ON-SITE TESTING OF SPECIAL TRANSFORMERS

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Abstract

The increased usage of the phase shifting transformers in various fields within power systems has introduced new challenges in performing on-site maintenance testing. These special transformers were used as converter transformers, rectifier transformers, harmonic mitigating transformers, zigzag transformers and quadrature boosters with unconventional vector groups, having an additional phase shift such as +/-7.5^0, +/-15^0 combined with normal 'Delta and Star' configurations. The challenges now faced by the increased use of these transformers are testing them for accuracy on the voltage ratio and phase shift at site during commissioning and maintenance. Different test methods were performed / studied and were compared. A prototype of a three-phase converter transformer with variable ratio taps and vector groups was constructed and tested. The prototype transformer is constructed to have variable parameters for test trials on different vector groups and ratios. The three phase converter transformer prototype will have options to regulate the output voltage on varying input voltage using the tap changer and also can vary the phase shift by varying the vector group combinations. On-site testing of ratio and phase shift will be done on different types of traction rectifier transformers. The approach for factory testing and onsite testing of the special transformers will be different. The effect on the phase shift values when the ratio taps are changed will be the focus and the results compared. The study on the importance of phase shift on these special transformers is presented. The test results of different test methods using modern portable test equipment and conventional classical methods were compared and presented. The results of the ratio testing and the phase shift measurement variation during vector group variation and tap change were presented.

1 Introduction

A Phase shifting transformer is a generic name for a wide range of applications. The most common types are rectifier transformers, converter transformers, harmonic mitigating transformers, zigzag transformers and quadrature boosters. Though the applications are totally different on the mentioned transformer types, one feature – unconventional phase shifting was the key design change that deviates from the classical power and auto transformers. The classical three phase vector group combinations using delta and star connections were further modified by different internal connection arrangements to achieve these unconventional phase shift values like +/-7.5^0, +/-15^0, +/-22^0, and so on. The connection types to achieve these phase shift variations are polygon or extended delta connection arrangements. These connection arrangements become complex when included with tap change arrangements on the primary winding.

Classical transformer testing involves ratio testing, excitation current testing, winding resistance testing, core balance testing, vector group check, Tan delta testing for Insulation, oil BDV tests, Dissolved Gas Analysis, and so on. Advanced tests like Frequency Response Analysis and Frequency Dielectric Spectrum for moisture analysis are the few other tests done by high powered transformer owners. Testing the ratio and verifying the vector group involves different test methods and is conventionally done by applying a single phase low voltage on primary and measuring the secondary voltages. For verifying vector groups, the like-phase short circuit between primary and secondary windings was the usual method along with manual calculations to verify. This method will be too complex when it comes to these special transformers and methods like three phase voltage source method and expensive power analyser usage becomes mandatory. Testing these transformers on-site during commissioning and periodic maintenance can be a laborious process and could be performed by different methods by different organisations. Standard single phase ratio testers were the solution for many years to perform ratio testing in a simplistic manner at site. The demand on these ratio testers increased to offer features like excitation current values, three phase and multi-tap values, phase angle values, automatic vector group recognition and so on. The phase shift measuring feature was in big demand by special transformer maintenance teams. The focus turned onto the phase shift and its importance in these transformers.

The special transformer application and the role of phase shifting feature in those transformers will be explained. This paper considers the concept of ratio testing, results of a site test, and tests performed on a prototype special transformer will be discussed. The effect of phase shift errors and the reality of phase shift values in HV transformers during tap change will be presented.

2 Special transformer applications

Special transformers are used on a wide range of applications. The most common types are converter transformers, rectifier transformers, harmonic mitigating transformers, zigzag transformers, phase angle regulators, and quadrature boosters. Converter transformers or rectifier transformers feed a 12 or 24 or 36 pulse converter or rectifier unit using multiple internally phase shifted transformers. Combination of these transformers feed the converters thereby reducing the harmonics on the source. Converter transformers or rectifier transformers are used on Traction stations, HVDC converter stations, Aluminium smelters and so on. Quadrature boosters are special transformers used for Power Flow Control on EHV transmission systems. The power flow control is achieved by varying the phase angle between the sending end and receiving end voltage [1]. The harmonic mitigating transformers are transformers used on LV systems that feed Variable Feed Drives, Motor controllers, Switched power sources and so on.

Phase shifting plays vital role in all the above mentioned applications. The phase shift between primary and secondary, phase shift between two windings of a three winding transformer or variable phase shifts may be the feature utilised to achieve the application. The cross-winding configurations of the transformer create these flexible phase shift values. The phase shifts used by these multi winding converter transformers depends on the number of pulses designed for the rectifier or converter. The different vector groups that are in the market of converter transformers for different pulse requirements are listed below [2]:
6 - Pulse: Dyn11
12 - Pulse: Dyn11d0
18 - Pulse: 1 x Dyn11; 1 x D(+10°)yn11; 1 x D(-10°)yn11
24 - Pulse: 1 x D(+7.5°)yn11d0; 1 x D(-7.5°)yn11d0
36 - Pulse: 1 x Yy(20°)y(0°)y(340°); Dy(350°)y(330°)y(310°)
From the list above its obvious that the converter transformers require special and non conventional vector groups. The additional phase shifts were based on the pulse requirements to suppress the harmonics on the source side.
One of the prototype special transformers used for testing has been explained in the next section.

3 Prototype Special transformer

The prototype specification was designed based on the output rating of the turns ratio tester that was validated and also made as a scaled down version of the high voltage transformer ratings. The following was the specification.

Transformer rating:

Voltage rating:	275 /33V Vrms (Ph-Ph)
Power rating:	50VA
Frequency:	50 Hz.
No of phases	3
No of primary voltage taps:	5
No of secondary voltage taps:	1
Primary voltage ratio:	(+5% / +2.5% / 275V / -2.5% / -5%) / (33V)
Nominal tap:	3
Vector Group options:	D (+15 deg) yn11 D (+7.5 deg) yn11 Dyn11 D (-7.5 deg) yn11 D (-15 deg) yn11

The required nominal vector group was Dyn11 which will be a Delta (D) connected primary winding and Star (y) connected secondary winding with accessible neutral (n) and a phase shift of 30^0, Secondary voltage leading Primary voltage (or Primary voltage lagging secondary voltage by 30^0) displayed in 11 O' clock position. The vector diagram and the winding configuration were as shown in Fig - 1.

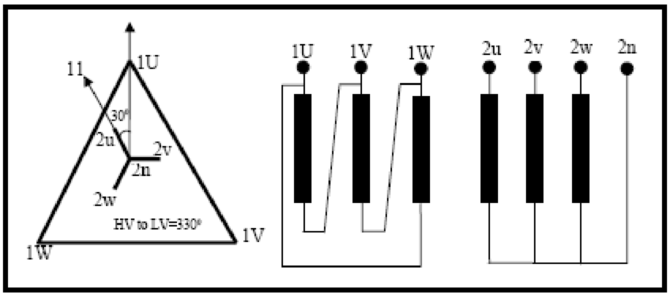

Figure -1: Dyn11 Vector diagram and winding configuration

The off-nominal vector groups required additional phase shifting options of $+7.5^0$, $+15^0$, -7.5^0, and -15^0 on the primary delta winding. The vector diagrams of the other vector group options were as shown in Fig – 2. Three possible winding options are in usage for achieving the 7.5 degree phase shift options: Extended Delta primary, Squashed Delta or Polygon primary, Extended Delta primary design with switched secondary Star.

One of the winding options for achieving the vector groups as shown in Fig – 2 was Extended Delta primary design with switched secondary Star as shown in Fig – 3. The notable features in this extended delta configuration were: a) the power supply phase sequence was found to be interchanged on primary side and also on secondary side for + 7.5^0 phase shifting vector group arrangement. b) Winding start and end on the delta winding in primary has been maintained during both positive and negative phase shift. c) The secondary winding neutral star point was taken from 'start winding shorted' for $+7.5^0$ and it was taken from 'end winding shorted' for -7.5^0 phase shift configuration. d) The secondary vector in both the +7.5^0 and -7.5^0 phase shift configuration were maintained at the 11 O’ clock relationship.

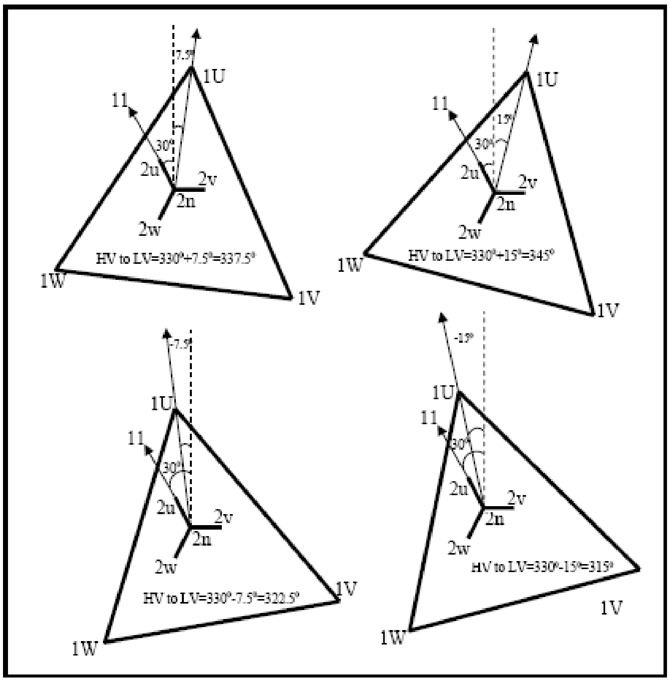

Figure - 2: Dyn11 Vector diagrams with +7.5, +15, -7.5 and 15 degree tilt

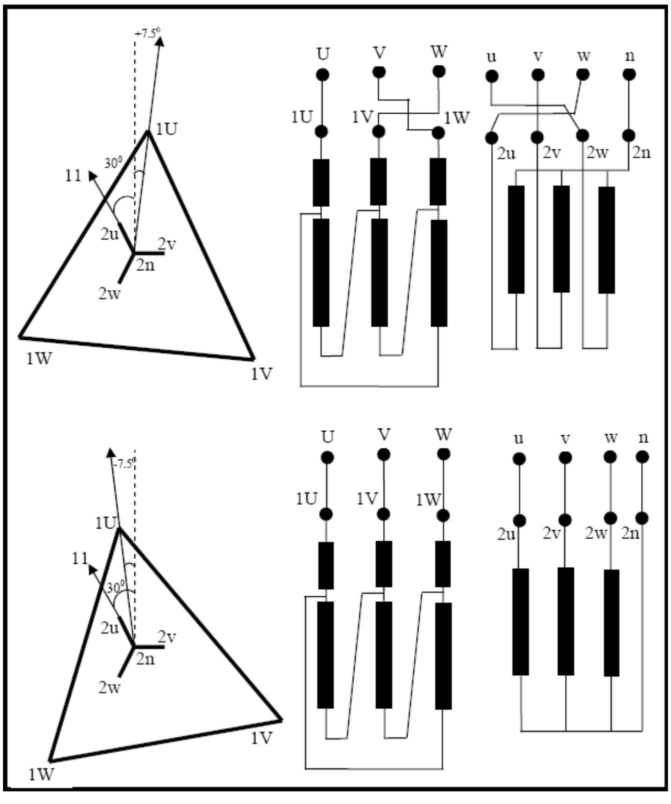

Figure - 3: Extended Delta design for positive and negative phase shifting with switched Star secondary.

4 Test Methodologies

In this section the different test methodologies available to perform on-site test on special transformers were detailed. The tests focused were ratio test and phase angle measurement or phase angle deviation from the set value. The test procedures discussed was the same for testing the prototype transformer that was constructed.

4.1 Ratio and vector group tests using single phase power

In this method the voltage ratio is measured by applying a single phase low voltage AC supply (V1) to the primary side using a variac and measuring the secondary voltage (V2) using a voltmeter. By manually calculating the ratio V2/V1, the ratio can be checked against the specification for errors. For checking the vector group, ‘U’ phase on both the primary side and secondary side will be shorted. In the shorted condition a single phase low voltage supply will be applied in the primary side in one phase and the voltage across all the other legs will be measured. The voltages measured will be in proportion to the vector deviation between phases. By verifying the voltages against the vector diagram the vector groups can be checked. If the measured voltage deviates, it denotes the variation in phase shift. The test process requires complex cabling arrangement and the test leads need to be swapped for each phase for performing ratio measurements in all three phases. Manual calculation of test results were required which were leading to increased errors and time consumption.

4.2 Ratio and vector group tests using TTR testers

Performing ratio test on single phase transformers manually using a variac and voltmeter involves simple ratio calculations. When testing three phase transformers with different vector group arrangements, the ratio calculations are not straight forward like V2/V1 and need to be matched for the delta or star configurations by dividing with Sqrt3 to find out the accurate turn ratio values. The turn ratio values will not be equal to the voltage ratio as such in a delta star or star delta configurations. Transformer Turn Ratio testers, were performing these ratio tests along with excitation measurement, and phase shift measurement automatically. This turn ratio tester performed the turn ratio tests phase by phase shorting the neighbouring phases that were not involved in the testing as recommended by the transformer standards. Testing a three phase converter transformer which has non conventional vector groups like D(+7.5)yn11, D(-15)yn11 and so on with a wide range of winding configurations involve mixing of phases and cores, half of the winding in core U may be fed by phase V supply and so on. This made the test algorithms for automatic testing more complicated. IEC61378-1 standard guides to perform turn ratio measurement to be done in single phase configuration by a cyclic permutation on these special transformers. Modern TTR models comes with direct menu options for ratio, excitation current and phase shift measurements for these unconventional vector groups. The accuracy and the practicality in using these TTR's were validated by multiple test configurations in the prototype and in on-site conditions.

4.3 Ratio and vector group tests using three phase power, power analysers:

Testing the transformers with three phase power supply is another interesting test methodology. This is not a practical method for performing on-site tests with three phase supply and was considered to be more of a laboratory type test. In this test method the ratio test was performed by applying a low voltage three phase AC simultaneously on all three phases of the primary winding of the transformer and by measuring the secondary side with three voltmeters. The phase deviations were measured using phase angle meters or power analysers and the vector groups were confirmed. The deviations were worked out by performing manual calculation. This method can be used for validation purposes as it involves straight forward application of three phase shifted voltage on all three cores simultaneously.

CAD plotting of the voltage measured as scaled values and measuring the Phase shifts from the vector diagram is a method followed by few manufacturers. This will be a cheapest and accurate method but will involve complex set up and result analysis to verify the values on each taps.

5 Tests and Discussion of results:

Tests were conducted in the prototype transformer and on traction Rectifier Transformer. The test methodology and the results were discussed in this section.

5.1 Prototype special transformer test

This test was performed on the prototype transformer using a modern Transformer Turn Ratio Tester (TTR). The TTR was capable of testing the transformer for the turn ratio, excitation current and phase angle deviation from the set or nameplate values. The new test option introduced in the TTR based on the IEC Standard 61378-1 was used. TTR can measure and report the value of cumulative phase shift between primary and secondary along with the cumulative transformer ratio. The three phase TTR was connected to the prototype transformer as shown in Fig - 4. The software which contained the IEC 61378 based testing feature controlled the TTR unit and performed the test as shown in Fig - 5. The test results were satisfactory and matched with the prototype converter transformer acceptance test results. The results recorded in multiple taps and phase shifts were sorted and analysed.

5.2 On-site Rectifier transformer test

This test was performed on a Traction substation rectifier transformer rated 11KV/250.4V using the same Transformer Turn Ratio Tester (TTR).

Test No.	Ratio measured and averaged (Classical)	Cummulative 3 phase ratio measured (TTR)	Ratio deviation	Vector	(PY-SY) Phase shift rated	Phase shift measured and averaged (Classical)	(PY-SY) Cummulative 3 phase - phase shift measured (TTR) - 1 *	(PY-SY) Cummulative 3 phase phase shift measured (TTR) - 2 *	Phase angle deviation (Degrees)
1	8.31	8.29	-0.19%	D(+15)yn11	345 ⁰	344.23	344.30	164.30	0.07
2	8.11	8.10	-0.16%	D(+15)yn11	345 ⁰	344.43	344.65	164.65	0.22
3	7.92	7.91	-0.15%	D(+15)yn11	345 ⁰	344.87	345.02	165.02	0.15
4	7.73	7.72	-0.12%	D(+15)yn11	345 ⁰	345.17	345.40	165.40	0.23
5	7.54	7.53	-0.09%	D(+15)yn11	345 ⁰	345.60	345.81	165.81	0.21
6	8.31	8.30	-0.15%	D (+7.5)yn11	337.5 ⁰	337.03	337.14	157.14	0.11
7	8.12	8.10	-0.19%	D (+7.5)yn11	337.5 ⁰	337.20	337.31	157.31	0.11
8	7.92	7.91	-0.08%	D (+7.5)yn11	337.5 ⁰	337.43	337.50	157.50	0.07
9	7.72	7.71	-0.14%	D (+7.5)yn11	337.5 ⁰	337.63	337.69	157.69	0.06
10	7.52	7.51	-0.18%	D (+7.5)yn11	337.5 ⁰	337.73	337.90	157.90	0.17
11	8.31	8.30	-0.15%	Dyn11	330 ⁰	330.07	329.99	149.99	-0.08
12	8.11	8.10	-0.15%	Dyn11	330 ⁰	330.07	329.98	149.98	-0.09
13	7.91	7.90	-0.16%	Dyn11	330 ⁰	330.07	329.98	149.98	-0.09
14	7.71	7.70	-0.18%	Dyn11	330 ⁰	330.00	329.99	149.99	-0.01
15	7.51	7.51	-0.07%	Dyn11	330 ⁰	329.97	329.99	149.99	0.02
16	8.31	8.30	-0.09%	D (-7.5)yn11	322.5 ⁰	142.90	322.84	142.84	-0.06
17	8.11	8.10	-0.12%	D (-7.5)yn11	322.5 ⁰	142.67	322.65	142.65	-0.02
18	7.91	7.90	-0.16%	D (-7.5)yn11	322.5 ⁰	142.53	322.47	142.47	-0.06
19	7.70	7.70	0.01%	D (-7.5)yn11	322.5 ⁰	142.33	322.28	142.28	-0.05
20	7.52	7.51	-0.14%	D (-7.5)yn11	322.5 ⁰	142.10	322.08	142.08	-0.02
21	8.31	8.29	-0.27%	D (-15)yn11	315 ⁰	135.27	315.68	135.68	0.41
22	8.12	8.10	-0.19%	D (-15)yn11	315 ⁰	135.10	315.34	135.34	0.24
23	7.92	7.90	-0.27%	D (-15)yn11	315 ⁰	135.03	314.97	134.97	-0.06
24	7.72	7.71	-0.17%	D (-15)yn11	315 ⁰	134.83	314.59	134.59	-0.24
25	7.53	7.52	-0.16%	D (-15)yn11	315 ⁰	134.63	314.19	134.19	-0.44

* Note: Phase shifts were calculated ArcTan values hence two possible phase angles were available to measure and display by the test equipment

Table – 1: Test results with comparison on the prototype transformer

The test setup was as shown in Fig - 6. The cumulative phase shift between primary and secondary along with the cumulative transformer ratio was measured and the results were found to be satisfactory. The results recorded in multiple taps were sorted and analysed.

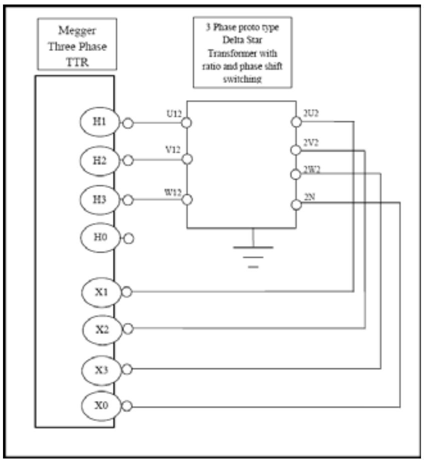

Figure – 4: Test connection used for Three Phase TTR tester

Figure - 5: Tests on the prototype transformer using the Three Phase TTR tester.

Figure – 6: Tests on the Rectifier transformer using the Three Phase TTR tester for ratio and phase shift.

	VOLTAGE (kV)	kVA	RATED I	# TAPS	NOMINAL	CHANGER	TAP SETTING
PRIMARY:	11	2,681	140.72	7	4	Off Load	
SECOND:	0.2504 / 0.145	2,681	6,181.61	1			

#	TAP H/L		Voltage H/L		Test V	TNR	Actual TNR	% error	Phase Angle (deg)	
1	R3 (1)	Nominal	10,175	250.4	80	40.635	41.41	1.86	338.09	158.09
2	R2 (2)	Nominal	10,450	250.4	80	41.7332	42.34	1.42	337.91	157.91
3	R1 (3)	Nominal	10,725	250.4	80	42.8315	43.27	1.00	337.74	157.74
4	Nominal	Nominal	11,000	250.4	80	43.9297	44.20	0.60	337.57	157.57
5	L1 (5)	Nominal	11,275	250.4	80	45.028	45.13	0.22	337.41	157.41
6	L2 (6)	Nominal	11,550	250.4	80	46.1262	46.05	0.16	337.27	157.27
7	L3 (7)	Nominal	11,825	250.4	80	47.2244	46.99	0.50	337.12	157.12

Figure – 7: Test results of the Rectifier transformer using the Three Phase TTR tester for cumulative ratio and phase shift.

5.3 Discussion of results

Fig – 8 shows the phase shift deviation from the theoretical value in graphical form on the Dyn11 vector group configuration. The measured values followed the theoretical values very closely. Fig 9 shows the phase shift deviation on the D (+7.5) yn11 vector group configuration. The test numbers are the ratio taps from 1 to 5. The phase shift remains stable.

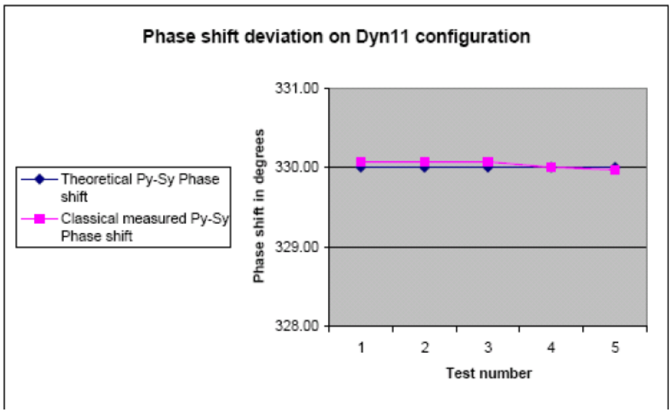

Figure – 8: Phase shift deviation on Dyn11 - Graphical representation.

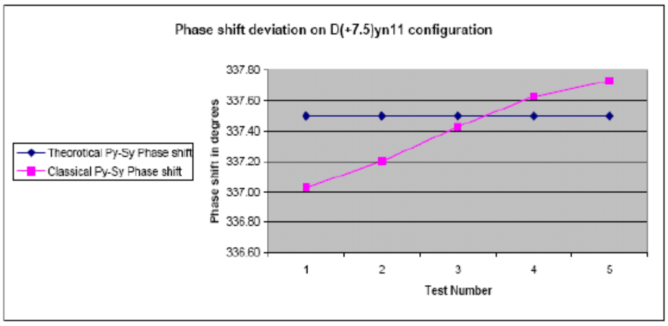

Figure – 9: Phase shift deviation on D (+7.5) yn11 - Graphical representation

The phase shift varies from 7.03 to 7.73 degrees over 5 taps on the prototype and from 7.12 to 8.09 degrees over 7 taps on the 11KV rectifier transformer. The closest nameplate values obtained were on the nominal taps on both the tests.

6 Effects of phase shift deviation

The aim of using phase shifting transformers on multi-pulse rectifiers is to achieve reduction in harmonics [3]. The phase angle values were designed to match the firing angle of switched converters, variable frequency drives, and rectifiers. The increase in phase angle deviation from the designed values between secondary windings may create unbalanced switching of rectifier outputs. This will reduce the effectiveness in harmonic mitigation process [4]. As the number of pulses increase the effect of errors or deviation in phase angle will reduce, but for lower pulsed rectifiers the phase angle values will be critical and needs further study.

7 Conclusion

A prototype three-phase converter transformer with variable ratio taps and vector groups switching was designed, constructed and tested successfully. The prototype replicated the high voltage transformer characteristics in each mode. The tap options can vary the ratio and the phase shift both on the positive and negative values from the nominal rating. An 11KV rectifier transformer on a traction substation was tested for the study on phase angle variation. The study was focused on the test methodology and on the phase angle deviation occurring during ratio change. The TTR tester designed to test the special transformer designs using the IEC61378 standard recommendation was providing the cumulative ratio and phase shift results during the validation tests which were found to be satisfactory. The key differences in the recordings were that the classical methods of ratio and phase angle test were providing individual phase recordings against the cumulative recordings by the TTR tester. Due to the complexity of other test methods as detailed in this paper, a ratio tester with inbuilt phase angle measuring feature will be an easiest and practical tool to test these special transformers on multiple taps.

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