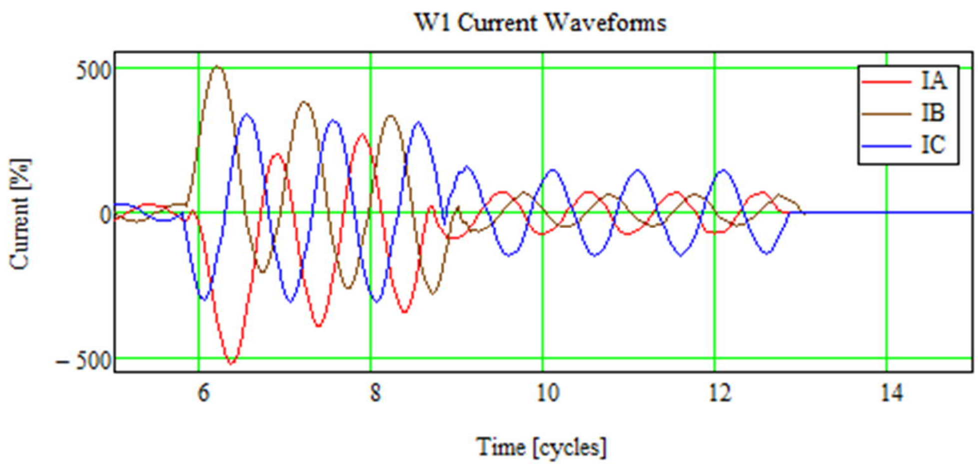

Figure C.1(a)

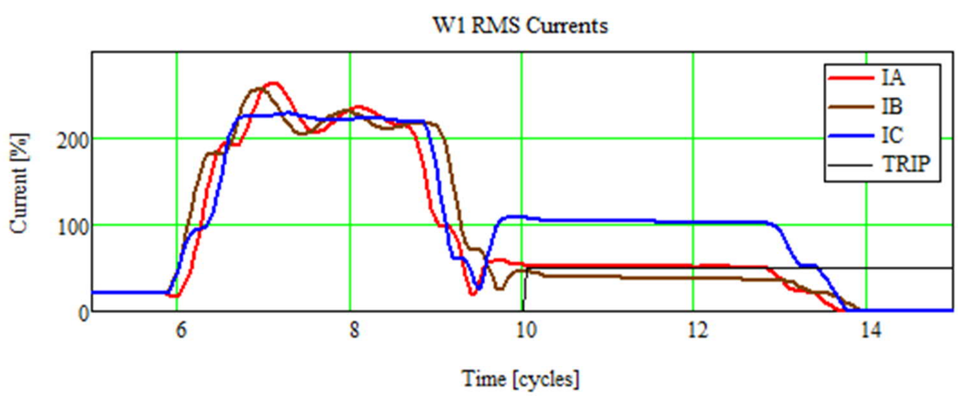

Figure C.1(b)

Figure C.2 shows the W2 115kV-side currents. Figure C.2(a) the current waveforms, and Figure C.2(b) the RMS currents.

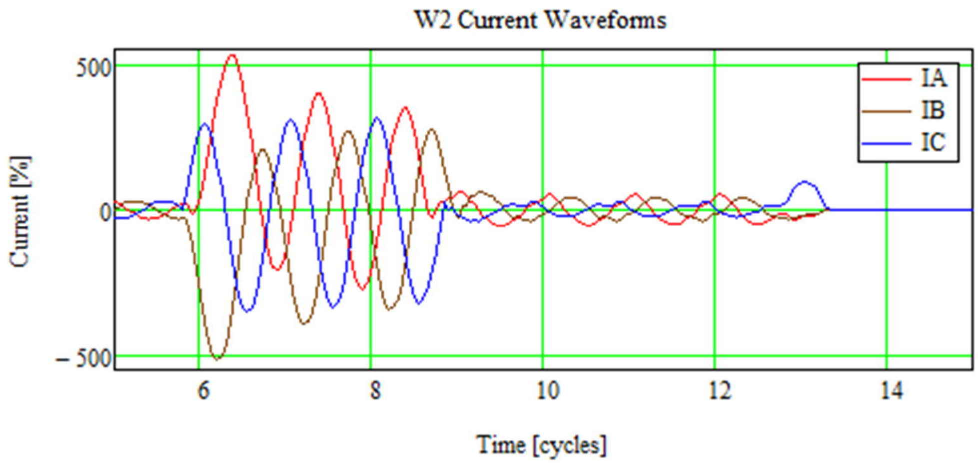

Figure C.2(a)

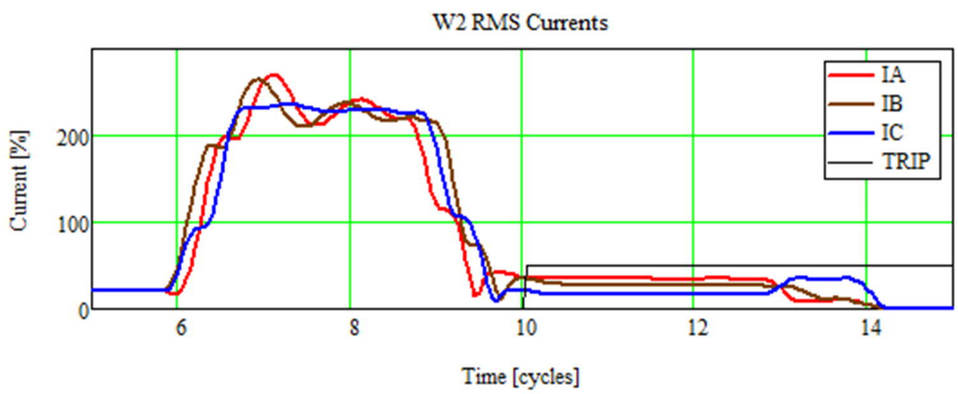

Figure C.2(b)

A computer software for engineering calculations is now used to calculate the differential currents from the recorded phase currents during the internal C phase fault. The objective is to use different matrix selections to show how matrix selection impacts the calculated differential currents.

Figure C.3 shows the calculated differential currents when the M0(30°) matrix is used on both the W1- and W2-sides (i.e. as if a delta-winding were being selected as the phase reference).

$$M0(30°) = \begin{bmatrix} 0.577 & -0.577 & 0.000 \\ 0.000 & 0.577 & -0.577 \\ -0.577 & 0.000 & 0.577 \end{bmatrix}$$

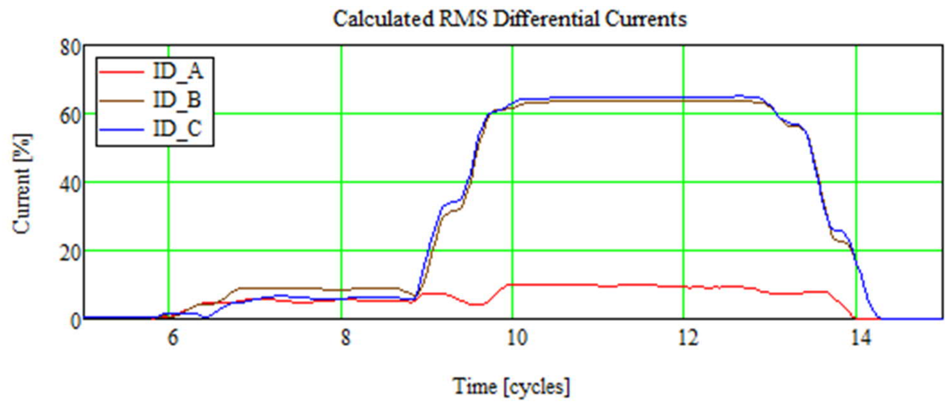

Figure C.3: Calculated differential currents when the M0(30°) matrix is used

Note the two equal differential currents calculated for phase C (the faulted phase) and phase B. The differential function would operate in these two phases, and give target indication showing this operation. There would be no clear indication of the limb in which this fault has occurred.

Figure C.4 shows the calculated differential currents when the M0(-30°) matrix is used on both the W1- and W2-sides (i.e. as if a delta-winding were being selected as the phase reference).

$$M0(-30°) = \begin{bmatrix} 0.577 & 0.000 & -0.577 \\ -0.577 & 0.577 & 0.000 \\ 0.000 & -0.577 & 0.577 \end{bmatrix}$$

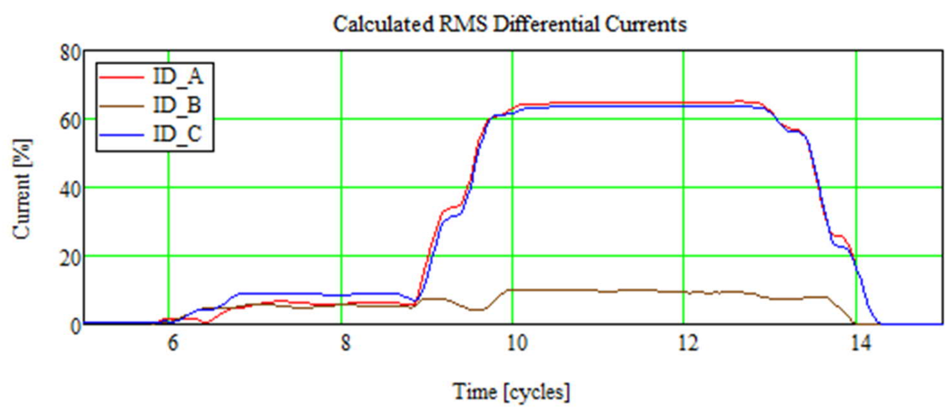

Figure C.4: Calculated differential currents when the M0(-30°) matrix is used

Note again the two equal differential currents calculated for phase C (the faulted phase) and this time phase A. Selecting the M0(-30°) matrix instead of the M0(30°) matrix just swops the two unfaulted phases in which the equal differential current is calculated. The differential function would operate in these two phases, and give target indication showing this operation. Again, there would be no clear indication of the limb in which this fault has occurred.

Figure C.5 shows the calculated differential currents when the M0(0°) matrix is used on both the W1- and W2-sides (i.e. making the (first) wye-winding the phase reference). The M0(0°) matrix subtracts the zero sequence currents.

$$M0(0°) = \begin{bmatrix} 0.667 & -0.333 & -0.333 \\ -0.333 & 0.667 & -0.333 \\ -0.333 & 0.667 & -0.333 \end{bmatrix}$$

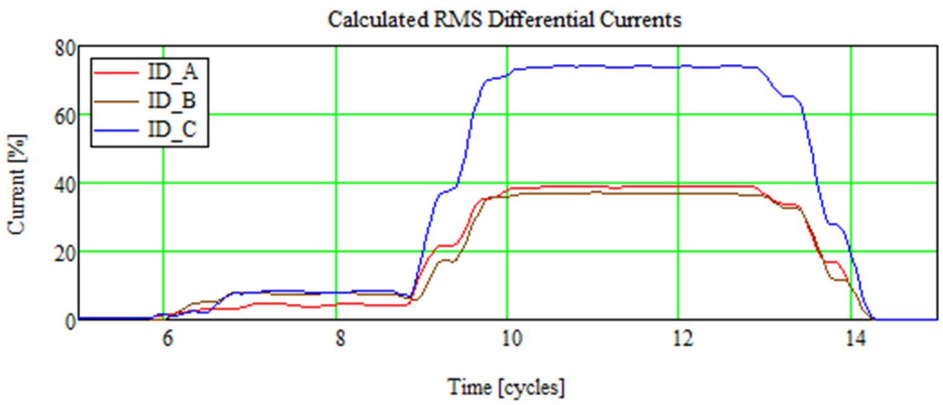

Figure C.5: Calculated differential currents when the M0(0°) matrix is used

In this case the differential current calculated for phase C is clearly the largest, and so gives clear indication of the limb in which this fault has occurred. Comparing Figure C.5 with Figures C.3 and C.4, the phase C differential current in Figure C.5 is 1.15 times larger than the differential currents calculated in the two phases in Figures C.3 and C.4.

Note that when using the M0(0°) matrix the differential function would most likely operate in all three phases, and give target indication showing this operation.

Figure C.6 shows the calculated differential currents when the M(0°) matrix is used on both the W1- and W2-sides (i.e. making the (first) wye-winding the phase reference). The M(0°) matrix does not subtract the zero sequence currents.

$$M(0°) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

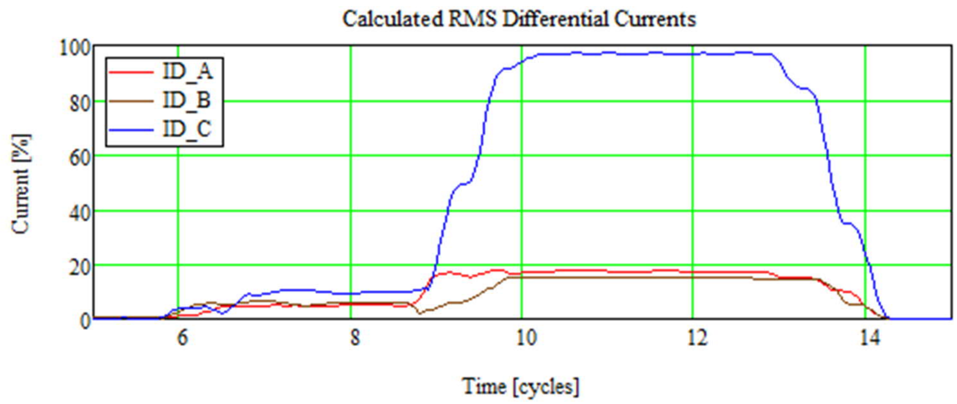

Figure C.6: Calculated differential currents when the M(0°) matrix is used

In this case the differential current calculated for phase C is again clearly the largest, but where Figure C.6 differs from Figure C.5 is that in Figure C.6:

- the differential current calculated for phase C is larger, thereby increasing the sensitivity, and
- the differential currents calculated for phases A and B are now very small.

If it were possible to use the M(0°) matrix, this would be very beneficial for internal single-phase faults as the differential function would operate only in the faulted phase, give target indication showing this operation, and so give clear indication of the limb in which this fault has occurred just by the target indication. However, the major disadvantage, unfortunately, is that using the M(0°) matrix in this case would make the differential protection highly susceptible to misoperation for external faults.

References

Zoran Gajić, Differential Protection for Arbitrary Three-Phase Power Transformers, doctoral dissertation, 2008

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Mike joined Hitachi ABB Power Grids (formerly ABB Inc.) in Raleigh, North Carolina as a Senior Applications / Product Specialist in November 2011. Prior to relocating to North America, Mike worked as a Senior Applications Specialist / Senior Regional Technical Manager for 12 years at the SA Product factory in Västerås, Sweden. Before joining ABB AB in Sweden in January 2000, Mike was Senior Consultant, Protection (Transmission) at Eskom (national power utility, South Africa). Mike joined Eskom as an engineer-in-training) in 1983 and rose to Protection Design Manager (Line Protection), before switching to Senior Consultant. Mike graduated from the University of Cape Town with a BSc (electrical engineering) degree (with honors) in 1980.

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