RECLAMATION

Managing Water in the West

Localized Saturation on Generator Neutral Current Transformers

Research and Development Office
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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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14. ABSTRACT A hydro generator at one of the Bureau of Reclamation's facilities tripped offline due to a differential relay element operation concurrent to an external single line to ground fault on the nearby 230 kV transmission system. Post analysis of the event indicated that the fault did not originate within the generator differential zone of protection and thus the generator should not have tripped Analysis of the generator differential relay data showed suggested an issue with the phase-B's neutral CT. Based on the physical orientation of the neutral bus connections, it was determined that the external magnetic flux generated by the fault current flowing on phase-A bus, the neutral shorting bar and phase-C bus caused local saturation of phase-B's CT. The saturation of the phase-B's CT caused the generator to unnecessarily trip. Research was able to recreate this mis-operation in our laboratory and the results of this work are discussed. This issues identified with this research have Reclamation and industry-wide implications as this neutral CT configuration is very common.

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Executive Summary

A hydro generator at one of the Bureau of Reclamation's facilities tripped offline due to a differential relay element operation in June of 2014. Concurrent to this event, an external single line-to-ground fault (phase-A) occurred on the nearby 230kV transmission system. Post analysis of the event indicated that the fault did not originate within the generator differential zone of protection. The generator step-up transformer is a 230/13.8kV with a wye-delta winding connection. For an external phase-A line-to-ground fault, generator fault current flows on phase-A and phase-C but should not cause differential relay element operation.

Analysis of the generator differential relay data showed that currents from the phase-B current transformers (CTs) did not sum to zero. The waveform traces suggested an issue with the phase-B's neutral CT. Based on the physical orientation of the neutral bus connections, it was determined that the external magnetic flux generated by the fault current on phase-A bus, the neutral shorting bar, and phase-C bus caused local saturation of phase-B CT. The saturation of the phase-B CT caused the current through the secondary leads to misrepresent the actual current flowing through the primary side. This misrepresentation, when summed with the phase-B generator terminal CT secondary current created an operate current above the differential relay element operate point.

Two potential solutions are planned to be pursued in an effort to mitigate such erroneous trip situations. First, implementation of new high-security relay settings that were recently developed for the SEL microprocessor relay installed at this facility; and second, utilizing CTs that are designed to reject external flux for use on the generator's neutral bus. Both solutions are proposed to be thoroughly tested in our laboratory next year using new research funding and results published in a subsequent report. One or both solutions will be implemented at Reclamation facilities where similar neutral CT configurations exist, to prevent future mis-operations.

Contents

1. Introduction

On June 3, 2014 at approximately 2000 hours, Generator G2 at a Reclamation Powerplant tripped off-line due to a differential relay element (87) operation. Generation protection is provided by a SEL-300G relay which recorded the event. The recorded data exported from the relay can be seen in Figure A1 (traces- Ia, Ib, Ic). Concurrent to this event, a phase-A line-to-ground fault occurred on the 230kV transmission system.

Post analysis of the SEL-300G trip records indicated that the fault did not originate within the generator differential zone. The generator step- up transformer is 230/13.8kV Y-Δ. For an external phase-A line-to-ground fault on the 230kV line, line-to-line fault currents on phases A and C will be present on the 13.8kV bus, which is evident in the fault waveform traces. For an external fault, the generator differential protection should not had tripped the unit off-line.

2. Differential Relay Operation

Differential (87) protection of the generator is accomplished by computing the difference, referred to as the "operate current," between the generator terminal CTs physically located at the unit breaker and the generator neutral CTs. When the operate current exceeds the differential pickup point the relay will trip. Figure A1 shows both the phase-B neutral CT current (solid red) along with the calculated phase-B terminal CT current (shown dotted red). The difference between these 2 signals is the operate current (Iop shown in orange). From the trace it can be seen that the orange trace exceed the differential (87) pickup level. Given these CT secondary current inputs the relay operated correctly and tripped.

The operation of the differential relay element was caused by a mismatch between the neutral and terminal phase-B secondary currents. Analysis of the 3-phase neutral CT secondary current waveforms shows that the 3 neutral phase currents did not sum to zero and the phase-B waveform is not sinusoidal. The waveform traces suggest that there was an issue with the neutral phase-B CT secondary current during the fault. The burden class of the neutral CT is C800 and the ratio is 5000:5.

3. CT Saturation

It has been documented in several papers [1],[2], and [3] that stray magnetic flux can produce errors in window type CTs. Stray magnetic flux is a non-uniform magnetic field that is present around a CT. The stray magnetic flux can be caused when the primary conductor is not centered in the CT window, the primary conductor changes direction close to the CT, and/or the other external phase conductors are in close proximity to the CT. From the photo shown in figure A2 it is evident that the neutral CTs meet the last two of these three criteria. The degree that stray magnetic flux can affect the CT operation depends on the magnitude of the primary currents and the window CT core cross-sectional area.

Stray magnetic flux creates non-uniform flux density within the core. In most situations the non-uniform flux density only slightly effects the operation of the CT by locally reducing the core material permeability and increasing magnetizing losses. However, correct CT operation is effected when the magnetic flux density within the CT core exceeds the core capability in a localized area. This causes the core to become saturated in a localized area. Localized CT saturation will cause significant CT errors.

Non-uniform magnetic flux density within the CT core can be caused by the location of both internal and external conductors. When the primary conductor does not pass through the center of the window CT it causes a lack on concentricity of the primary conductor magnetic field. Non-uniform flux density can also be caused by magnetic fields that originate external of the CT window from adjacent conductors. The neutral CTs were installed with the primary conductor centered within the CT window; however, the CT is located very close to external conductors. In addition the cross-sectional area of these particular CTs are relatively small (the core is about ½ inch thick between the inner and outer diameter) compared to CTs installed at other Reclamation facilities.

4. Characterizing Local CT Saturation

G2 tripped off line during an external 230-kV line-to-ground fault. The line-to-ground fault on the 230-kV system resulted in line-to-line fault current at the generator due to the 230/13.8kV Y-Δ transformer. This can be seen in the fault traces for phase-A and -C, the phase fault current magnitude is around 15,000 amps (A) and 180 degrees out of phase. The phase-B current magnitude remains relatively unchanged although it does have a DC offset when the fault occurred. As shown in Figure A2, the fault current from phase-A and -C in-circle the phase-B CT and thus the magnetic flux produced by the fault current is additive at the phase-B CT. Because the magnetic flux adds during the fault, a strong external magnetic flux density is present at the phase-B CT.

To measure the impact that this external stray magnetic flux has the neutral phase-B CT, a spare CT was tested in the laboratory. The position of the CT with respect to external conductors was simulated by mounting the CT on a 4x8 piece of plywood and a looping an external conductor around the outside of the CT at the same spacing as the conductors exist at the generator neutral, see Figure A3. Ten turns of 4-AWG wire was used to simulate the primary conductor. A 480-V autotransformer and a 500/50V transformer were used to energize the loop. With this configuration about 100A of continuous current could be supplied to the loop with a maximum short term load of about 250A. At 10 turns, this is equivalent to 1,000A and 2,500A, respectfully.

Flux density within the CT core was measured by winding a search coil around the CT and measuring its output voltage. The search coil used for these tests consisted of 10 turns. The output voltage of the search coil to proportional to the derivative of the flux passing through the coil. The relationship between the search coil root mean square voltage (Vrms) magnitude to core peak flux magnitude is:

$$V = 4.44 \times f \times N \times A \times B_p \;\; or\; V \propto B_p \qquad (1)$$

Where

V = Search coil voltage (Vrms)
f = frequency (60Hz)
N = number of turns
A = area of core (m)
B_p = Magnetic Flux Density (Tesla peak)

This equation demonstrated that the measured voltage is proportional to the magnetic flux density.

4.1 Localized magnetic flux density due to external flux

To measure the localized magnetic flux density, the search coil voltage was measured at various points around the CT window while passing an equivalent of 1,000A through the external conductor. A radar plot of these measurements is shown in figure A4. From this plot it is evident that the flux density within the CT core is not uniform. The data show that the maximum magnetic flux density occurs at 0 and 180 degrees, or in the same plane as the external conductors.

4.2 Core saturation

Non-uniform flux density within the core effects the operation of the CT when the core starts to saturate. The saturation characteristics of a CT are measured by means of a CT excitation test. An excitation test was performed on the spare CT and the results can be found in figure A5. The 45 degree knee point on the curve is measured at 560V, 23mA. Below this point on the curve the CT core is not saturated and the secondary current is proportional to the primary current (ratio=1000:1). The excitation current remains small. Above the knee the CT starts to saturate, the excitation current becomes significant, and the secondary current is no long proportional to the primary current. As shown in figure A5 at 900V secondary voltage, the excitation current is 1.4A.

The search coil voltage during an excitation test can be calculated from this curve. The CT ratio is 1,000:1, thus there are 1,000 turns on the secondary winding. Given that the search coil has 10 turns the ratio between the secondary CT winding and the search coil winding is 100:1. During the excitation test the search coil voltage also was measured and this calculated ratio was verified. From the excitation curve it is now possible to calculate the degree of core saturation based on the search coil voltage measurement. The core will start to saturate at a search coil voltage of 5.6Vrms (560V/100) and at 9Vrms (900V/100) the core will be significantly saturated.

To demonstrate the effect that saturation has on the CT performance, the CT was intentionally saturated by placing a 1,000 ohm resistor on the CT secondary leads. At 900A primary current the resultant secondary current waveform is shown in Figure A6. The search coil voltage was measured at 9Vrms.

4.3 Impact of external conductor current

The flux density in air around a conductor is defined by the equation:

$$B = \frac{\mu_0}{2\pi r} x\, I \ \ or\ B \propto I \qquad (2)$$

Where

B=Magnetic Flux Density (Tesla)
$\mu_0 = 4\pi \times 10^{-7}$ H/m
r=distance from cable (m)
I = current (A)

At a given distance (r), flux density is proportional to current. Given the linear relationship of both equations 1 and 2, the ratio between loop current (I), flux density (B), and search coil voltage (V) remains constant:

$$V \propto B \propto I \qquad (3)$$

Thus the flux density level, measured using the search coil, recorded at low test currents can be scaled to fault current levels by maintaining the same ratio between the measured and calculated values. Given this relationship, the search coil voltages as plotted in Figure A4 that were recorded at 1,000A can be scaled up to fault current levels as high as 17,000A as shown in figure A7. Additional measurements were also recorded up to 2,700A to demonstrate the linear relationship.

From the discussion in the previous section it was shown that the core in significantly saturated when the search coil voltage is 9V. From Figure A7, an external current of 12,000A will result in a search coil voltage of 9V. Thus for an external loop current above 12,000A, the phase-B neutral CT will experience localized saturation.

This effect is observed in the original fault traces shown in Figure A1. Phase-A current reaches a peak of the 17,000Arms during the first cycle of the fault. It is when the phase-A magnitude exceeds about 12,000A that the phase-B secondary current becomes non-sinusoidal and the waveform deviates from the phase-B terminal CT current. This non-linear behavior is the result of local saturation of the phase-B CT core. The localized saturation of the CT core caused the differential relay to operate and trip the unit offline.

5. Recommendation

To prevent this situation from occurring in the future there are several methods that can be used to prevent CT core localized saturation including the following:

- Magnetic Shielding – Stacks of laminations are used between the CT and source of stray flux
- New CT with a larger core – Increasing the CT core cross-sectional area will decrease flux density in the core
- New CT that incorporated core balance compensation – The CT is wound with sectionalized parallel CT secondary windings in addition to the secondary winding. The parallel CT windings allow current to flow between different sections of the winding to counter the non-uniform magnetic flux in the core.

Magnetic shielding is not an option for this application as it would require extensive rework of the generator CT neutral leads.

New neutral CTs on the differential circuit are recommended as they present the easiest method to correct this localized saturation issue. As mentioned above the new CTs should have a larger core, or incorporate a core balance compensation circuit.

The cross-sectional area the neutral CTs are relatively small (the core is about ½ inch think between the inner and outer diameter) compared to CT installed at other Reclamation facilities. If the core cross-sectional area of new CTs were twice the existing core area (double the core thickness) then the flux density would be reduced by roughly half. The interaction between the dimensions of a new CT core with the external stray flux that is produced at this location would be difficult to calculate, but a larger core would most likely not experience local saturation that occurred during this event. The small cross-sectional area of these CT cores helps to explain why this issue is not widespread throughout Reclamation. Other CTs within Reclamation tend to have a much larger cross-sectional area so they are less susceptible to localized saturation.

Core balance compensation CTs have also become more common in the power industry. As equipment and switchgear physical sizes have been reduced, it has become necessary to minimize the effect of external stray magnetic flux. The big advantage of this option is that the size, weight, and cost of these CTs are similar to CTs that do not incorporate this feature. A quick search of available generator CTs revealed the following model that could be used to replace the existing neutral CTs:

- ABB Type PSG-981.

The core balanced compensation CT performance will be verified in the near future. Just as the effect of stray flux on the performance of the existing neutral CTs was analyzed in the laboratory, as described in this report, the performance of this new CT can be evaluated to ensure it will function correctly in the presence of stray magnetic flux.

Another approach has recently been introduced by Schweitzer Engineering laboratories (SEL) that also may help prevent differential relay mis-operation due to CT saturation. SEL has incorporated a new high-security differential relay setting for their microprocessor based generator relays [4]. It appears that the use of this feature will prevent differential relay trips due to CT saturation. The use of this new feature will be tested in our laboratory using the CT current data that was recorded during the external fault event. It will also be vetted to insure that real differential events that also include CT saturation are correctly identified.

6. References

1. A Gajic, A. Holst, D Bonmann, and R Hedding, Stray Flux and Its Influence on Protective Relays, *65th Annual Conference for Protective Relay Engineers,* 2012.

2. N Charbkaew, T. Bunyagul, and T. Chompusri, Experience of Stray Flux Interference of CT (Case Study of a Power Plant in Thailand), *IET 9th International Conference on Developments in Power System Protection,* 2008.

3. Kent Jones and Matt Alcock, Addressing Window Type Transformer Proximity Errors, *Line Power, 59th Annual Conference for Protective Relay Engineers*, 2006.

4. Marcos Donolo, Armando Guzman, Mangapathirao Mynam, Rishabh Jain, and Dale Finey, Generator Protection Overcomes Current Transformer Limitations, *41st Annual Western Protective Relay Conference,* 2014.

Appendix A - Figures

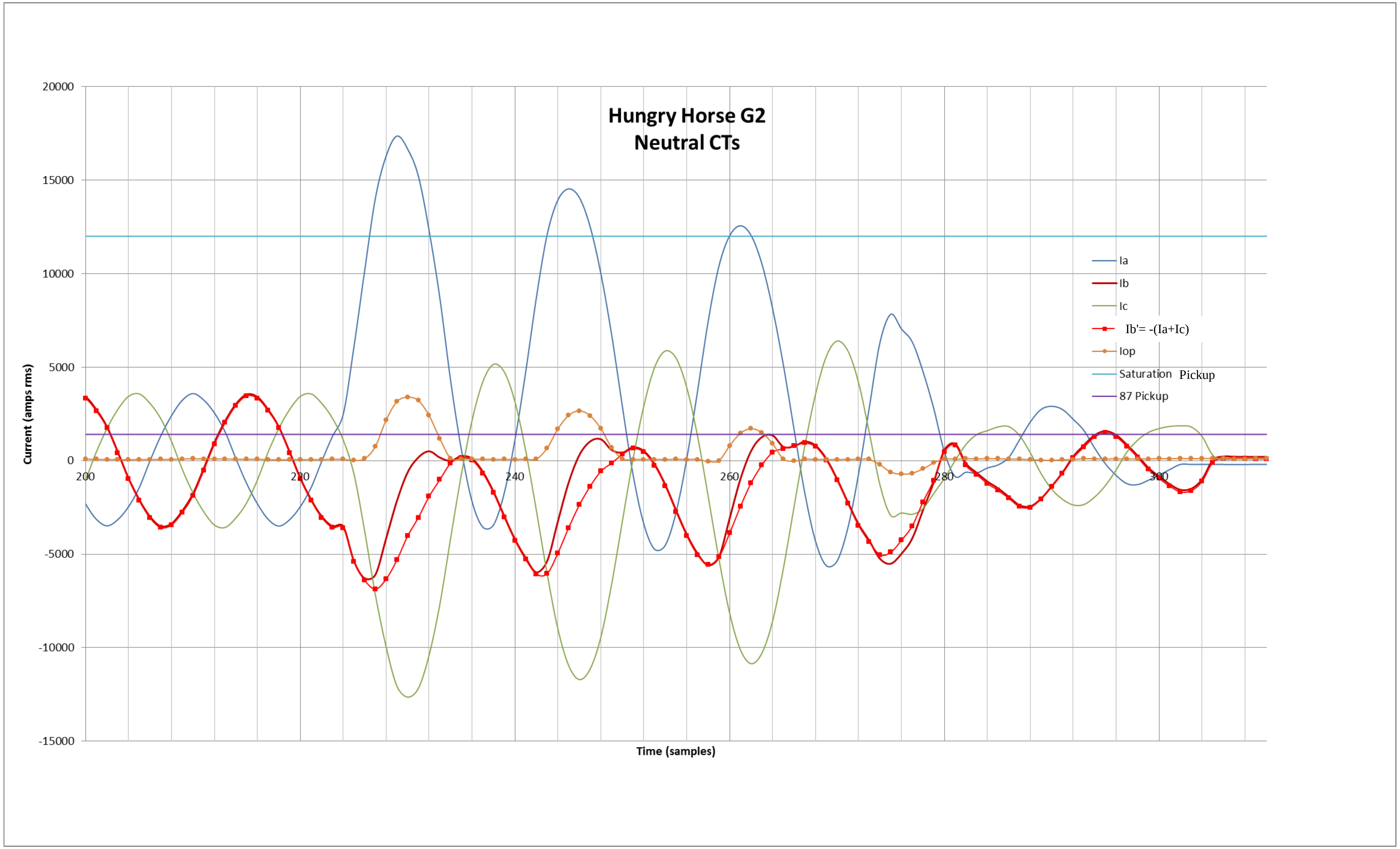


Figure A1 - G2 Neutral CT Current Traces (Ib' = calculated Ib secondary current without CT saturation.)

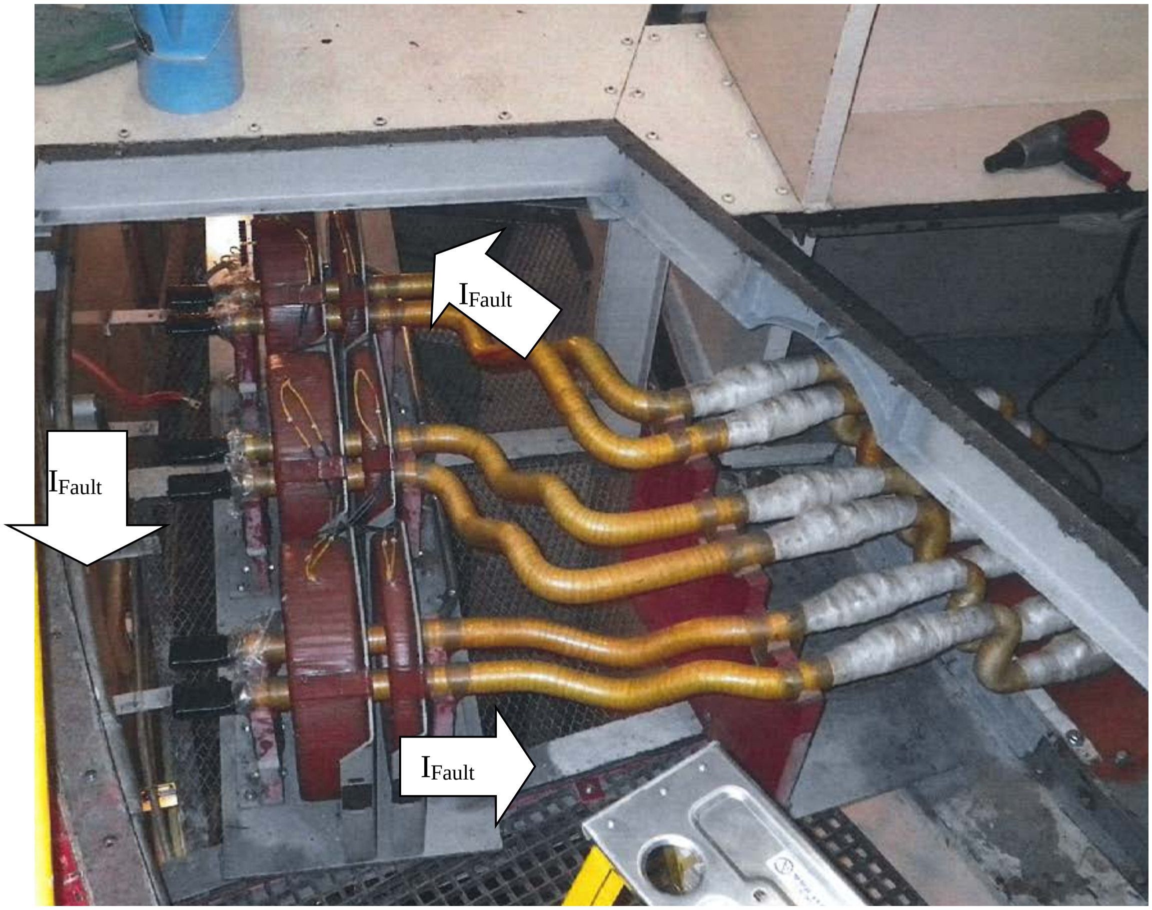


Figure A2 - Photo of Neutral CT Leads (note: the neutral shorting bar between phase A, B and C is removed in this picture)

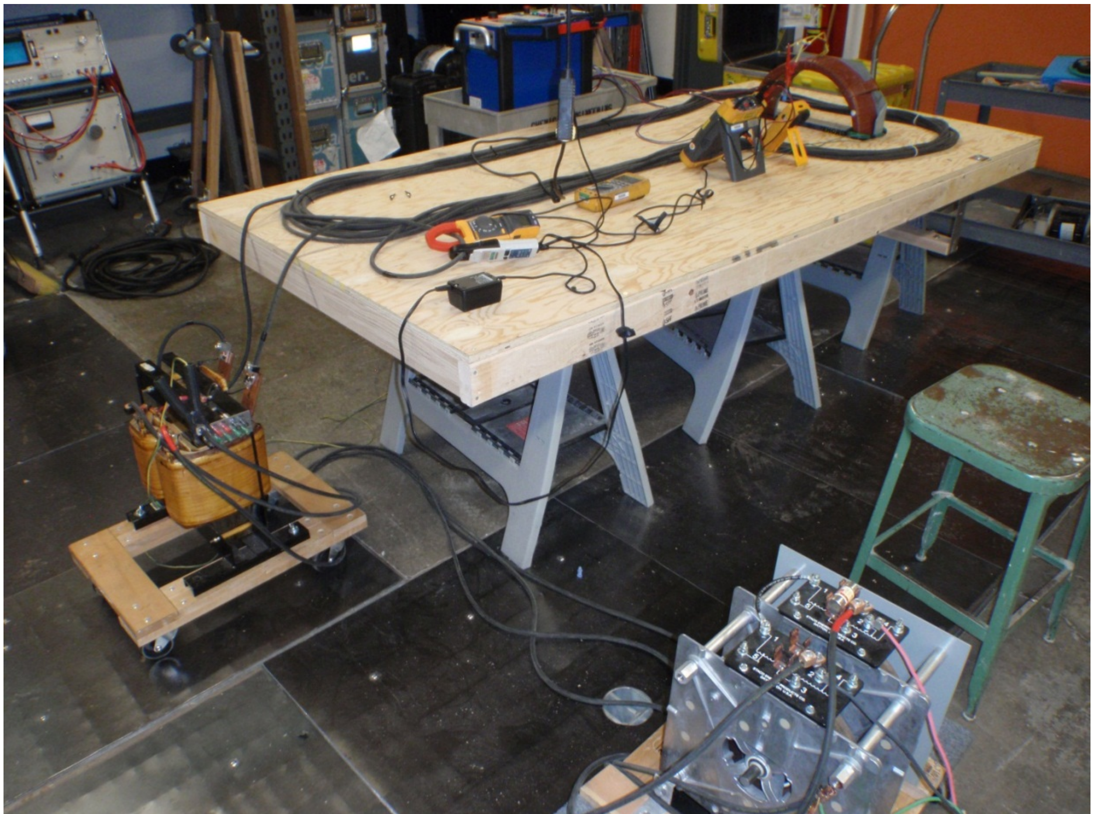


Figure A3 - Spare CT under test in the laboratory (overview and close up)

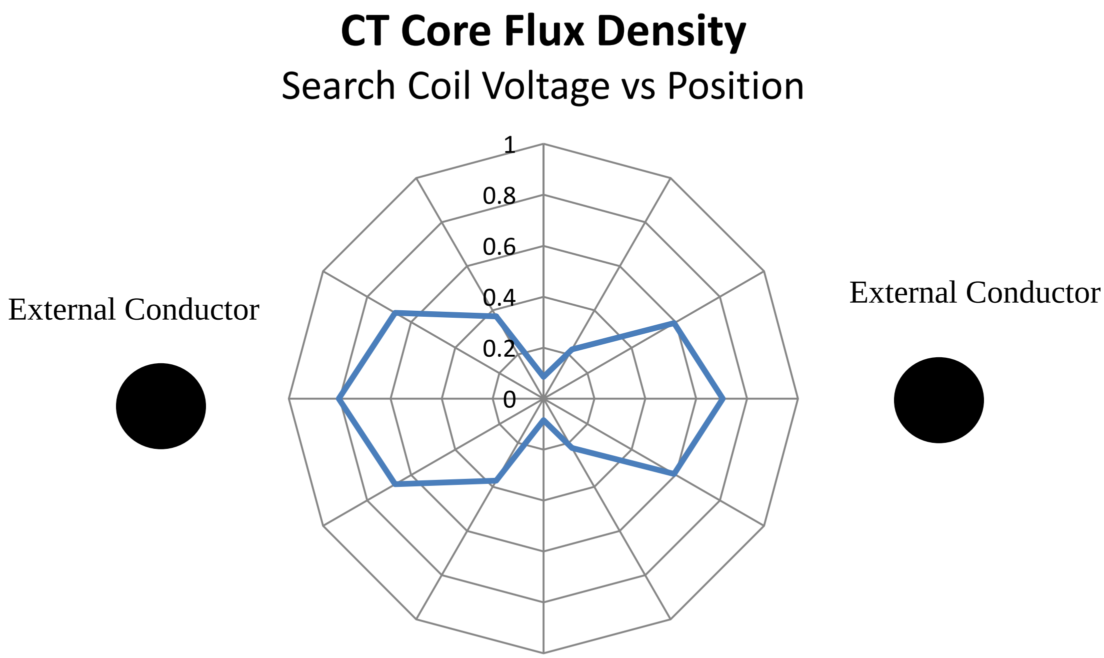
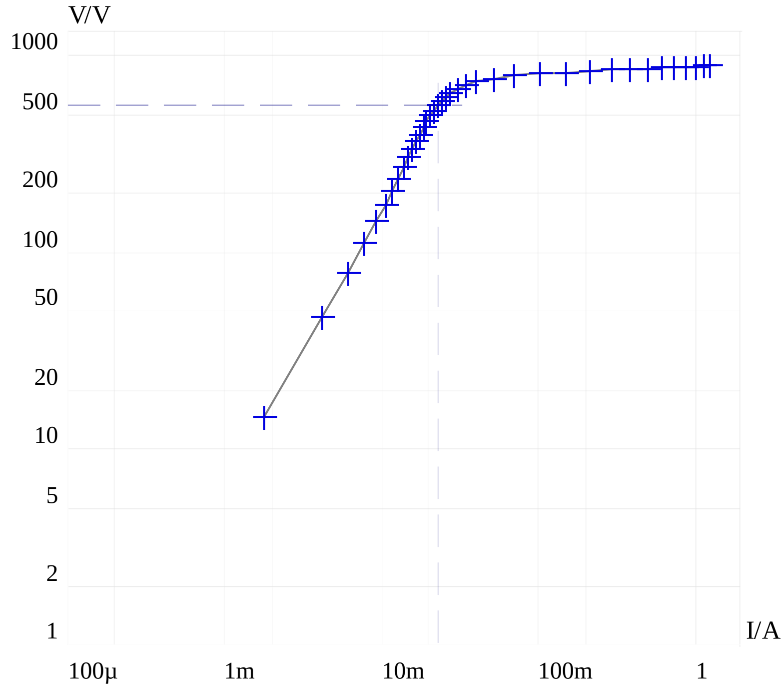
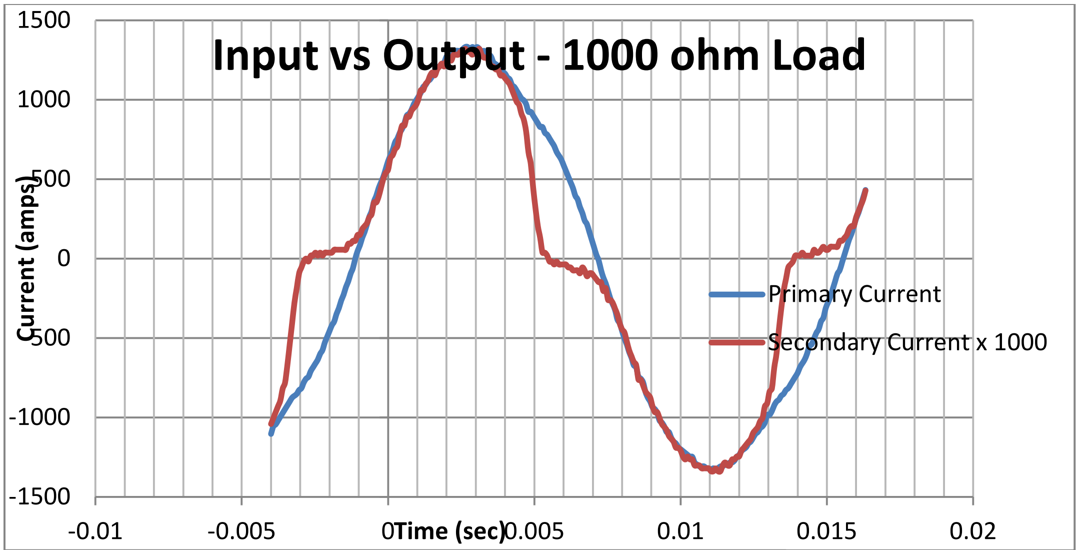


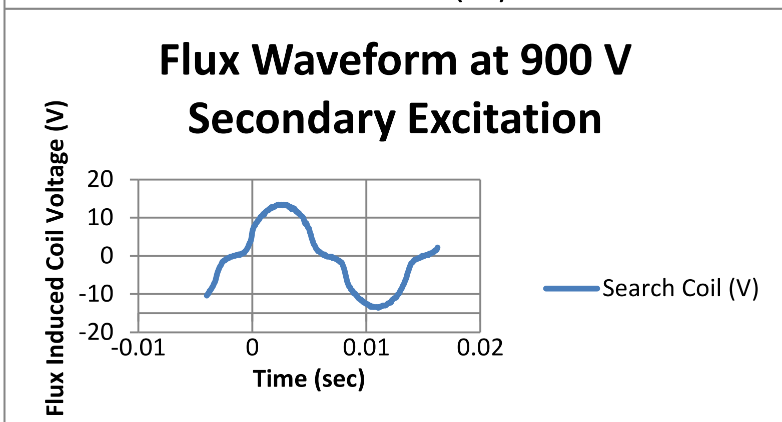
Figure A4 - CT core flux density test



ANSI 45deg knee = 560V at 23mA, significant saturation at 900V, 1.4A.

Figure A5- CT excitation test





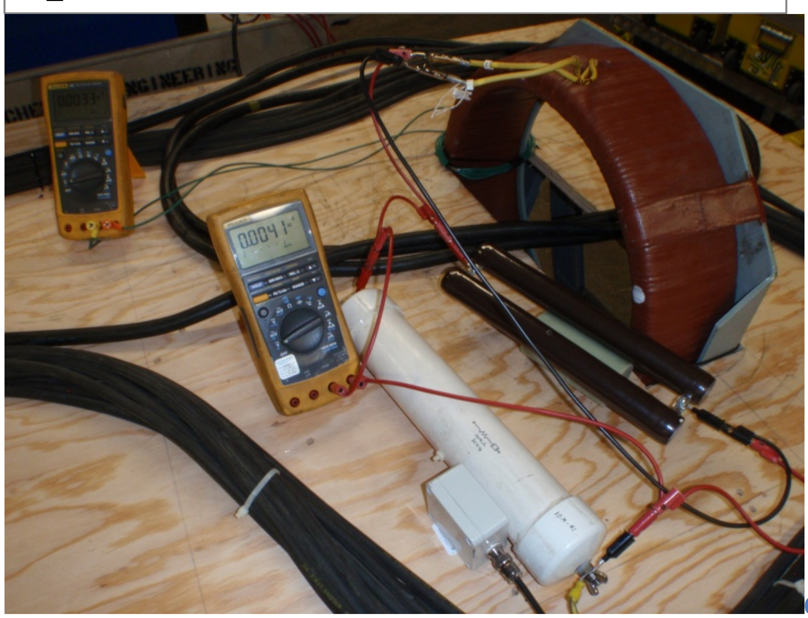


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Figure A6 – Effect of saturation on CT secondary current (search coil voltage = 9Vrms)

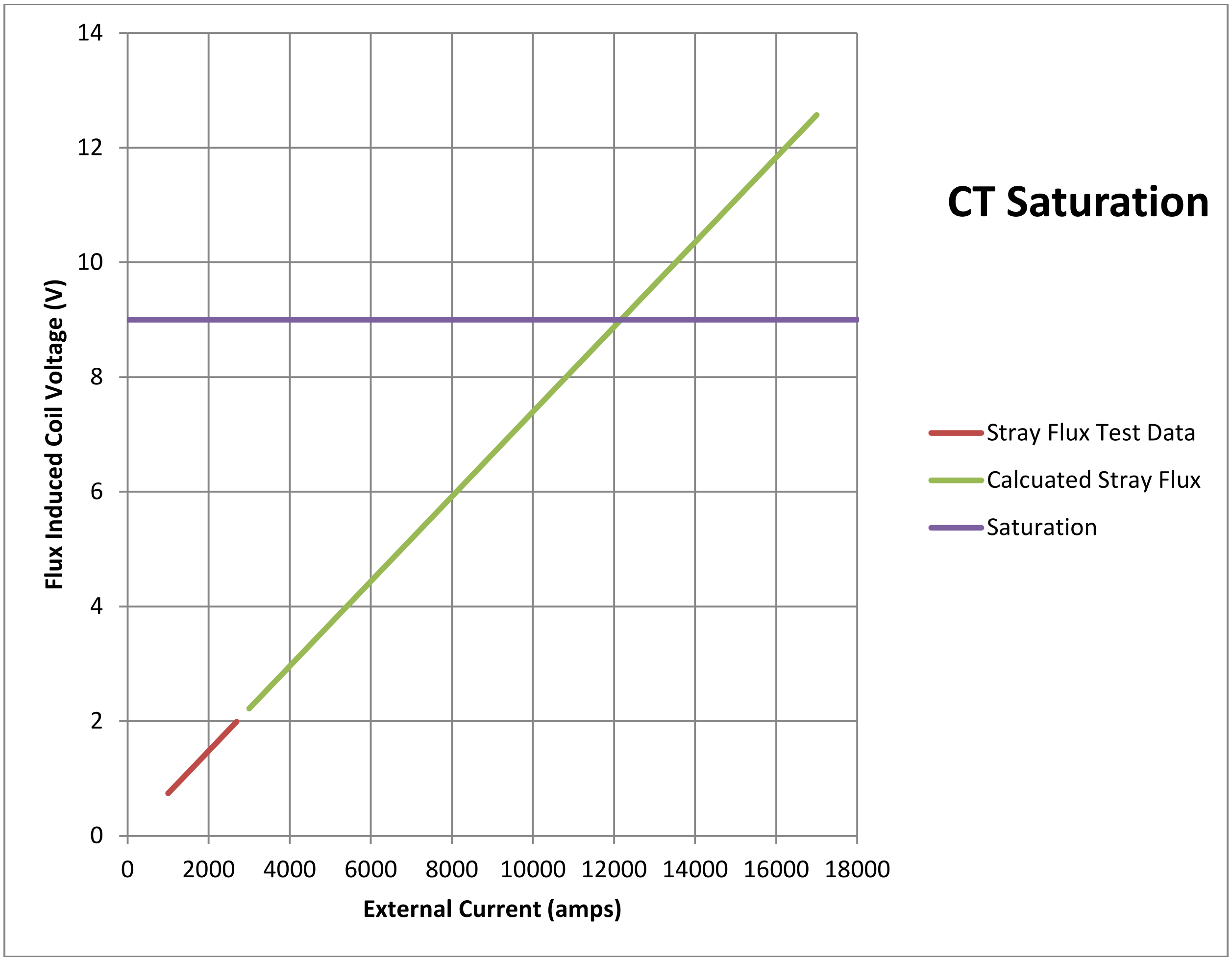

Figure A7 - Linear relations between loop current and magnetic flux