# WHEN EXISTING RECOMMENDATIONS FOR PST PROTECTION CAN LET YOU DOWN

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## Abstract

The paper will present implemented protection scheme on two, symmetrical, double core design Phase Shifting Transformers (PST) [6], each rated at 600MVA, 400kV, 866A, 50Hz, ±40º with in total 64 tap positions (32 advance and 32 retard). Thus, every individual tap introduce phase angle shift of 1,25º.

The used PST protection scheme follows the protection recommendations published by IEEE [1]. It shall be noted that this IEEE recommendation is mainly based on information available in reference [2].

However during execution of this project new challenges were faced due to following reasons:

- Slightly different construction of PST
- Numerical differential relays are used instead of electro-mechanical ones originally suggested in [1,2]

Due to these differences this paper will:

- Indicate at which statements IEEE publication [1] is wrong due to slightly different PST design
- Provide design and setting guidelines for 87P and 87S functions when modern numerical transformer differential protection is used

## 1 Introduction

References [1] and [2] provide quite clear guidelines for protection scheme of symmetrical, double core PST design. However they are written more than ten years ago for a particular variant of double core PST design [6].

In reference [2] PST with the following rated data were used for most calculations: 450MVA, 345kV, 753A, 60Hz, ±25º with in total 32 tap positions (16 advance and 16 retard). Thus, every individual tap introduce phase angle shift of 1,56º.

It is obvious that new PST has much bigger number of tap positions. In principle this shall not influence the protection scheme because of the fact that proposed scheme in [1,2] do not need any tap changer information for its correct operation. However it will be shown that this statement is actually wrong! Thus even for symmetrical double core PST, the design of the protection scheme can actually be construction dependent!

Proposed protection scheme in [1] and [2] was based on two differential protection relays. The first differential relay (called primary protection system or 87P in [1,2]) is based on the first Kirchhoff's low. Thus in principle one can say that it is similar to the standard busbar or generator differential protection relay (i.e. 87B or 87G). This differential relay has three restraint inputs and measures three CT sets marked with numbers 1, 2 and 3 in Figure 1. Note that all three CT sets shall be star connected in accordance with [1,2].

The second differential relay (called secondary protection system or 87S in [1,2]) is based on the ampere-turn-balance between three windings existing inside of the series transformer. Thus, one can say that it is the same principle as used by the differential protection relays applied for standard power transformers (i.e. 87T). Ampere-turn-balance of the series transformer is used because this is the only transformer which has fixed number of turns in this type of PST design. The 87S differential relay has three restraint inputs and measures three CT sets marked with numbers 1, 2 and 4 in Figure 1. First two CT sets shall be delta connected in order to facilitate phase angle shift compensation and zero-sequence current reduction, while the third CT set is star connected in accordance with [1,2].

However it shall be noted that these two differential relays do not provide complete redundancy for each other. For example the 87P do not provide any protection for faults within the secondary winding of either series or exciting transformer. Therefore two additional ground fault overcurrent relays are suggested in the two star points of the exciting transformer [1,2]. Their pickup and time delay settings depend very much on particular PST construction details (e.g. three versus five limb core design, test winding arrangements, etc.).

Note that separate CT cores are required for these two differential relays because of the different main CT connections required on S- and L-side of the PST.

## 2 Influence of slightly different construction

First it shall be understood that voltage in the secondary, delta connected winding of the series transformer must be swopped (i.e. reversed for 180º) for advance and retard mode of PST operation. This swopping can be achieved in different ways

depending on particular construction details of each individual double core PST.
PST described in [1,2] had in total only 32 tap positions (16 advance and 16 retard). Thus, it was technically possible and most economical that this voltage reversal is integrated and performed within the on-load tap-changer itself, by reversing direction of current flow through the secondary winding of the exciting transformer. Therefore if one looks "from outside PST" such switching arrangement has effect of reversing a vector group connection of the exciting transformer from Yy0 to Yy6 for advance and retard operating modes respectively. Such switching has no influence on secondary differential relay which is based on ampere turn balance of the series transformer windings.
The PST used in our project has in total 64 tap positions (32 advance and 32 retard). Thus, it was not technically feasible to arrange this voltage reversal in the same way as in previous design. Instead an advance-retard (A/R) switch, a separate mechanical device from the on-load tap-changer itself, is located within connections towards the delta-connected winding of the series transformers (see Figure 1). Therefore if one looks "from outside PST" such switching arrangement has effect of reversing a vector group connection of the series transformer delta-connected winding from d3 to d9 (see the next section of the paper for more details regarding series transformer clock numbers) for advance and retard PST operating modes respectively. Such internal switching arrangement has great influence on the secondary differential relay which now needs extra facilities in order to remain stable due to this effective change of the protected transformer vector group during normal relay operation.
Additionally this internal PST switching is done in a quite special way. Namely all corners of the secondary, delta-connected winding of the series transformers are first temporary grounded (for couple of seconds) while this switching is performed. This corresponds to an intentional three-phase short circuit within the protected zone of the differential relay. Thus, the secondary differential protection relay will be entirely de-balanced during this "switching time" and its restraint stage must be completely blocked while the operation of the advance-retard switch is in progress.
To summarize: For this PST construction the secondary differential relay needs the following three external binary signals for its proper operation:

- Advance mode of PST operation
- Retard mode of PST operation
- Advance-retard switch operation is in progress

The first two binary signals are required in order to facilitate effective vector group change of the protected series transformer. This for example can be done by intentionally inverting (i.e. turning for 180º) individual phase currents measured in the exciting transformer secondary winding star point, during retard operating mode of the PST. Alternatively, some other way to facilitate the protected transformer vector group change can be engineered depending on a particular differential relay used in the project. The third binary signal shall be used in order to block the restraint stage of the secondary differential relay. Commissioning test shall be done in order to verify that this binary signal has good timing in comparison with operation of the primary contacts of this switch. If this is not the case some other alternative solution shall be arranged. It is strictly recommended to perform this "timing test" in both operating directions of the tap-changing sequence (i.e. from advance to retard mode and vice-versa). Note that operation of the advance-retard switch is done when on-load tap-changer is in middle (zero) position (i.e. for PST phase angle shift of zero degrees).

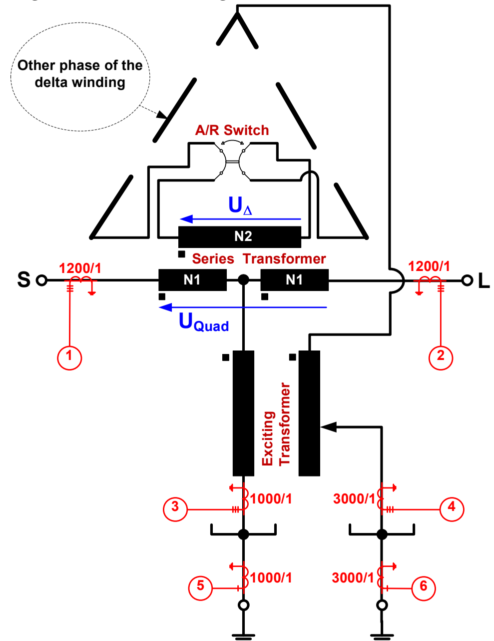


Figure 1: PST construction and CT information

## 3 Influence of numerical differential relays

References [1] and [2] are written for old electro-mechanical differential relays. All setting calculations for secondary differential relay is based on a k-factor (i.e. series unit turns ratio). This k-factor is defined in [1,2] as:

$$k = \frac{N1 + N1}{N2} = \frac{U_{Quad}}{U_{\Delta}} \qquad (1)$$

where N1 and N2 are exact turn numbers of the series transformer windings and $U_{Quad}$ and $U_{\Delta}$ are no-load voltages across series transformer windings. For exact definitions of all used symbols in Equation (1) see Figure 1.
Modern numerical differential relay for standard three-phase power transformers [3] typically requires only the rated data of the protected power transformer (i.e. rated apparent three-phase power, rated ph-to-ph voltage for each winding, rated phase current for each winding and power transformer vector group [5]) in order to automatically balance itself. Therefore in order to properly apply for example secondary differential protection for a PST application one now need to derive rated data of an equivalent three-phase power transformer which corresponds exactly to the series transformer used inside of the PST.

### 3.1 Solution for the primary differential protection 87P

Primary differential protection is based on the first Kirchhoff's low. However in practice very often standard differential protection for a three winding, three-phase power transformer is used instead. Therefore for relay setting values, one needs to enter data for "an equivalent three-phase power transformer". In this application one can easily check that the rated current of a PST on S- or on L-side is 866A at rated voltage of 400kV. That corresponds to 600MVA. Therefore rated data for "the equivalent three-winding, three-phase power transformer" are: 600MVA, 400/400/400kV; 686/686/686A, Yy0y0. All three CT sets shall be star-connected and typically stared towards the protected object as shown in Figure 1. Zero sequence current reduction shall be disabled on all three sides in order to maximize the sensitivity of the primary differential protection for internal ground faults. For one particular make of the numerical differential relay [3], actual setting parameters are given in Figure 2.

| T3D1 | | | |
|---|---|---|---|
| RatedVoltageW1 | | 400,00 | kV |
| RatedVoltageW2 | | 400,00 | kV |
| RatedVoltageW3 | | 400,00 | kV |
| RatedCurrentW1 | | 866 | A |
| RatedCurrentW2 | | 866 | A |
| RatedCurrentW3 | | 866 | A |
| ConnectTypeW1 | | WYE (Y) | |
| ConnectTypeW2 | | WYE (Y) | |
| ConnectTypeW3 | | WYE (Y) | |
| ClockNumberW2 | | 0 [0 deg] | |
| ClockNumberW3 | | 0 [0 deg] | |
| ZSCurrSubtrW1 | | Off | |
| ZSCurrSubtrW2 | | Off | |
| ZSCurrSubtrW3 | | Off | |

Figure 2: 87P Compensation settings for 600MVA PST

This paper will not go in more details regarding the pickup (i.e. operating characteristic) setting for the used 87P relay.

### 3.2 Solution for the secondary differential protection 87S

Secondary differential protection is based on the ampere-turn-balance between three windings installed around the magnetic core of the series transformer. In practice very often differential protection for a standard, three winding, three-phase power transformer is used for such application. Therefore as setting values, one needs to enter data of "an equivalent three winding, three-phase power transformer" for the PST series transformer. Let us assume that CT located in PST S-bushings are used for winding 1 (W1) input, CT located in PST L-bushings are used for winding 2 (W2) input and CT located in exciting transformer secondary winding star point are used for winding 3 (W3) input.

This equivalent transformer can be understood in an easiest way if one imagine a fictitious star point in the middle of the two 400kV windings of the series transformer (i.e. at the point where exciting transformer primary winding is connected). If this is done than the series transformer can be represented as a standard, three-winding, Yyd power transformer. Now only rated power, rated ph-to-ph voltages, rated phase currents and vector group numbers (i.e. clock numbers) shall be derived for such equivalent standard, three winding, three-phase power transformer.

The rated voltage of the two "y-connected", 400kV windings connected in series between S and L PST bushings can be calculated form PST rating data and maximum phase angle shift as follows:

$$U_{Quad} = \frac{400kV}{\sqrt{3}} * 2 * \sin\left(\frac{40^o}{2}\right) = 157,97kV \qquad (2)$$

Thus, the ph-to-gnd voltage of one star-winding will only be one half of this value (i.e. 78,99kV). The corresponding ph-to-ph voltage of the equivalent star connected winding will be $\sqrt{3}$ times bigger (i.e. $\sqrt{3}$*78,99kV=136,8kV ).

The rated voltage of the secondary delta-connected winding of the series transformer can be obtained in one of the following ways:

- By reading it from PST rating plate (if available)
- Calculated form $U_{Quad}$ by using k-factor (if available)

For this particular PST k-factor was available and it has value of 1,6156. Thus the ph-to-ph voltage for the delta winding can be calculated by using equation (1) as follows:

$$U_{\Delta} = \frac{157,97kV}{1,6156} = 97,8kV \qquad (3)$$

The rated power of the series transformer can be calculated from the PST rating data and maximum phase angle shift as follows:

$$S_{ST} = 600MVA * 2 * \sin\left(\frac{40^o}{2}\right) = 410,42MVA \qquad (4)$$

From this power value and available ph-to-ph voltages rated phase current for every winding can be calculated as follows:

$$I_{W1} = I_{W2} = \frac{410,42MVA}{\sqrt{3} * 136,8kV} = 1732A \qquad (5)$$

$$I_{W3} = \frac{410,42MVA}{\sqrt{3} * 97,8kV} = 2423A \qquad (6)$$

Note that rated current of the first two windings is exactly two times bigger than the PST rated current (i.e. 1732A=2*866A). The reason is that the calculated power of the series transformer (i.e. 410,42MVA) is actually only valid for the delta connected winding. Power from this delta-connected winding, splits into two equal parts which are then transferred into two primary "y-connected" windings (i.e. W1 and W2). Thus the two 400kV, series-connected windings are actually only thermally rated for one half of the total calculated power of the series transformer (4). However for the series transformer differential protection function the base is the maximum power among all three windings [4]!

Regarding the clock numbers one need the detail internal PST connections in order to derive them. However due to the fact that quadrature voltage (i.e. ±90º shift) is introduced by the series transformer, the vector group of this transformer shall reflect this fact and in practice typically is Yy6d9 for advance operating mode and Yy6d3 for retard mode of PST operation.

Therefore the data for "the equivalent three-winding, three-phase power transformer" of the series transformer is: 410,42MVA, 136,8/136,8/97,8kV; 1732A/1732A/2423A, Yy6d9 for this PST.

All three CT sets shall be star-connected and typically stared towards the protected transformer as shown in Figure 1. Zero sequence current reduction shall be enabled for two "y-connected" windings (i.e. W1 and W2) in order to prevent unwanted operation of the 87S differential protection for external ground faults in surrounding 400kV network. For one particular make of the numerical differential relay [3], actual setting parameters are given in Figure 3.

| T3D2 | | | |
|---|---|---|---|
| RatedVoltageW1 | | 136,80 | kV |
| RatedVoltageW2 | | 136,80 | kV |
| RatedVoltageW3 | | 97,80 | kV |
| RatedCurrentW1 | | 1732 | A |
| RatedCurrentW2 | | 1732 | A |
| RatedCurrentW3 | | 2423 | A |
| ConnectTypeW1 | | WYE (Y) | |
| ConnectTypeW2 | | WYE (Y) | |
| ConnectTypeW3 | | Delta (D) | |
| ClockNumberW2 | | 6 [180 deg] | |
| ClockNumberW3 | | 9 [90 deg lead] | |
| ZSCurrSubtrW1 | | On | |
| ZSCurrSubtrW2 | | On | |
| ZSCurrSubtrW3 | | Off | |

Figure 3: 87S Compensation settings for 600MVA PST

This paper will not go in more details regarding the pickup (i.e. operating characteristic) setting for the used 87S relay.

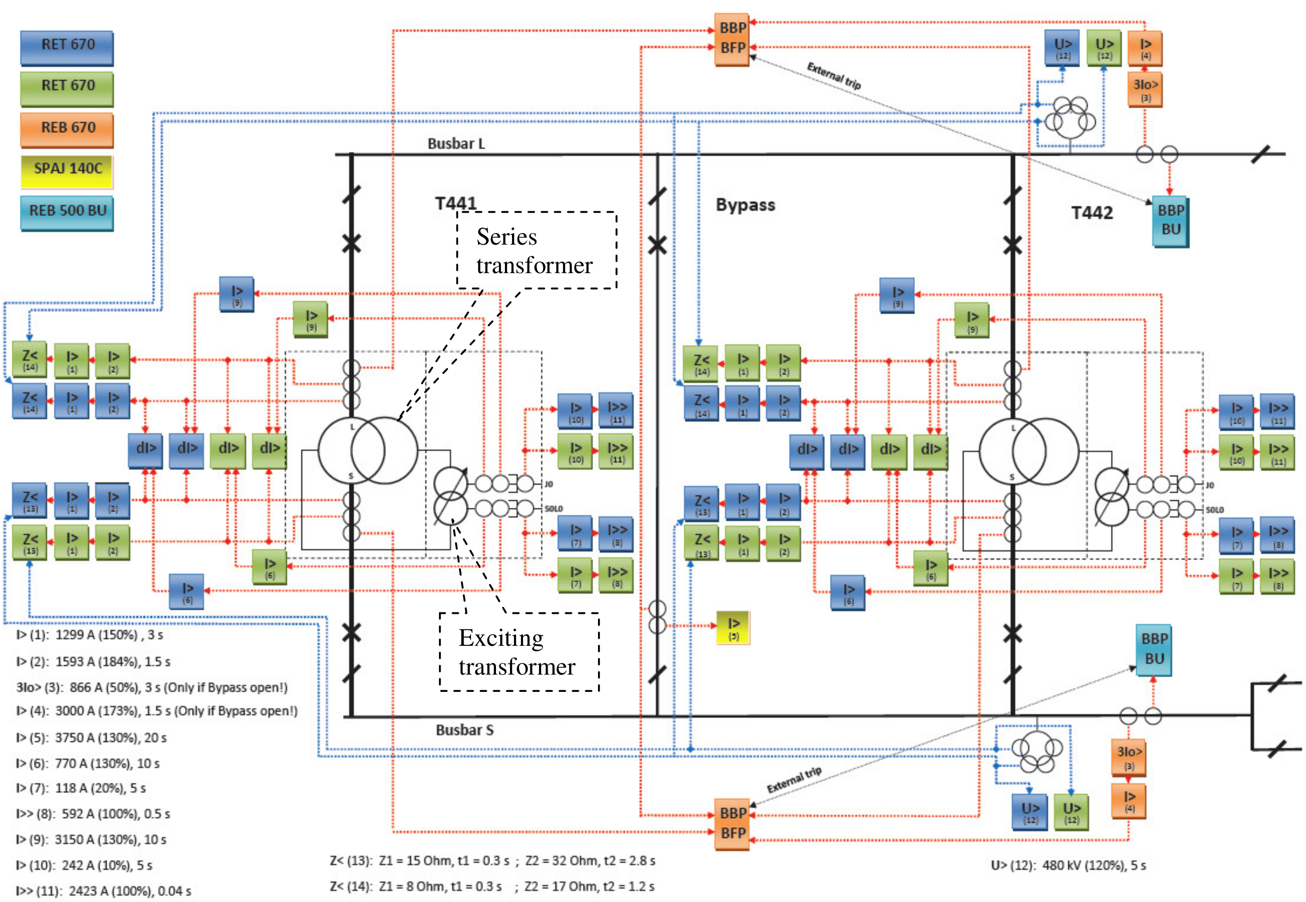


Figure 4: SLD and associated protection scheme for the two PSTs and associated bypass bay

## 4 Implemented protection scheme

Protection block diagram for the PST and associated bypass bay is shown in Figure 4. Due to processing capability of used numerical IED [3] complete protection scheme recommended by IEEE [1,2] (and even more) can be implemented with one IED only. The following functions are available in a single protection IED used in this PST installation:

- 87P differential protection
- 87S differential protection
- I> (1)&(2) S-side overcurrent protection
- I> (1)&(2) L-side overcurrent protection
- Z< (13) S-side underimpedance protection
- Z< (14) L-side underimpedance protection
- I> (6) HV-NP side overcurrent protection
- I> (9) LV-NP side overcurrent protection
- I> (7)&(8) HV-NP side earth-fault protection
- I> (10)&(11) LV-NP side earth-fault protection
- U>(12) S- and L-side overvoltage protection

Note that function symbols used in the above list correspond to symbols used in Figure 4. Actual function pickup values and set operating time delays are also given in Figure 4. Protection scheme redundancy is obtained by IED duplication. Thus, two IEDs with identical functionality, as listed above, are used on each PST (see Figure 4 for details).

## 5 Field recordings

This PST protection scheme is in full commercial operation on both PSTs since December 2010. Its operation is completely satisfactory. Due to limited space only one recording captured during the PST commissioning is presented in Figure 5. It shows process of changing the advance-retard switch position from retard to advance state. The following traces captured by IED are shown in Figure 5 (note that all shown currents are given in primary amperes):

a) CT1 (see Figure 1) three phase currents waveforms
b) CT2 (see Figure 1) three phase currents waveforms
c) CT3 (see Figure 1) three phase currents waveforms
d) CT4 (see Figure 1) three phase currents waveforms
e) 87P differential protection bias current and three-phase differential currents (RMS values)
f) 87S differential protection bias current and three-phase differential currents (RMS values)
g) Relevant binary signals (see section 2 of the paper)

The numbers from 1 to 8 added to Figure 5 indicates the most important events in this record. Their short description is:

1) In progress signal of the advance-retard switch appears and 87S protection is immediately blocked.
2) Indication that PST is in retard operating mode disappears
3) CT4 currents disappear (i.e. all corners of the series transformer delta winding are shorted to ground).
4) Without CT4 currents 87S protection is unbalanced and calculates false differential currents but it is already blocked and do not cause unwanted tripping of the PST.
5) After few seconds CT4 currents reappear again.
6) 87S protection still calculates false differential currents due to a fact that vector group of series transformer have been changed by the advance-retard switch operation!
7) Indication that PST is in advance operating mode appears.
8) CT4 currents are now intentionally inverted in the IED software which causes proper differential current calculation within 87S function. After that point 87S trip signal can be enabled again.

This record clearly indicates all points discussed in Section 2. At the same time it confirms that 87S differential protection is properly set for this PST. Note the following facts:

- Record is 11s long
- Advance-retard switch operation takes about 9,5s
- CT1 and CT2 currents do not change at all during this record
- CT3 currents are practically zero because PST has 0º phase angle shift (OLTC is in middle position)
- 87P differential protection is not affected at all during these events.

## 6 Conclusion

Existing recommendation for PST protection shall be used wisely. If on the contrary they are followed blindly one can be very much surprised when troubles are encountered during PST commissioning or even PST operation.
The paper also provides guidance how to set modern numerical 87T differential relays for dual core PST 87P and 87S differential applications.

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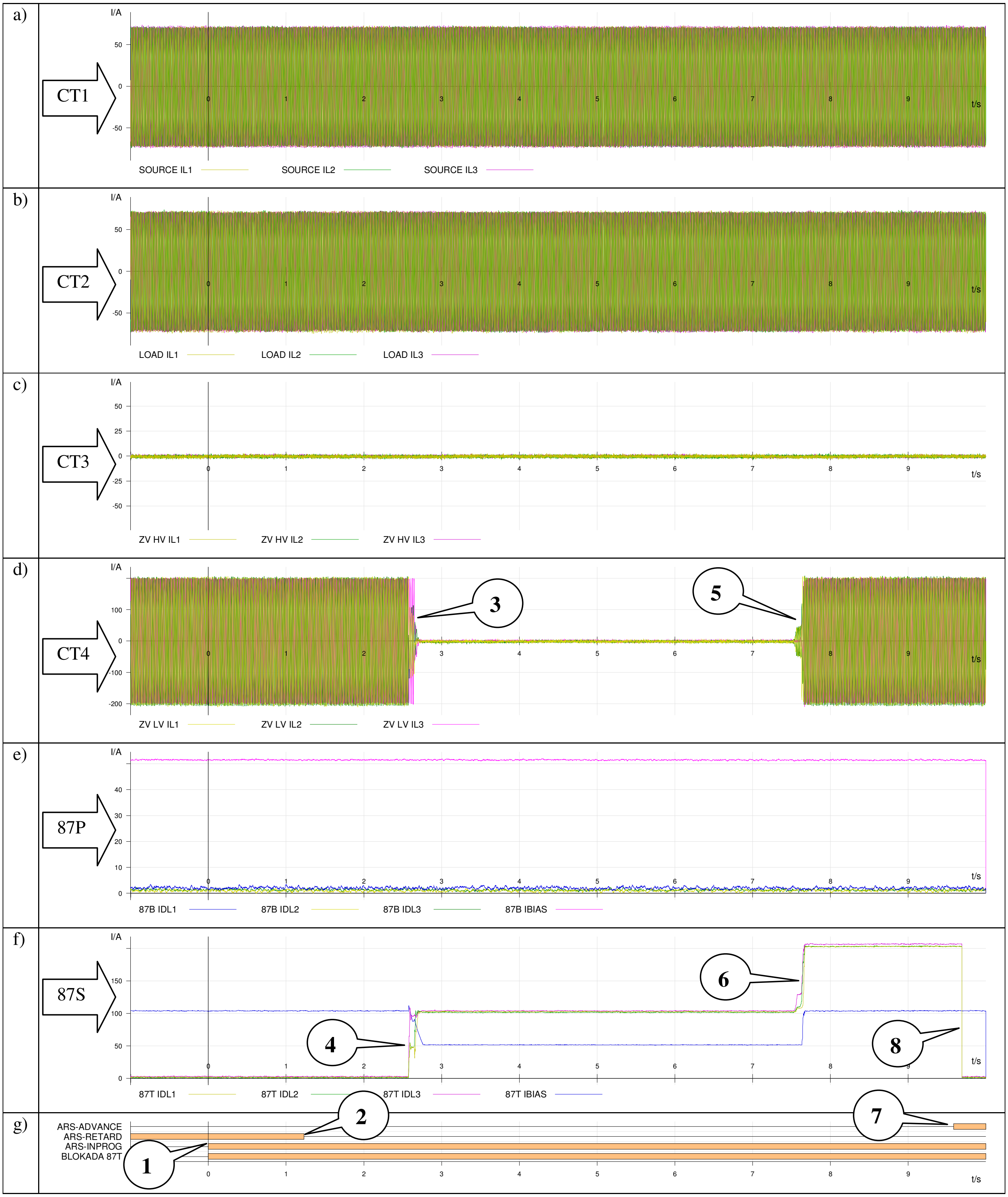


Figure 5: DR captured by the IED under operation of advance/retard switch during PST commissioning