Primary Current Injection (Through-fault) Testing of Large Power Transformers

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Introduction

The installation or replacement of a large power transformer (10MVA and larger) requires the proper connection of numerous conductors to transformer bushings, windings, current transformers (CTs), protective relaying, cooling system power, controls and alarms. Following the transformer installation/replacement, all conductors must be properly connected in order to ensure that the transformer and its protective relaying function properly during energization, normal operation, system transients and faulted conditions.

Especially critical to the proper operation and protection of the transformer (and the adjacent electric power system) is the correct connection of all CT conductors that provide inputs to the transformer 50/51, 50/51N, 51G, 51 and 87T protective relays. Figure 1 below shows the typical protective relaying for a large power transformer. The 63 sudden pressure relay (SPR) does not receive inputs from any CTs.

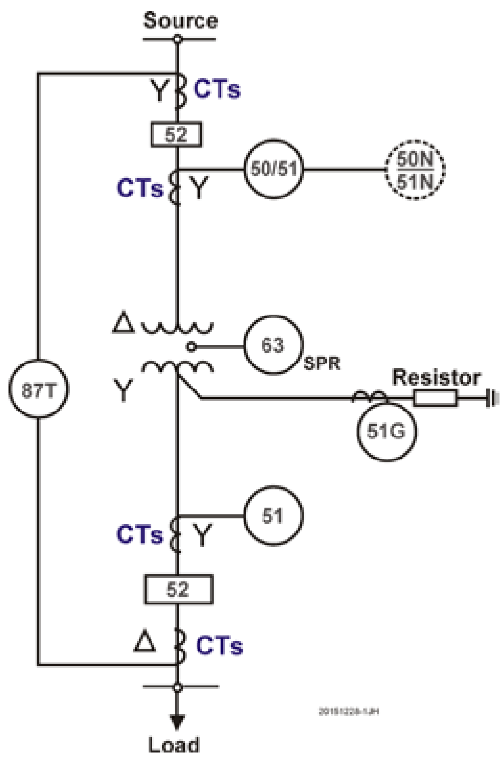

Figure 1 - Typical Protective Relaying for a Large Power Transformer

The correct connection of the transformer differential (87T) relays is of vital importance because the incorrect connection of any single CT conductor in these circuits is all that is needed for either (1) a false trip of the transformer to occur, or (2) a failure to trip of the transformer to occur. Some transformer differential relaying circuits can be very complex with auxiliary CTs, delta-wye and wye-delta connections installed that make it nearly impossible to test these CT circuits accurately using point-to-point continuity measurement techniques.

How can one be absolutely certain that all transformer, CT and protective relay wiring are 100% correct following a large transformer installation/replacement? It is the opinion of the author that Primary Current Injection (Through-fault) Testing is the absolute best testing methodology available for ensuring that all transformer, CT and protective relay wiring are 100% correct following the installation/replacement of a large power transformer. The terms "through-fault test" and "three-phase through-fault test" will be used interchangeably throughout the remainder of this bulletin because most through-fault tests are three-phase tests (although single-phase tests can be performed when warranted).

Why is Through-fault testing necessary?

There have been numerous instances at U.S. Power plants, Transmission Substations (TSSs) and Transmission Distribution Centers (TDCs) where the incorrect wiring of CTs in large power transformer protective relaying circuits has resulted in (1) false trips or (2) failures to trip of the transformer with significant impact and consequences.

Licensee Event Report (LER) 237-98008 documents one such instance where (1) a design change was made to protective relaying on a Unit Auxiliary Transformer (UAT) at a U. S. Nuclear Power Plant, (2) an error existed in the new design that was not detected by plant engineering or by testing and (3) the UAT falsely tripped at approximately 60% rated power (unit) resulting in a main generator, main turbine and reactor trip. The estimated economic impact was lost generation of approximately 64,751 Megawatt-hours, in addition to the resources required to determine the root cause and to bring the unit back online following this event. A three-phase through-fault test would have detected the design error and would have prevented this event.

What is Through-fault testing?

Through-fault testing utilizes a 3-phase voltage source (test source) to inject 3-phase currents (test currents) into the windings and through all CT primaries of a large power transformer, thus allowing for the measurement of current magnitudes and phase angles on all CT secondaries and transformer protective relays. Figure 2 below shows the typical through-fault test configuration for a large power transformer. For simplicity, only the transformer differential (87T) relays are shown. However, the 50/51, 50/51N, 51G and 51 relay circuits shown in Figure 1 are also tested during the through-fault test.

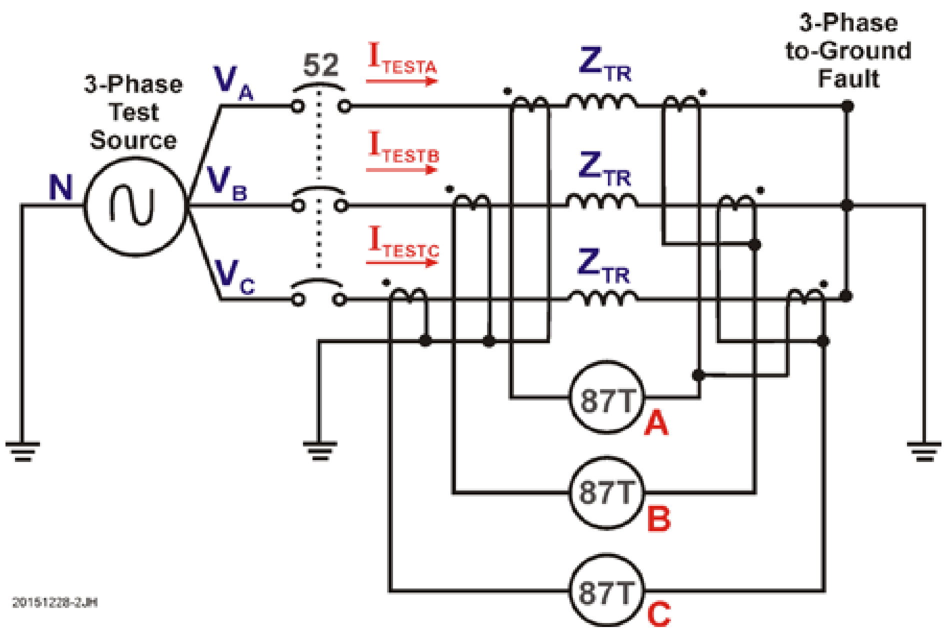

Figure 2 - Typical Through-fault Test Configuration

To create the flow of test currents (I_{TEST}) through the transformer windings, CT primaries and CT secondaries, a "3-phase-to-ground" fault is intentionally placed on one side of the transformer, thus creating a circuit where the test source voltage (V_{TEST}) is in series with the transformer impedance (Z_{TR}). The use of a "3-phase-to-ground" fault to facilitate the flow of test currents is the primary reason that this test is oftentimes referred to as a "through-fault" test. The test source voltage and the location of the "3-phase-to-ground" fault i.e. on the transformer high-side or low-side, are determined based upon the transformer impedance and CT ratios (CTRs). Based upon experience, V_{TEST} and I_{TEST} are significantly lower than the ratings of the transformer and CTs and are not perfectly balanced due to slight differences in the A, B and C phase test source voltages and transformer impedances. Possible test sources include: (1) a diesel generator, (2) a diesel generator and step-up transformer or (3) a low or medium-voltage power feed (480V - 34kV).

Test Acceptance Criteria

Acceptance criteria for a through-fault test are calculated prior to performing the test using (1) the test source voltage (V_{TEST}), (2) the transformer impedance (Z_{TR}) and (3) CT ratios. The test currents (I_{TEST}) that flow through the transformer windings and also through the CT primaries during the through-fault test are calculated in accordance with the following equations:

$$|I_{TEST}| = \frac{|V_{TEST}|}{|Z_{TR}|} \cong |I_{TESTA}| = \frac{|V_{AN}|}{|Z_{TR}|} \cong |I_{TESTB}| = \frac{|V_{BN}|}{|Z_{TR}|} \cong |I_{TESTC}| = \frac{|V_{CN}|}{|Z_{TR}|}$$

The transformer high-side and low-side currents are then calculated in accordance with the following equation:

$$\frac{|I_{LOW-SIDE}|}{|I_{HIGH-SIDE}|} = \frac{|V_{HIGH-SIDE}|}{|V_{LOW-SIDE}|}$$

The CT secondary currents are then calculated using the CT primary currents and CT ratios for all CTs and protective relays using the following equation:

$$I_{CT\ SECONDARY} = \frac{I_{CT\ PRIMARY}}{CTR}$$

The minimum required current on all CT secondaries is 10mA in order for digital phase angle meters to provide accurate phase angle measurements. Based upon experience, the tolerance band for the measurement of current magnitudes should be +/- 33% of the calculated current magnitudes. This tolerance band allows for instrument error, CT ratio errors and test current imbalances, while allowing for the detection of delta, wye wiring errors, which would be indicated by a +/- 173% difference between the measured and the calculated current magnitudes.

Also, based upon experience, the tolerance band for the measurement of phase angles should be +/- 10 degrees of the calculated phase angles. This tolerance band allows for instrument error and test current imbalances, while allowing for the detection of delta, wye wiring errors, which would be indicated by a +/- 30 degree difference between the measured and the calculated phase angles. This tolerance band also allows for the detection of "rolled" or "switched" conductors, which would be indicated by a +/- 120 degree difference between the measured and the calculated phase angles.

Through-fault Test Execution and Measurements

All transformer protective relay trips are disabled prior to performing the through-fault test and are restored following the satisfactory completion of the test. With the transformer connected in accordance with the test configuration shown in figure 2, the circuit breaker (52) is closed to inject test currents into the transformer windings and thus through all CT primaries and secondaries. With currents flowing through the primaries and secondaries of all the transformer CTs, the magnitudes and phase angles of the currents flowing in the 50/51, 51 and 87T protective relaying circuits are all measured with a digital phase angle meter and compared to the calculated test acceptance criteria. Measurements for the 50/51N and 51G protective relay circuits are taken with B and C phases of the test source disconnected. This causes test current to flow through the transformer neutral, the neutral CT and the 50/51N, 51G relays.

All CT secondary current magnitudes and phase angles must be measured with respect to a common reference voltage. The A-phase-to-neutral voltage (V_{AN}) of the test source is typically used because it has a zero (0) phase angle, making the acceptance criteria calculations very clean. The current measurements are taken by inserting a current probe (also referred to as a current stab) into test switches which are designed specifically for the measurement of currents in protective relaying circuits. A common convention must be used when inserting the current stab into every test switch. A "Black-to-Blade" convention is typically used because it is very easy to remember, but this does not prohibit the use of another convention, as long as it is used consistently.

In order for through-fault test results to be considered satisfactory, all measurements must be within the calculated acceptance criteria tolerance bands. Measurements that fall outside of the calculated acceptance criteria tolerance bands are indicative of a potential wiring error (or other problem) that must be corrected prior to placing the transformer into service for long-term, continuous operation.

Conclusion

Proper testing of large power transformers and their protective relaying circuits following installation or replacement is vital to their proper and continued long-term operation as well as that of the adjacent electric power system. Primary current injection (through-fault) testing is the absolute best testing methodology available for ensuring that all transformer, CT and protective relay wiring are 100% correct following the installation or replacement of a large power transformer.

The Plant Services Group at Fauske & Associates, LLC (FAI) has extensive experience preparing through-fault test procedures and test acceptance criteria calculations for large power transformers and can also do the same for generators, large motors and other differential protective relaying schemes.

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