Relay Protection and Substation Automation of Modern Power Systems
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S1-7: New and re-discovered theories and practices in relay protection

Differential protection solution for arbitrary phase shifting transformer

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Introduction

Diverse differential protection schemes for Phase Shifting Transformers (PST) [5] are presently used. These schemes tend to be dependent on the particular construction details and maximum phase angle shift of the protected PST [3] and [4]. A special report has been written by IEEE-PSRC which describes possible protection solutions for typical PST applications [4]. There it is indicated that the standard transformer differential protection relays can not be used due to variable phase angle shift across the PST.

Thus, if a numerical power transformer differential relay is directly applied for the differential protection of a PST, and set for Yy0 vector group compensation, the differential relay will not be able to compensate for variable phase angle shift Θ caused by PST's on-load tap-changer (i.e. OLTC) operation. As result a false differential current would exist which will vary in accordance with the coincident PST phase angle shift. However, in this paper it will be shown that with use of numerical technology it is actually possible to apply the standard power transformer differential protection for PST protection in accordance with Figure 1.

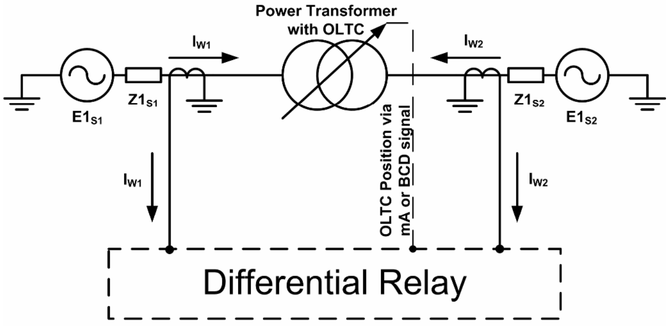


Figure 1: Typical connections for new PST differential relay

New Differential Protection Solution for PST

In order to apply the standard numerical transformer differential protection on a PST, in accordance with Figure 1, the following compensation shall be provided:

- primary current magnitude difference on different sides of the protected PST (i.e. current magnitude compensation);
- phase angle shift difference across PST (i.e. phase angle shift compensation); and

- zero sequence current elimination (i.e. if zero sequence current is not properly transferred across the PST).

Current Magnitude Compensation

In order to achieve the current magnitude compensation, the individual phase currents must be normalized on each transformer side (e.g. Source and Load side in case of PST [5]) by dividing them with the base current. Base current in primary amperes has a value, which can be calculated for each transformer side as:

$$I_{Base\_Wi} = \frac{Sr_{\max}}{\sqrt{3} \cdot Ur_{Wi}} \qquad (1.1)$$

where:

- I_{Base_Wi} is winding i base current in primary amperes
- S_{rMax} is the maximal rated apparent power of the protected transformer or PST
- U_{rWi} is winding i rated phase-to-phase no-load voltage (i=1 or 2 for a PST)

Note that depending on PST construction (e.g. symmetrical or asymmetrical) U_{rWi} might have different values for different OLTC positions on one or even both sides of the protected PST. In such case the base current will have different values on that side of the protected PST for different OLTC positions as well. Thus, a different I_{Base} value shall be used for every OLTC position in order to correctly compensate for winding current magnitude variations caused by OLTC operation. Once this normalization of the measured phase currents is performed, the phase currents from the two sides of the protected PST are converted to the same per unit scale and can be used to calculate the differential currents.

Note that the base current in equation (1.1) is in primary amperes. Differential relays may use currents in secondary amperes to perform their algorithm. In these circumstances, the base current in primary amperes obtained from equation (1.1), shall be converted to the CT secondary side by dividing it by the ratio of the main current transformer located on that PST side.

Phase Angle Shift Compensation

In this section it will be assumed that current magnitude compensation of individual phase currents from the two PST sides has been performed. Hence, only the procedure for phase angle shift compensation will be presented.

The common characteristic for all types of three-phase power transformers is that they introduce the phase angle shift Θ between winding 1 and winding 2 sides no-load voltages. The only difference between standard power transformer and a PST is that:

- Standard three-phase power transformer introduces a fixed phase angle shift Θ of $n*30^o$ (n=0, 1, 2, …, 11) between its terminal no-load voltages (i.e. $\Theta=150^o$ for Yd5 connected transformer)
- Phase shifting transformer introduce a variable phase angle shift Θ between its terminal no-load voltages (e.g. 0º - 18º in thirty-two steps of 0.6º, as shown in Figure 4a)

As shown in reference [1], strict rules do exist for the phase angle shift between sequence components of the no-load voltage from the two sides of the power transformer or PST, as shown in Figure 2, but not for individual phase voltages from the two sides of the transformer.

As shown in Figure 2 the following will hold true for the positive, negative and zero sequence no-load voltage components:

- the positive sequence no-load voltage component from winding 1 side will lead the positive sequence no-load voltage component from winding 2 side by angle Θ;
- the negative sequence no-load voltage component from winding 1 side will lag the negative sequence no-load voltage component from winding 2 side by angle Θ; and
- the zero sequence no-load voltage component from winding 1 side will be exactly in phase with zero sequence no-load voltage component from winding 2 side, when zero sequence no-load voltage components are at all transferred across the transformer.

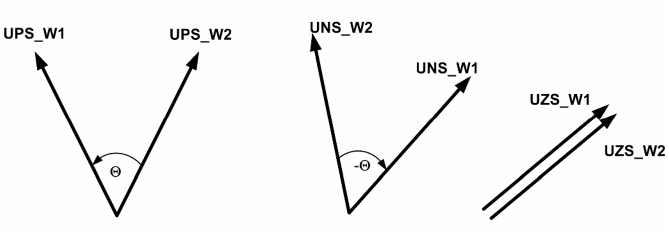
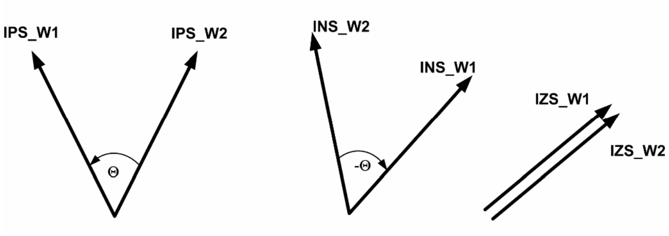


Figure 2: Phasor diagram for no-load positive, negative and zero sequence
voltages components from the two sides of the power transformer

However, as soon as the power transformer is loaded, this voltage relationship will not longer be valid, due to the voltage drop across the power transformer impedance. However it can be shown that the same phase angle relationship, as shown in Figure 2, will be valid for sequence current components, as shown in Figure 3, which flow into the power transformer on winding 1 side and flow out from the power transformer on winding 2 side [1]. As shown in Figure 3, the following will hold true for the sequence current components from the two power transformer sides:

- the positive sequence current component from winding 1 side will lead the positive sequence current component from winding 2 side by angle Θ (same relationship as for positive sequence no-load voltages);
- the negative sequence current component from winding 1 side will lag the negative sequence current component from winding 2 side by angle Θ (same relationship as for the negative sequence no-load voltages); and
- the zero sequence current component from winding 1 side will be exactly in phase with the zero sequence current component from winding 2 side, when zero sequence current components are at all transferred across the transformer (same relationship as for the zero sequence no-load voltages).



Figur 3: Phasor diagram for positive, negative and zero sequence
current components from the two sides of the loaded power transformer

For transformer differential protection, currents from all sides of the protected transformer are typically measured with the same reference direction towards the protected object (see Figure 1). From this point, all equations will be written for the current reference direction as shown in Figure 1.

From the rules stated above the sequence differential currents for a PST or a power transformer can be calculated with following equations (note new current reference directions as shown in Figure 1):

$$Id\_PS = IPS\_W1 + e^{j\Theta} \cdot IPS\_W2 \qquad (1.2)$$ (the positive sequence differential current)

$$Id\_NS = INS\_W1 + e^{-j\Theta} \cdot INS\_W2 \qquad (1.3)$$ (the negative sequence differential current)

$$Id\_ZS = IZS\_W1 + IZS\_W2 \qquad (1.4)$$ (the zero sequence differential current)

By using the basic relationship between sequence and phase quantities given in reference [2] the following relationship can be written for phase-wise differential currents:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = A \cdot \begin{bmatrix} IZS\_W1 \\ IPS\_W1 \\ INS\_W1 \end{bmatrix} + A \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{j\Theta} & 0 \\ 0 & 0 & e^{-j\Theta} \end{bmatrix} \cdot \begin{bmatrix} IZS\_W2 \\ IPS\_W2 \\ INS\_W2 \end{bmatrix} \tag{1.5}$$

where:

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{1.6}$$

$$a = e^{j120^\circ} = cos(120^\circ) + j \cdot sin(120^\circ) = -\frac{1}{2} + j \cdot \frac{\sqrt{3}}{2} \tag{1.7}$$

After some mathematical derivations it can be shown that the following will hold true:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = M(0^\circ) \cdot \begin{bmatrix} IL1\_W1 \\ IL2\_W1 \\ IL3\_W1 \end{bmatrix} + M(\Theta) \cdot \begin{bmatrix} IL1\_W2 \\ IL2\_W2 \\ IL3\_W2 \end{bmatrix} \tag{1.8}$$

where matrix transformation M(Θ) is defined by:

$$\text{M}(\Theta) = \frac{1}{3} \cdot \begin{bmatrix} 1+2 \cdot cos(\Theta) & 1+2 \cdot cos(\Theta+120^\circ) & 1+2 \cdot cos(\Theta-120^\circ) \\ 1+2 \cdot cos(\Theta-120^\circ) & 1+2 \cdot cos(\Theta) & 1+2 \cdot cos(\Theta+120^\circ) \\ 1+2 \cdot cos(\Theta+120^\circ) & 1+2 \cdot cos(\Theta-120^\circ) & 1+2 \cdot cos(\Theta) \end{bmatrix} \tag{1.9}$$

Note that Θ is the angle for which the winding two side positive sequence, no-load voltage component shall be rotated in order to overlay with the positive sequence, no-load voltage component from winding one side. Angle Θ has a positive value when rotation is in an anticlockwise direction. Refer to Figure 2 for more information. The M(0^o) is a unit matrix, which can be assigned to the first power transformer winding which is taken as reference for phase angle compensation (i.e. the other winding currents are aligned with the first side currents).

Zero Sequence Current Compensation

Sometimes it is necessary to remove the zero sequence current component from one or possibly both sides of the protected PST because the zero sequence current is not properly transferred from one side of the transformer to the other. This can be simply provided by subtracting the zero sequence current component from three phase currents on that PST side, as shown in equation (1.10).

New Differential Protection Method

If now all compensation techniques described in previous three sections are combined in one equation, the following general equation for differential current calculations for any power transformer or PST, in accordance with Figure 1, can be written:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{I_{Base\_W1}} \cdot M(0^\circ) \cdot \begin{bmatrix} IL1\_W1 - k_{w1} \cdot I_0\_W1 \\ IL2\_W1 - k_{w1} \cdot I_0\_W1 \\ IL3\_W1 - k_{w1} \cdot I_0\_W1 \end{bmatrix} + \frac{1}{I_{Base\_W2}} \cdot M(\Theta) \cdot \begin{bmatrix} IL1\_W2 - k_{w2} \cdot I_0\_W2 \\ IL2\_W2 - k_{w2} \cdot I_0\_W2 \\ IL3\_W2 - k_{w2} \cdot I_0\_W2 \end{bmatrix} \tag{1.10}$$

where:

- I_0_W1 is zero sequence current component on side 1 of the protected object
- I_0_W2 is zero sequence current component on side 2 of the protected object
- k_{w1} and k_{w2} are setting parameters which can have values 1 or 0 and are set by the end user to enable/disable the zero sequence current reduction on any of the two sides.

Note that the elements of M(Θ) matrix are always real numbers. Therefore, the presented differential method can be used to calculate the fundamental frequency phase-wise differential currents, the sequence-wise differential currents and the instantaneous differential currents [7].

Application Examples

Differential protection applications for two most commonly used PST arrangements, as well as for symmetrical and asymmetrical PST designs [5], are presented in the following two paragraphs. However, note that this method can be applied to any other PST regardless its construction details.

Asymmetrical, dual-core PST

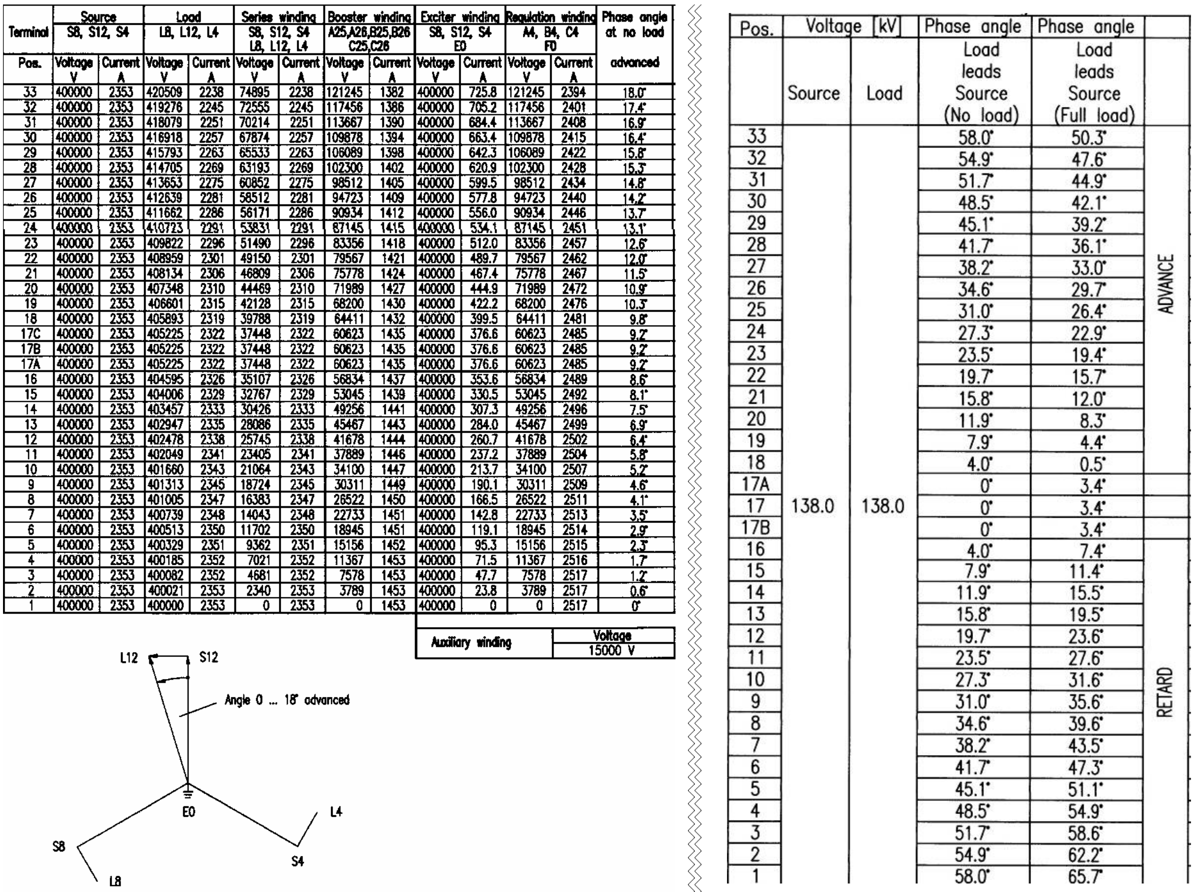
In this example the application of the transformer differential protection method will be illustrated for an actual 1630MVA; 400kV; +18°; 50Hz PST of asymmetric, two-core design. This type of PST is also known as the Quad Booster [5]. For such an asymmetric PST design, the base current and the phase angle shift are functions of OLTC position. All necessary information for application of the differential protection method can be obtained directly from the PST nameplate. A relevant part of PST name plate is shown in Figure 4a.

The first column in Figure 4a represents available OLTC positions, in this case 33. From column three it is obvious that the base current for PST Source side is constant for all positions and has a value of 2353A. Column five in Figure 4a gives the base current variation for PST Load side. Finally the last (i.e. fourteenth) column in Figure 4a shows how the no-load phase angle shift varies across the PST for different OLTC positions. Note that the phase angle shift on the PST name plate is given as a positive value when the load side positive sequence, no-load voltage leads the source side positive sequence, no-load voltage [5] (i.e. advanced mode of operation). Therefore if the phase shift from Figure 4a is associated with the load side (i.e. source side taken as reference side for phase angle compensation) the angle values from the name plate must be taken with the minus sign (see vector diagram in Figure 4a).

This particular PST has a five-limb core construction for both internal transformers (i.e. serial and excitation transformer). Therefore the zero sequence current will be properly transferred across PST and zero sequence current elimination is not required on any side. Thus, for every OLTC position, the appropriate equation for differential current calculation, in accordance with equation (1.10), can now be written. The equation for OLTC position 30 will only be presented here:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{2353} \cdot M(0°) \cdot \begin{bmatrix} I_{L1\_S} \\ I_{L2\_S} \\ I_{L3\_S} \end{bmatrix} + \frac{1}{2257} \cdot M(-16.4°) \cdot \begin{bmatrix} I_{L1\_L} \\ I_{L2\_L} \\ I_{L3\_L} \end{bmatrix} \tag{2.1}$$

In a similar way this matrix equation can be written for any OLTC position if appropriate values from Figure 4a are given for the base current and the phase angle shift on the load side of the PST.



Terminal	Source S8, S12, S4		Load L8, L12, L4		Series winding S8, S12, S4 L8, L12, L4		Booster winding A25,A26,B25,B26 C25,C26		Exciter winding S8, S12, S4 E0		Regulation winding A4, B4, C4 F0		Phase angle at no load
Pos.	Voltage V	Current A	Voltage V	Current A	Voltage V	Current A	Voltage V	Current A	Voltage V	Current A	Voltage V	Current A	advanced
33	400000	2353	420509	2238	74895	2238	121245	1382	400000	725.8	121245	2394	18.0°
32	400000	2353	419276	2245	72555	2245	117456	1386	400000	705.2	117456	2401	17.4°
31	400000	2353	418079	2251	70214	2251	113667	1390	400000	684.4	113667	2408	16.9°
30	400000	2353	416918	2257	67874	2257	109878	1394	400000	663.4	109878	2415	16.4°
29	400000	2353	415793	2263	65533	2263	106089	1398	400000	642.3	106089	2422	15.8°
28	400000	2353	414705	2269	63193	2269	102300	1402	400000	620.9	102300	2428	15.3°
27	400000	2353	413653	2275	60852	2275	98512	1405	400000	599.5	98512	2434	14.8°
26	400000	2353	412639	2281	58512	2281	94723	1409	400000	577.8	94723	2440	14.2°
25	400000	2353	411662	2286	56171	2286	90934	1412	400000	556.0	90934	2446	13.7°
24	400000	2353	410723	2291	53831	2291	87145	1415	400000	534.1	87145	2451	13.1°
23	400000	2353	409822	2296	51490	2296	83356	1418	400000	512.0	83356	2457	12.6°
22	400000	2353	408959	2301	49150	2301	79567	1421	400000	489.7	79567	2462	12.0°
21	400000	2353	408134	2306	46809	2306	75778	1424	400000	467.4	75778	2467	11.5°
20	400000	2353	407348	2310	44469	2310	71989	1427	400000	444.9	71989	2472	10.9°
19	400000	2353	406601	2315	42128	2315	68200	1430	400000	422.2	68200	2476	10.3°
18	400000	2353	405893	2319	39788	2319	64411	1432	400000	399.5	64411	2481	9.8°
17C	400000	2353	405225	2322	37448	2322	60623	1435	400000	376.6	60623	2485	9.2°
17B	400000	2353	405225	2322	37448	2322	60623	1435	400000	376.6	60623	2485	9.2°
17A	400000	2353	405225	2322	37448	2322	60623	1435	400000	376.6	60623	2485	9.2°
16	400000	2353	404595	2326	35107	2326	56834	1437	400000	353.6	56834	2489	8.6°
15	400000	2353	404006	2329	32767	2329	53045	1439	400000	330.5	53045	2492	8.1°
14	400000	2353	403457	2333	30426	2333	49256	1441	400000	307.3	49256	2496	7.5°
13	400000	2353	402947	2335	28086	2335	45467	1443	400000	284.0	45467	2499	6.9°
12	400000	2353	402478	2338	25745	2338	41678	1444	400000	260.7	41678	2502	6.4°
11	400000	2353	402049	2341	23405	2341	37889	1446	400000	237.2	37889	2504	5.8°
10	400000	2353	401660	2343	21064	2343	34100	1447	400000	213.7	34100	2507	5.2°
9	400000	2353	401313	2345	18724	2345	30311	1449	400000	190.1	30311	2509	4.6°
8	400000	2353	401005	2347	16383	2347	26522	1450	400000	166.5	26522	2511	4.1°
7	400000	2353	400739	2348	14043	2348	22733	1451	400000	142.8	22733	2513	3.5°
6	400000	2353	400513	2350	11702	2350	18945	1451	400000	119.1	18945	2514	2.9°
5	400000	2353	400329	2351	9362	2351	15156	1452	400000	95.3	15156	2515	2.3°
4	400000	2353	400185	2352	7021	2352	11367	1453	400000	71.5	11367	2516	1.7°
3	400000	2353	400082	2352	4681	2352	7578	1453	400000	47.7	7578	2517	1.2°
2	400000	2353	400021	2353	2340	2353	3789	1453	400000	23.8	3789	2517	0.6°
1	400000	2353	400000	2353	0	2353	0	1453	400000	0	0	2517	0°

Auxiliary winding	Voltage
	15000 V

Pos.	Voltage [kV]		Phase angle	Phase angle	
	Source	Load	Load leads Source (No load)	Load leads Source (Full load)	
33	138.0	138.0	58.0°	50.3°	ADVANCE
32			54.9°	47.6°	
31			51.7°	44.9°	
30			48.5°	42.1°	
29			45.1°	39.2°	
28			41.7°	36.1°	
27			38.2°	33.0°	
26			34.6°	29.7°	
25			31.0°	26.4°	
24			27.3°	22.9°	
23			23.5°	19.4°	
22			19.7°	15.7°	
21			15.8°	12.0°	
20			11.9°	8.3°	
19			7.9°	4.4°	
18			4.0°	0.5°	
17A			0°	3.4°	
17			0°	3.4°	
17B			0°	3.4°	
16			4.0°	7.4°	RETARD
15			7.9°	11.4°	
14			11.9°	15.5°	
13			15.8°	19.5°	
12			19.7°	23.6°	
11			23.5°	27.6°	
10			27.3°	31.6°	
9			31.0°	35.6°	
8			34.6°	39.6°	
7			38.2°	43.5°	
6			41.7°	47.3°	
5			45.1°	51.1°	
4			48.5°	54.9°	
3			51.7°	58.6°	
2			54.9°	62.2°	
1			58.0°	65.7°	

a) Asymmetrical, dual-core PST

b) Symmetrical, single-core PST

Figure 4: Name Plates for two presented PSTs

Symmetrical, single-core PST

In this example the application of the transformer differential protection method will be illustrated for an actual 450MVA; 138kV; ±58^{o}; 60Hz PST of symmetric, single-core design [5]. For symmetric PST design, only the phase angle shift is a function of the OLTC position. The base power for this PST is 450MVA, and against this value the base primary current is calculated and it has a value of 1883A on both PST sides. All necessary information for the application of the method can be obtained directly from the PST nameplate, a part of which is shown in Figure 4b. The first column in Figure 4b represents available OLTC positions, in this case 33. The fourth column in Figure 4b shows how the no-load voltage phase angle shift varies across the PST for different OLTC positions. Note that the no-load phase angle shift shall be used for differential protection phase angle compensation and not a phase angle shift under load conditions which is given in column five. The no-load phase angle shift is associated with the Load side (i.e. Source side taken as reference side for phase angle compensation). Thus, the angle values from the name plate must be taken with the minus sign for advanced mode [5]. This particular PST has no internal grounding points, thus the zero sequence current will be properly transferred across the PST, and zero sequence current elimination is not required on any side. For every OLTC position the appropriate equation for differential current calculation can now be written in accordance with equation (1.10). The equation for the OLTC position 8 (i.e. retard mode) will only be presented here:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{1883} \cdot M(0°) \cdot \begin{bmatrix} I_{L1\_S} \\ I_{L2\_S} \\ I_{L3\_S} \end{bmatrix} + \frac{1}{1883} \cdot M(34.6°) \cdot \begin{bmatrix} I_{L1\_L} \\ I_{L2\_L} \\ I_{L3\_L} \end{bmatrix} \qquad (2.2)$$

In a similar way this equation can be written for any OLTC position if appropriate angle values from Figure 4b are given to M matrix transformation on the Load side of the PST.

Testing of the proposed method

In this section the disturbance files from two identical PSTs positioned at the beginning of two parallel 380kV overhead lines (OHL) are presented. The two PSTs are of asymmetrical type, dual core design. The ratings of the PST are listed below:

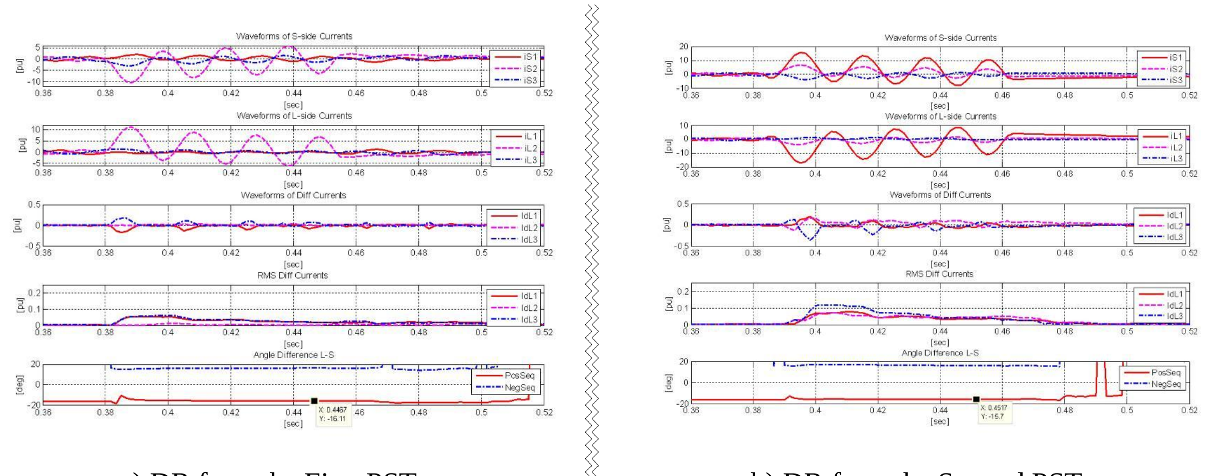
- Rated power: 1630 MVA;
- Rated voltages: 400/400 kV;
- Frequency: 50 Hz;
- Angle variation: 0º - 18º (at no-load)

and a part of their nameplate is shown in Figure 4a. More information about this PST is given in section “Asymmetrical, dual-core PST” above.

The captured incident involved two simultaneous single phase to ground faults. On OHL #1 it was a phase L2 to ground fault and on OHL #2 it was a phase L1 to ground fault. Existing protection schemes on both PSTs maloperated during this incident, the first by operation of Buchholz relay due to tank vibrations and the second by operation of the existing differential protection relay. The OLTC was on position 30 when the faults occurred (corresponds to phase angle shift of 16.4^o), thus the equation (2.1) shall be used to calculate the differential currents in accordance with the new method.

The captured recordings were made by two existing numerical differential relays having sampling rates of twelve samples per power system cycle. The S-side and L-side currents recorded by the relay were run in the MATLAB model of the new differential protection. In Figures 5a and 5b the following traces, either extracted or calculated from this DR files, are presented:

- PST Source-side individual phase current waveforms in pu;
- PST Load-side individual phase current waveforms in pu;
- Instantaneous differential current waveforms calculated by the new method in pu;
- RMS values of differential currents calculated by the new method in pu; and
- Calculated phase angle difference between positive and negative sequence current components from the two PST sides (see Figure 3 for more information).



a) DR from the First PST

b) DR from the Second PST

Figure 5: Evaluation of DR files for two asymmetrical, dual-core PSTs

Two figures show that for this heavy external fault the differential current RMS values remains within 0,15pu (i.e. 15%) of the PST rating for both transformers, indicating that the new differential relays will remain completely stable during this special external fault. The measured phase angle shift of 16.1^o corresponds well with actual shift angle and confirms the rules stated in Figure 3.

Conclusion

The equation (1.10) represents the general method to calculate the differential currents for any phase shifting transformer. This equation can be used to calculate differential currents, in accordance with Figure 1, for any PST with arbitrary phase angle shifts and current magnitude variations. The presented method provides clear relationship between sequence and phase current quantities for any PST or power transformer. By using this method the differential protection for any PST will be ideally balanced for all symmetrical and non-symmetrical through-load conditions and external faults irrespective of actual PST construction details and OLTC position. This differential protection method shall eliminate any need for buried current transformers within PST tank as usually required by presently used PST differential protection schemes [4]. Note that inrush and overexcitation stabilization (e.g. 2nd and 5th harmonic blocking) is still required for such differential protection.

However, this method is dependent on the correct information regarding actual PST OLTC position. The on-line OLTC position reading and compensation for phase current magnitude variations caused by OLTC movement has been used for standard numerical transformer differential protection relay [6] since 1998. This approach has shown an excellent track record and is the de-facto industry standard in many countries. In this paper the feasibility of advanced on-line compensation for variable phase angle shift across a PST has been demonstrated. Thus, by using the numerical technique the differential protection for arbitrary PST can be provided in accordance with Figure 1. By doing so, simple but effective differential protection for PSTs can be achieved, which is exactly the same as the already well-established numerical differential protection schemes for standard power transformers [6], [7]. The only difference is that elements of $M(\Theta)$ matrix used to provide phase angle shift compensation shall not be fixed, but instead calculated on-line based on actual OLTC position by using equation (1.9). Due to the relatively slow operating sequence of the OLTC, these matrix elements can be computed within the differential relay on a slow cycle (e.g. once per second). This method has been extensively tested by using disturbance files captured in actual PST installations and RTDS simulations based on practical PST data. All tests indicate excellent performance of this method for all types of external and internal faults. Previous publications regarding such differential protection could not be found. Thus, it seems that this work is unique and completely new in the field of protective relaying for phase shifting transformers. The presented differential method can also be used to check the output calculations from any short circuit and/or load flow software packages for power systems which incorporate arbitrary power transformers and/or PSTs.

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