ANALYSIS OF FUNDAMENTAL DIFFERENCES IN TRANSFORMER 87T DIFFERENTIAL PROTECTION

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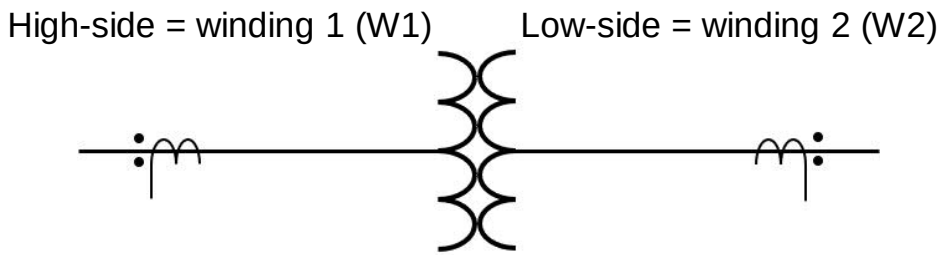
Common expectations for 87T functions

- To eliminate common modes of failures, relays from different manufactures are often deployed at HV voltage levels and above
- These relays protect the same object, the transformer, and common expectations for the 87T functions could be that they'd
  - have the same settings
  - operate identically
  - report the same target indications for the same fault

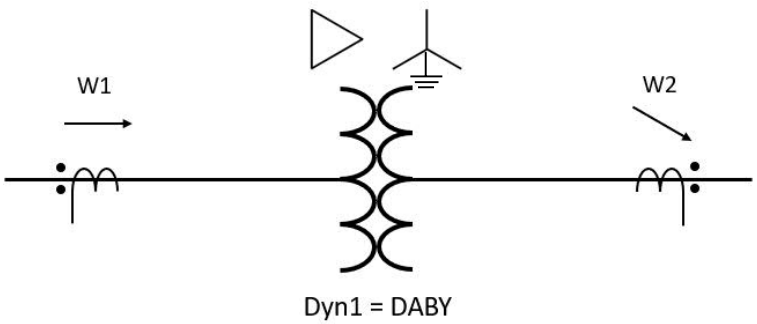
Transformer differential 87T principle of operation

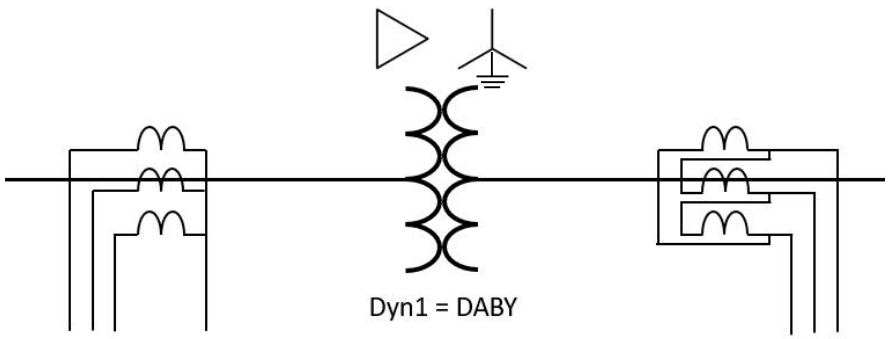


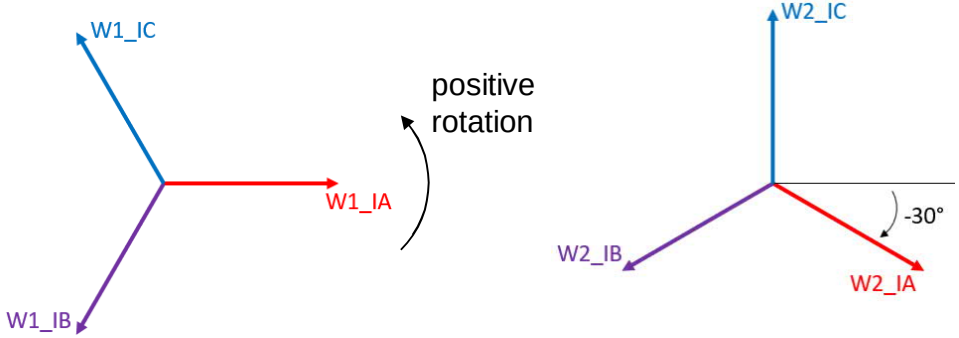
- 87T transformer differential protection – factors to consider
  - transformation (turns) ratio; winding type; vector group; flow of zero sequence current
- Solution
  - bring all current magnitudes to the same magnitude reference (magnitude compensation)
  - align all current phase angles to the <u>same phase reference</u> (phase angle compensation)
    - phase reference side – no rotation of currents
    - non phase reference side – rotate currents to align with the phase reference side currents
      - eliminate the zero-sequence currents (that can flow on only one side)

Transformer differential 87T principle of operation

- Pre-microprocessor relays
  - magnitude compensation: CT ratios and relay tap selection
  - phase angle compensation: CT secondary connection to the relay







- Note:
  - W2 lags W1 → negative angle
    → if W1 is the phase reference, W2 currents require a positive anti-clockwise rotation to align with the W1 phase reference

Transformer differential 87T principle of operation

- Pre-microprocessor relays
  - Balanced rated load flow

Delta-connection rotates W2 secondary currents anti-clockwise +30°

Calculated

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

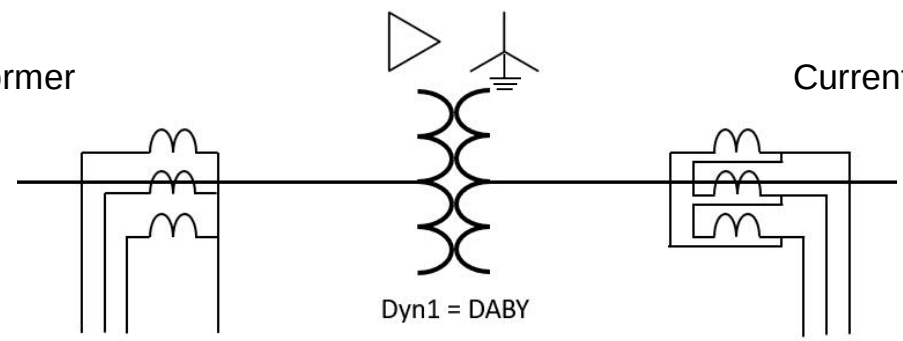
$IA_W2 = 502.0\angle -30°A_{pri}$
$IB_W2 = 502.0\angle -150°A_{pri}$
$IC_W2 = 502.0\angle 90°A_{pri}$

$IA_W2 = 4.35\angle 0°A_{sec}$
$IB_W2 = 4.35\angle -120°A_{sec}$
$IC_W2 = 4.35\angle 120°A_{sec}$

Current flow 'towards' the transformer

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

Phase reference side



Current flow 'away from' the transformer

$IA_W2 = 4.35\angle 180°A_{sec}$
$IB_W2 = 4.35\angle 60°A_{sec}$
$IC_W2 = 4.35\angle -60°A_{sec}$

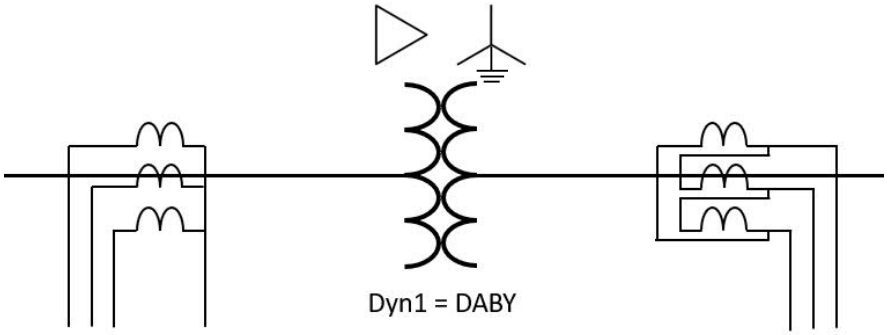
$IA_W1 = 1.00\angle 0°A_{pu}$
$IB_W1 = 1.00\angle -120°A_{pu}$
$IC_W1 = 1.00\angle 120°A_{pu}$

$IA_W2 = 1.00\angle 180°A_{pu}$
$IB_W2 = 1.00\angle 60°A_{pu}$
$IC_W2 = 1.00\angle -60°A_{pu}$

Apply tap scaling to both W1 and W2 currents to achieve common per unit base

Transformer differential 87T principle of operation

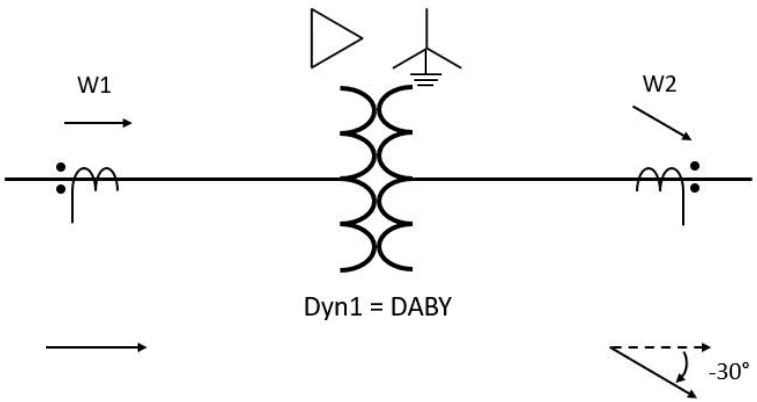
- Pre-microprocessor relays

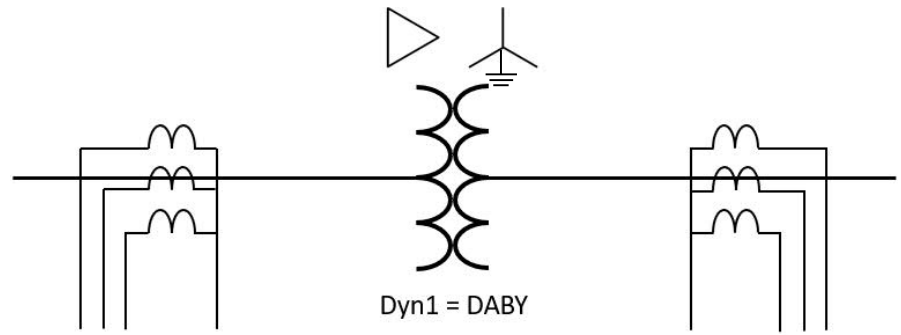


  - The delta-side served as the phase reference side (CT secondary wye-connection)
  - The CT secondary delta-connection on the wye-side served two purposes
    - Rotated the wye-side currents to align with the delta-side phase reference currents
    - Trapped the zero-sequence currents that can flow only on the wye-side – eliminated these zero-sequence currents from the differential measurement

Transformer differential 87T principle of operation

- Microprocessor relays





- matrix equation:

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = A * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + \frac{V_{rated_W2}}{V_{rated_W1}} * B * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

Transformer differential 87T principle of operation

- Microprocessor relays

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = A * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + \frac{V_{rated_W2}}{V_{rated_W1}} * B * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

IA_W1, etc = primary values

- A and B are 3X3 matrices
- The elements of A and B depend on
  - winding connection type, i.e. wye or delta
  - transformer vector group, DABY (Dyn1), DACY (Dyn11), etc.
  - whether the subtraction (elimination) of zero sequence current is enabled or not

Transformer differential 87T principle of operation

- Microprocessor relays

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = \underbrace{A * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix}} + \underbrace{\frac{V_{rated_W2}}{V_{rated_W1}} * B * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}}$$

IA_W1, etc = primary values

$$= \begin{bmatrix} DCCA_W1 \\ DCCB_W1 \\ DCCC_W1 \end{bmatrix} + \begin{bmatrix} DCCA_W2 \\ DCCB_W2 \\ DCCC_W2 \end{bmatrix}$$

Commonly termed the compensated currents

- where

$|ID_A| = |DCCA_W1 + DCCA_W2|$

$|ID_B| = |DCCB_W1 + DCCB_W2|$

$|ID_C| = |DCCC_W1 + DCCC_W2|$

Transformer differential 87T principle of operation

- Microprocessor relays

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = A * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + \frac{V_{rated_W2}}{V_{rated_W1}} * B * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

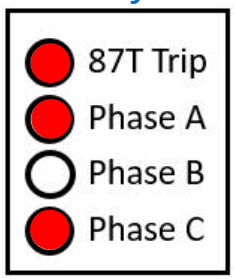
IA_W1, etc = primary values

- Magnitude compensation
- Phase angle compensation
  - Phase reference side – matrix multiplication must not introduce any phase shift in the currents
  - Non phase reference side – matrix multiplication must introduce a phase shift in the currents such that the non phase reference side currents are shifted in phase to align with the phase reference side currents
  - Matrix multiplication must comply with the above, as well as subtract the zero-sequence component from the phase currents if required (enabled) to do so

Transformer differential 87T principle of operation

- In-service Delta-wye transformer was protected by two microprocessor relays (A and B)

Relay A

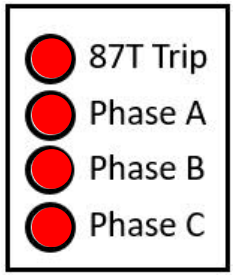


- Relay A was set with the Delta-side as phase reference
- Relay B was set with the wye-side as phase reference

Internal single-phase fault occurred

- Relay A 87T function operated …in 2 phases
- Relay B 87T function operated …in 3 phases

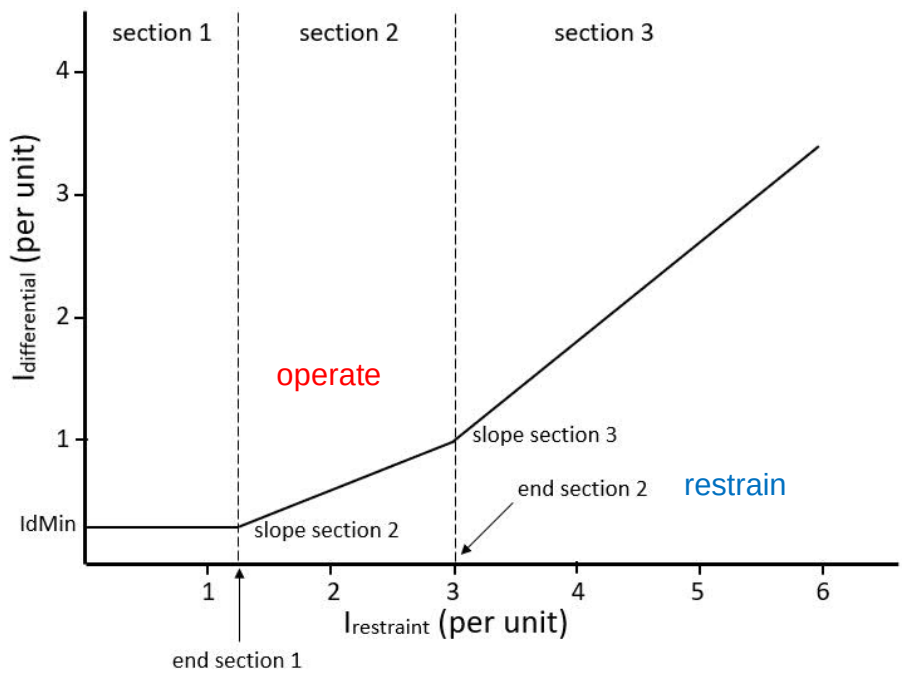
Relay B



- Both relays operated correctly

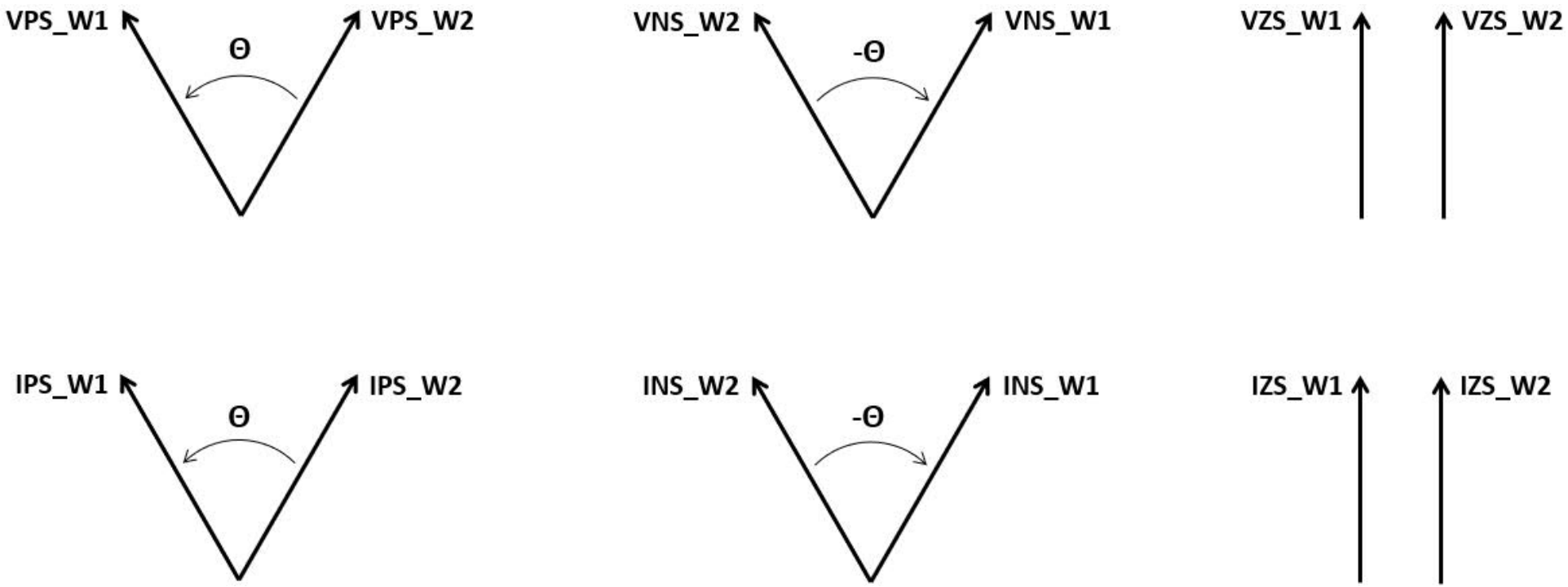
Transformer differential 87T principle of operation

- Typical 87T characteristic



Transformer differential 87T theoretical overview

- Strict rules only exist for the phase angle shift between the sequence components



Transformer differential 87T theoretical overview

$$ID_PS = IPS_W1 + e^{j\Theta} * IPS_W2$$

$$ID_NS = INS_W1 + e^{-j\Theta} * INS_W2$$

$$ID_ZS = IZS_W1 + IZS_W2$$

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = M(0°) * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + M(\Theta) * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

- Note:
  - This analysis considers only the procedure for phase angle shift compensation
  - Magnitude compensation is of course still required

- Remember, from an earlier slide

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = A * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + \frac{V_{rated_W2}}{V_{rated_W1}} * B * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

Transformer differential 87T theoretical overview

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = M(0°) * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + M(\Theta) * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

or

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = M(-\Theta) * \begin{bmatrix} IA_W1 \\ IB_W1 \\ IC_W1 \end{bmatrix} + M(0°) * \begin{bmatrix} IA_W2 \\ IB_W2 \\ IC_W2 \end{bmatrix}$$

- M(Θ) matrix does not subtract the zero sequence currents
- M0(Θ) to be used when the zero sequence currents must be subtracted

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

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

Transformer differential 87T selection of phase reference side

- Typical application / settings rules

  - if a delta-winding exists, select the first delta-side (W1 → W2) as the phase reference side …
    - Delta-wye transformer: select the W1 Delta-side; Wye-delta transformer: select the W2 delta-side

    … then select the appropriate matrices to rotate the currents from all other sides to align with the phase reference delta-side
  - if no delta-winding exists, select …..

  - if a wye-winding exists, select the first wye-side (W1 → W2) as the phase reference side …
    - Wye-delta transformer: select the W1 Wye-side; Delta-wye transformer: select the W2 wye-side

    … then select the appropriate matrices to rotate the currents from all other sides to align with the phase reference wye-side
  - if no wye-winding exists, select …..

Transformer differential 87T selection of phase reference side

- DABY (Dyn1) transformer
  - External faults (3ph, ph-ph, 1ph); through load flow
    - for all cases, the calculated differential currents in all phases are zero, irrespective of whether the W1-side or the W2-side is 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
  - Internal faults
    - matrix selection (resulting from selection of which side is the phase reference) comes into play more for internal faults because most of them are single-phase faults and <u>the calculated differential currents will be different for different matrix selections</u>

Transformer differential 87T selection of phase reference side

- DABY (Dyn1) transformer: Internal single-phase fault in the winding on limb A
  - <u>Delta-winding selected as the phase reference</u> (mimics the traditional pre-microprocessor 87T relay application)

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 579.7\angle{-90°} \\ 0.0 \\ 579.7\angle{90°} \end{bmatrix}}_{\begin{bmatrix} 579.7\angle{-90°} \\ 0.0 \\ 579.7\angle{90°} \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}}$$

$|ID_A| = 579.7A$

$|ID_B| = 0.0A$

$|ID_C| = 579.7A$

  - equally large differential currents would be calculated in two phases, and so the 87T function would operate in both phases
  - the calculated differential currents would not correspond to one physical limb of the protected transformer

Transformer differential 87T selection of phase reference side

- DABY (Dyn1) transformer: Internal single-phase fault in the winding on limb A
  - <u>wye-winding selected as the phase reference</u> (microprocessor relays only)

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 579.7\angle -90° \\ 0.0 \\ 579.7\angle 90° \end{bmatrix}}_{\begin{bmatrix} 669.4\angle -90° \\ 334.7\angle 90° \\ 334.7\angle 90° \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}}$$

$|ID_A| = 669.4A$

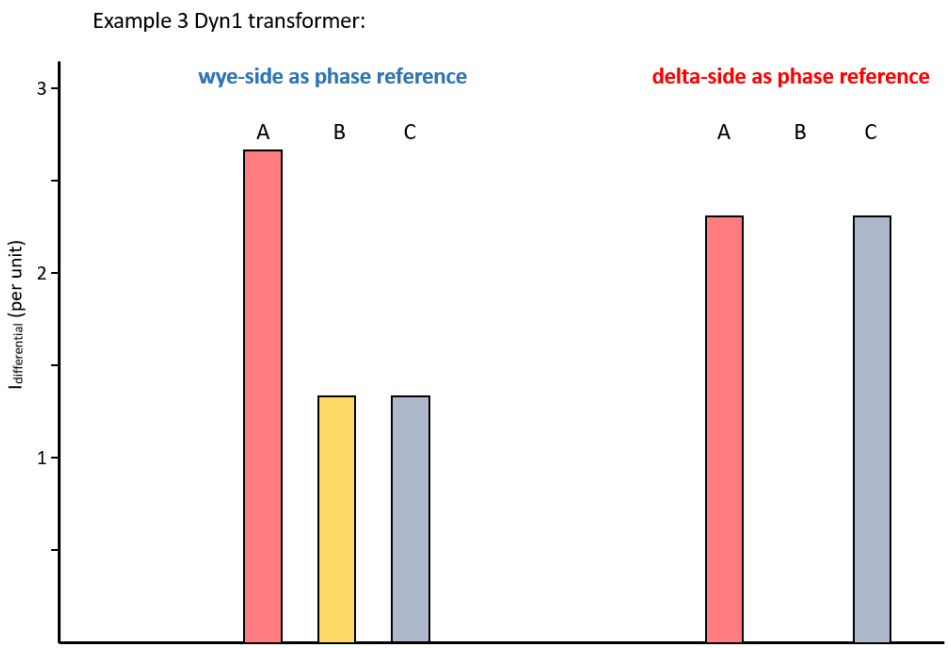
$|ID_B| = 334.7A$

$|ID_C| = 334.7A$

  - the calculated differential currents correspond to a higher degree to the limb with the fault – this is even true when the subtraction of zero sequence currents is enabled
  - when the subtraction of zero sequence currents is enabled, more phases can operate due to the applied matrix that mixes all three phases on the wye-side
  - still, the biggest differential current would appear in phase A for an internal single-phase fault in the winding on limb A, clearly indicating the actual faulted limb

Transformer differential 87T selection of phase reference side

- DABY (Dyn1) transformer: Internal single-phase fault in the winding on limb A



- wye-side as the phase reference → the differential current calculated for the phase on the faulted limb is 1.155 times larger than the differential currents calculated for the same fault when the delta-side is the phase reference

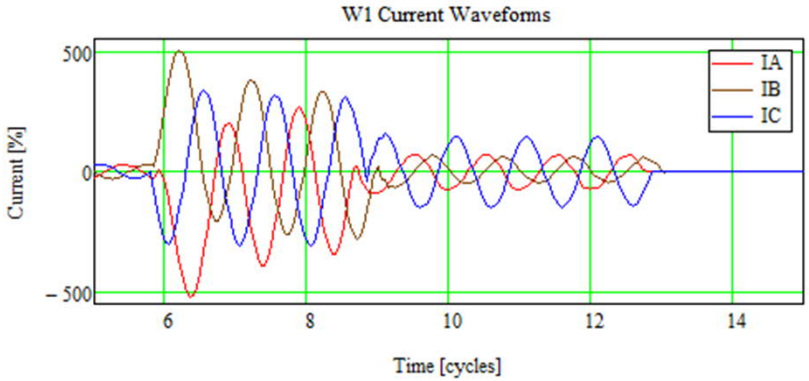
$$\text{wye-reference : delta-reference} = \frac{2}{3} : \frac{1}{\sqrt{3}} = 0.667 : 0.577$$

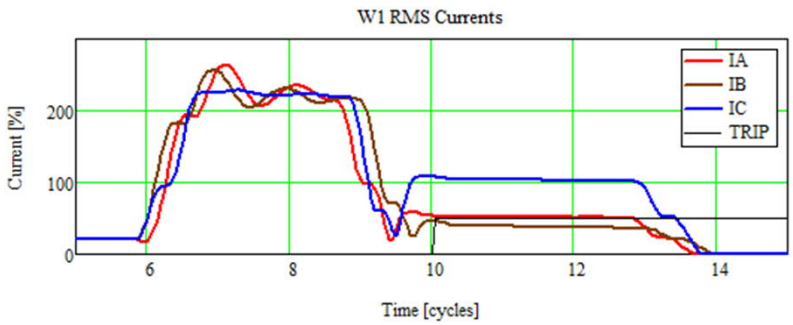
Transformer differential 87T actual recording to substantiate theory

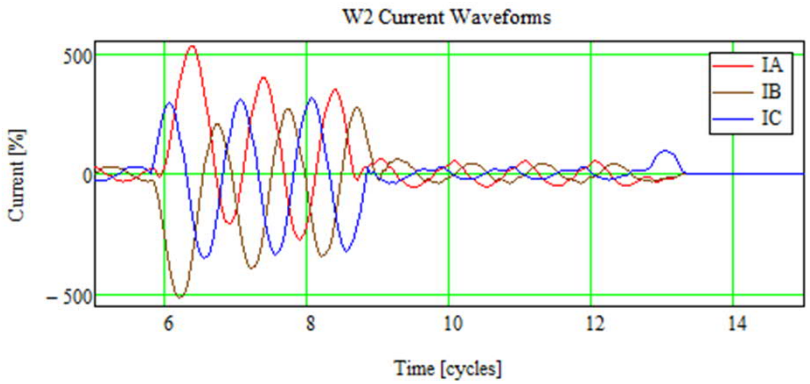
- Autotransformer YNyn0(d) – d-winding is not used
  - 150MVA
  - W1/W2/W3 = 220kV/115kV/(10.5kV)
  - W1 I_{rated} = 394A; W2 I_{rated} = 753A
  - W1 CT ratio: 600/1; W2 CT ratio: 750/1
  - W1 secondary base current = 0.656A; W2 secondary base current = 1.004A
  - this transformer is protected with a 2-winding 87T function
  - the differential currents are calculated from the recorded phase currents during an internal C-phase fault using a computer software for engineering calculations
  - the objective is to use different matrix selections to show how matrix selection impacts the calculated differential currents for the internal single-phase fault

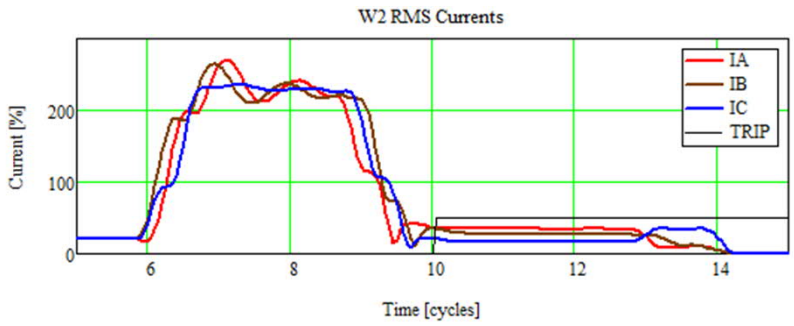
Transformer differential 87T actual recording to substantiate theory

- Winding currents





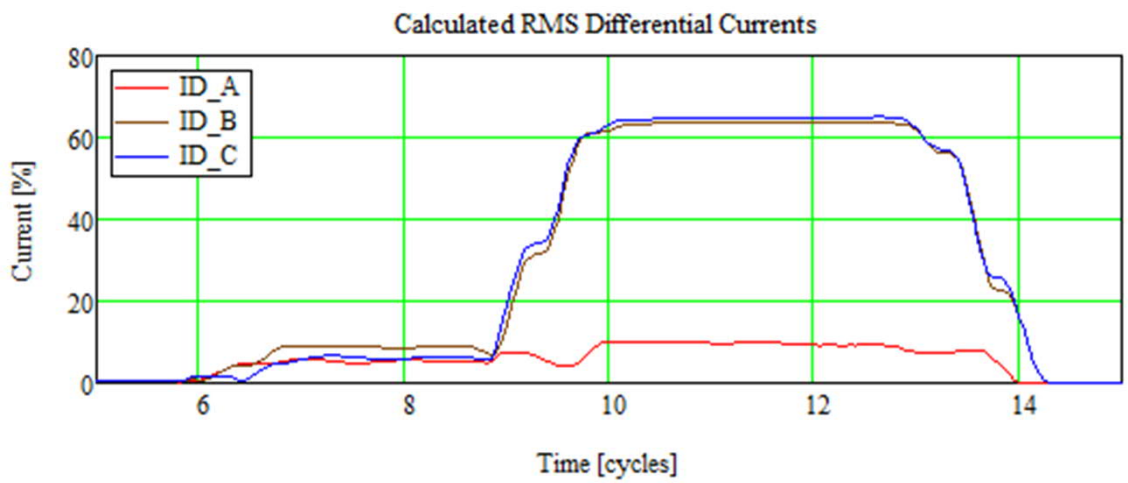




Transformer differential 87T actual recording to substantiate theory

- Use the M0(30°) matrix – autotransformer so the same matrix is used for both W1- and W2-sides

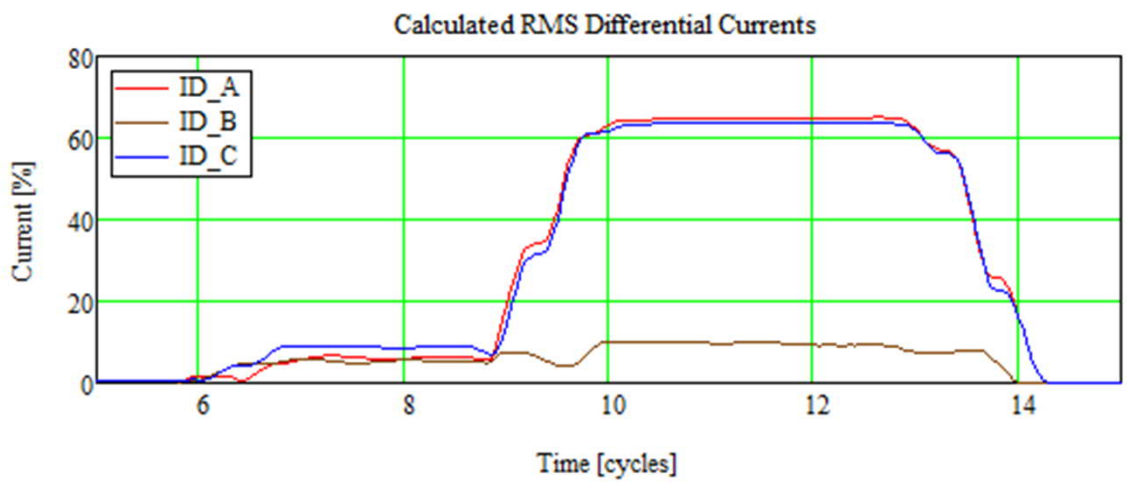
$$M0(30°) = \begin{bmatrix} 0.577 & -0.577 & 0.000 \\ 0.000 & 0.577 & -0.577 \\ -0.577 & 0.000 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$



Transformer differential 87T actual recording to substantiate theory

- Use the M0(-30°) matrix – autotransformer so the same matrix is used for both W1- and W2-sides

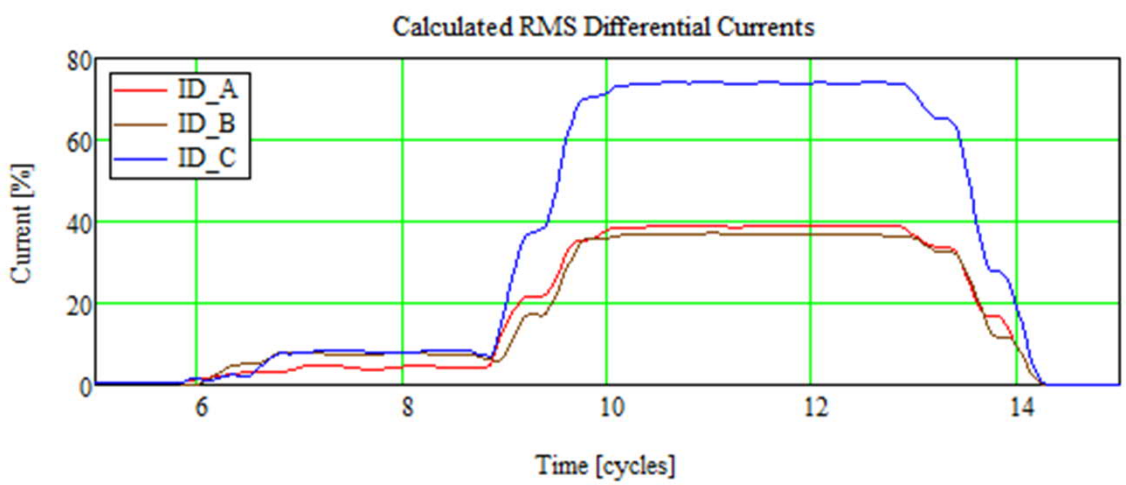
$$M0(-30°) = \begin{bmatrix} 0.577 & 0.000 & -0.577 \\ -0.577 & 0.577 & 0.000 \\ 0.000 & -0.577 & 0.577 \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}$$



Transformer differential 87T actual recording to substantiate theory

- Use the M0(0°) matrix – autotransformer so the same matrix is used for both W1- and W2-sides

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



Transformer differential 87T impact of restraint current calculation method

- Frequently encountered methods
  - 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

$$|I_{restraint}_A| = ½(|DCCA_W1| + |DCCA_W2|)$$

$$|I_{restraint}_B| = ½(|DCCB_W1| + |DCCB_W2|)$$

$$|I_{restraint}_C| = ½(|DCCC_W1| + |DCCC_W2|)$$

Transformer differential 87T impact of restraint current calculation method

- DABY (Dyn1) transformer: External ph-ph (BC) fault on the transformer W2 wye-side
  - <u>Delta-winding selected as the phase reference</u>

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 502.0\angle 0° \\ 1{,}004.1\angle 180° \\ 502.0\angle 0° \end{bmatrix}}_{\begin{bmatrix} 502.0\angle 0° \\ 1{,}004.1\angle 180° \\ 502.0\angle 0° \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1{,}739.1\angle 0° \\ 1{,}739.1\angle 180° \end{bmatrix}}_{\begin{bmatrix} 502.0\angle 180° \\ 1{,}004.1\angle 0° \\ 502.0\angle 180° \end{bmatrix}}$$

- the calculated differential currents are zero for the external ph-ph fault (no CT saturation)

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

Transformer differential 87T impact of restraint current calculation method

- DABY (Dyn1) transformer: External ph-ph (BC) fault on the transformer W2 wye-side
  - <u>wye-winding selected as the phase reference</u>

$$\begin{bmatrix} ID_A \\ ID_B \\ ID_C \end{bmatrix} = \underbrace{\frac{1}{\sqrt{3}}\begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} 502.0\angle 0° \\ 1{,}004.1\angle 180° \\ 502.0\angle 0° \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 180° \\ 869.6\angle 0° \end{bmatrix}} + \underbrace{\frac{115}{230} * \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} 0.0 \\ 1{,}739.1\angle 0° \\ 1{,}739.1\angle 180° \end{bmatrix}}_{\begin{bmatrix} 0.0 \\ 869.6\angle 0° \\ 869.6\angle 180° \end{bmatrix}}$$

- the calculated differential currents are zero for the external ph-ph fault (no CT saturation)

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

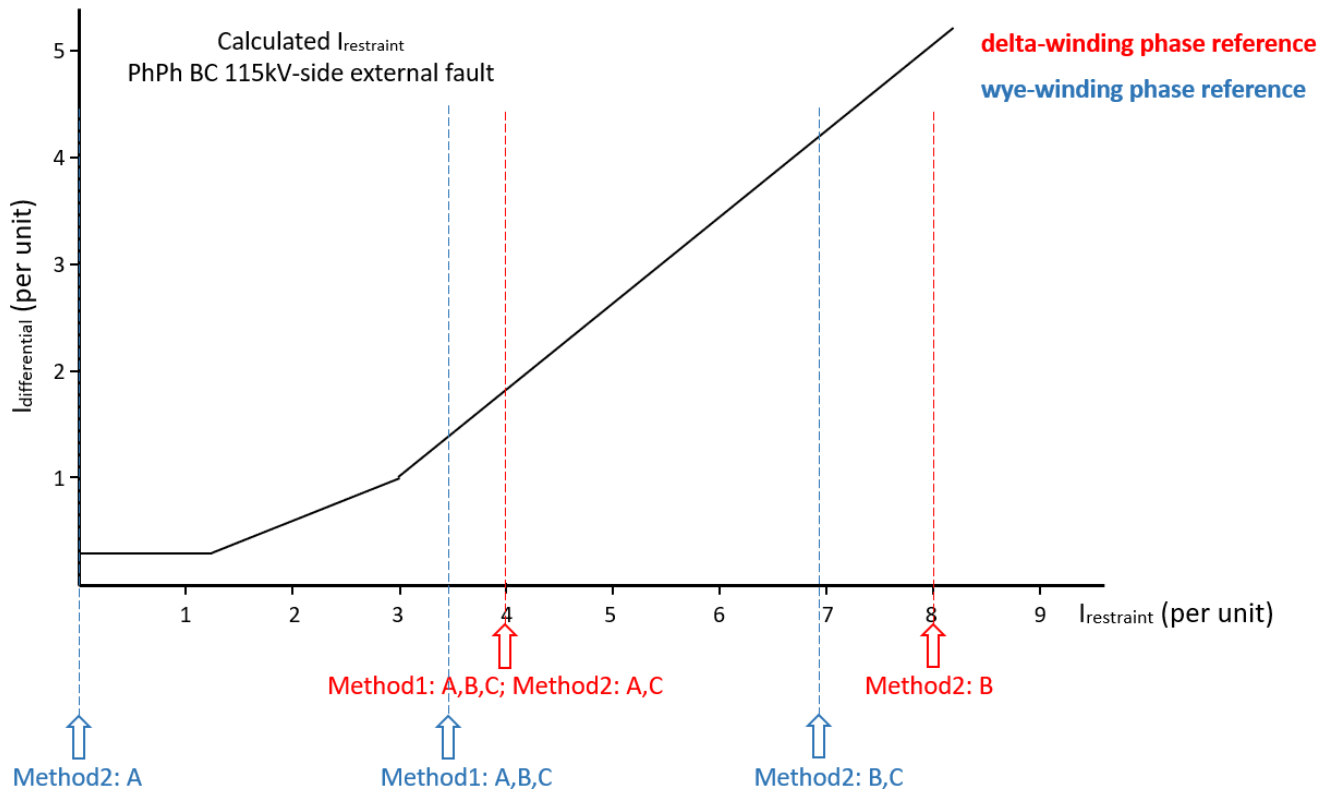
$|I_{restraint}_A| = 0.0A = 0.00$ per unit

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

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

Transformer differential 87T impact of restraint current calculation method

- DABY (Dyn1) transformer
  - external ph-ph (BC) fault on the transformer W2 wye-side
    - Comparison: method 1 vs method 2 for restraint current calculation



Transformer differential 87T impact of restraint current calculation method

- DABY (Dyn1) transformer
  - external ph-ph (BC) fault on the transformer W2 wye-side
    - delta-winding as phase reference
      - for both methods 1 and 2 sufficient restraint current will be calculated to ensure through fault stability for the external ph-ph fault
    - wye-winding as phase reference
      - for method 1 sufficient restraint current will be calculated to ensure through fault stability for the external ph-ph fault
      - method 2 $I_{restraint}$_A = 0
        - 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 → gives rise to potential for unwanted operation for external ph-ph fault

Transformer differential 87T impact of restraint current calculation method

- DABY (Dyn1) transformer
  - Selection of phase reference
    - method 2 for calculating the restraint currents → select the delta-side as the phase reference
    - method 1 for calculating the restraint currents → can select either the wye- or the delta-side as the phase reference
      - by choosing the wye-side, can take advantage of certain benefits, like slightly increased sensitivity for an internal single-phase faults, and a more definite indication of the actual limb of the magnetic core where the fault occurred, as the calculated differential current will have the highest magnitude in the phase on the limb with the fault

Conclusion

- Consider again the common expectations for the 87T functions
  - have the same settings NO
  - operate identically NO
  - report the same target indications for the same fault NO
- The same best practice application rules and settings guidelines no longer apply generally for microprocessor-based 87T functions
- No “best fits all” common setting rules exist, as each 87T function has its own settings rules to follow
- Knowing, understanding and following these is key to achieving best performance

Questions

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