Limits of Sensitivity for Detecting Inter-turn Faults on an Energized Power Transformer

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Abstract-- This paper presents an experimental investigation of inter-turn faults on a three-phase transformer. The procurement of a transformer custom made with the turns between taps designed to survive inter-turn faults is described. The experimental setup with an emphasis on the shorting mechanism and data acquisition system is described. Results from short circuits imposed separately on both an outside and inside leg over a range from 2% to 10% of the turns are presented. Tests were conducted with the transformer connected in wye-wye and delta-wye with the tertiary connected delta.

I. Introduction

Determining the limits of sensitivity to inter-turn faults on an energized power transformer was a senior design project during the 2006-2007 school year at the University of Idaho. The objective of the project was to conduct tests to determine the feasibility of a negative sequence differential element for detecting inter-turn faults on an energized power transformer. Several short circuit tests were conducted on a custom-built transformer in the spring of 2007. Data was collected during the tests, and then analyzed to determine if a negative sequence element could be used to detect inter-turn faults.

Effectively protecting large transformers from inter-turn faults is a major problem in the electric power industry. Large power transformers cannot easily be removed from their location and replaced. Many large power transformers are built in Europe and shipped to North America. This construction and transportation process can take several years. As a result of this long replacement time and the fact that large transformers cost several million dollars, the protection of transformers is of high priority.

Most transformer faults originate as smaller inter-turn faults resulting from insulation break down. Unfortunately, the existing methods for detecting inter-turn faults on energized power transformers are not always accurate or reliable. Devices such as the Buchholz relay can send false alarms when a transformer is over-heating due to load and through-fault conditions. A traditional differential relay is not sensitive enough to see inter-turn faults under heavy loading conditions, and may not trip until the fault has caused extensive damage to the transformer.

A need has arisen for a new method of detecting inter-turn faults based on their signature in the phase quantities. If this method could be utilized, power engineers could accurately determine the condition of a transformer, and electric utilities and cooperatives could save time and money in the event of an internal fault.

II. Transformer Design and Procurement

The original design specifications called for a 50kVA, 240V/240V/24V, three phase, three winding transformer. The design specifications also called for 0.5 volts per turn with taps at 1, 2, 4, 8, and 10 turns. The taps were to be configured such that a shorting mechanism could be placed across different percentages of the total winding. To prevent damage to the transformer the windings on each leg were to be rated to withstand repeated faults.

The design constraints for this project were particularly rigid, which did not allow much variation in the design. However, the original specification for the transformer could not be completely met due to practical constraints. Safety played a major role in the design of the transformer with the tests to be conducted in an educational lab with a maximum source voltage of 240 volts. The constraints dealt with physical dimensions of the transformer. Some of the practical constraints were window size, current carrying capacity of the windings, volts per turn on the windings, and how the transformer would be operated.

Procuring the transformer began with preparing a specification sheet based off of the original specifications. A U.S. transformer manufacturer, who specializes in building custom transformers was the only company we contacted that expressed interest in designing a transformer to our specifications. Not many manufacturers build custom transformers of this size.

The selected manufacturer agreed to build the transformer with the original specifications. The specifications were then examined by a design engineer who determined that the transformer could not be built

as specified. One key specification was that the 50kVA, 240V/240V/24V transformer be designed to have one-half volts per turn and have taps on the primary at 1, 2, 4, 8 and 10 Volts. With the number of turns specified for this initial design, the resistance of the windings would have been driven up so high that the secondary voltage would collapse as soon as any load was applied.

The ratings on the transformer windings needed to be increased to prevent damage due to the amount of current in an inter-turn fault. The turns between the intermediate taps were rated for four times the nominal value to withstand the anticipated fault current

A second set of specifications was completed and called for an increase of volts per turn (4.8V/turn), 480A rating on the intermediate taps, and taps at 2, 4, 8 and 10 percent of the secondary winding.

The final design did not meet the original specifications for the desired transformer, but turned out to be the only option available. With the low tap at two percent of the secondary winding, or 4.8V, the second design still provided enough resolution for the method to be tested effectively.

III. Transformer Description

The transformer used for testing is a three phase, three winding transformer with taps at 2, 4, 6, and 10 percent of the windings. The ends of each winding were left open in order to connect the transformer in wye or delta configuration. The primary is rated for 55kVA at 240 volts, the secondary is rated for 50kVA at 240 volts and the tertiary is rated for 5kVA at 24 volts. This transformer allowed for tests to be conducted with varying percentages of windings being shorted together. One turn, or 2% of the total winding, could be shorted out on each leg of the transformer. The custom built transformer can be seen in Fig. 1.

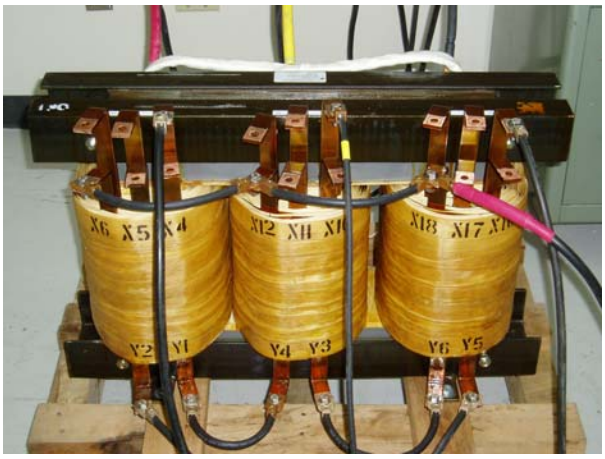


Fig. 1: The Secondary Side of the Custom-built 55kVA Transformer

IV. Experimental Setup

Figure 2 shows the laboratory setup used for the inter-turn fault testing. The circuit was energized by a 240V laboratory supply. Two resistive three phase load banks were operated in parallel in order to fully load the transformer. The primary and secondary phase currents were measured with window-type current transformers connected to a microprocessor relay. A three-line diagram of the laboratory setup can be seen in Fig. 3.

A 200A three phase magnetic contactor was connected across the appropriate taps to short out 2, 4, 6 or 10% of the winding. The contactor's armature was wired through a switch to a 120Vac outlet. When the switch was closed, the contactor would close and initiate the fault. A three-phase fuse block with three 100A fuses was placed in series with the contactor in order to clear the fault within a few cycles to prevent damage to the transformer. The shorting circuit can be seen in detail in Fig. 4.

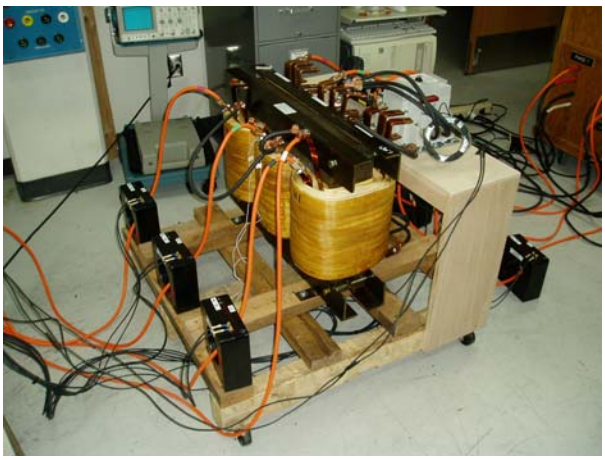


Fig. 2: Laboratory Setup for Fault Testing

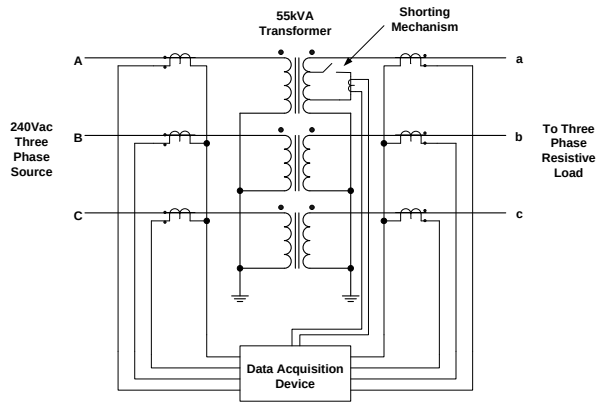


Fig. 3: Three Line Diagram of the Laboratory Setup Showing the Shorting Mechanism on A Phase.

The leads for the shorting circuit were run through the window of a 1320:1 current transformer used to measure the short circuit current. This CT can be seen on the left in Fig. 4.

The contactor was rated for 200A per leg. All three legs of the contactor were used in order to boost the current carrying capacity of the contactor.

The fuse casings were Bussmann REN-100, with multiple fuse elements used in each case in order to increase the fusing current. The fuses were sized to burn and clear the fault within 5 to 10 cycles of inception. Clearing the fault within a few cycles was done to prevent thermal stress on the transformer windings.

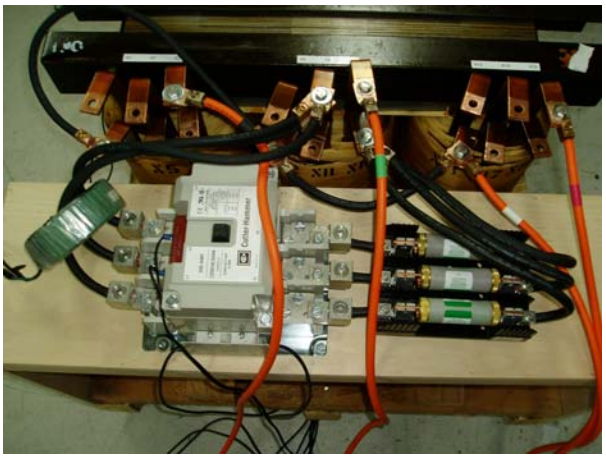


Fig. 4: Shorting Mechanism Consisting of Motor Contactor, Fuse Block, and Current Transformer

After conducting several tests, it was determined that the fuses were clearing the fault faster than 5 cycles. Clearing faster than 5 cycles did not allow for enough data to be collected. Later tests were conducted using first insulated 14 awg wire, and then 14 awg solid copper wire. For these tests, the switch connected to the contactor armature was switched on and off manually in order to initiate and clear the fault. Each strand of wire would only last for a few tests and would eventually melt or disintegrate. During some of the tests, the current in the short circuit would gradually decay. Current decay was due to the wire in the fuse casings going into a liquid state, which causes its resistivity to increase significantly.

Three toroidal 200:5 C20 current transformers were connected to measure the currents on the primary and secondary sides of the transformer. Each set of CTs was connected to measure current into the transformer as in a current differential. The secondaries of the CTs were wired to the two sets of current inputs on a relay. An additional 1320:1 current transformer was placed in the shorting circuit to measure the fault current during testing. The relay was equipped with only six current inputs, so one voltage input was converted to a current input. For some tests, the phase voltages on either the primary or secondary winding were recorded. The primary and secondary voltages could not be measured simultaneously due to the conversion of the voltage inputs to a current input.

Existing production relays do not contain a negative sequence element to detect inter-turn faults, so the relay had to be externally triggered to begin collecting event report data. The 52a contact on the motor contactor was wired in series with an optoisolated input in the data collecting device. The 125Vdc wetting voltage for this circuit was supplied by an Adaptive Multi-Channel Source. The word bit for the input was assigned to the event report trigger in the relay logic so the relay would begin recording the fault data as soon as the fault was closed in.

Once the event report had been collected by the relay, it could be retrieved in COMTRADE format with a PC. COMTRADE files were used because they have high resolution and a fixed sampling rate.

IV. Tests

The objective of the testing was to determine how the negative sequence differential would react to faults across different percentages of the winding. This was completed by placing a shorting mechanism across 2% to 10% of the winding. The load on the transformer was varied to see how it would affect the sensitivity of the negative sequence element.

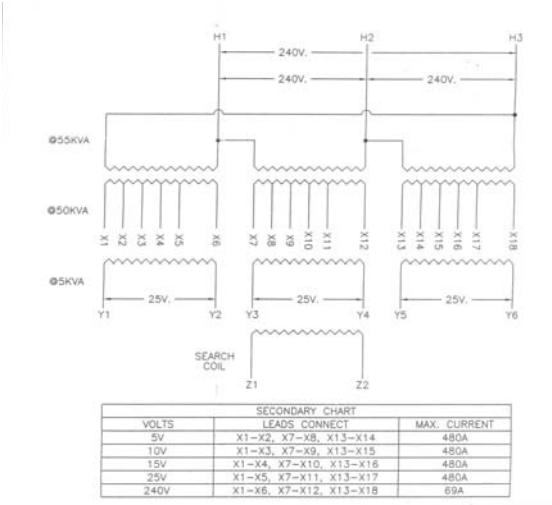
The initial tests were conducted on an outside leg of the transformer. A variety of tests were completed and ranged from 2% to 10% of the windings being shorted.

Tests were also completed on the center leg of the transformer, which also ranged from 2% to 10%. All tests were completed with the transformer connected in a wye-wye or delta-wye with the tertiary connected delta. As mentioned previously, the load current for these test ranged from 25 Amps RMS for the initial tests to 90 Amps RMS for final tests. After each short circuit test, the transformer was de-energized and allowed to cool down. Then the transformer was run for a short period of time before the following test to allow for any DC offset in the phase currents due to inrush to decay. A summary of the short circuit tests that were performed can be found in Table I.

Table I. Transformer Configurations for Short Circuit Testing.

Test	% Winding Shorted	Shorted Taps	Connection	RMS Load Current
1	10	X1-X5	Y-Y	25A
2	10	X1-X5	Y-Y	50A
3	6	X1-X4	Y-Y	50A
4	6	X1-X4	Y-Y	50A
5	4	X1-X3	Y-Y	50A
6	4	X1-X3	Y-Y	50A
7	4	X1-X3	Y-Y	50A
8	2	X1-X2	Y-Y	50A
9	2	X1-X2	Y-Y	50A
10	2	X1-X2	Y-Y	50A
11	2	X1-X2	Y-Y	90A
12	4	X1-X3	Y-Y	90A
13	2	X7-X8	Y-Y	90A
14	6	X7-X9	Y-Y	90A
15	10	X7-X11	Y-Y	90A
16	2	X1-X2	Δ-Y	90A
17	6	X1-X4	Δ-Y	90A
18	10	X1-X5	Δ-Y	90A

The transformer wiring diagram in Fig. 5 shows the tap locations and winding current ratings. The wiring diagram shows the primary tied in a delta, but the delta was cut open to allow for the winding to be wye or delta connected. On each leg of the transformer, there were four intermediate taps that allowed for 2% to 10% of the windings to be shorted. For example, for a short across 10% of the winding the shorting mechanism was connected to taps X1 and X5. For a short across 6% of the winding, the shorting mechanism could be connected to taps X1 and X4. The 4% short would be a connection from X1 to X3, and a 2% short would be a connection from X1 to X2. The shorting mechanism could also be placed across different combinations of taps to achieve a short across 2% or 4% of the winding.



SECONDARY CHART		
VOLTS	LEADS CONNECT	MAX. CURRENT
5V	X1–X2, X7–X8, X13–X14	480A
10V	X1–X3, X7–X9, X13–X15	480A
15V	X1–X4, X7–X10, X13–X16	480A
25V	X1–X5, X7–X11, X13–X17	480A
240V	X1–X6, X7–X12, X13–X18	69A

Fig. 5: Wiring Diagram for the 55kVA Transformer

V. Results

The first fault tests were conducted with 10% of the secondary winding shorted. An event report capture for one of these fault cases can be found in Fig. 6. The waveform for Ifl is the current in the short circuit in kilo Amps. The winding "W" currents correspond to the primary winding and the winding "X" currents correspond to the secondary winding. The current in the short circuit reached a maximum RMS value of approximately 7.4kA. The primary current increased to 640 Amps RMS during the fault. There was a little disturbance in the secondary currents.

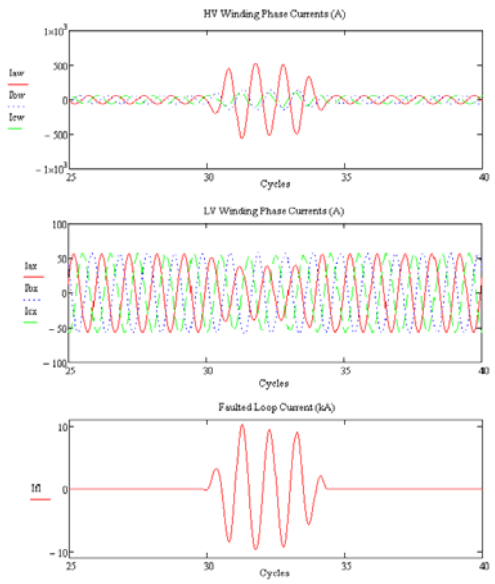


Fig. 6: Event Report Waveforms for a Fault Across 10% of the Winding

Fig. 7 shows the oscillography for a fault across 6% of the secondary winding. The waveform labeled VAY is actually the short circuit current in kilo Amps. With 6% of the winding shorted, the RMS current through the shorting mechanism reached about 7.8 kA RMS; a slight increase from the fault current for the short across 10% of the winding. While the short circuit current increased slightly compared with the 10% tests, the disturbance in the primary currents due to the fault began to decrease. With 6% of the winding shorted, the primary current was 500 Amps RMS during the fault.

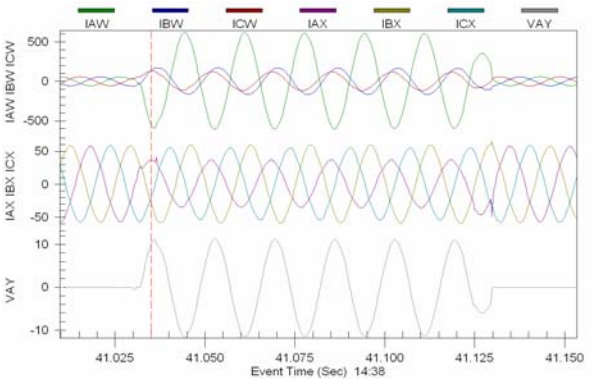


Fig. 7: Event Report Waveforms for a Fault Across 6% of the Winding

Results for the tests with 4% of the winding shorted are shown in Fig. 8. From the figure, it can be seen that the RMS current in the shorting circuit for the 4% faults was around 6.3kA. The current on the primary for this case decreased further to 250 Amps RMS.

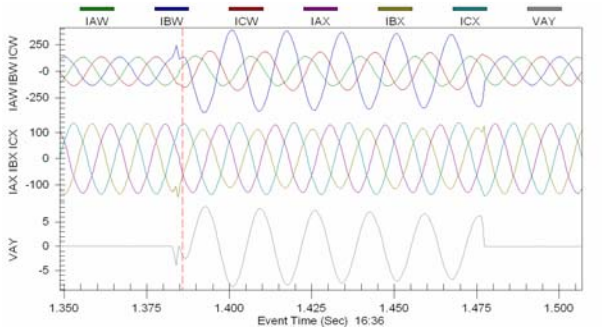


Fig. 8: Event Report Waveforms for a Fault Across 4% of the Winding

Several tests were performed at the 2% tap setting with load currents ranging between 50 and 90A. Figures 9 and 10 show waveforms for faults with 50 and 90A standing load, respectively. The short circuit current for these tests remained around 3.5 kA RMS. The primary current during the fault tests with 90A RMS of standing load reached a value of 140 Amps RMS. This value was higher than the primary current on the previous test at 50 Amps RMS load current. However, it can clearly be seen that as the load current increases, the fault signature on the primary winding begins to become less apparent. The ratio of the primary current during the fault to the normal load current is smaller for the 90A load case, despite the fact that the primary current during the fault is larger than for the 50 Amp case. These ratios were 2 and 1.57 for the 50 Amp load case and 90 Amp load case, respectively.

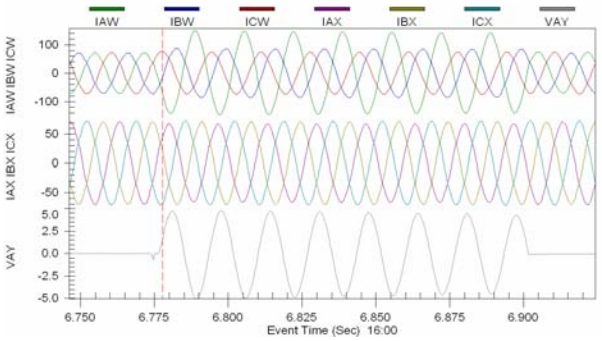


Fig. 9: Event Report Waveforms for a Fault Across 2% of the Winding with a 50 Amp RMS Load

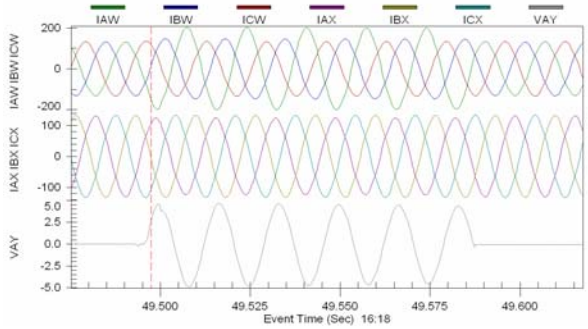


Fig. 10: Event Report Waveforms for a Fault Across 2% of the Winding with a 90 Amp RMS Load

From these tests it becomes apparent that as the number of shorted turns decreases, the fault signature on the primary is less noticeable. The fault signature also decreases in magnitude as the load current is increased. The same series of tests were also conducted with the transformer connected wye-delta. The results from these tests showed the same general trend as the wye-wye tests.

The purpose of the inter-turn fault tests was to test the feasibility of a negative sequence differential element for detecting the fault. A MathCAD model of a digital filter was used to obtain the RMS negative sequence currents from the event report data. The event reports that were recorded were downloaded onto a PC in COMTRADE format and then run through the

MathCAD sheet. The MathCAD relay model used for the analysis was used to generate plots of the RMS sequence components.

The plots in Fig. 11 show the sequence components of the currents on the primary and secondary windings during a fault across two percent of the secondary winding with 50 Amps RMS of load. As in the event report waveforms, it can be seen that the secondary currents remain relatively balanced during the fault. The disturbance in the primary phase currents corresponds to an increase in positive, negative and zero sequence currents.

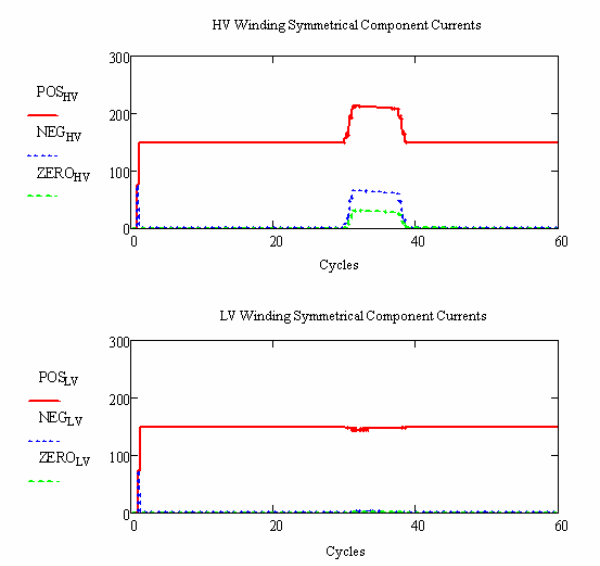


Fig. 11: Sequence Components for a Fault Across 2% of the Winding with 50 Amp RMS Load

A similar test was run with the load current increased to 90 Amps RMS. The sequence currents for this test run can be found in Fig. 12. For this test, the disturbance in the positive sequence is lessened from that seen for the same test with less load current. Though the positive sequence fault characteristic is being swallowed up by the load, the negative sequence currents between the two windings remains contrasted.

The MathCAD model used to generate the RMS sequence components also contains a model of a simple negative sequence differential element. The plot in Fig. 13 shows that the element restrains during normal operation, but will operate for a fault across 2% of the winding.

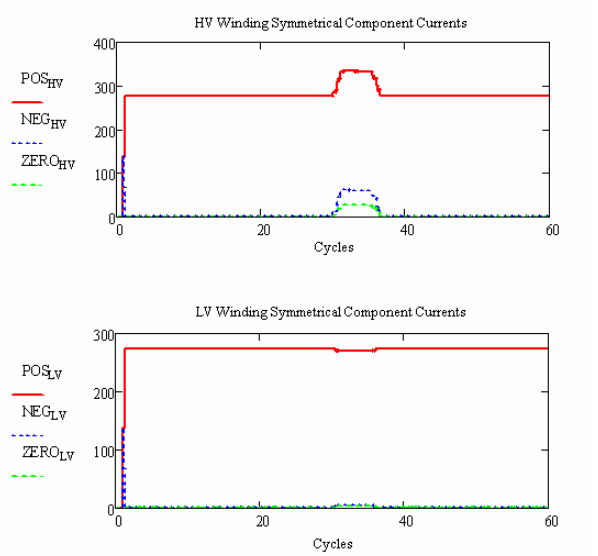


Fig. 12: Sequence Components for a Fault Across 2% of the Winding with 90A Load

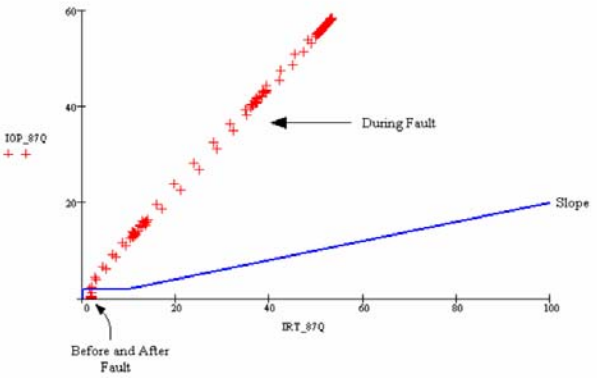


Fig. 13: Negative Sequence Differential Element Operation for a Fault Across 2% of the Winding with an RMS Load Current of 90A

The winding voltages were measured for several of the fault tests. The voltages on the primary and secondary of the transformer were nearly identical and very little disturbance was observed.

As mentioned before, the short circuit currents for the 10% and 6% tests were about the same, with a slight increase for the 6% test. It was originally thought that as the percentage of turns decreased the overall shorting circuit current would increase. However, this is not the case. The current per turn increases, but the overall current in the shorting mechanism decreases. The per turn current for the 2% short is significantly higher than the 10%. As the percentage of turns being shorted begins to decrease the current through the shorting circuit acts in a non-linear manner and can be seen in

Fig. 14. This nonlinearity is something that needs to be further researched.

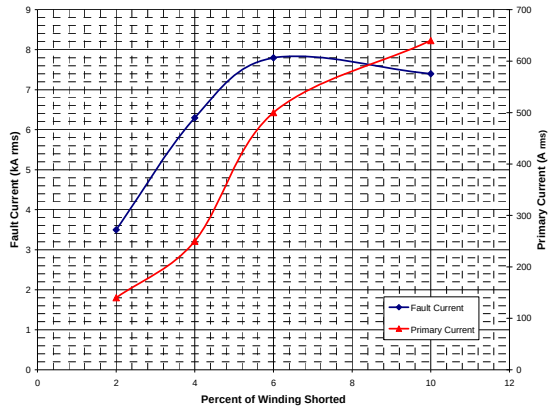


Fig. 14: Short Circuit Current and Primary Current vs. Percent of Winding Shorted

Two major results can be seen from these tests. As the load current increases, the fault signature in the phase quantities is decreased which would desensitize a traditional differential element. We can also infer that based on the test results with varying amounts of the winding faulted, that on a larger transformer with a much greater number of turns, a fault between just a few turns would be almost impossible to detect with a traditional differential relay. The negative sequence differential could prove very valuable under these conditions due to its immunity to load current.

VI. Conclusion

The negative sequence differential element successfully picked up a fault across the two percent of the transformer winding. The differential element also detected faults at 4%, 6%, and 10% of the winding. The testing provided a good feel for what the current through a fault would look like for faults across different percentages of the winding. In addition, some general trends in the fault signature on the primary were observed.

From the data collected during the fault tests, it was shown that as the short is placed across a decreasing number of turns, the disturbance on the primary is greatly decreased. For the 10% fault tests, the primary current jumps to 640 Amps RMS, but for a similar test conducted at 2% of the winding, the primary current only reaches a value of 100 Amps RMS. On a large power transformer with a much greater number of turns, it is likely that a fault between one or two turns will be very difficult to detect. Furthermore, as the load current is increased, the test results showed that the fault signature begins to be "swallowed up" by the load current. Once the load current is high enough, or the number of shorted turns low enough, the fault will no longer be as apparent on the event waveforms. At this point, the proposed negative sequence differential element will be used to detect the faults.

The magnitude of the current in the shorting mechanism has raised questions. The short circuit currents for the 10% and 6% tests were almost identical, but the magnitude of fault current begins to decrease as the percentage of turns being shorted decreases. However, the amount of short circuit current per shorted turn is greater for a 2% fault than for a 10% fault.

VII. Acknowledgements

We would like to thank Schweitzer Engineering Laboratories for donating the relay and the funds for the transformer, CTs, and contactor. We also thank Normann Fischer for mentoring the senior design project. Special thanks to Ted Martin of Control Transformer for working with us to arrive at a practical design for the custom transformer.

VIII. Biographies

Jacob Pomeranz received his Bachelor of Science in Electrical Engineering from the University of Idaho in 2007. He is currently employed in Alaska by Electric Power Systems.

Jared Mraz graduated suma cum laude with a B.S.E.E. from the University of Idaho in 2007. He is currently employed as a system studies engineer at POWER Engineers, Inc.

Joseph Law earned a B.S.E.E. from the University of Idaho in 1980. He earned a M.S. and Ph.D. in Electrical Engineering from the University of Wisconsin-Madison in 1985 and 1991 respectively. He is a registered Professional Engineer. He is presently a member of the Department of Electrical and Computer Engineering Faculty at the University of Idaho.

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