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Application of Standard 87T Differential Protection on Phase-Shifting Transformers

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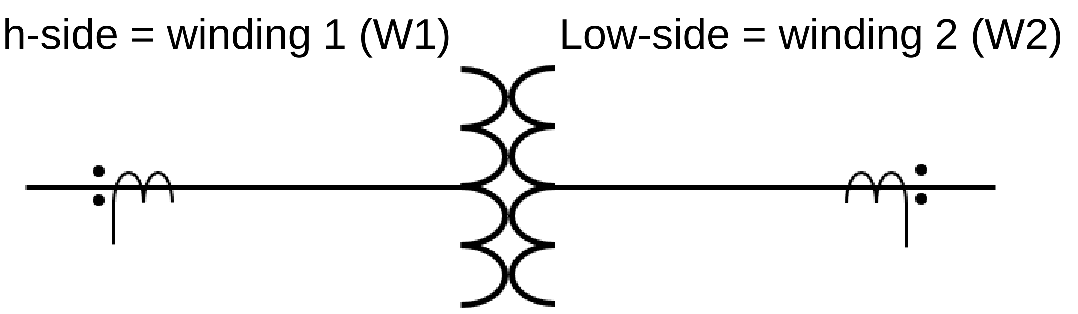
Introduction

- Standard two-winding 87T protection
  - principle of operation, typical settings
- Self-adapting differential protection for PSTs
  - principle of operation, typical settings
- Customer TenneT: testing and pilot installation
- Customer ConEd: selection requirements and commissioning recording
- Conclusions

Phase-angle shift across a transformer

- A phase-angle shift Θ occurs between the no-load voltages and between the through-going currents on the two sides of the transformer
  - standard two-winding three-phase power transformers introduce a fixed phase-angle shift Θ of n*30° (n=0, 1, 2, …, 11) – n is defined by the transformer vector group at manufacture
  - phase shifting transformers introduce a variable phase-angle shift Θ, for example ±24° in total, having ±32 OLTC steps of approximately 0.75° per step

Standard 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 same phase reference (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)

Standard transformer differential 87T principle of operation

- Microprocessor relays – matrix equation
  - all currents/voltages shown below are in primary values

Ratio (magnitude compensation)

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

$$= \begin{bmatrix} DCCA\_W1 \\ DCCB\_W1 \\ DCCC\_W1 \end{bmatrix} + \begin{bmatrix} DCCA\_W2 \\ DCCB\_W2 \\ DCCC\_W2 \end{bmatrix}$$

Commonly termed the compensated currents

- where

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

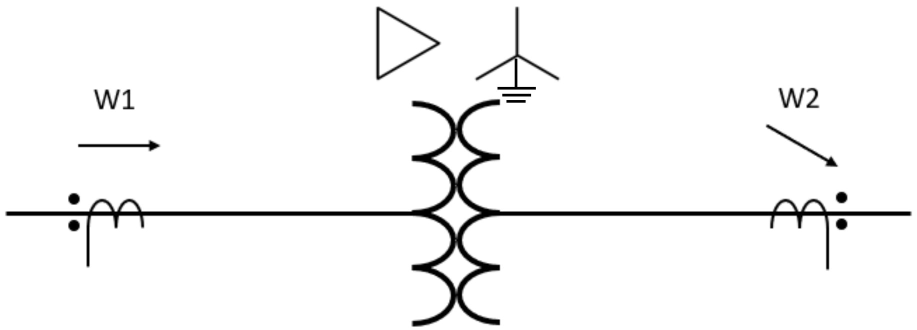
$|ID\_B| = |DCCB\_W1 + DCCB\_W2|$

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

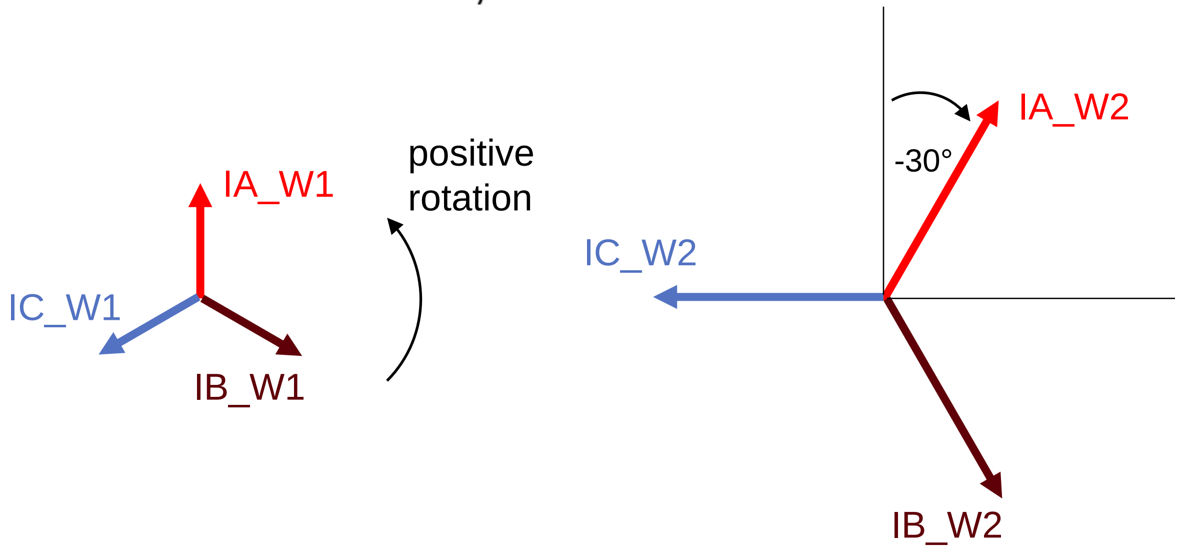
- A and B are 3X3 matrices
  - the elements of A and B depend on
    - winding connection type, i.e. wye or delta
    - transformer vector group, DABY (Dyn1), DACY (Dyn11), etc.
    - whether the subtraction (elimination) of zero-sequence current is enabled or not
    - the selected phase reference side
  - matrix multiplication
    - phase reference side – introduces no phase shift in the currents
    - non phase reference side – phase shifts the currents to align with the phase reference side
    - subtract zero-sequence if required

Standard transformer differential 87T principle of operation

- Settings example (microprocessor relay): Dyn1 (DABY) transformer



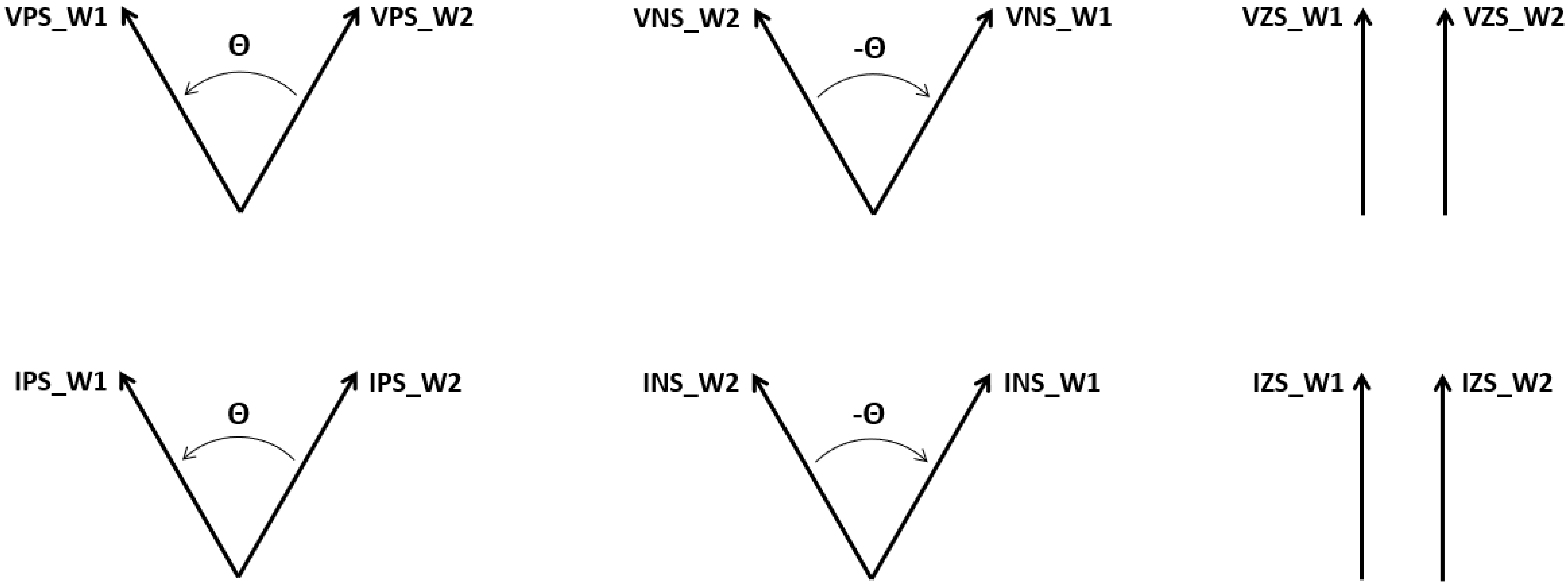
Dyn1 = DABY



- typical 87T function settings to set the transformer details
  - V_{rated_W1}
  - I_{rated_W1}
  - V_{rated_W2}
  - I_{rated_W2}
  - W1 connection DELTA
  - W2 connection WYE
  - W2 clock position with respect to W1 1 ‘o clock
  - W1 zero-sequence subtraction Off/On
  - W2 zero-sequence subtraction Off/On

Transformer differential 87T theoretical overview

- Strict rules exist only for the phase-angle shift between the sequence components, and not the individual phase quantities



Transformer differential 87T theoretical overview

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

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

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

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

OR

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

Transformer differential 87T theoretical overview

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

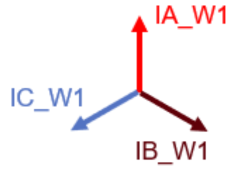
- M(Θ) matrix does not subtract the zero sequence currents
- M0(Θ) matrix to be used when the zero sequence currents must be subtracted

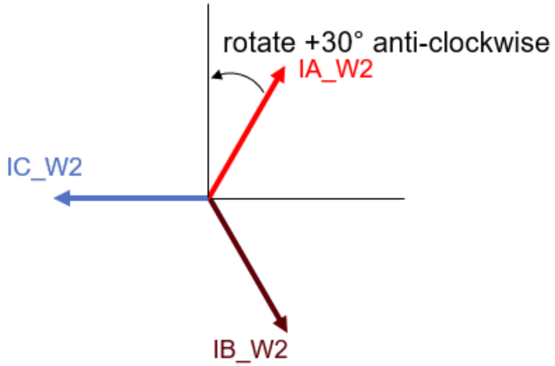
$$M0(\Theta) = \frac{2}{3}\begin{bmatrix} \cos(\Theta) & \cos(\Theta+120°) & \cos(\Theta-120°) \\ \cos(\Theta-120°) & \cos(\Theta) & \cos(\Theta+120°) \\ \cos(\Theta+120°) & \cos(\Theta-120°) & \cos(\Theta) \end{bmatrix}$$

Standard transformer differential 87T principle of operation

- Dyn1 (DABY) transformer
  - delta-winding (W1) as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{V_{rated\_W2}}{V_{rated\_W1}} * \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$





no zero-sequence subtraction is required, so use the M(0°) matrix

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

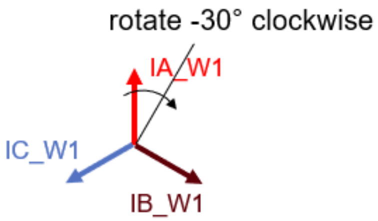
use matrix M0(30°) as it is necessary to subtract the zero-sequence

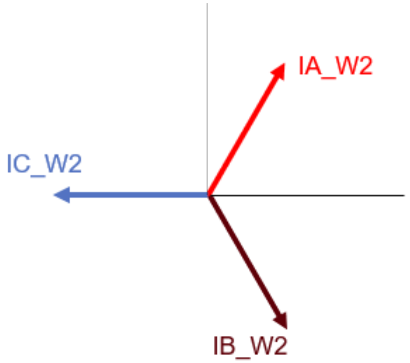
$$\begin{bmatrix} 0.577 & -0.577 & 0.000 \\ 0.000 & 0.577 & -0.577 \\ -0.577 & 0.000 & 0.577 \end{bmatrix}$$

Standard transformer differential 87T principle of operation

- Dyn1 (DABY) transformer
  - wye-winding (W2) as the phase reference

$$\begin{bmatrix} ID\_A \\ ID\_B \\ ID\_C \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix} * \begin{bmatrix} IA\_W1 \\ IB\_W1 \\ IC\_W1 \end{bmatrix} + \frac{V_{rated\_W2}}{V_{rated\_W1}} * \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} * \begin{bmatrix} IA\_W2 \\ IB\_W2 \\ IC\_W2 \end{bmatrix}$$





there is no zero-sequence in the measured currents, but anyway can use the M0(-30°) matrix

$$\begin{bmatrix} 0.577 & 0.000 & -0.577 \\ -0.577 & 0.577 & 0.000 \\ 0.000 & -0.577 & 0.577 \end{bmatrix}$$

use matrix M0(0°) as it is necessary to subtract the zero-sequence

$$\begin{bmatrix} 0.667 & -0.333 & -0.333 \\ -0.333 & 0.667 & -0.333 \\ -0.333 & 0.667 & -0.333 \end{bmatrix}$$

Phase shifting transformer differential protection

- 87T for PST
  - 87T protection that requires voltage measurement (needs VTs on the S- and L-sides – single-phase or three-phase)
  - has on-line measurement of phase-angle shift and transformation ratio (PSTs have varying phase-angle shift and maybe also varying ratio)
  - is suitable for any PST regardless of its construction (symmetrical or asymmetrical; single-core or double-core)
  - does not require OLTC position
  - is similar to the standard 87T function for two-winding transformers

Phase shifting transformer differential protection

- 87T for PST
  - Fundamental frequency differential currents

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

S-winding = W1 L-winding = W2

- where
  - Θ is the negative of the actual phase-angle shift across the PST (in degrees)
  - Ratio is the actual PST transformation ratio
  - W1 is the reference side for current magnitude (W2 currents are transferred to W1 magnitude by the ratio factor) and for phase-angle shift (W2 currents are rotated by angle Θ to align with the W1 currents)
  - M0 matrices subtract the zero-sequence currents – if this subtraction is not required, can then use the M matrices
    - two typical situations when the zero-sequence currents must be subtracted on both sides:
      - the PST incorporates a closed tertiary delta-winding, the PST is of an asymmetrical design

Phase shifting transformer differential protection

- 87T for PST
  - continuously performs on-line estimation of transformation ratio and phase-angle shift

$$\text{Complex Current Ratio (CCR)} = \frac{-I_{W2}}{I_{W1}} = \frac{|I_{W2}|}{|I_{W1}|} e^{j(\angle I_{W2} + 180° - \angle I_{W1})}$$

$$= |CCR|\, e^{jI\_Angle}$$

$$I\_Ratio = \frac{1}{|CCR|}$$

- I_{W1} and I_{W2} are the positive-sequence current phasors from the two transformer sides

$$\text{Complex Voltage Ratio (CCR)} = \frac{V_{W2}}{V_{W1}} = \frac{|V_{W2}|}{|V_{W1}|} e^{j(\angle V_{W2} - \angle V_{W1})}$$

$$= |CVR|\, e^{jV\_Angle}$$

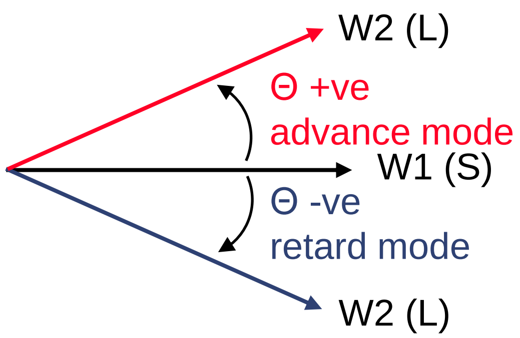
$$V\_Ratio = |CVR|$$

- V_{W1} and V_{W2} are the selected voltage phasors (one from each side)

Phase shifting transformer differential protection

- 87T for PST

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



I_Ratio or V_Ratio → DIFRATIO

I_Angle or V_Angle (mult by -1) → DIFANGLE

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

- pre-programmed rules determine which of the on-line estimated values are used
  - if both W1 and W2 positive-sequence current magnitudes ≥ 10% of I_{rated}, the values from the current calculation are used
  - if either positive-sequence current magnitude < 10% of I_{rated}, only then are values from the voltage calculation used

Phase shifting transformer differential protection

- 87T for PST
  - negative-sequence differential function

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

    - where
      - ID_NS is the negative-sequence differential current phasor, and INS_W1 and INS_W2 are the W1 and W2 negative-sequence current phasors
        - the provided features are equally applicable to the 87T for PST as for the standard transformer 87T

Phase shifting transformer differential protection

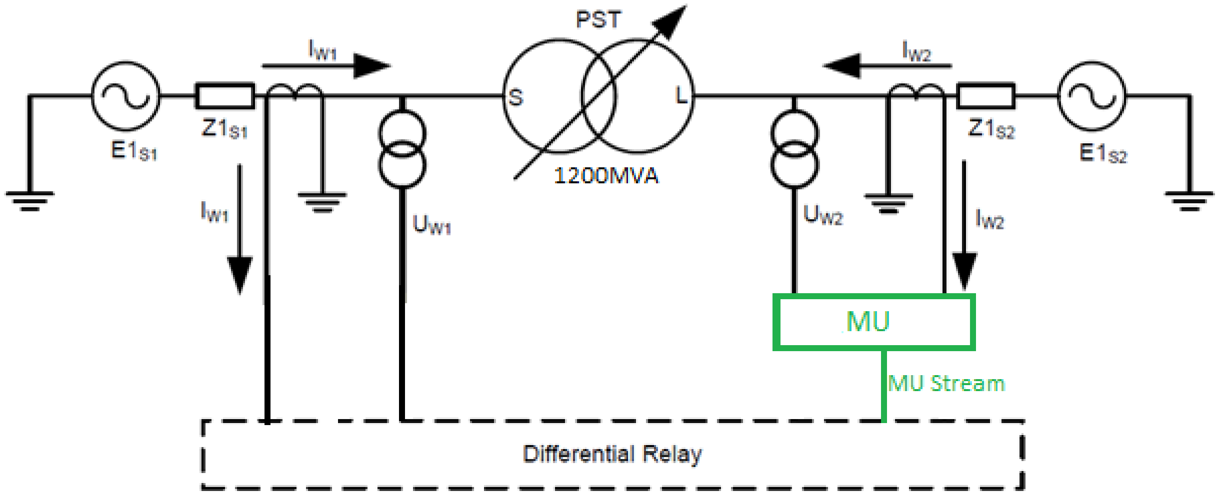
- Settings
  - Typical settings for standard 87T
    - V_{rated_W1}
    - I_{rated_W1}
    - V_{rated_W2}
    - I_{rated_W2}
    - W1 connection DELTA
    - W2 connection WYE
    - W2 clock position 1 ‘o clock
    - W1 zero-sequence subtraction Off/On
    - W2 zero-sequence subtraction Off/On
  - Typical settings for 87T for PST
    - V_{rated_W1}
    - I_{rated_W1}
    - V_{rated_W2}
    - I_{rated_W2}
    - W1 zero-sequence subtraction Off/On
    - W2 zero-sequence subtraction Off/On
    - W1 and W1 voltage input selection

Phase-shifting transformer differential protection

- Settings
  - Typical settings for standard 87T
    - mimimum pickup sensitivity
    - restrained characteristic
    - high-set unrestrained trip level
    - 2nd / 5th harmonic block / restrain levels
    - cross block On / Off
    - negative-sequence function settings
  - Typical settings for 87T for PST
    - mimimum pickup sensitivity
    - restrained characteristic
    - high-set unrestrained trip level
    - 2nd / 5th harmonic block / restrain levels
    - cross block On / Off
    - negative-sequence function settings

Customer: TenneT TSO GmbH, Germany

- Secondary injection testing using a test set
- Secondary injection of simulated external and internal fault conditions
- Pilot installation of the 87T-PST (since March 2021)
  - existing dual-core, symmetrical PST having the following rated data:
    - 1200MVA; 400/400kV; 50Hz; ±24° (32 OLTC positions in advance direction, and 32 OLTC positions in retard direction, with an advance-retard switch due to the large number of taps)



- PST has operated at various loads and OLTC positions, as well as different positions of the advanced-retard switch
- several primary faults have happened during this time in the vicinity of the PST
- the 87T-PST differential protection has remained stable

Customer: TenneT TSO GmbH, Germany

- 87T-PST testing during new PST FAT at the transformer factory
  - same PST type as where pilot was installed
  - same analog input arrangement as for pilot
  - all 65 tap positions were checked under load by tapping from position 32A to position 32R – every tap transition was recorded

Customer: TenneT TSO GmbH, Germany

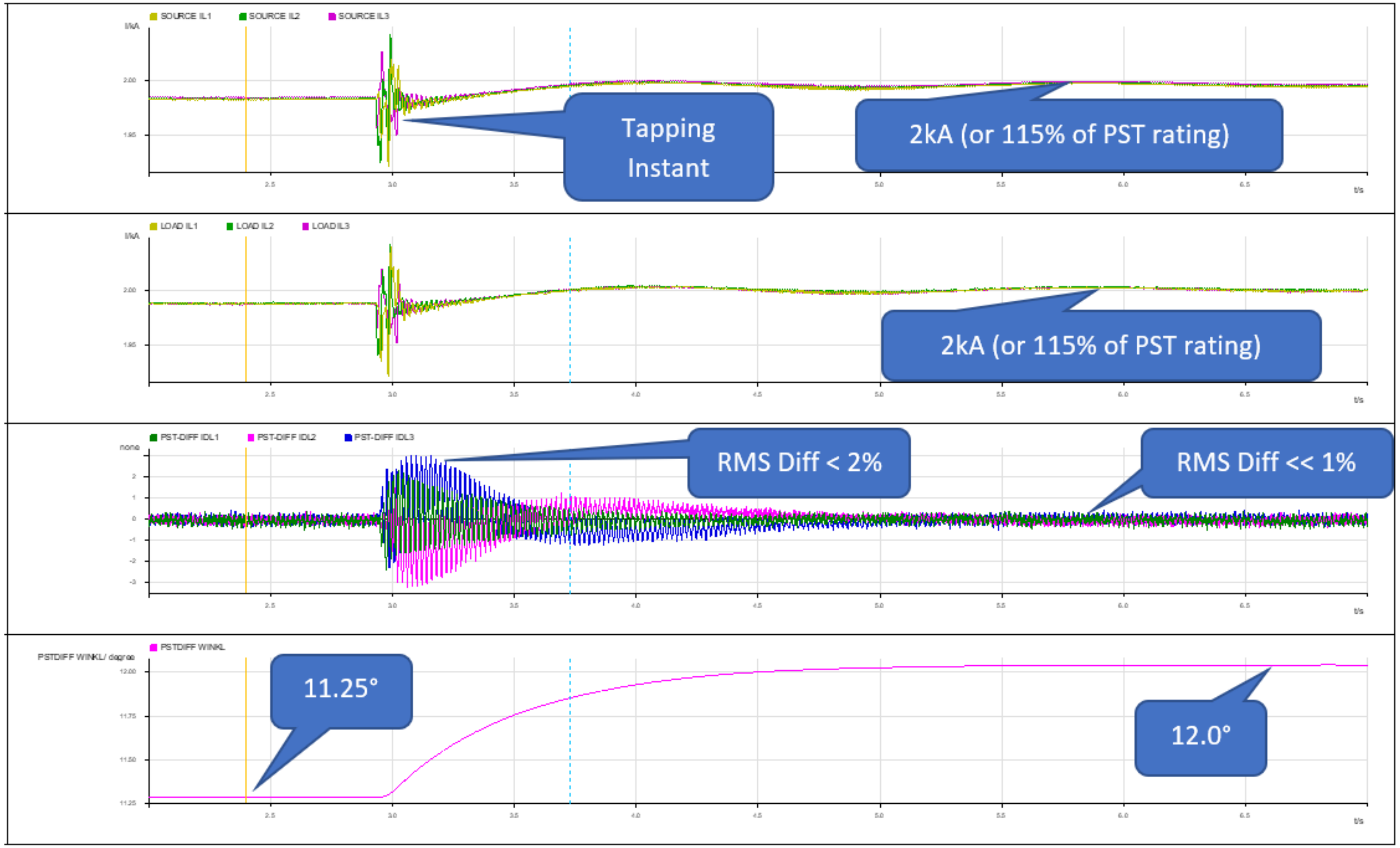
- 87T_PST testing during new PST FAT at the transformer factory – tap change under full load

RMS values of the measured S-side currents in kA (W1)

RMS values of the measured L-side currents in kA (W2)

Internally calculated instantaneous differential currents in percent of PST rating

Internally calculated phase-angle shift across the PST in degrees



Customer: TenneT TSO GmbH, Germany

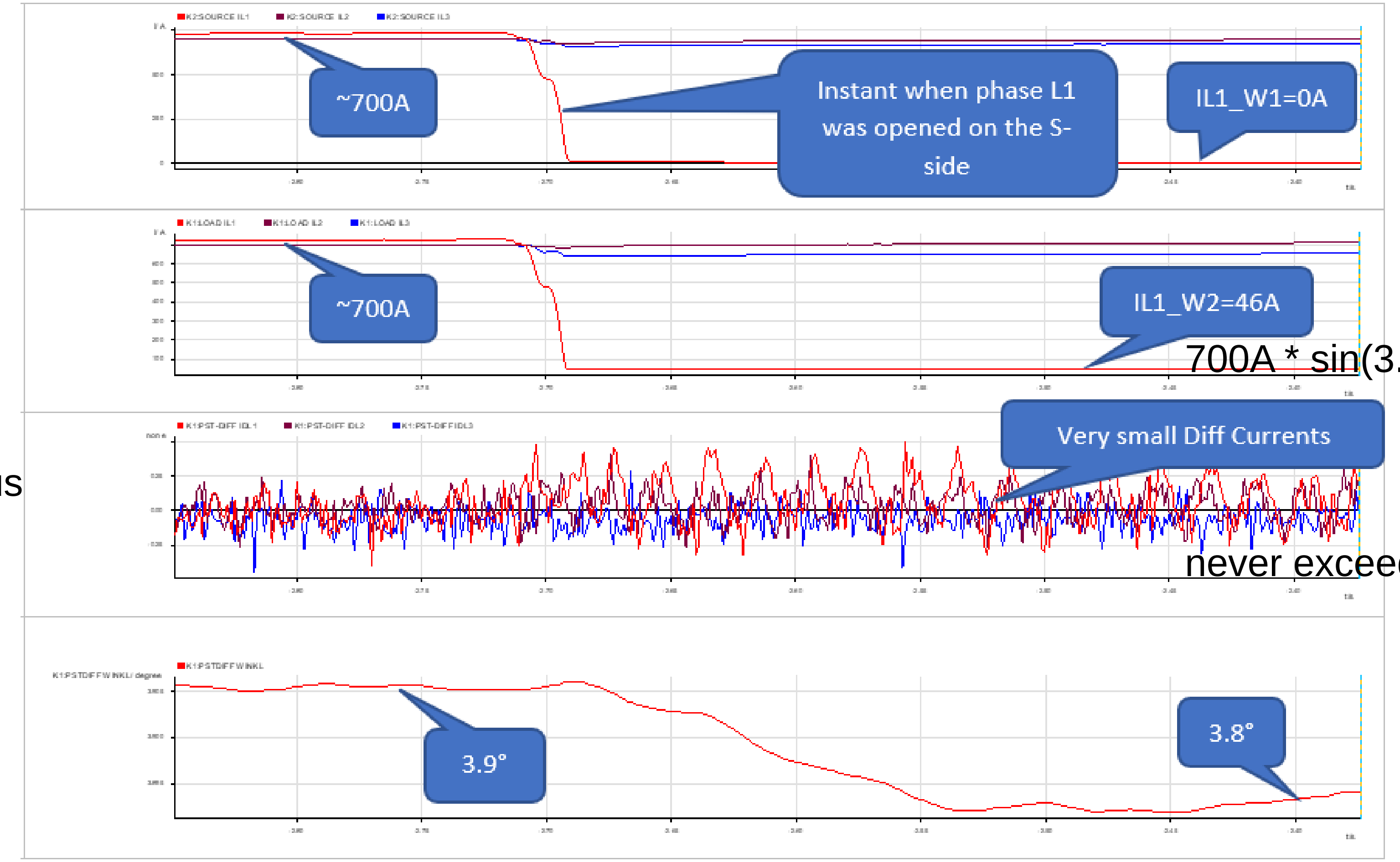
- 87T_PST testing – in-service PST, single-pole opened on S-side (PST on tap 5 advance = 3.75°)

RMS values of the measured S-side currents in kA (W1)

RMS values of the measured L-side currents in kA (W2)

Internally calculated instantaneous differential currents in percent of PST rating

Internally calculated phase-angle shift across the PST in degrees

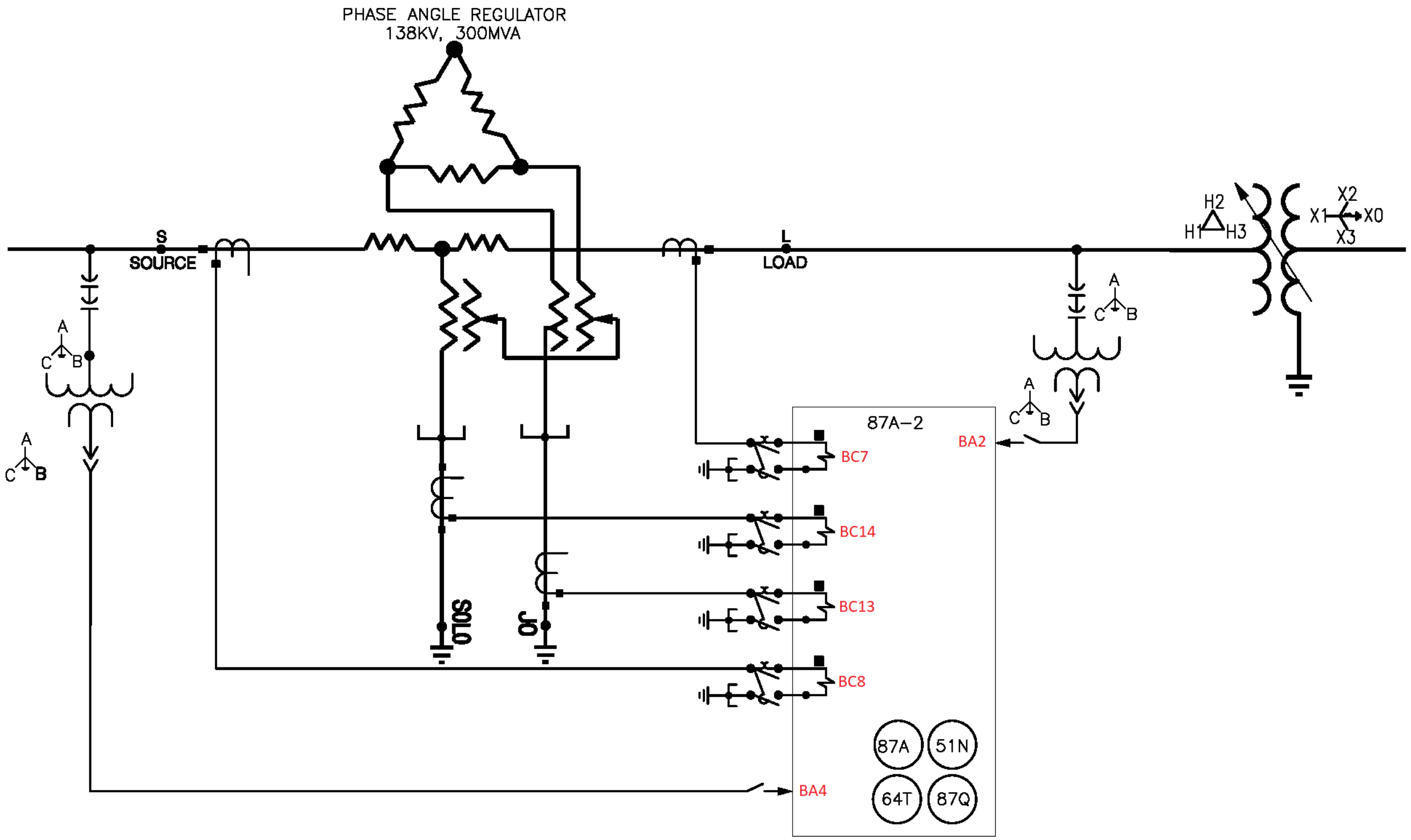


700A * sin(3.75°) = 46A

never exceeded 0.5%

Customer: ConEd, NY, USA

- PSTs are used to control active power flow
- Commissioned a new 300MVA; 60Hz; 138kV; ±25°; symmetrical double-core PST in 2022
- Protected by two different systems, one incorporating the 87T for PST function

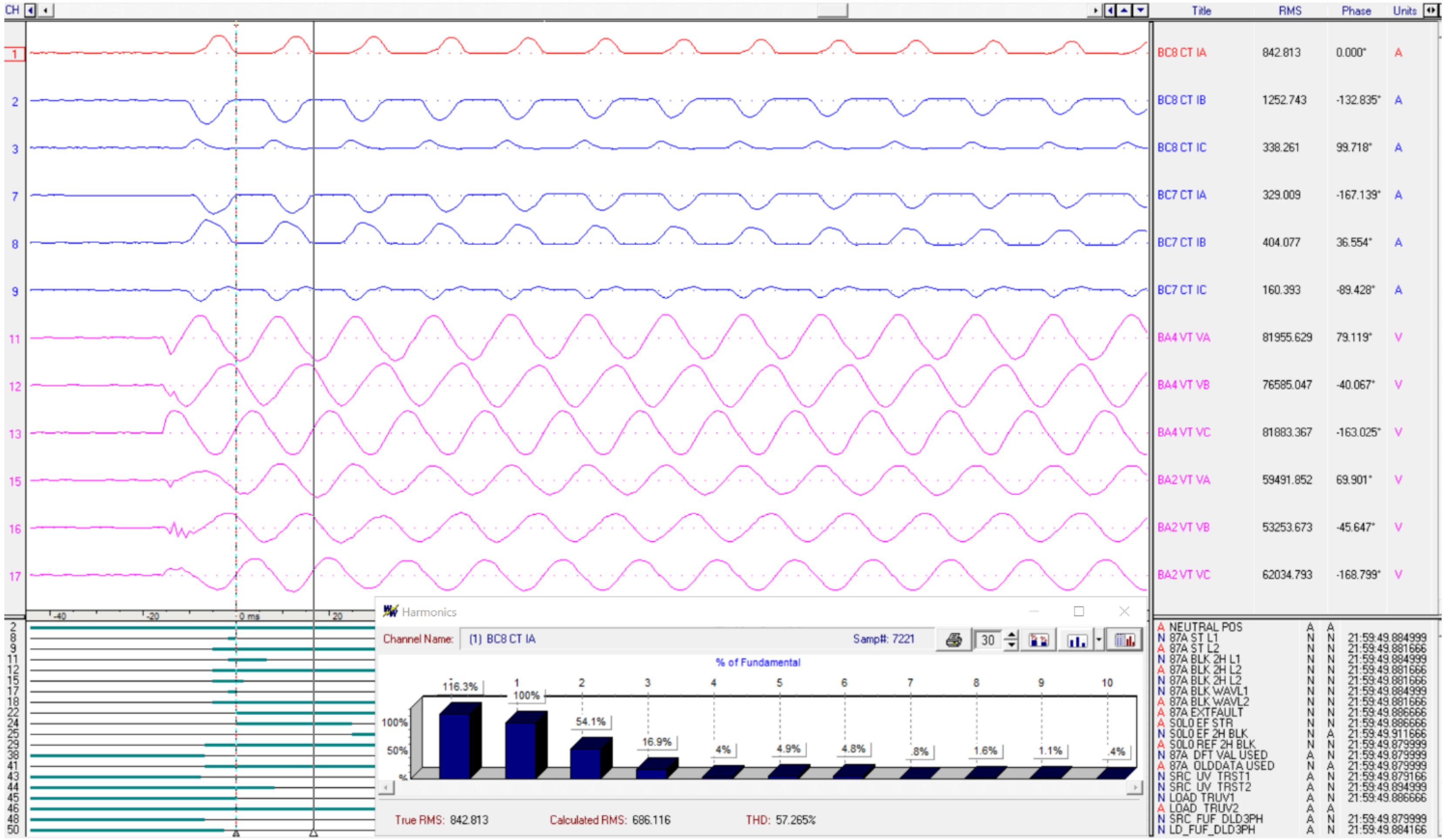


Customer: ConEd, NY, USA

- Customer: ConEd, NY, USA
  - protection system must provide complete PST protection for all high- and low-level internal faults, as well as backup protection for all external ground faults
  - new solution, with 87T for PST
    - one relay, where traditionally many were required
    - low-level internal faults (turn-to-turn) covered, where traditionally had to rely on sudden pressure and/or Buchholz devices (overcurrent supervised)

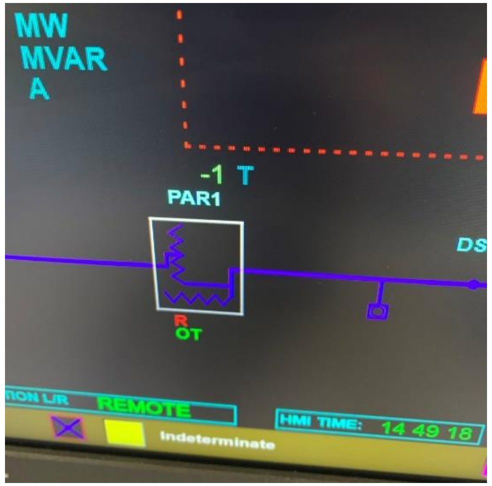
Customer: ConEd, NY, USA

- Energization of the PST - phase quantities
  - high DC offset and 2nd harmonic content in the source-side inrush currents – remained stable (no operation)



Customer: ConEd, NY, USA

PST's OLTC tap position on the substation HMI screen (tap 1 retard)



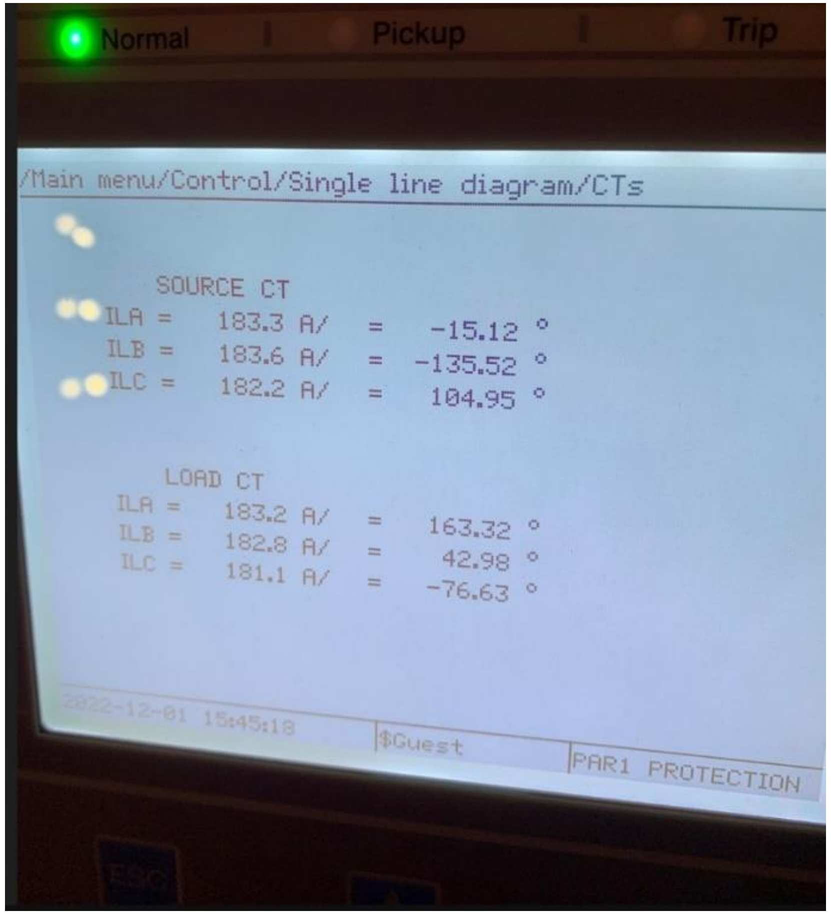
PST nameplate

	NA		NR		17
	N		N	0.0	K
	NR		NA		1
	1R		1A	-1.6	2
	2R		2A	-3.2	3
	3R		3A	-4.8	4
	4R		4A	-6.3	5
	5R		5A	-7.9	6
	6R		6A	-9.5	7
	7R		7A	-11.1	8
Retard	8R	Advance	8A	-12.6	9
	9R		9A	-14.2	10

L-side current will lag S-side current by 1.6°

S-side current into PST; L-side current from PST

Therefore IED perceived angle difference = 178.4° lead



PhaseA: 178.44°

PhaseB: 178.50°

PhaseC: 178.42°

Conclusions

- 87T for PST only requires one three-phase current set and at least one phase-to-ground voltage from each side of the protected PST – internally buried CTs within the protected PST tank are not required
- Position of any internal OLTC is not required
- 87T for PST is suitable for any PST regardless of its construction (symmetrical or asymmetrical; single-core or double-core) – protects the complete PST against all internal faults
- Transformation ratio and phase-angle shift are estimated on-line
- Typically, a minimum pickup of 20%, based on the PST rating, can be achieved for the differential protection
- Negative-sequence based differential protection provides additional sensitivity for low level turn-to-turn faults
- Possible to use 87T for PST on standard two-winding transformer with OLTC where compensation for tap position is required (traditionally accomplished by connecting tap position to the 87T function) – 87T for PST continuously calculates on-line the “Ratio” without requiring connection of tap position