ROUTINE IMPULSE TESTING

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INTRODUCTION

IEEE Standard C57.12.00 specifies that impulse testing of distribution transformers is a required test instead of a design test. It's been a long time coming. A conveyorized system with capability of impulse testing 50 transformers per hour was operating 50 years ago at a GE plant in Holyoke Massachusetts. Then as today engineers feared that insulation could be punctured with the applied impulse without indicating a fault in the transformer. To minimize any chance of this happening an electronic device was invented that automatically detected even a single turn fault. As the years went by, many manufacturers either adopted impulse testing as a routine test, as an audit test, or could at least perform impulse tests when specified.

A study presented to the IEEE Transformers Committee in 1982 indicated that lightning caused about 50% of all premature failures of distribution transformers. Transformer manufacturers also reported that routine impulse testing found more than twice as many manufacturing defects as the total found by doing applied potential and induced potential tests. The conclusion was that although routine impulse testing of low voltage windings would be impractical because of the low surge impedance that many manufacturers were already using some form of impulse testing of primary windings and there was a need to standardize the test and make it mandatory.

IEEE Standard 57.12.00 was changed in 1993 as a result of these earlier efforts. The test procedure is specified in a revision of IEEE Standard C57.12.90 Section 10.4. A Recommended Practice for Routine Impulse Tests for Distribution Transformers IEEE Standard C57.138 was issued in 1997. This presentation is a summary of information on impulse testing of distribution transformers, particularly as it pertains to single turn fault detection. The capacitive current shunt and analog detector developed 50 years ago is still used today, however, digital measurement systems have made it possible to greatly improve the fault detection sensitivity.

ROUTINE IMPULSE TEST STANDARD

. The required test is to apply one or two 100% amplitude full wave lightning impulses to all primary terminals. Failure detection is by comparison of the 100% amplitude test current wave to a reduced test current wave on the same transformer or by comparison of two 100% current waves to a 100% or reduced test current wave on a reference transformer. The low voltage windings of a transformer must not be shorted during the impulse test because the additional short circuit current prevents proper fault detection. Care must also be taken in grounding primary terminals of a three-phase transformer because lowering the effective transformer impedance can also reduce the single turn fault sensitivity. No permanent record of the impulse test is required and the test must be performed before the low frequency dielectric tests. High voltage windings with series or multiple connections or with delta or wye connections must be impulsed "on each connection at its assigned BIL". The fault detector must have the sensitivity to detect a staged fault consisting of a loop of wire placed over the coil being tested.

SPECIAL NEEDS

All major distribution transformer manufacturers have impulse testing equipment. However, it is not possible to perform an impulse test, even a simplified one, on every transformer made using equipment designed for making a couple of ANSI lightning impulse tests per day. Fault detection, which is the

heart of routine impulse testing, needs to be automatic for high volume testing and in any case all faults should be clearly indicated. A major insulation fault, such as terminal to ground or terminal to a low voltage winding is an easy fault to detect. Typically this kind of fault can be detected by observing noise, smoke, and bubbles. Another means is to compare the magnitude or shape of the voltage or current curves of a reference pulse and test pulse.

Other faults are more difficult to detect using standard impulse testing techniques. If a fault occurs layer to layer or turn to turn any change in the voltage curve can be so insignificant that it is impossible to detect on a surge oscilloscope even when a direct curve comparison is made. IEEE Guide C57.98 Section 11 describes fault detection by comparing ground current traces. This is the most sensitive method of fault detection for a full wave lightning impulse test. For power transformers, particularly of disc winding design, the inductive component of current is large in comparison to the capacitive component. This is important because it is the inductive current that changes when a fault occurs. In fact it has been shown that a single turn fault can be found in a power transformer by the ground current method even when all other windings have been shorted.

Finding a single turn fault in a distribution transformer is more difficult. The layer wound coil is very compact and the capacitances are relatively high. During the high rate of rise of the 1.2 microsecond front the capacitive current may be 100 amperes or more. In contrast, the inductive current is a few milliamperes for the duration of the impulse wave
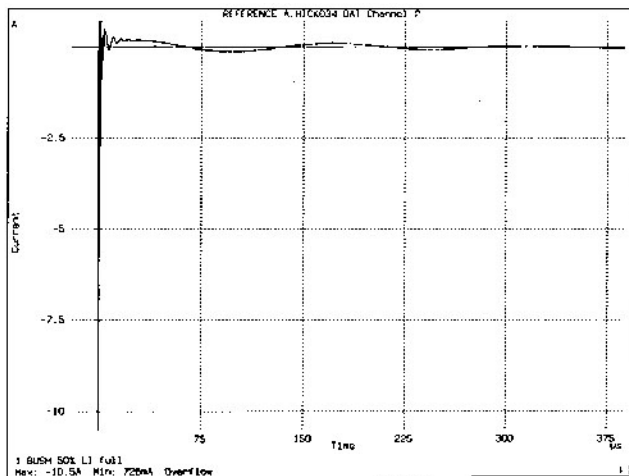

FIGURE 1. Impulse current curve on a Distribution Transformer

. Figure 1 is the ground current curve on a typical 25kva distribution transformer. The applied impulse is

16 kV. The current after the high pulse is about 150 ma.

A distribution transformer may have as many as 7000 turns in the high voltage winding. If one turn is shorted the capacitive current is unchanged but the inductive current is significantly increased. However, the change in inductive current although significant is unnoticeable because the inductive current is so small to start with. Figure 2 is a comparison of ground current curves on a 37kva, 14400 primary volt, 240 secondary volt pole type transformer. The overlaid curves are with no fault on the transformer and with a simulated single turn fault made by wrapping a loop of wire around the core yoke. A longer oscillatory pulse of about 150 milliamperes follows the short pulse with the 10.5-ampere crest. It would be difficult to detect a single turn fault on this transformer by observation of the curve difference.
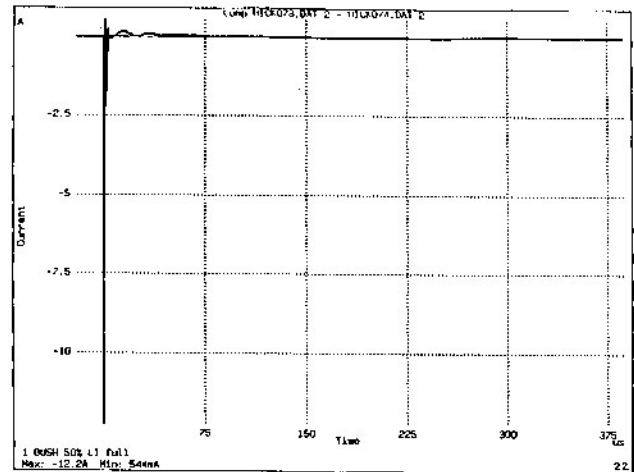

FIGURE 2. Comparison of Impulse Current Curves

Figure 3 is the same comparison of ground current curves but the oscilloscope is scaled so that most of the high current pulse is off scale. The difference between the curves is now obvious to anyone analyzing the oscillogram but in a production situation such a small difference could very easily slip by.
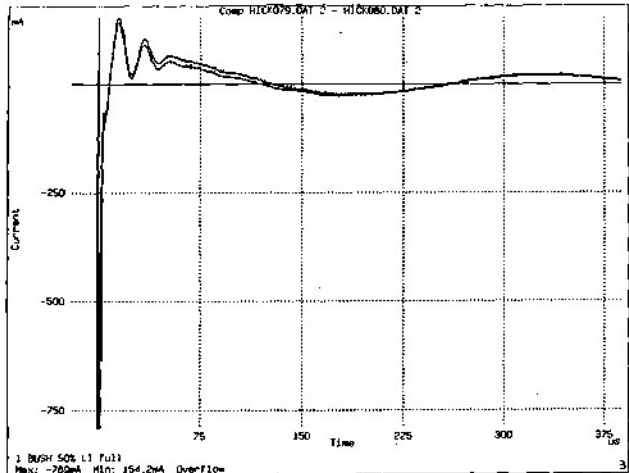
FIGURE 3. Current Comparison with Increased Sensitivity

AUTOMATIC FAULT DETECTION

The perfect fault detector would ignore the capacitive current spike and integrate the inductive current over several hundred microseconds. A typical fault detector used today has a shunt made up of a capacitor with a bleeder resistor instead of a pure resistive shunt. This is called a neutral impedance. The capacitor reduces the high current pulse and integrates the inductive portion of the impulse current wave. The output from the shunt is ideally in the several hundred-volt range and the first zero crossing is several hundred microseconds. Manual detection is done by displaying the output on an analog or digital surge scope. Automatic detection is accomplished either by discrimination of curve amplitude using an analog or digital detector or comparison of curve areas using a digital detector.
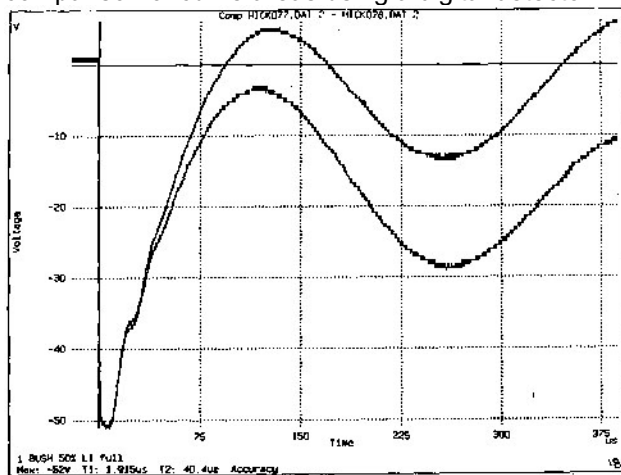

FIGURE 4. Comparison of Neutral Impedance Curves

Figure 4 is a test on the previously described transformer but the resistive shunt has been replaced with a neutral impedance. Now the fault is easily detected visually and automatic detection is a good possibility.

DIGITAL MEASUREMENT SYSTEMS

Digital oscilloscopes are used in most test laboratories and are being applied to impulse testing. An 8-bit scope with a 250-kilohertz bandwidth has the resolution and speed to record the fault detection signal across the neutral impedance. However, an off the shelf test bench oscilloscope will produce erroneous results and not last long unless it is well protected from the impulse laboratory EMI. Also, a 10-megahertz bandwidth is required for making measurements of the lightning impulse applied wave and a 10-bit oscilloscope is recommended for making impulse curve comparison for general impulse testing. In most cases it would be better to buy a product built for impulse testing rather then spend a considerable amount of effort hardening a test bench scope and writing the software.

Several impulse test equipment manufacturers can provide impulse oscilloscopes or impulse measuring systems that have been hardened to the impulse laboratory environment. These systems capture the impulse curves, store them, display them with editing capabilities, analyze them in time or frequency domain, and print the results. They are computer based and either come with a personal computer or can be interfaced to a personal computer. Seeing as how the systems are single purpose and have a limited market the ability to customize is stressed. The vendor either provides custom software or provides a means of tailoring the standard software to the application and interfacing application software to it. Figures 5 shows an example of an input screen used for production line impulse testing. An application program provides input to the measurement system simplifying the test operation
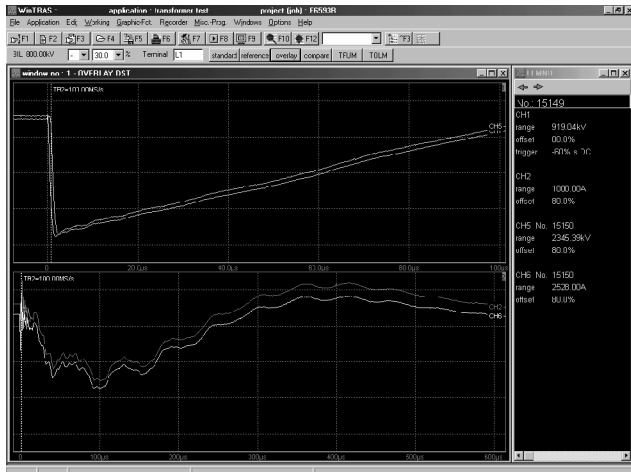
FIGURE 5. Input Screen

FIGURE 6 Current Curve No Fault

A digital measurement system used as fault detector has several advantages over an analog system. One major advantage is the flexibility. Once an analog detector is built any significant changes requires that the equipment be taken out of service and rewired. Installing a new program changes a digital system. Another advantage is the ability to store test data for later analysis. If a fault occurs on an automatic system the data can be saved for manual interpretation of the fault. The computer or computer interface that is normally provided with a digital system simplifies the integration of the fault detector into an automatic test system. But probably the greatest advantage is the ability to use mathematical manipulation of the digital data to increase the sensitivity of the fault detector.

FAULT ANALYSIS

Fault analysis with a digital system starts with processing data points of the reference and test curves. The curves representing the impulse current contain the fault information and to do anything with these curves they must be matched in time and scaled in amplitude. This is not a trivial task. First, the exact amplitude of the current is not known and a conservative estimate of the amplitude may result in the curve being much less than half the full range of the instrument. Secondly, if a fault occurs the current amplitude will be affected. Both these factors make it less desirable to use the current curve data points to match up the curves. Figures 6 &7 show how the current curves can be improperly matched. Figure 6 indicates the positive peak of the curve is 187 MA but when it is compared to a failure in figure 7 the scale indicates a peak of about 100 MA.
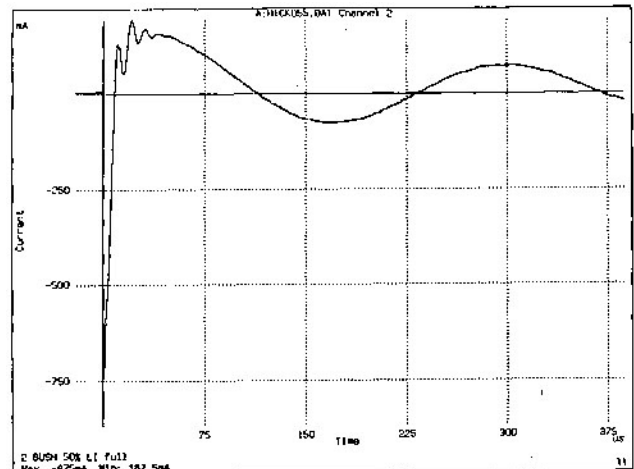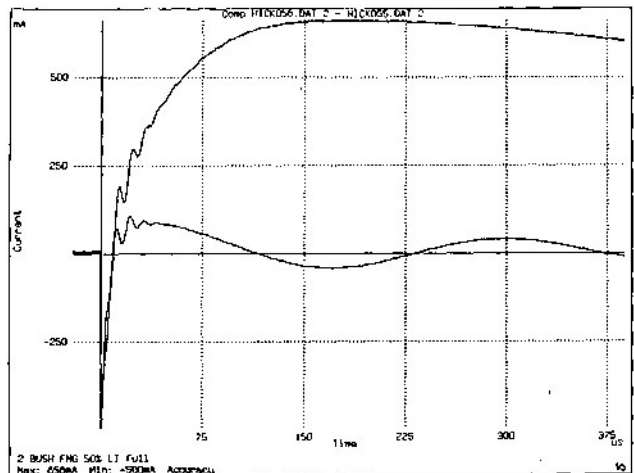

FIGURE 7 Current Comparison Mismatch

A better method is to use a two channel system, capture the applied voltage curves which are of a known amplitude and form, match the voltage data points, and use the timing and scaling information to match the current curves. This, of course, requires that the two channels be sampled simultaneously and that the data files be related. If it is impossible to match the voltage curves a major fault has occurred and no additional analysis is required. Figures 8 & 9 show the voltage and current curves on a transformer failure. Analysis of the applied voltage wave shape indicates a major insulation failure.
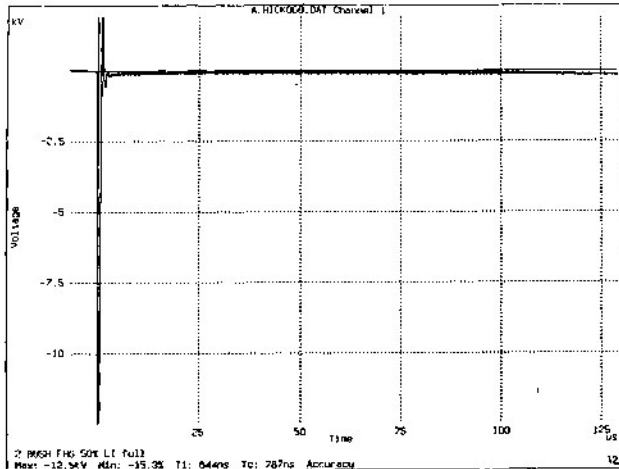
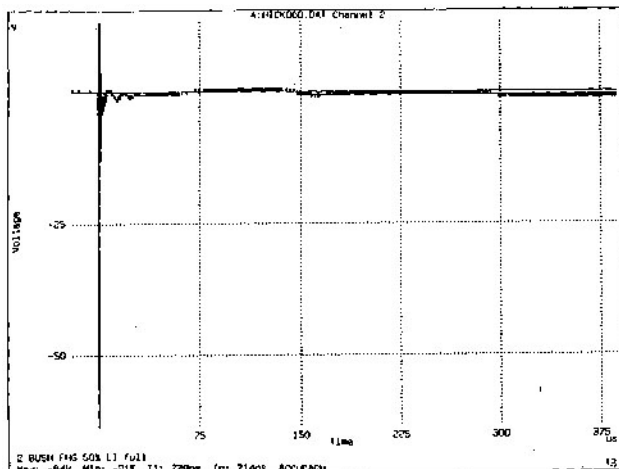FIGURE 8 Voltage Curve, Ground Fault

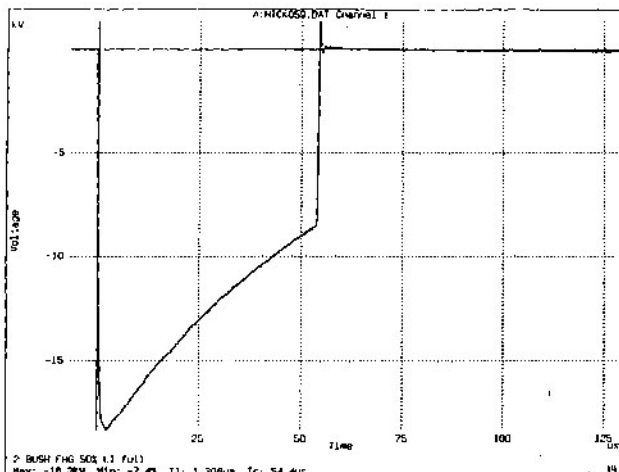FIGURE 9 Current Curve, Ground Fault

FIGURE 10 Voltage Curve, Ground Fault

Figures 10 & 11 show another failure but the breakdown occurred after the half crest point. A

major insulation failure is again indicated by simple comparison of the applied voltage wave.
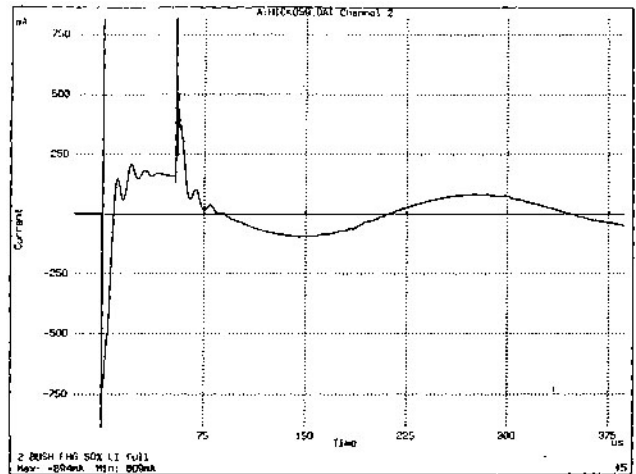

FIGURE 11 Current Curve, Ground Fault

Figures 12 & 13 show the comparison of reference and test curves for a primary to secondary failure. The voltage curves barely indicate a failure but the current curves show a failure that involves a major portion of the winding. A simple comparison of the current waves would find this fault in all transformers. In this case the neutral impedance shunt is 0.1 microfarads and 100 k ohms and the primary winding is isolated from the tank.
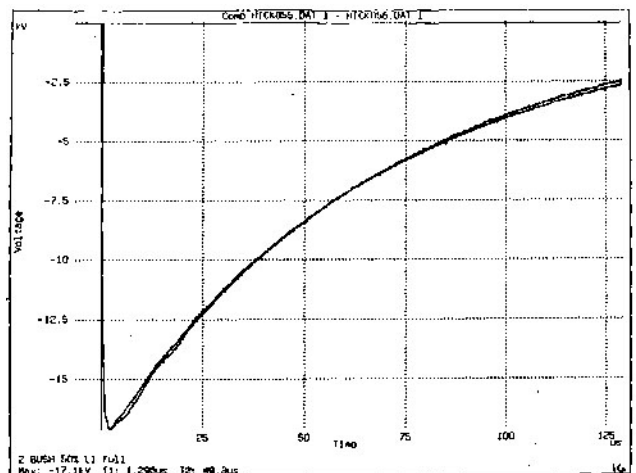

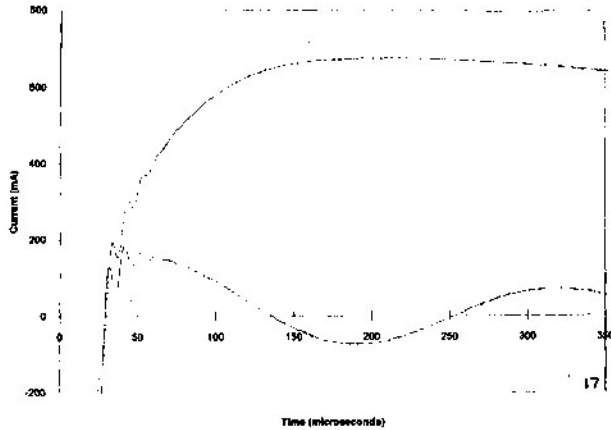FIGURE 12 Voltage Curve, Fault To Secondary

FIGURE 13 Current Curve, Fault To Secondary

SINGLE TURN FAULT DETECTION

The above curves demonstrate failures that are easy to detect manually by comparison of the raw current and applied voltage curves. They also can be automatically detected by subtracting the test curves from the reference curves. If the absolute difference is more than a predetermined percentage of full scale or maximum curve amplitude a failure is indicated. Sometimes the fault will occur between two adjacent turns. Figure 14 shows the comparison of current curves on a small transformer with and without a simulated one-turn fault. The simulated fault is a loop of wire wrapped around the core.
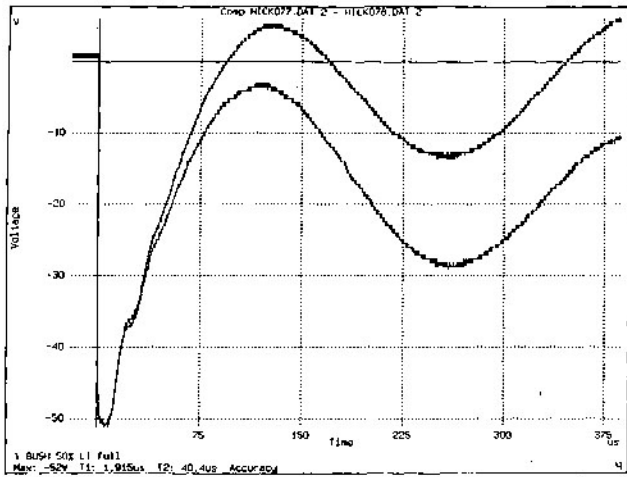

FIGURE 14 Neutral Impedance Curves,
Comparison of Single Turn Fault

The fault curve closely matches a curve produced when two adjacent turns are shorted together on the primary coil (see Figures 17 & 18). The difference in the curve caused by the fault can be relatively large as in the case of a higher kVA, lower primary voltage transformer or it can be vanishingly small as in the

case of a 5 kVA, 34 kV transformer. Another difficult fault to find is between different strands on a multistrand conductor winding.

The neutral impedance voltage curve can vary from an overdamped exponential to a damped oscillation. Significantly, a faulted turn or several faulted turns results in more negative current throughout the first 200 microseconds or more of the impulse wave. The neutral impedance curve may not change shape enough to be obviously different but will have a dc offset. The accumulative affect is always significant. Figure 15 shows difference of the comparison made in Figure 14. Figure 16 shows the accumulative difference. The neutral impedance shunt is 0.1 microfarads and 100 k ohms and the primary winding is connected to the tank.
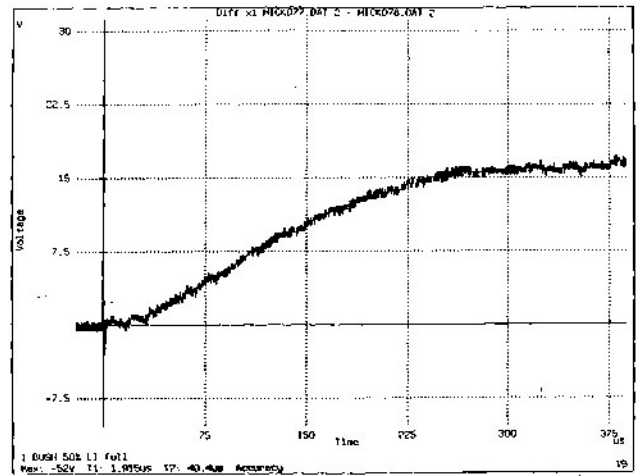

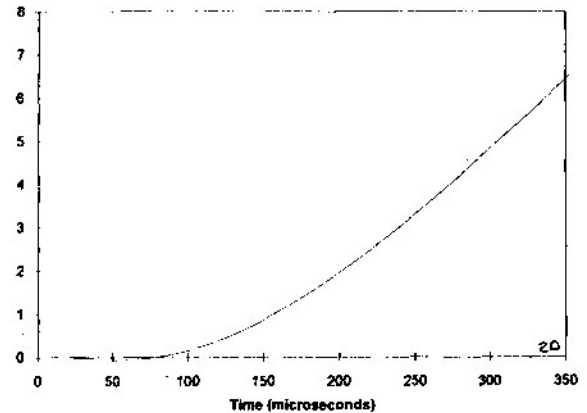FIGURE 15 Neutral Impedance Curves,
Difference of Single Turn Fault

FIGURE 16 Neutral Impedance Curves,
Accumulated Difference

The compared curves of Figure 14 track together for the first 30 microseconds and then deviate for the

next several hundred microseconds. This is typical of what will occur for any winding fault on any distribution transformer. Seeing there is no useful information in the first part of the neutral impedance curve those data points need not be included in the analysis. The difference of the neutral impedance curves should be accumulated for the remaining part of the first 300 or 400 microseconds after the start of the impulse wave. The applied voltage curves need to be compared for about 150 microseconds. These are conservative estimates and with more experience the amount of data to be analyzed, which is significant, could possibly be reduced.

NEUTRAL IMPEDANCE SELECTION

The capacitance of the transformer to be tested and the capacitance of the neutral impedance c form a voltage divider. In testing a transformer with an isolated primary winding such as a single phase two bushing transformer the capacitance of the primary winding C_H forms the high voltage arm of the divider. In this case the equation

$$C \approx C_H \frac{BIL}{V}$$

can be solved for the neutral impedance capacitance. BIL is the full wave voltage applied to the test piece and V is the voltage which will be input to the oscilloscope or other fault detector circuit. About 50% of full scale on the fault detector is a good design parameter to allow for test piece variance.

If the primary winding is connected to the tank as in a single phase, single bushing transformer the tank must be isolated from ground so that the neutral impedance can be inserted in the impulse current path. Capacitances to ground and between windings increase the amplitude of the current pulse and the high voltage arm of the divider is a complex arrangement of capacitances.

The resistor in the neutral impedance depends somewhat on the type of fault detection. If manual detection is used or if an automatic system is used with no further integration about a 10-millisecond RC time constant is appropriate. With a second stage of integration a 1 millisecond RC time constant is good.

FAULT DETECTION WITH A RESISTIVE SHUNT

A neutral impedance with the proper combination of capacitor and resistor increases the sensitivity of the fault detector many folds over the resistive shunt. The resistive shunt is normally sized to capture the whole wave that includes the high current pulse. Put what if

the current spike is ignored? Figure 17 is the comparison of curves showing the affect of a one-turn fault. A 20-ohm shunt was used. Figure 18 is the same comparison but a 500-ohm shunt was used. By using a 25 times larger shunt a difficult detection situation becomes an easy one. This method is nearly as sensitive as the neutral impedance method and the real time information is still available. One use of this information would be to save the data files for all tests that concerned a transformer failure. Manual analysis could then determine more about the nature of the fault. On the negative side, to use this method either the current spike must be chopped down without distorting the remaining wave or the oscilloscope must have a voltage withstand 25 times the selected range. Further processing of the signal is the same for the resistive shunt as for the neutral impedance.
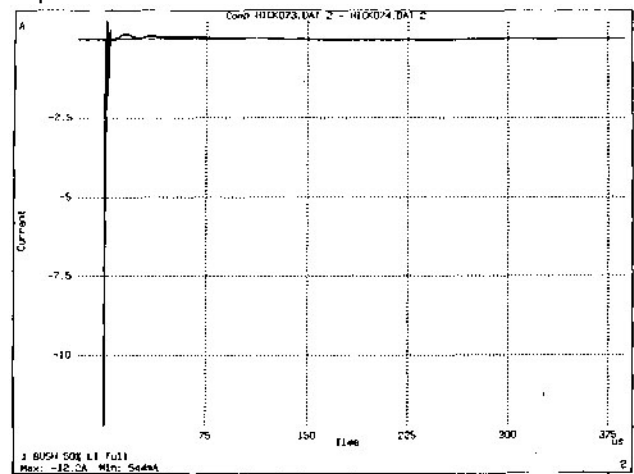

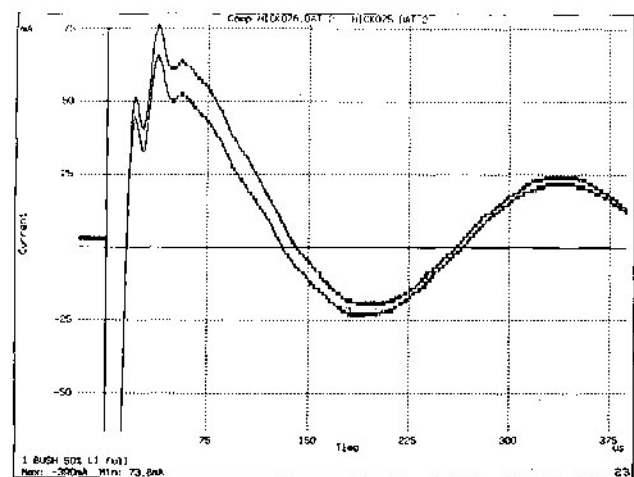FIGURE 17 Current Curves, 20 Ohm Shunt

FIGURE 18 Current Curves, 500 Ohm Shunt

FAULT DETECTION WITH A CURRENT TRANSFORMER

A current transformer can be used in place of the neutral impedance or the resistive shunt. Signal isolation and lower energy protection circuits are advantages of this method. The current transformer will tend to saturate because of the dc in the current wave and requires a prebias circuit

VERIFICATION OF EXPERIMENTAL METHODS

Most of the single turn faults in the curves shown are simulated with a loop of wire around the core yoke. To verify that this is a fair simulation the 37 kVA transformer was shorted turn to turn by removing wire insulation and forcing a screw between the turns. The transformer is a core type and the faults were made on the outside layer of the primary coil away from the lead being impulsed. Figure 19 shows a short at the top of the coil and Figure 20 shows a short at the bottom of the coil. A simulated fault on the same transformer is shown in Figure 14.
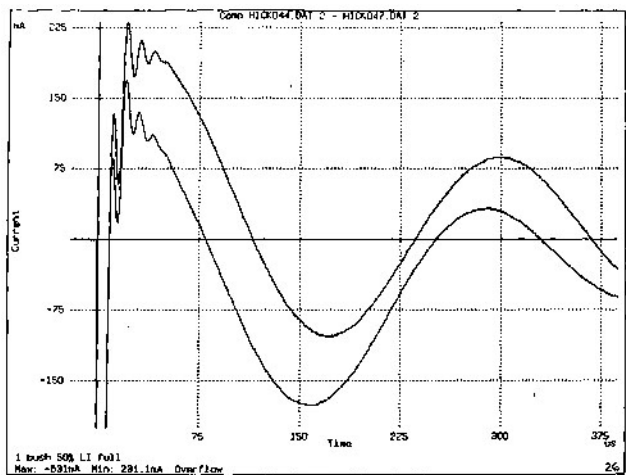

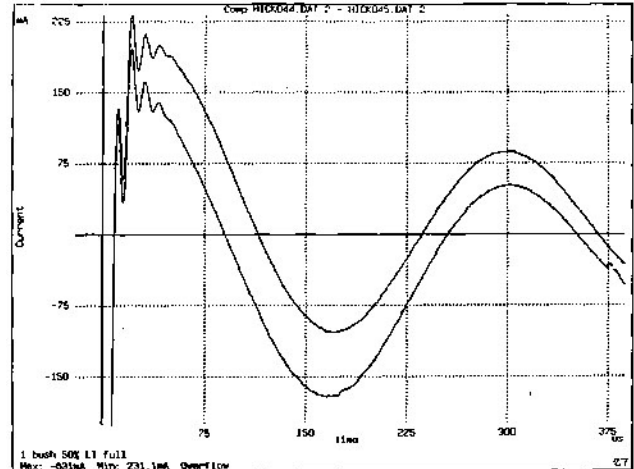FIGURE 20 Comparison, Actual One Turn Fault

FIGURE 19 Comparison, Actual One Turn Fault

DETERMINING DETECTOR SENSITIVITY

Routine Impulse Test Standard C57.12.90 Section 10.4 specifies that the sensitivity of the failure detection system be checked by placing a loop of wire around the transformer core as a staged fault. This method can be proven to be adequate but is only practical on a limited basis. There are considerable differences in the current waveforms depending on transformer size, form, and winding connections. A small quantity of transformers could be built with switchable staged faults and tested on a routine basis to certify the sensitivity of the fault detection system. It also may be possible to inject signals into the shunt, which simulate the current from the various transformer types. Another method that has been used for many years is to connect a properly sized resistor across the secondary terminals to simulate a fault.

Making a few conservative assumptions knowing that only an approximate answer is necessary derived the equation used for the resistor calculation. First, if the impedance of the shorted turn is known as well as the voltage induction the current flowing in the shorted turn can be determined. If the number of turns in the winding being tested is known the change in test current due to the shorted turn can be calculated. The impedance of a shorted turn is made up of resistance and self-inductance. Self inductance is small compared to the resistance of the turn especially for small transformers. An estimate of the impedance of a shorted turn can be made by dividing the power frequency impedance of the winding being tested by the turns in the winding. The actual impedance will be less than the estimate.

The effect of the shorted turn is approximated by a current flowing in the low voltage winding equal to the current in the hypothetical shorted turn divided by the number of low voltage turns. The voltage induced across the low voltage bushings of a distribution transformer during lightning impulse testing is approximately the turns ratio voltage. If the secondary impedance is assumed to be small compared to the current limiting resistance a minimum resistance value to place across the secondary winding when checking detector sensitivity would be

$$R \approx \frac{\%Z \bullet V_{HV} \bullet V_{LV} \bullet T_{LV}}{10^5 \bullet KVA}$$

where R is the minimum resistance to be used in checking sensitivity. The other variables are the primary and secondary voltage ratings ($V_{HV} \& V_{LV}$) and the secondary turns and the transformer power rating ($T_{LV} \& KVA$).

CIRCUIT PROTECTION

WHEN DESIGNING A FAULT DETECTION SYSTEM REMEMBER THAT THE FULL ENERGY AVAILABLE TO TEST A TRANSFORMER WILL BE DISCHARGED INTO THE FAULT DETECTOR SHUNT WHEN A FAILURE OCCURS. Protection devices must absorb this energy and reduce the voltage to a level that the circuitry can withstand. Also, the system must be designed to recognize that the protection circuitry has functioned and indicate a failure even on a reduced shot.

CONCLUSIONS

The Routine Impulse testing of Distribution Transformers has to be performed quickly and reliably. Fault detection should be automatic for high volume testing and in any case all faults should be clearly indicated. It is generally accepted that a shorted single turn is the most difficult fault to detect. It is also expected that a small, very high voltage transformer would be most difficult in which to detect a one-turn fault. The location of the turn in the coil is also of some importance. Testing has been done which indicates that a single turn fault can be detected even when testing a worse case transformer.

There are real advantages to using a digital system and making a comparison between a reduced level and 100% level impulse on the same transformer. Using a reduced wave from the transformer being tested as a reference is a much simpler system because there is no need to have an elaborate system for storing prior test results and relating them to other transformers. A digital system is more flexible and easier to modify than the analog system. Digital data can be stored as long as needed and the system automated by interfacing to a computer. By using a comparison of the voltage curves to detect ground faults and the accumulated difference of the current curves to detect winding faults a foolproof fault detection system can be realized.

The neutral impedance shunt stands the test of time. A high impedance resistive shunt has the advantage of keeping the time information in the current wave but application experience is minimal. A current transformer can also be used. Whether a neutral impedance or resistive shunt is used no more than four or five are needed for all sizes of distribution transformers. The shunt needs to be protected with a spark gap or other high voltage protective device and it must be installed in such a way that the fault detector is not bypassed.

In practice shorting a turn on a Distribution Transformer to check the fault detection circuit sensitivity is costly and not done on a regular basis. But a shorted turn can be simulated by placing a resistor across the low voltage bushings of a transformer under test.

IEEE C57.138 is a good reference for getting guidance on performing the required impulse test. Not only is the procedure explained in detail but also there are diagrams showing how to connect any single phase or three phase transformer.