TRANSMISSION & DISTRIBUTION WORLD

THE VALUE OF POWER FACTOR TESTING

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NATIONAL GRID DISCOVERED A HIGH POWER FACTOR DURING ACCEPTANCE TESTING of a new 40-MVA transformer in 2004. The unit was then returned to the factory for repairs, burdening both the utility and manufacturer with additional costs and delays. This article reviews the information gathered and lessons learned from this event, including testing and root-cause determination results from the teardown/repair process.

National Grid's electricity delivery companies in the United States serve 3.3 million electricity customers in New England and upstate New York through more than 1200 substations. As part of a substation expansion project, a 24/32/40-MVA, 115-kVD/13.2-kVY transformer was purchased and installed at a National Grid substation in New England.

The transformer was delivered to the substation. The radiators and bushings were installed. The unit was vacuum processed, filled under vacuum and tested by the transformer manufacturer's personnel. The following tests were performed at the substation after the unit was oil filled:

- Transformer turns ratio on all taps
- Insulation power factor of transformer and all bushings (C1 and C2)
- 10-kV excitation on all taps
- Core ground and winding resistance
- Oil quality and dissolved gas analysis (DGA).

The power factor of the high-voltage winding was elevated. The measured value of 0.58% did not meet industry-standard acceptable values or National Grid's required values. All other tests results were acceptable.

POWER FACTOR TESTING

Insulation power factor tests are used to measure dielectric losses, which relate the wetness, dryness or deterioration of transformer insulation. Both factory and field testing are performed to verify the insulation integrity of substation transformers. Power factor testing a two-winding transformer is conducted by energizing the winding at a known ac voltage (typically 10 kV for windings rated greater than 10 kV) with the common winding bushings shorted together.

The results of overall power factor tests on power transformers reflect the insulation condition of the windings, barriers, tap changers, bushings and oil. Modern oil-filled power transformers should have power factors of 0.5% or less, corrected to 20°C (68°F), for individual windings to ground (C_H and C_L) and interwinding insulations (C_{HL}). The National Grid transformer specification states that the power factor of the insulation system shall not exceed 0.5% at 20°C.

As part of the investigation into the high power factor, the transformer manufacturer retested the power factor with similar results. The high-voltage bushings were replaced and the unit was retested. The results did not change.

The unit was drained and an internal inspection was performed; nothing was found. The vendor performed a 24-hour hot oil and vacuum process to rule out the possibility of moisture in the insulation. The power factor was again retested and still had high C_H results. Both the seller and purchaser agreed that the unit should be returned to the factory for further investigation.

REVIEW OF INITIAL FACTORY TESTS PERFORMED

The results of the factory tests performed initially when the transformer was built were reviewed.

- Temperature rise tests were acceptable.
- Preliminary tests of resistance, polarity, phase relation, ratio, no-load loss and excitation current, impedance and load loss, excitation and power factor were all acceptable.
- Dielectric impulse, applied and induced potential tests were acceptable, following IEEE guidelines, although enhanced voltage test results were elevated.
- DGAs taken before tests and after OA and FA heat run tests were acceptable.
- DGA results after high-voltage tests indicated a problem.

Due to the gassing, the unit had been drained, reprocessed and vacuum filled. The induced voltage test and DGA tests were repeated with acceptable results. The unit was shipped.

INDUCED VOLTAGE TESTING

The purpose of the induced voltage test is to prove the insulation strength between parts of the same winding and insulation to ground that was not proved during the applied potential test. It also proves the condition of the insulation between windings and between phases. The voltage applied during the induced voltage testing is on the order of 1.5 to 2 times the rated voltage. Weaknesses in dielectric design, processing or manufacturing may cause partial-discharge (PD) activity during this test. PD is generally monitored on all line terminals rated 115 kV or higher during the induced voltage test. A special generator with a frequency greater than 60 Hz must be used so the core does not saturate due to the higher-than-normal voltage that is induced in the windings. For most power transformer testing, this generator is 120 Hz, 180 Hz or 240 Hz. The induced voltage test is the final dielectric test. All class II power transformers shall be induced voltage tested with the required test levels induced in the high-voltage winding. The taps shall be selected so that the test levels developed in the other windings are 1.5 times their maximum operating voltage. The voltage is raised to the one-hour level and held long enough to verify there are no PD problems. The voltage is then raised to the enhanced level and held for 7200 cycles. The voltage is then reduced to the one-hour level and held for one hour. During the one-hour period, PD measurements should be recorded at 5-minute intervals on each terminal 115 kV and above. The test is performed with the neutral terminals solidly grounded; this will stress the insulation at the same per unit of voltage.
The test frequency is increased relative to the operating frequency to avoid core saturation per IEEE standard C57.12.90.

EVALUATION OF INDUCED VOLTAGE TEST

Per IEEE C57.12-2000, the following criteria shall be met:

- Failure may be indicated by the presence of smoke and bubbles rising in the oil, an audible sound such as a thump or a sudden increase in test current. Any such indication should be carefully investigated by observation, by repeating the test or by other tests to determine whether a failure has occurred.
- In terms of interpretation of PD measurements, the results shall be considered acceptable and no further PD tests required under the following conditions:
  a. The magnitude of the PD level does not exceed 100 µV.
  b. The increase in PD levels during the 1-hour test does not exceed 30 µV.
  c. The PD levels during the 1-hour test do not exhibit any steadily rising trend, and no sudden, sustained increase in levels occurs during the last 20 minutes of the tests.
- Judgment should be used on the 5-minute readings so that momentary excursions of the radio-influence voltage (RIV) meter caused by cranes or other ambient sources are not recorded. Also, the test may be extended or repeated until acceptable results are obtained.
- Unless breakdown occurs or very high PDs are sustained for a long time, this test is considered as nondestructive. A failure to meet the PD acceptance criterion shall, therefore, not warrant

immediate rejection, but lead to consultation between purchaser and manufacturer about further investigations.

DISSOLVED GAS ANALYSIS RESULTS

DGA of oil during factory testing will assist in determining if any arcing, corona discharge, low-energy sparking, overloading and overheating has occurred. The detection of gases greater than the allowable limits shall require further investigation. DGA samples should be taken before, during and after thermal performance and high-voltage tests to determine the amount of gas generated during testing. The limits listed in the table on page 58 are National Grid maximum allowable increases for gases from the beginning of any testing to the completion of all testing. Any results higher than those listed in the table would require further investigation.

BACK TO THE MANUFACTURER FOR RETESTING

As agreed upon by National Grid and the manufacturer, the transformer was returned to the manufacturer for inspection. The core and coils were removed from the tank, the high-voltage delta connection was broken, and single-phase winding power factor tests were performed with the unit on the drip pad.

DISCUSSION OF POWER FACTOR RESULTS

Treeing on the phase barrier board between H2 and H3 was found on the surface of barrier board at the base of the coils where the windings are the closest to one another.

The normal watts loss/power factor of H1 and higher watts loss/power factor on both H2 and H3 indicates the problem is common to H2 and H3 windings.

The barriers were then removed and retested, the H1 remained unchanged and the H2 and H3 watts loss/power factor lowered to the H1 values. This indicates that the contamination was related to H2-H3 barriers.

DISCUSSION OF INDUCED VOLTAGE TESTS BEFORE INITIAL SHIPMENT

The enhanced voltage test results indicated a normal level on H3 and higher level on H1 and H2. This appeared contradictory to what was visually found. Further analysis of the winding arrangement, location of the treeing and higher-than-expected micro-volt and pico-coulomb test results all indicated a problem at the base of #2 and #3 windings. This was because the H1 lead is connected to the bottom of the #2 winding and the H2 lead is connected to the bottom of the #3 winding stressing the bottom of the H2/H3 barrier board.

TEARDOWN, POWER FACTOR AND INDUCED VOLTAGE TESTS

The power factor testing during the teardown helped in identifying the location of the contamination. The winding design and location of the contamination accounted for the higher losses identified during the initial enhanced voltage test. We can assume the contamination caused arcing during the initial enhanced voltage test. The DGA results confirm that arcing occurred. The high voltage most likely burnt away the majority of the debris during the test and left a carbon tree. The subsequent oil processing and vacuum filling at the factory may have cleaned the area enough to partially cure the problem. Therefore, the second induced voltage test, prior to initial shipment, was acceptable and the DGA showed no arcing at that time.

LABORATORY ANALYSIS OF BARRIER BOARD

The transformer H2/H3 barrier pressboard was removed from the unit and brought to the Doble Materials Laboratory in Watertown, Massachusetts, U.S., for analysis. An initial visual examination of the pressboard showed that discharge treeing was quite distinct. An adjacent board was also inspected and there was no discharge treeing visible. The Doble Materials Laboratory was asked to aid in determining the cause of the discharge treeing in the pressboard. Unfortunately, the pressboards were not stored in a controlled environment at the transformer manufacturer after they were removed from the transformer, thus making it impossible to determine if moisture and metal particle contamination were present on the barrier board when the transformer was assembled.

FACTORY REPAIR

The top yoke was removed and the coils were un-nested. A complete visual inspection of the coils was performed. The barrier insulation, top and bottom insulation, and leads were replaced. The unit was reassembled and fully re-tested. All factory test results after the repair were acceptable and the unit was shipped. The unit was delivered to the substation, dressed, vacuum filled and tested by the vendor. All field test results were acceptable.

LESSONS LEARNED

- It is important to set power factor limit for acceptance testing.
- It is important to set DGA limits for factory testing.
- Require reporting of all factory test results in the final test report.
- Factory power factor testing should be performed before and after thermal/high-voltage tests.
- Specification should include limits for the induced voltage test during the enhanced voltage period.
- Specifications should include a statement similar to: “If the transformer fails any test, the purchaser shall be notified immediately. The purchaser shall be consulted about the failure, and based on the test results, the purchaser may require a complete retest of all tests.”
- Preservation of removed parts in controlled environments is essential when performing root-cause analysis.

In conclusion, there is great value in analyzing all test results, as each test represents a different component that verifies the design and manufacturing process. All test results should be reviewed prior to releasing a transformer for shipment. National Grid believes there is value in performing a power factor test before and after factory testing. In this case, induced voltage testing was acceptable but power factor testing revealed a problem. Final power factor test results also will assist the purchaser when performing field acceptance testing. The manufacturer who supplied this transformer now performs power factor tests before and after high-voltage testing.

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Insulation Tested	% Power Factor Corrected to 20°C
C_H	0.58
C_L	0.21
C_{HL}(UST)	0.15
Oil	0.02

Power factor acceptance test.

Insulation Tested	% Power Factor Corrected to 20°C
C_H	0.21
C_L	0.18
C_{HL}(UST)	0.14

Initial factory power factor testing prior to high-voltage testing.

Kv P-P	% of Enhancement	Time (min)	H1		H2		H3	
			pC	uV	pC	uV	pC	uV
0	0		0	9	0	12	0	11
52	25		0	9	0	12	0	11
104	50		5	9	5	12	0	11
156	75		19	13	20	17	0	11
208	100		478	250	581	700	34	35

182	87.5	0-60	5-20	16-50	0-8	23-40	0-5	20-35

Factory-induced voltage testing dated April 26, 2004, prior to shipment.
(Enhanced 120L-G/208P-P — One Hour 105L-G/182P-P)

Date	4/24/04	4/25/04	4/26/04	4/26/04	Test Limits
Note	Before all tests	After OA Heat Run	After FA Heat Run	After all Tests	
Hydrogen	1	8	8	16	10
Methane	0	0	0	0	5
Ethane	0	0	0	0	2
Ethylene	0	0	0	1	2
Acetylene	0	0	0	5	0
Carbon Monoxide	4	20	48	67	30
Carbon Dioxide	25	62	149	153	300

Initial factory DGA test results.

Gas name	Gas symbol	ppm limit
Hydrogen	H_2	10
Methane	CH_4	5
Ethane	C_2H_6	2
Ethylene	C_2H_4	2
Acetylene	C_2H_2	0
Carbon Monoxide	CO	30
Carbon Dioxide	CO_2	300

National Grid maximum gas limits.

Test #	Insulation	Test Connection			Mode	kV	% PF	Cap.
		Energize	Ground	Guard				
1	CH1	H1	-	LV, H2, H3	GST	2.5	0.44	267.39
2	CH2	H2	-	LV, H1, H3	GST	2.5	1.95	227.30
3	CH3	H3	-	LV, H1, H2	GST	2.5	1.92	237.29

Power factor (PF) testing of transformer (115kV delta connection cut — on drip pad).

Test #	Insulation	Test Connection			Mode	kV	mA	Watts	% PF	Cap.
		Energize	Ground	Guard						
4	CH1	H1	-	LV, H2, H3	GST	2.5	0.253	2.4	0.39	268.79
5	CH2	H2	-	LV, H1, H3	GST	2.5	0.212	2.4	0.45	220.90
6	CH3	H3	-	LV, H1, H2	GST	2.5	0.219	2.0	0.35	230.26

Power factor testing of transformer (barriers removed).