

## Pushing past the limitations of power factor testing

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This article describes cross-check and open DETC test procedures, the transformer winding configurations for which these methods are most effective, and provides a case study wherein these methods provided useful supplemental information to help characterize the problem at hand in a faulted transformer.

### Cross-check tests

Unlike the preparation required for traditional power factor testing, transformer windings are not short-circuited for Cross-check tests. Therefore, when voltage is applied to a bushing terminal, (1) the winding is now being excited and (2) voltage distributes non-uniformly across the winding.

Highest voltage stress is placed upon the insulation closest to the energized terminal. In this way, the CH (for example) insulation system measured in a traditional overall power factor test by shorting all 3 phase windings together, can now be sectionalised into thirds. It is expected, therefore, that the results (mA, Watts and capacitance) for the 3 (segmented)

cross-check tests should add to equal the results measured in the traditional overall power factor test. It is noted here that cross-check tests for the CL insulation system are not provided because in many cases, the current requirement to excite the low voltage winding is greater than most field portable test instruments can provide.

**GST Per Phase (CH):** One primary terminal is energized while guarding the other two terminals and X0. (X1, X2 and X3 bushings are floated.) The DETC is left on tap. The sums of the watts, milliamps, and capacitances for all three tests should match the overall CH values. The GST per phase may be performed at up to rated voltage provided the guarded excitation current does not exceed the output of the test equipment. The H1, H2, H3 tests are designated as ICH1, ICH2, and ICH3 respectively.

**UST Per Phase (CHL):** One primary terminal is energized while guarding the other two terminals. Output from X0 terminal is measured. X1, X2 and X3 bushings are floated. The DETC is left on tap. The sums of the watts, milliamps, and capacitances for all three tests should match the overall CHL values. The UST crosscheck may be performed at up to rated voltage provided the guarded excitation current does not exceed the output of the test equipment. H1, H2 and H3 tests are designated as ICHL1, ICHL2, and ICHL3 respectively.

### Open DETC Tests

In the cross-check tests above, the visibility of an anomaly is proportional to its proximity to the voltage source. In the open DETC protocols, the entire section of energized winding is at the same potential since the low voltage winding terminals are short-circuited. This enables the detection of anomalies in the centre of the winding, which may be difficult to pinpoint with the cross-check tests.

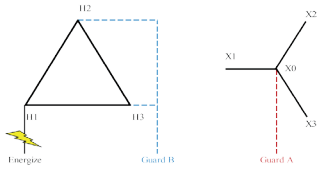
This sectionalisation of the primary also enables the technician to determine the location of an anomaly in relation to the DETC. If a fault in the centre of a primary winding radially propagates sufficiently to involve numerous coil layers, it may be detectable as seen from both sides of the open DETC.

**Open DETC GST (Table 3):** DETC is placed at a midway position between taps. One primary terminal is energized while guarding the other two primary terminals and all secondary terminals (LV winding short-circuited). The sums of the watts, milliamps, and capacitances for all three tests should match the overall CH values. The DETC open GST crosscheck is performed at a maximum of 500 volts. H1, H2 and H3 tests are designated as CH1, CH2, and CH3 respectively. In this configuration individual sections of the delta primary are isolated and energized. If an anomaly is suspected to be located in the centre portion of a winding, the open DETC test will determine the location of the anomaly in relation to the DETC.



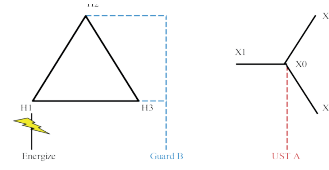
## Overview of Supplementary Tests

### Standard GST per phase test



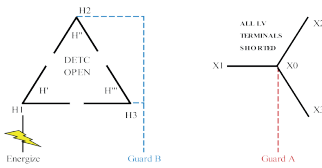
Test	Energize	Float	Guard
CH <sup>1</sup>	H1	X1,X2, and X3	H2,H3, and X0
CH <sup>2</sup>	H2	X1,X2, and X3	H1,H3, and X0
CH <sup>3</sup>	H3	X1,X2, and X3	H1,H2, and X0

### Standard UST per phase test



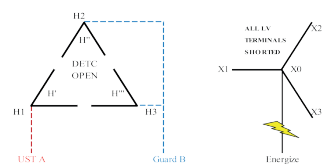
Test	Energize	Float	Guard	UST
CHL <sup>1</sup>	H1	X1,X2, and X3	H2,H3	X0
CHL <sup>2</sup>	H2	X1,X2, and X3	H1,H3	X0
CHL <sup>3</sup>	H3	X1,X2, and X3	H1,H2	X0

### Open DETC - GST per phase test



Test	Energize	Float	Guard
CH <sup>1</sup>	H1	None	H2,H3, X1, X2, X3, and X0
CH <sup>2</sup>	H2	None	H1,H3, X1, X2, X3, and X0
CH <sup>3</sup>	H3	None	H2,H3, X1, X2, X3, and X0

### Open DETC - UST per phase test



TEST #	UST	Float	Guard	Energize
CHL <sup>1</sup>	H1	None	H2,H3	X1, X2, X3, and X0
CHL <sup>2</sup>	H2	None	H1,H3	X1, X2, X3, and X0
CHL <sup>3</sup>	H3	None	H2,H2	X1, X2, X3, and X0

Open DETC UST (Table 3): DETC is placed at a midway position between taps. Secondary terminals are short-circuited and energized at the same voltage as in the overall test. One primary terminal is measured while guarding the other two terminals. The sums of the watts, milliamps, and capacitances for all three tests should match the overall CHL values. The tests are designated in terms of the primary terminal that is measured. H1, H2 and H3 tests are designated as CHL1, CHL2, and CHL3 respectively.

### Transformer configurations and limitations

**Delta-Wye Configuration:** The ideal test subject is a delta-wye configuration with a three-leg core. Delta-wye is the only configuration on which the entire set of supplemental tests may be performed without geometry-induced errors. In distribution core configurations, the CH2 measurements for the centre phase are inaccurate because the core configuration severely impedes current flow for CH per phase tests.

**Delta-Delta Configuration:** If a cross-check, per-phase test is performed on a three-phase winding with a delta secondary, the primary exciting current induces circulating currents in the secondary, which make it impossible to collect accurate data. The open DETC tests (Table 3) are the only supplemental tests that may be used on this configuration.

**Wye-Delta Configuration:** The open DETC GST test is the only protocol guaranteed to yield usable data with this winding configuration. Open DETC UST tests may not yield useable data because the secondary winding interface is normally located between the DETC and neutral. When the crosscheck, per-phase protocol is performed on the wye-delta configuration, the unit must be treated as a delta-wye, meaning that the tests must be performed by energizing the X winding. This however is not possible if the exciting current required by the secondary winding is beyond the capacity of the test equipment.

**Wye-Wye Configuration:** The wye secondary configuration enables the cross-check, per-phase CH and CHL tests to be performed as given in Table 4. With the wye primary configuration only one primary winding is energized per test when each phase terminal is energized, making the protocol a true per-phase test. While the CH0 and CHL0 tests are not useful for localization of anomalies, the data is used to compare the sums of watts, mA, and capacitances to the overall values. For the reasons stated in the wye-delta section above, the open DETC UST test may not yield useable data. The open DETC GST test may be performed, as table 5 shows.

### Wye-Wye Autotransformer and 3 Phase Regulators:

The cross-check, per-phase method is used in this configuration to investigate questionable CH values. As in the other configurations, the sum of the watts, milliamps, and capacitances from the cross-check tests should equal the respective values from the overall test. Cross-check, per phase tests are performed as given in Table 6.

	Mode	Energize	Ground	Guard	UST	Measurement
1	GST	HV	LV			ICH+ICHL
2	GST	HV		LV		ICH
3	UST	HV			LV	ICHL
4	GST	LV	HV			ICH+ICLH
5	GST	LV		HV		ICL
6	UST	LV			X1,X2,X3	ICLH
7	GST	H1	H2,H3,X0	-	X1,X2,X3	ICH <sup>1</sup>
8	GST	H2	H1,H3,X0	-	X1,X2,X3	ICH <sup>2</sup>
9	GST	H3	H1,H2,X0	-	X1,X2,X3	ICH <sup>3</sup>
10	UST	H1	H2,H3	X0	X1,X2,X3	ICHL <sup>1</sup>
11	UST	H2	H1,H3	X0	X1,X2,X3	ICHL <sup>2</sup>
12	UST	H3	H2,H3	X0	X1,X2,X3	ICHL <sup>3</sup>

Table 2: Overall and Cross-Check Per-Phase Tests for Delta-Wye Transformer Configurations\*

Test	Mode	Energize	Guard	UST	Measurement
1	GST	H1	H2,H3,X0,X1,X2,X3	-	ICH <sup>1</sup>
2	GST	H2	H1,H3,X0,X1,X2,X3	-	ICH <sup>2</sup>
3	GST	H3	H1,H2,X0,X1,X2,X3	-	ICH <sup>3</sup>
4	UST	X0,X1,X2,X3	H2,H3	H1	ICHL <sup>1</sup>
5	UST	X0,X1,X2,X3	H1,H3	H2	ICHL <sup>2</sup>
6	UST	X0,X1,X2,X3	H1,H2	H3	ICHL <sup>3</sup>

Table 3: Open DETC Tests

Test	Mode	Energize	Guard	UST	Measurement
1	GST	H1	H0,H2,H3		ICH1
2	GST	H2	H0,H1,H3		ICH2
3	GST	H3	H0,H1,H2		ICH3
4	GST	H0	X0,H1,H2,H3		ICH0
5	UST	H1	H0	X0	ICHL1
6	UST	H2	H0	X0	ICHL2
7	UST	H3	H0	X0	ICHL3
8	UST	H0	H1,H2,H3	X0	ICHL0

Table 4: Cross-Check, Per-Phase Tests for Wye-Wye Configurations (DETC on Tap)

## CASE STUDY: Root cause failure analysis of a 69 kV substation transformer with secondary ground fault

The #2 South B Bank from Tulare Substation was removed from service. Relay targets had indicated a differential fault on C phase. Substation personnel performed insulation resistance tests on the transformer which indicated that the unit had failed. At this point the transformer was cut off the pad and sent to the SCE Large Apparatus Repair Facility for further testing.

Ratio test results were within specification with no indication of abnormalities. Insulation resistance tests yielded values of 605 MΩ, 7.35 GΩ, and 48 MΩ for CHL, CH, and CL respectively. Exciting current tests were successfully performed at 10kV. Overall power factor test results are shown in Table 7.

Among other problems, it was noted that the CHL power factors on lines 3 and 6 deviated by nearly 0.1%. The assumption was made that a voltage dependent problem was present as a result of the failure. A power factor tip-up test was performed for CHL, CH, and CL (Figure 1).

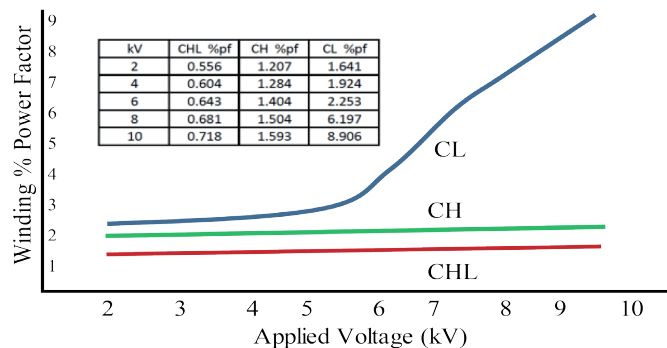


Figure 1 Power Factor Voltage Tip-up for failed 69 kV bank

The test data revealed power factor tip-up values of approximately 0.16 and 0.4% for CHL and CH respectively, most likely due to carbon contamination. CL power factor on the other hand increased dramatically as voltage was increased to 10 kV. The tip-up test in conjunction with the insulation resistance values indicated the CL as the principle fault location. The exciting current and ratio tests however did not indicate the phase in which the fault originated. The standard supplementary tests were performed to obtain "per phase" power factor values for GST and UST tests. The unit was constructed with a standard 3 leg core configuration, which allowed for collection of accurate GST and UST cross-check data.

Elevation of CH3 in combination with depression of CHL2 values indicated conclusively that the CL fault occurred in the C phase winding (H2-H3). Because the CHL fault for C phase was indicated in CHL2, this verified that the H2 lead jumper enters the C phase primary winding at the inside edge of the primary winding adjacent to the inter-winding barrier. The CH fault was not detected to a significant degree in the CHL2 test, therefore it may be deduced that the location of the fault was in close proximity electrically to the end of the C phase winding from which the H3 bushing lead originates.

Because the fault occurred in C phase, the CH1 and CHL1 per phase values accurately reflected the condition of the primary windings away from the fault zone. The H1 lead is not common to C phase, making any C phase anomaly invisible as seen from CH1 and CHL1 measurements.

Test	Mode	Energize	Guard	Measurement
1	GST	H1	H2,H3,H0,X0X1,X2,X3	ICH <sup>1</sup>
2	GST	H2	H1,H3,H0,X0,X1,X2,X3	ICH <sup>2</sup>
3	GST	H3	H1,H2,H0, X0,X1,X2,X3	ICH <sup>3</sup>
4	UST	H0	H1,H2,H3,X0,X1,X2,X3	ICH <sup>0</sup>

Table 5: Standard DETC Open Per-Phase Tests for Wye-Wye Configurations

Test	Mode	Energize	Guard	Float	Measurement
1	GST	H1	H2,H3,H0X0	x1,x2,x3	ICH <sup>1</sup>
2	GST	H2	H1,H3,H0X0	x1,x2,x3	ICH <sup>2</sup>
3	GST	H3	H1,H2,H0X0	x1,x2,x3	ICH <sup>3</sup>
4	GST	H0X0	H1,H2,H3	x1,x2,x3	ICH <sup>0</sup>

Table 6: Per Phase Tests for Wye-Wye Autotransformers and 3 Phase Regulators

For procedural reasons, the DETC could not be operated. If the DETC could have been placed between taps, the open DETC per phase protocol would have been performed which negates the power factor shift as seen in the standard per phase protocol (resulting from the CL ground fault) and yields accurate per phase power factor data.

The winding was untanked and a physical inspection was performed. As expected the C phase secondary winding had sustained a ground fault in proximity to the interwinding barrier, validating the CHL2 value. It was also discovered that the C phase static shield had failed validating the CH3 value (which indicated CH damage in close proximity to the H3 lead).

## Conclusion

The strength of the per-phase protocol is the localisation of incipient problems to their respective windings, but other methods such as dissolved gas analysis and sweep frequency response analysis should also be employed in order to determine the physical basis of the anomaly.

A thorough understanding of the winding arrangement and internal geometry is essential for proper interpretation of the per-phase data. Winding arrangements and internal connections will vary significantly, depending on size and voltage class of unit.

They may be performed in cases where the CH or CHL are elevated above the baseline values obtained in the commissioning tests. Another tool that SCE uses to investigate problems is a recommended routine screening test known as the Narrow-band dielectric frequency response test (DFR) test (also called variable frequency power factor). This will be the focus of the last part of this series in the next issue of our news from Megger.

Measurement	Test kV	mA	Watts	% FP
ICH + ICHL	10,0	35,367	3,423	0,958
ICH	10,0	10,605	1,65	1,540
ICHL	10,0	24,756	1,794	0,718
ICL + ICLH	5,0	69,377	10,759	1,535
ICL	5,0	44,615	9,300	2,064
ICLH		24,752	1,557	0,623

Table 7 Overall Power Factor Results 69 kV Bank

Measurement	Test kV	mA	Watts	% FP	CAP (pF)
ICH1	5,0	3,373	0,187	0,555	894,6
ICH2	5,0	3,301	0,096	0,292	875,7
ICH3	5,0	3,898	1,128	2,894	1033,7
		10,572	1,411		2804,0
ICHL1	5,0	8,109	0,185	0,228	2150,9
ICHL2	5,0	8,535	1,119	1,311	2263,7
ICHL3	5,0	8,101	0,207	0,256	2148,9
		24,745	1,511		6563,6

Table 8 Cross-Check, Per Phase Winding Power Factor Tests 69 kV Bank

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