ABSTRACT

Three-phase transformer testing using three-phase excitation with three-phase measurements and symmetrical component analysis can detect and locate shorted turns, turn ratio errors, and anomalous losses. Such determinations are made based on one test and do not require references to the factory or earlier test results.

KEYWORDS:

Symmetrical Components; Transformer Maintenance Testing; Diagnostics; Short turns; Imbalance

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Application of symmetrical components to three-phase transformer maintenance testing

Introduction

It is proposed to conduct maintenance testing of three-phase power transformers using three-phase excitation, three-phase measurements, and symmetrical component calculations. The results of such measurements are much more sensitive in detecting problems in transformers than single-phase excitation and provide immediate information regarding the health of the transformer with respect to shorted turns, anomalous core losses or incorrect turn ratios.

Current technology & practice

Maintenance testing of power transformers has been conducted on electric power systems for many years. Such testing reduces the rate of transformer failure as well as system outages. Typical tests involve the measurement of electrical insulation quality, as well as the measurement of electromagnetic properties of the core and coil assembly. The electromagnetic properties are of interest here, and their measurement typically includes the measurement of open circuit and short circuit characteristics providing ratio, resistance, impedance, and losses.

Once completed, such measurements are compared to nameplate data, previous measurements or measurements performed at the factory. Differences between measurements are assessed to determine if they indicate a fault or an incipient fault.

Differences expressed by the negative sequence component are extremely accurate as they are measured at the same time, using the same instrument, at the same voltage and frequency and at the same temperature

As all readings are sensitive to influences such as temperature, test equipment, and test voltage, the differences tend to be masked and become insensitive to the small differences we are looking for.

For some time now, technicians have observed that the *changes in the differences between the readings of individual phases* were much more reliable indicators of potential problems than comparisons to earlier readings. Indeed, the differences between phases must be much more reliable because they are obtained at the same time, the same temperature, the same test configuration, and the same test voltage and frequency.

It must be noted that typical test sheets provide guidance as to the determination of the differences between nameplate data and the readings but do not deal with differences between different phases. The same applies to the lack of guidance regarding the comparison of such differences with differences from previous measurements.

Once we recognize that we are looking for an accurate determination of the differences between the phases, symmetrical components come to mind. Such analysis uses well-established techniques that accurately determine the *differences between phases* on the three-phase test transformer. It should be noted that there should not be any differences between the phases in principle. Thus, a difference indicates a problem within the transformer. In this way, a single measurement allows one to assess the transformer condition and does not need to be compared to previous measurements or to factory tests.

Symmetrical component technology

Most power transformers are three-phase transformers, and taking three-phase measurements using three-phase excitation allows us to perform a symmetrical component analysis of the results. Such analysis uses well-established techniques to determine the differences between the phases. *Differences expressed by the negative sequence component are extremely accurate as they are measured at the same time, using the same instrument, at the same voltage and frequency and at the same temperature.* It can be shown that three-phase measurements using three-phase excitation provide accuracy in the differences that are proportional to the linearity and resolution of the test set and not to the transformer test result accuracy. This automatically provides a tenfold improvement in the accuracy and, therefore, the sensitivity of tracing any problems within the transformer.

It must be noted that in an ideal three-phase transformer, with its individual phases behaving in the same way, a negative sequence component will not be generated. This is especially true when excited with a symmetrical three-phase excitation. There will be a residual negative sequence component present in a practical transformer, the primary cause of this being the difference in the excitation losses of the three phases. With this residual loss being extremely small, typically around 0.02%, very small differences between the phases can be readily identified, and problems with the transformer traced and identified. Readily identifiable problems include turn-ratio errors, shorted turns, and anomalous core losses.

In summary, three-phase measurements and symmetrical system component analysis provide the following advantages over conventional testing:

1. The negative sequence component is always an indicator of a problem, with its magnitude and phase indicating the nature and location of the problem.
2. Recognition of the problem on a test transformer is independent of any previous measurements (trending), depending only on the current condition and measurement.
3. The magnitude of the negative component is fundamentally independent of the test voltage, frequency, and temperature of the test transformer.
4. The negative sequence components are typically 10 times more accurate and nearly 50 times more sensitive in identifying problems on the transformer than conventional methods of measuring and comparing the ratio, resistance, impedance, and loss.,

What and how do we measure?

The primary assignment is to perform a three-phase ratio measurement on the test transformer. This means exciting the test transformer with a three-phase source and performing an open circuit test measuring:

1. The voltages on the primary windings (H)
2. The voltages on the secondary windings (L)
3. The excitation current in each phase (A)

From these measurements, calculate:

4. The positive, negative and zero sequence components of the primary winding voltages (H+), (H-), (H0).
5. The positive, negative and zero sequence components of the secondary winding voltages (L+), (L-), (L0).
6. The positive, negative and zero sequence components of the excitation current (A+), (A-), (A0).
7. Transformer ratio **R** = [(H+)/(L+)].
8. The geometric difference of the negative sequence components – secondary minus the primary [(H-) – (L-)*R].
9. The distortion index, **D** = [(H-) – (L-)*R]/(H+).
10. Core loss imbalance, **W** = (A-)/(A+).

The loss imbalance, W, is a complex number where the magnitude indicates the imbalance, while the phase points to the transformer's phase, causing the imbalance, which is the "middle phase" in a typical fault-free transformer

The transformer ratio, **R**, between the (H) and (L) windings is a complex number where the magnitude indicates the ratio, while the phase indicates the phase relationship between the (H) and (L) windings. This automatically identifies the transformer's phasing regardless of the winding configurations, be they Y, D or Z.

The distortion index, D, indicates a lack of symmetry in the transformer. This is primarily caused by turn ratio errors between the phases and, to a lesser extent, by core loss asymmetry. The distortion index, **D**, is a complex number with the magnitude indicating the amount of distortion and the phase pointing to the transformer's phase causing the distortion.

The core loss imbalance, **W**, is always present due to the differences in the core geometry of all three phases. The imbalance increases when a phase experiences larger losses, such as those caused by shorted turns or grounded core bolts. The loss imbalance, **W**, is a complex number where the magnitude indicates the imbalance, while the phase points to the transformer's phase, causing the imbalance. In a typical fault-free transformer, the phase would be pointing to the "middle phase" having less loss than the average.

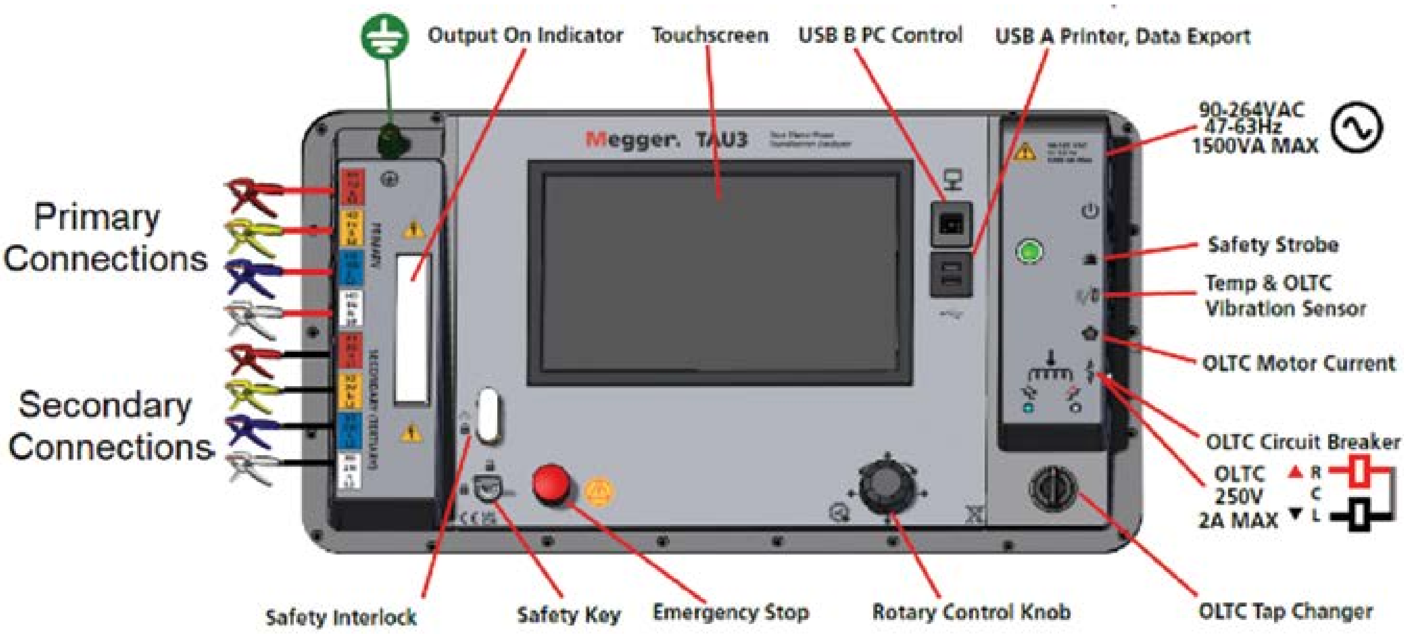
Testing scenarios

Transformer with no faults

A transformer in good condition which is properly demagnetized should provide the ratio, R, within 0.5% of the nameplate ratio; the distortion index, D, of less than 0.03%; and a core loss imbalance, W, of <10%.

A magnetized transformer may show a distortion index, D, up to 0.1% and a core loss imbalance, W, of as much as 60%. For this reason, it is highly desirable that the transformer be fully demagnetized prior to testing. It is important to note that while the distortion index and core loss imbalance readings of a demagnetized transformer will basically provide the same readings at different test voltages, a magnetized transformer will show higher readings of D and W at a lower excitation than at a higher one.

This characteristic can be effectively used to determine the magnetization level of



The core loss imbalance for the transformer with shorted turns will indicate a significant imbalance, while the phase of the imbalance will point to the phase with the problem

the transformer core. A magnetized transformer will show readings approximately twice as high at 24 volts than at a 48-volt excitation.

If any transformer in a demagnetized condition shows readings higher than those shown above, it should be investigated for possible faults.

Transformer with an incorrect turns ratio

A transformer with incorrect turns on one phase will show the ratio, R, which is the average of the ratios of the three phases. It will show the distortion index, D, equal to 1/3 of the turns error, and the phase will point to the transformer's phase with the problem. It is notable that for a positive turns ratio error in phase A, it will show 0*, while for a negative turns ratio error in phase A it will show 180*. Turns ratio errors, if present in other phases, will be indicated by appropriate phase angles.

The core loss imbalance, W, would remain <10% as in a transformer with no faults unless the turns ratio error is exceptionally large.

Transformer with shorted turns

A transformer with shorted turns on one phase will show the ratio, R, which is the average of the ratios of the three phases. It will show the distortion index, D, equal to approximately 1/3 of the shorted turns in magnitude, and the phase will point to the transformer's phase with the problem.

The core loss imbalance, W, will indicate a large imbalance, typically in the range of 10% to 60%, depending on the number of shorted turns. The phase of the imbalance will point to the phase with the problem. It must be noted that both the distortion index, D, and the core loss imbalance should point to the same phase on the transformer.

Transformer with anomalous core losses

A transformer with anomalous core losses on one phase will show the ratio, R, which is the average of the ratios of the three phases. The distortion index, D, may be somewhat higher than normal (>0.03%) and depends on the ratio of the anomalous core loss to the average core loss. The phase of the distortion index will point to the phase with anomalous losses but may not be very definitive if the distortion index is small (<0.03%).

The core loss imbalance, W, will indicate a large imbalance, typically in the range of 10% to 60%, depending on the ratio of the anomalous loss to the average loss. The phase of the imbalance will point to the phase with the problem.

Transformer with a magnetized core

A transformer with a magnetized core will show the ratio, R, which is the average of the ratios of the three phases. The distortion index, D, will be somewhat higher than normal, approaching 0.1%, depending on the degree of magnetization. The phase of the distortion index will point approximately to the phase with the highest residual magnetism.

The core loss imbalance, W, will indicate a large imbalance, typically in the range of 10% to 30%, depending on the degree of magnetization. The phase of the imbalance will approximately point to the phase with the highest residual magnetism.

Three-phase testing of three-phase power transformers, together with symmetrical component analysis, offers a new method of detecting turn errors and shorted turns on power transformers

To check for residual magnetism, the test is to be repeated at a different excitation level. If the excitation level is doubled, the core loss imbalance, W, will be reduced. A reduction of core loss imbalance W by approximately 50% would indicate maximum residual magnetism.

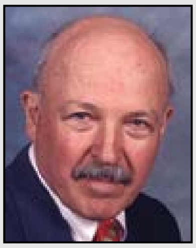
Conclusion

Three-phase testing of three-phase power transformers, together with symmetrical component analysis, offers a new method of detecting turn errors and shorted turns on power transformers. The method is based on the premise that the transformer must not generate negative sequence components when in service, as such generation is associated with errors within the transformer and causes losses within the transformer and in the power system.

The method is definitive and absolute in that it does not depend on factory or previous test results but relies only on the results of current measurements. As such, an instrument working on these principles can automatically identify shorted turns, anomalous core losses and turn ratio errors. One might suggest that a test, as described, should become mandatory before the transformer leaves the factory.

Currently, there are Megger instruments on the market, the TTRU3 - ***"True 3Φ Transformer Ratiometer"*** as well as the new TAU3 – ***"True 3Φ Transformer Winding Analyzer"*** that can be programmed to possess the intelligence described in this article, namely - to detect turn ratio errors, shorted turns, and anomalous core losses, automatically.

Author



Oleh Iwanusiw P. Eng. graduated from the University of Alberta in 1957, with a BSc. degree in electrical engineering. Also, in 1957, Oleh tested his first transformer while employed at the Ontario Hydro Research Laboratory. He continued working at the laboratory for 21 years before embarking into the design and manufacturing of test equipment for the electric power industry. His subsequent positions include Vice President at OLMAN Instruments Ltd.; Manager of New Development at MULTI-AMP Canada Ltd.; Technical Director at AVO MULTI-AMP Canada Ltd.; and independent consultant operating under the name of MIKRO-KOD Consulting Ltd. He developed a simple C&DF test set, CB100, that was manufactured over a span of more than 50 years under the name of Instrument Associates, Olman Instruments, MULTI-AMP, and Megger. He developed a true three-phase turns ratiometer, the TTRU3, US Patent #11,105,838 B2, assigned to MULTI-AMP Corporation. Member of AIEE and IEEE. He is the author of the photo album CHURCH in RUINS, ISBN 0-9691657-3-0, 1987.