MITIGATION OF REMANENCE FLUX IN POWER TRANSFORMERS USING PREDETERMINED METHOD OF DE-ENERGIZATION

A THESIS IN
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MASTER OF SCIENCE

by
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MITIGATION OF REMANENCE FLUX IN POWER TRANSFORMERS USING PREDETERMINED METHOD OF DE-ENERGIZATION

Akhila Charlapally, Candidate for the Master of Science Degree

University of Missouri-Kansas City, 2017

ABSTRACT

Energization of large power transformers are subject to many transients that may complicate the successful completion of this process and ultimately reduce the expected life of these critical components. The first-time energization (commissioning), subsequent energizations (operational), methods of energization (abrupt or controlled energizations from the high voltage or low voltage winding) and the possibility/improbability of these transformers being preloaded all affect the transformer's longevity. The consequences of such energizations during the conditions are inrush currents and voltage stresses on the affected components that may not be foremost on the designer's mind. The designer may be more concerned with proper parameter application and not the effects of commissioning and operation on these massive components. These behemoths are a bit akin to elephants whose longevity is dependent on the sum of their life experiences and the scars they endure during this period. The reliability of electric system is directly affected by these series connected behemoths.

The construction of power transformers has been optimized by the advent of computers (especially finite analyses) to the point that stray flux, eddy current, hysteresis loss and harmonic loss (embodied and represented within the non-linear R_P element and known as "core Watt losses") have all attained significant improvements witnessed by their 99.8+ percent efficiency. The difficulties that remain are magnetizing inrush and remanence embodied within X_P which occur dependent on three parameters. The parameters are primary resistance R_S (dependent on the location of same for the equivalent circuit used), the time dependent voltage at the point on the voltage wave when the transformer is energized (referred to as "Point of Wave") and the remanent (or residual flux) and its polarity all at the instant of energization.

The magnetizing inrush problem has been thoroughly researched and commercial products exist to mitigate such difficulties by control system add-ons. This research recognizes that knowledge of Point on Wave has effectively mitigated the problems with transformer energization at zero voltage.

The results obtained after hundreds of runs confirms a direct relationship between the point of the wave where current is extinguished for a fast acting air switch and minimal to zero remanence flux in a single-phase shell form transformer. This minimal to zero residual flux appears at the peak of the equivalent sinusoidal current wave (increasing or decreasing) without the effects of saturation.

The conclusion of the experimental runs was that the use of multiple Hall-Effect transducers (multiple installations suggested for manufacturing errors or wiring failures) within the laminations of a transformer which would be used to confirm the near zero remanent flux once the current was extinguished as described above. These findings and recommendations are still subject to testing at nameplate loads of varying power factors upon three phase transformers of shell and core constructions.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering, have examined a thesis titled "Mitigation of Remanence Flux in Power Transformers using Predetermined Method of De-Energization" presented by Akhila Charlapally, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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To My Parents

CHAPTER 1

INTRODUCTION

1.1 Introduction

Transformer is an important part of a power system and is considered the heart of electrical transmission and distribution systems which are nowadays, significantly dependent on transformers. Invention of transformers made the long-distance transmission possible with practical dimensions of transmission cable. Its performance is considered vital in power system's stability determination.

Energization of large transformers is considered a critical issue in power system operation and it draws a huge amount of transient current and some of the consequences of this being

- Harmonics in the input current, subjecting the transformer to mechanical stress;
- Temporary overvoltage in weak systems which in turn causes winding failure;
- False tripping of the Protective relays;
- Failure of circuit components.

These transients would diminish the longevity of the transformers (accelerated ageing) or even damage them.

1.2 Motivation

The motivation for this research is to identify a process and a pattern using presently available technology (Hall Effect transducers imbedded within the transformer core) to anticipate the point on the current wave whereat residual flux may be minimized for single phase transformers when re-energized. A secondary goal of this paper is to improve on the useable life of these critical components.

If overcurrent relays are used for protection, the threshold must be set to a certain value which is a little bit above the maximum power, so that the relay would trip for higher amount of fault current. In the case of transformer protection, inrush current during the energization of the transformer being many times greater than the rated current of the transformer would trip the overcurrent relay (false tripping). Hence the threshold must be raised above the typical value of the inrush current. This would not protect the transformer under faulted conditions. Due to this problem of inrush current, transformers are now being protected with differential and impedance relays which are extremely expensive. Usage of excessive cost impedance and differential relays in the protection of power transformers is the main motivation for this research.

1.3 Objective

Protection of transformers when first energized has been quite difficult due to the physics of its internal non-linearity. The protection difficulties are concentrated in the shunt elements (excitation elements shown below), R_p and X_p, as shown in Figure 1-1, both of

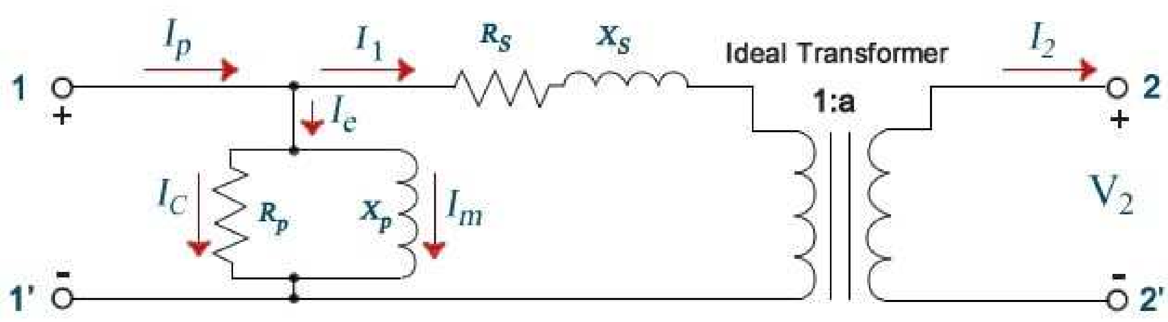

Figure 1-1: Equivalent Circuit Diagram of a Low Frequency Power Transformer

which are non-linear, sensitive to "frequency squared" (mainly due to harmonics) and "applied voltage" respectively.

The construction of power transformers has been optimized by the advent of computers (especially finite analyses) to the point that stray flux, eddy current, hysteresis loss and harmonic loss (embodied and represented within the non-linear R_p element and known as "Core Watt Losses") have all attained significant improvements witnessed by their 99.8+ percent efficiency. The difficulties that remain are magnetizing inrush and remanence embodied within X_p which occur dependent on three parameters. The parameters are primary resistance R_s, the time dependent voltage at the point on the voltage wave when the transformer is energized (referred to as "Point of Wave") and the remanence flux (or residual flux) and its polarity all at the instant of energization.

The magnetizing inrush problem has been thoroughly researched and commercial products exist to mitigate such difficulties by control system add-ons. These control systems knowledgeable of the peaking order and breaker closing time will send a close signal to each phase to approximate the closure of that pole when the energizing voltage is at a maximum. Mathematically, this closure results in the term $[\varphi - \tan^{-1}(\omega L/R)] = 0$ equation shown below, which results in a null value for the exponential term and the magnetizing current is instantly in steady-state; and, therefore, no magnetizing current offset exists and the total current i(t) is symmetrical as shown in Figure 1.1 (given that there is no remanence flux in existence).

$$i(t) = e^{-(R/L)t}\left\{\frac{-E_{max}}{\sqrt{R^2+\omega^2L^2}}\sin\left[\varphi - \tan^{-1}(\frac{\omega L}{R})\right]\right\}$$

$$+\frac{E_{max}}{\sqrt{R^2+\omega^2L^2}}\sin\left[\omega t + \varphi - \tan^{-1}(\frac{\omega L}{R})\right]$$

In Figure 1-2 are waveforms of voltage (e), magnetic flux (Φ) and current (i) illustrating a symmetrical yet non-linear magnetization current due to Point on Wave switching when the transformer is first energized.

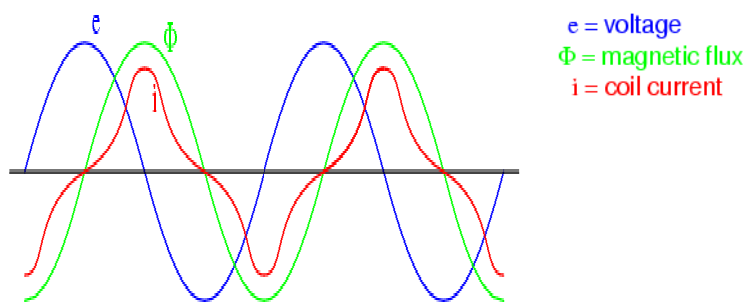

Figure 1-2: Symmetrical Waveforms of Voltage, Current and Magnetic Flux

Below in Figure 1-3 are waveforms of (top) source voltage, (middle) flux density [both magnetization and remanence] and (bottom) magnetizing current. Also on the bottom chart is the value of magnetizing current during periods of (a) steady state voltage, (b) interruption of the voltage at negative maximum voltage and (c) re-energization of the voltage starting from zero voltage "Point of Voltage" wave from the top graph. Employing the previously described Point on Wave for energization, the only remaining problem is resultant inrush current due to remanence (the focus of this research).

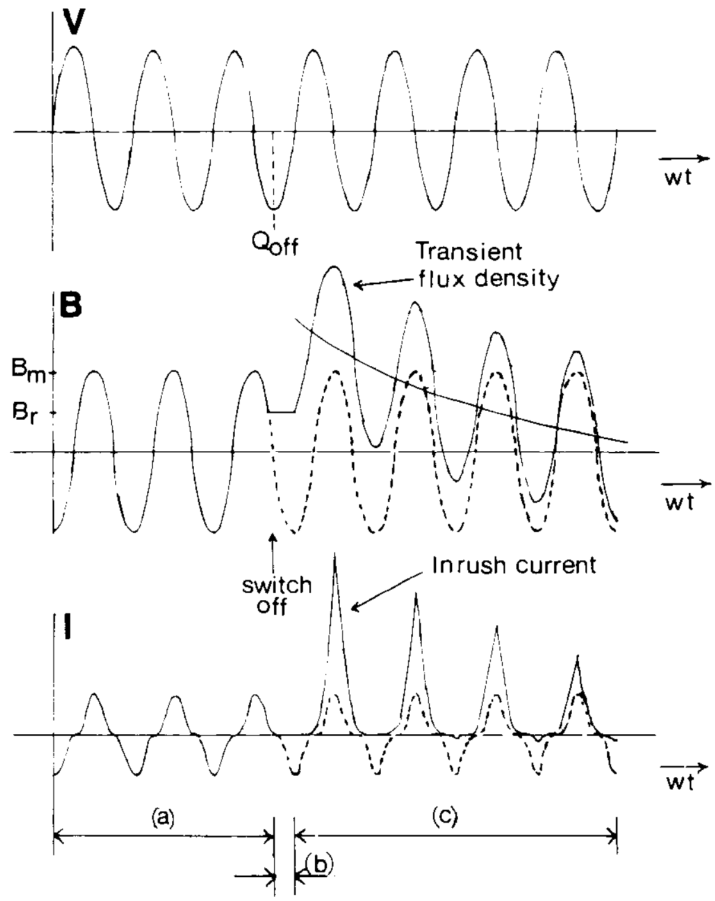

Figure 1-3: Waveforms during energization

Both problems affect the transformers' protective relaying. The X_p element is a much more difficult element to quantify as this element represents the permeability of the transformer core which is relatively low. This element represents the non-linear reaction of the inductive core to point of wave and the permeability changes of the core as manifested by the voltage/current result when impacted by hysteresis. This research recognizes that knowledge of Point on Wave has effectively mitigated the problems with transformer energization at zero voltage. So, the objective for this research is to identify a process and a pattern using presently available technology (Hall Effect transducers imbedded within the transformer core) to anticipate the point on the current wave whereat residual flux may be minimized for single phase transformers when de-energized. This fact will nearly eliminate the remanence flux inrush component when the transformer is re-energized.

1.4 Inrush Current

The main causes of inrush current are

i. Voltage angle during energization (Point of Wave)

ii. Remanence Flux

iii. Source Impedance

iv. Leakage impedance

1.4.1 Energization Angle

The inrush current is mainly dependent on point on voltage wave where it is turned on. Flux (ϕ_m) produced in the core is in quadrature with the voltage applied (E.sin(ωt)) as

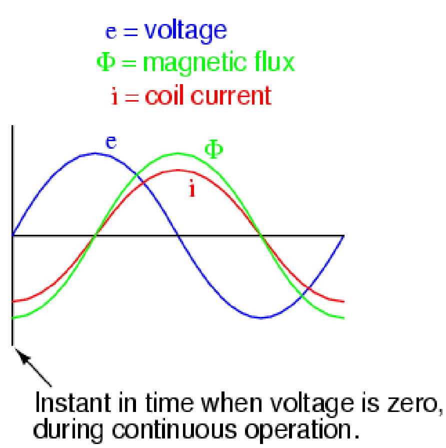

Figure 1-4: Voltage Current and Flux during Normal Linear Operation

shown in Figure 1-4, which means if voltage is switched on at its zero value, theoretically flux should be negative maximum or positive maximum.

However, flux will be zero at the instant of turn-on as there will be no prior flux linkage. To attain this value of flux immediately at the instant of turn-on, transformer draws huge current. Hence, the flux starts at zero and goes to twice its maximum steady state value at the end of the voltage half cycle as shown in Figure 1-5.

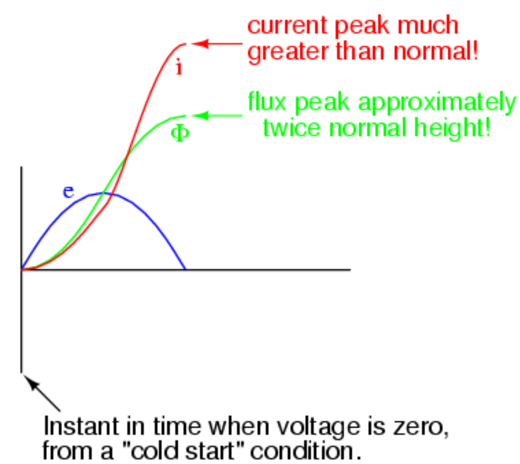

Figure 1-5: Voltage Current and Flux during Energization

The transformer core is usually saturated after the steady state value of flux is reached and hence to further reach the higher flux, even high currents are drawn. When inrush current exceeds saturation current, magnetic property of the core is affected.

1.4.2 Remanence Flux

When a ferromagnetic material is subjected to an external magnetic field and after it is removed, part of flux is retained by the material, known as Remanence flux. In engineering applications, it is also termed as Residual flux or Retentivity measured in the units of Magnetic Flux Density.

When a transformer with positive remanence flux as shown in Fig 1-6 [2] is energized at the zero crossing while going from negative polarity to positive polarity, it is driven into deep saturation. At this point, the permeability is close to unity and the transformer core acts almost like air and even a slight change in flux would draw huge amount of current. Therefore, the transformer core must be demagnetized before re-energizing.

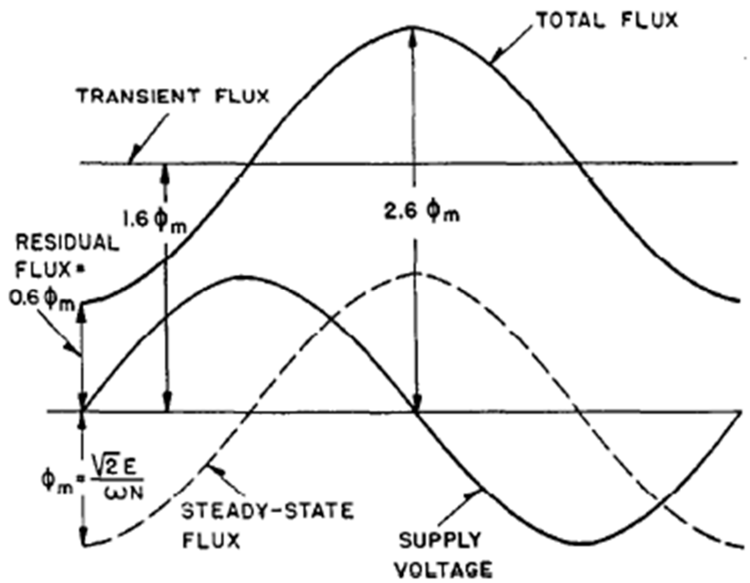

Figure 1-6: Energized at Zero Voltage and 60% Remanence Flux

1.4.3 Source Impedance and Leakage Impedance

Power transformers experience inrush current (as shown in Fig 1-7 [2]) in accordance with the degree of saturation which results from the energization of the transformer's magnetic circuit. The magnitude of this inrush current is a direct effect of the polarity of the remanence flux (residual flux), the point on the voltage wave at the time of energization and the source impedance of the circuit. The worst inrush will occur when the voltage wave is at a minimum, the polarity of the resulting flux aids saturation and the source impedance is mainly reactive and close to zero magnitude. A reduction in the inrush current would result by the increase of the reactance of the source impedance which would directly affect this current as the inrush current is nearly completely reactive. Orthogonal effects would be present should the source impedance be complex.

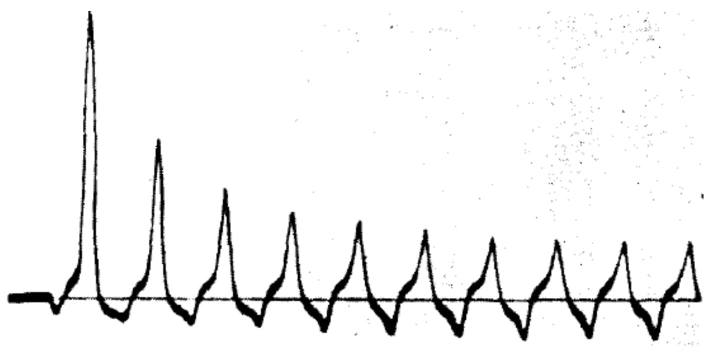

Figure 1-7: Inrush Current

1.5 Demagnetization

Magnetic materials can be demagnetized using the following methods

i. Through mechanical vibration

ii. By heating the material up to Curie Temperature

iii. Electrical demagnetization

The first two methods are very effective however, they cannot be applied to transformers. The best way to demagnetize the transformer core can be electrical demagnetization. It can be achieved by slowing reducing the voltage applied on primary through steps and bring the magnetization to zero as shown in Fig 1-8.

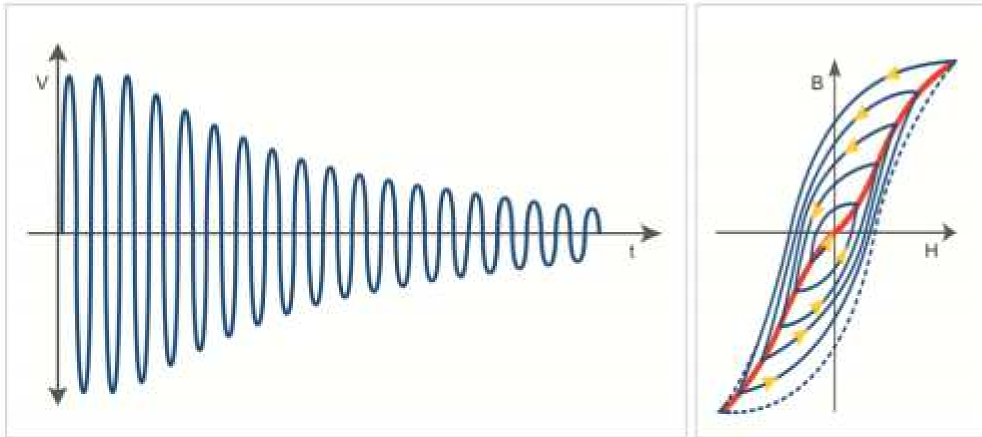

Figure 1-8: Demagnetization Using Sinusoidal Voltage Signal

This method would not be possible on-site as there would not be any adjustable voltage source to supply the voltage in steps to the transformer.

CHAPTER 2

PSCAD MODELLING OF REMANENCE IN TRANSFORMERS

2.1 PSCAD Model

At the outset, we attempted to model the physical transformer (0.225 kVA) in our lab to Manitoba Hydro's PSCAD/EMTDC, Version 4.6.1 program. The dialog panels in Figure 2-1 describe the data entered from the experiments made to quantify the physical transformer.

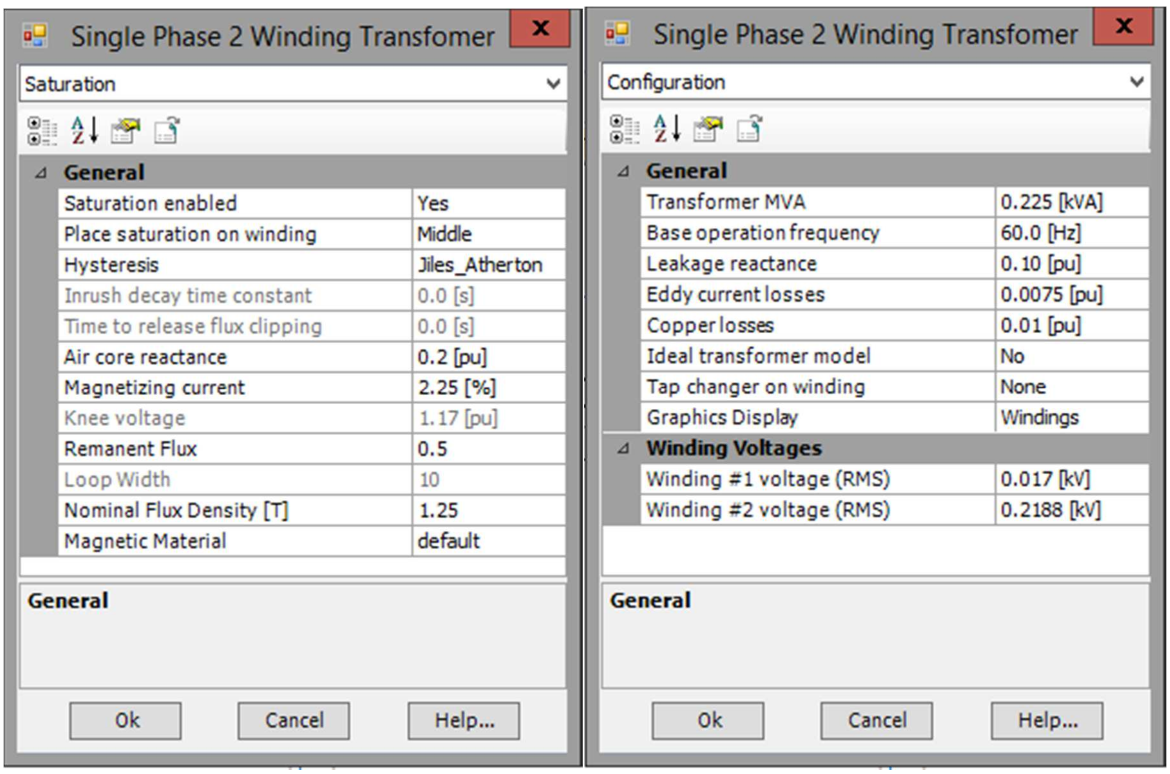

Figure 2-1: Final parameters that yielded congruent wave-forms for Symmetrical Saturation when comparing PSCAD to the Physical Model

The only three alternatives we had for the Hysteresis model were, None, Basic and Jiles_Atherton. Since our investigation requires hysteresis effects, we were left with the Basic and Jiles_Atherton models. The Basic Core Model and had no ability to alter the value or sign of the maximum Remanence value while the Jiles_Atherton Core Model would allow the modification of both and so the Jiles_Atherton model was selected. We tuned the Jiles_Atherton model to fit the experimental values of the physical transformer determined by various experiments to determine saturation effects, impedance, knee of the voltage curve, and waveforms at various values of positive and negative. Remanence and terminal voltage (plus and minus 10% of the Knee point). Figures 2-2 and 2-3 illustrates the control we found with the Jiles_Atherton Model when Remanence flux was input.

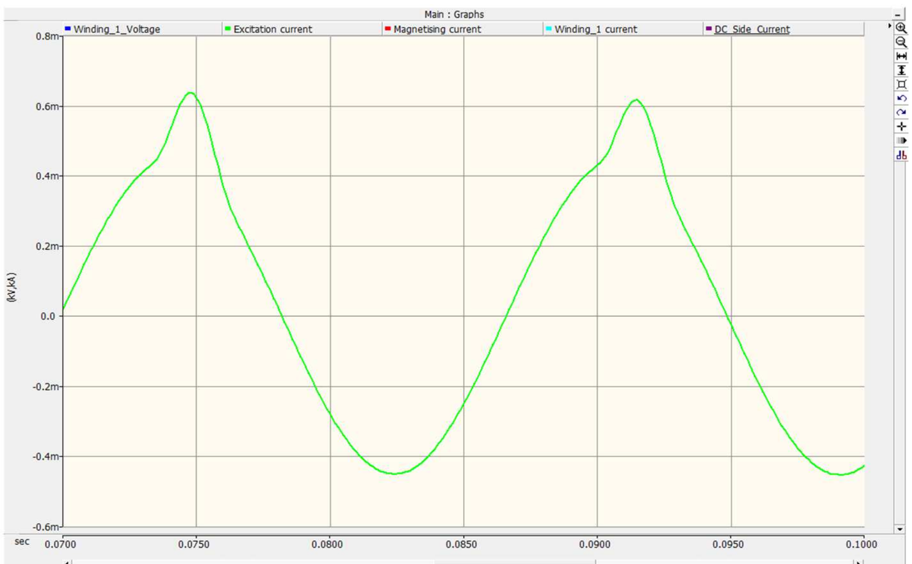

Figure 2-2: Asymmetrical Waveform at 0.6[pu] remanent flux in PSCAD

We could easily see the effects of Remanence moving down the excitation wave form as the magnitude of Remanence was increased. We could even produce the Remanence in the physical transformer which would approximate the Remanence waveforms built in the PSCAD model as shown in Figure 2-4.

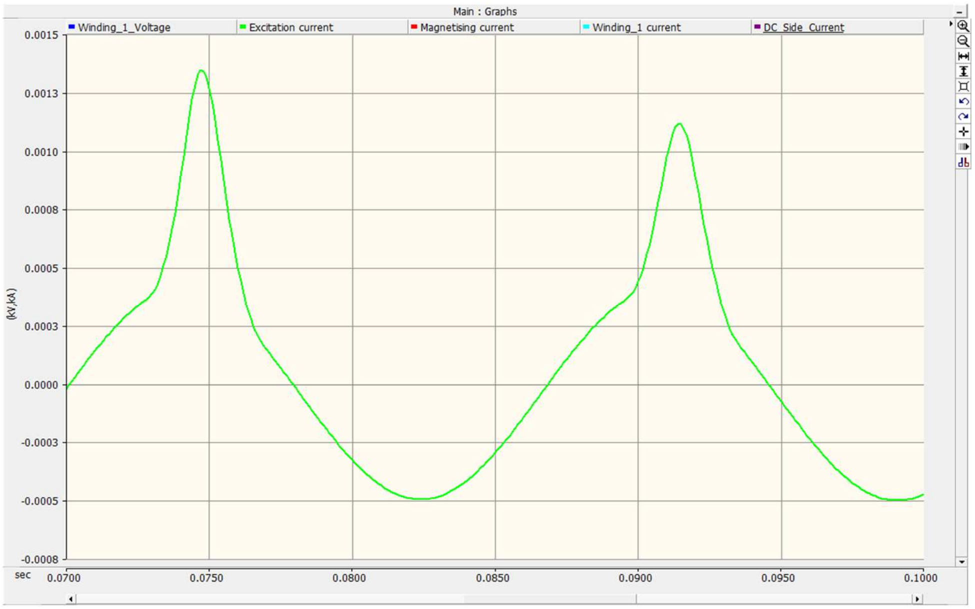

Figure 2-3: Asymmetrical Waveform at 0.8[pu] remanent flux in PSCAD

But as we turned off the Remanence in the PSCAD Model (by injecting DC into the secondary of the transformer), we noticed a disturbing result. Although the PSCAD model and the physical model produced very similar excitation effect curves, some anomalies were noted.

The anomalies stemmed from the way PSCAD modeled Remanence. The modeling is a single data entry which most certainly affects the shape of the saturation curve and may even be cancelled by injecting sufficient flux opposite to the inputted remanence flux. This cancellation was accomplished via Figure 2-5 where DC was injected to a level to cancel the effect of Remanence produced by an input value.

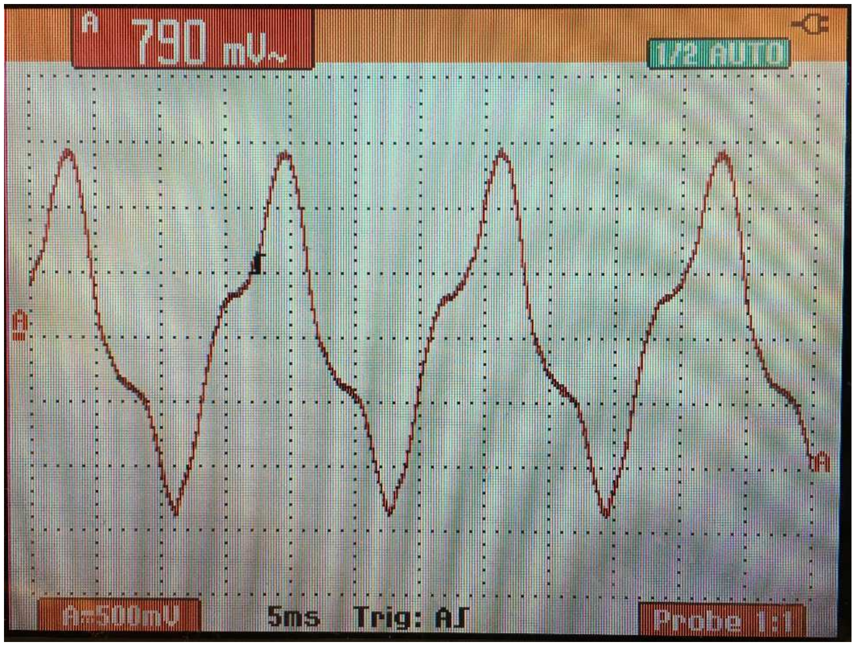

Figure 2-4: Asymmetrical Waveform in Physical Transformer under Low Value of Remanence

This cancellation even resulted in a symmetrical excitation curve with results that only illustrated the slight non-linear effects of the B-H curve which were to be expected. What was not expected was the inability of Remanence in PSCAD once cancelled to remain cancelled. In effect, we had verification of the cancellation of the effect of Remanence in PSCAD but not the cancellation of Remanence itself. On the other hand, the physical model when subjected to DC in the secondary similar to Figure 2-5, could actually cancel not only the effect but also the very existence of Remanence. This result was extremely important as the hypothesis is based upon bringing a power transformer to near zero Remanence when de-energized which should result in no remanence current when re-energized later and if the now existing point of wave technology is employed, no inrush at all!

In deference to the PSCAD model, the physical model was subjected to Remanence by external magnets, and ultimately by just randomly and abruptly de-energizing the physical transformer. But even these measures had their short comings. The ac ripple in our DC supply was slowly reducing the remanence and we had little control over the amount of Remanence that was being applied whether we used the strong external magnets or the random de-energizations as we had no zero-flux reference calibrator. As our budget excluded the purchase or rental of a Zero Flux calibrator, we were again in a quandary on how to prove the hypothesis. During these false starts, we were improving on our procedure to take substantial number of measurements once we could get a handle on how to induce a known value of Remanence that could also be cancelled as it was now obvious that the PSCAD model would have to be abandoned. This was the unfortunate position we were left in as the only way to model a transformer in PSCAD with zero Remanence was to input a simple zero into the PSCAD model, not a very independent result. By this time, we had amassed a considerable number of runs on the physical transformer.

This large database though showed a very interesting trend. Each time we turned the physical transformer off, we had a positive resulting Remanence and only a couple zero Remanence values. Probabilistically this was not possible. Since we were just randomly switching the current off in a very brief time (while waiting for the Remanence to stabilize) the average should have been closer to zero and not a preponderance of positive values and not one negative value.

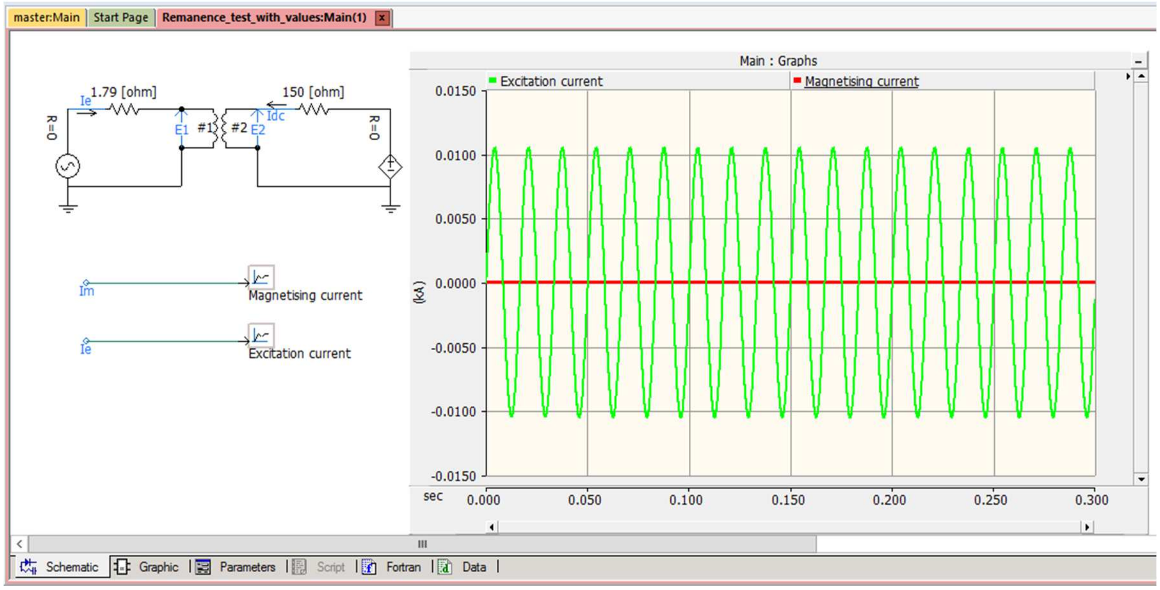

Figure 2-5: Illustration of Inputted Remanence and Associated Asymmetrical Current being Cancelled by External DC Injected Current all in PSCAD

This dilemma turned out to be an advantage for many reasons, but the most important was substantiating a zero Remanence in the single-phase transformer. We continued our random switching and once the procedure was known and repeatable (described in a later section), we took the average of the numerous values to date. We then continued the switching until the Remanence was the same value as the numerical average and then we zeroed the probe.

We then made further random switching operations and the average Remanence was nearly always zero (with data values as high as 30 mT (in air), we had just as many -30 mT and many very near zero Tesla on the Gauss meter. We continued this procedure of averaging our many data collection points and if required, we made corrections to the average but few varied by more than 0.001 mT. We are quite confident that we had found a numerical probabilistic method of zeroing the Gauss meter that was quite correct and repeatable and upon which we incorporated this procedure into our data collections routine and abandoned the use of the PSCAD model.

CHAPTER 3

EQUIPMENT

3.1 Power Transformer

Figure 3-1 illustrates the physical transformer that was used for determining the pattern of current extinction which resulted in zero or near zero residual flux.

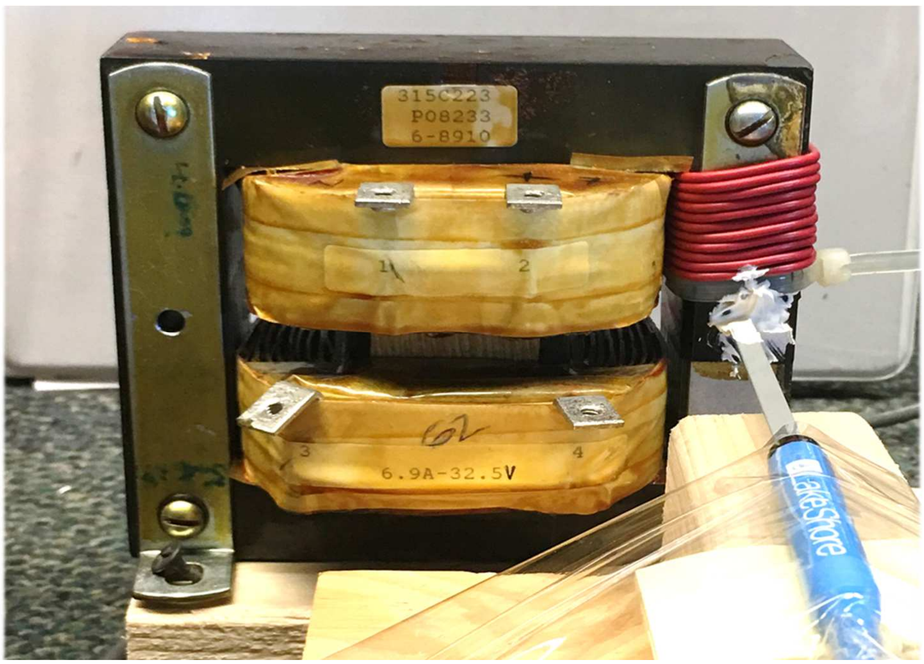

Figure 3-1: Power Transformer

3.1.1 Parameters

Table 1 illustrates the parameters for the physical transformer which were developed through experiments describe later, physical dissection of a duplicate transformer and concurrence with PSCAD model for other parameters based on identical voltage, current and flux waveforms.

Table 1. Transformer Parameters

Rating	225VA
Turns Ratio	62/798
Knee Voltage (62 Turns)	16.99V
Impedance	$109.26\angle 26°$ Ω +/- 5^0
X/R Ratio	0.49
Maximum Flux Density	1.24T

3.1.2 Knee Voltage

Knee Voltage of the transformer (16.99V - Bottom Winding) and current at that value of voltage (155.5 mA) is obtained from the graph (Figure 3-2) plotted using experimental data (see Table 2).

Table 2. Saturation Characteristics

Voltage (in V)	Current (in mA)
0	0
2.006	45.4
4	66.3
6.02	82.15
7.95	94.99
10.04	108.35
12.03	120.8
14.04	134.1
15.02	140.9

16.01	148.2
16.99	155.5
18.04	164.45
20	181.75
22.05	205.5
25	250

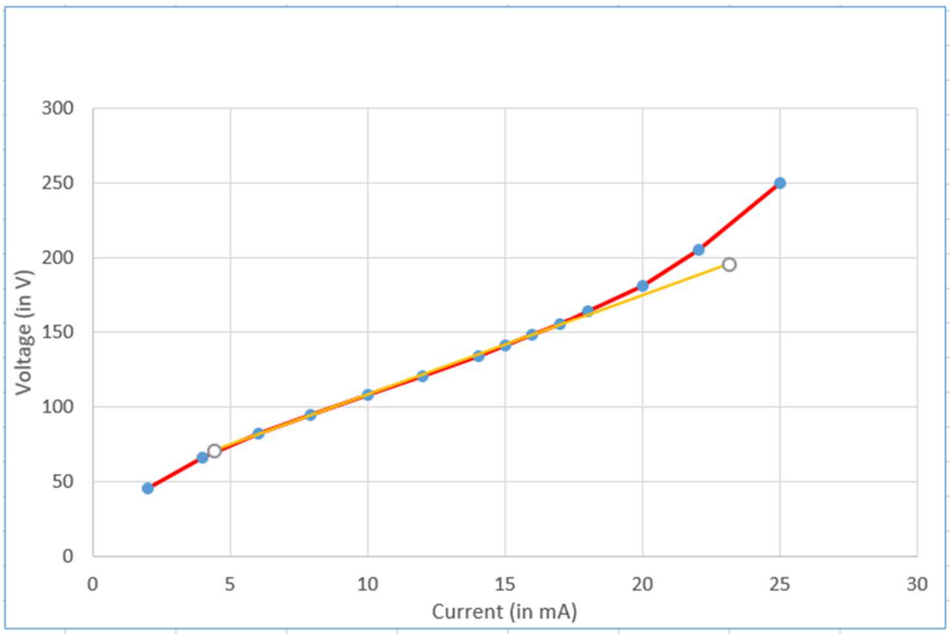

Figure 3-2: Saturation Characteristics, $V_{applied}$ and $I_{excitation}$

3.1.3 Impedance

Impedance angle is the phase difference between voltage across the winding $V_{applied}$ (blue waveform in Figure 3-3) and the current through the transformer $I_{excitation}$ (red waveform in Figure 3-3).

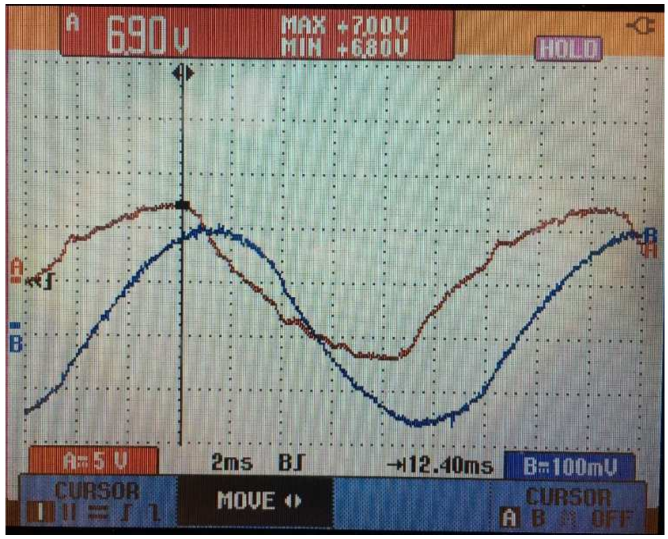

Figure 3-3: V and I of Transformer ($V_{applied}$ and $I_{excitation}$)

Impedance of the transformer $|Z| = V/I = 16.99/0.1555 = 109.26\ \Omega$

$\bar{Z} = 109.26\angle 26°\ \Omega$; $R = 98.2022\ \Omega$; $X = 47.89643\ \Omega$;

X/R ratio

$X/R = 47.89643/98.2022 = 0.49$

Maximum Flux Density

$(B_{max}) = \phi_{max}/A$

A = Cross Section of the Core = $3.6cm \times 4.4cm = 15.84 \times 10^{-4}\ m^2$

ϕ_{max} can be calculated from Transformer EMF equation

$E_{RMS} = 4.44\ f\ N\ \phi_{max}$

$32.5 = 4.44 \times 60 \times 62 \times \phi_{max}$

$\phi_{max} = 1.97$ mWb

$B_{max} = 1.97 \times 10^{-3}/8.14 \times 10^{-4}$

$= 1.24$ T

3.2 Gaussmeter

The 421 model Gaussmeter was manufactured by Lake Shore Cryotronics, Inc. It features:

- Large Vacuum Fluorescent Display
- Resolution to $4\frac{3}{4}$ Digits
- Serial Interface
- Analog Voltage Outputs
- Max Hold and Relative Reading
- Alarm with Relay

Figure 3-4: Lakeshore 421 Gaussmeter

The Gaussmeter displays the value of magnetic fields in both Gauss (G) or Tesla (T) by pressing the Gauss Tesla key on the Gaussmeter. It measures both AC and DC and toggles between them by pressing AC/DC key.

3.2.1 Transverse probe

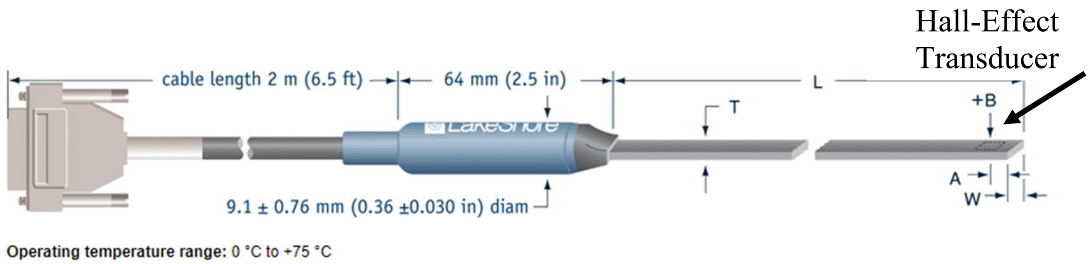

Figure 3-5: Transverse Probe

Stem material of the probe is Aluminum. Frequency range is DC and 10Hz – 100Hz. It has hall effect sensor on its tip. The probe is inserted/placed at the point of flux measurement. It should be placed perpendicular the direction of magnetic flux density (B). It must be zeroed by pressing the Zero Probe key on Gaussmeter to cancel out the zero offset or small values of magnetic fields.

3.3 Tektronix Digital Oscilloscope

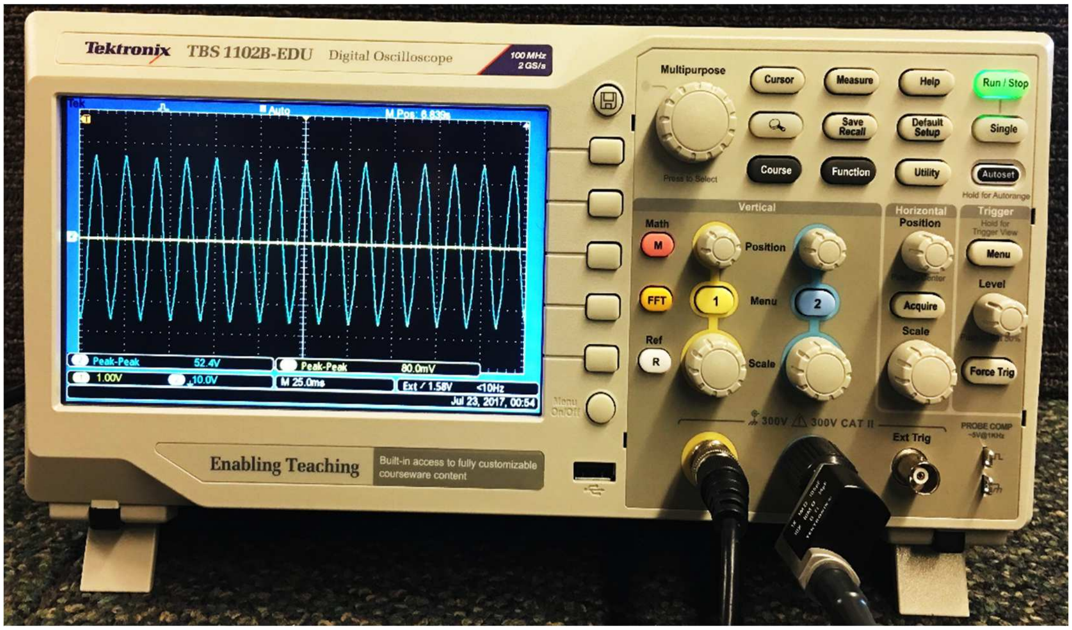

Figure 3-6: TBS 1102B Digital Oscilloscope

3.3.1 Features

- Bandwidth: 100MHz
- Channels: 2
- Sample rate on each channel: 2.0GS/s
- Record length: 2.5k points at all-time bases
- Selectable 20MHz bandwidth limit
- Setup and Waveform Storage

3.4 Power Supply and Snap Action Toggle Switch

Figure 3-4 illustrates the power supply that was used as the source for the multiple runs of switching experiments. Approximately 16.99 Volts were developed between terminals 4 and Neutral. This voltage was switched via first a push button switch (on the left) which we discovered was dampened internally and led to multiple connections and disconnections producing recovery voltages (results of Lenz's Law, sputtering). We changed the switch to a high speed fast acting toggle switch (on the right) which had few if any sputtering occasions.

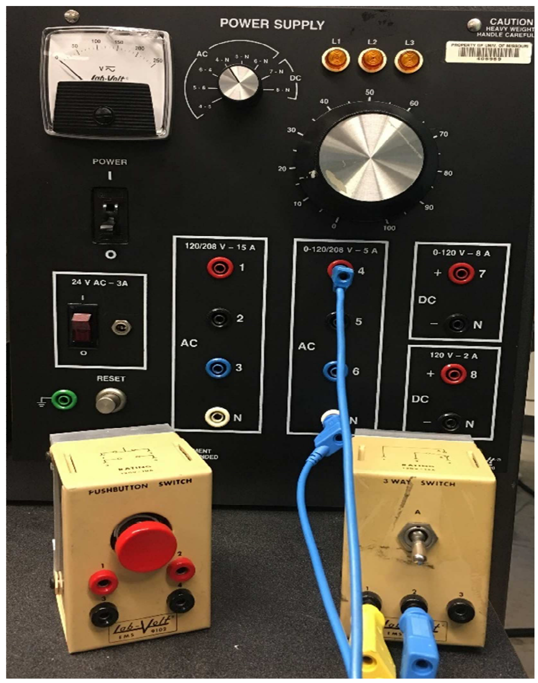

Figure 3-7: Power Supply and Fast
Acting Toggle Switch

CHAPTER 4

EXPERIMENT AND RESULTS

4.1 Precautions

4.1.1 Zeroing the Gaussmeter probe

The transverse probe must be zeroed before using.

4.1.2 Isolating ground from Oscilloscope

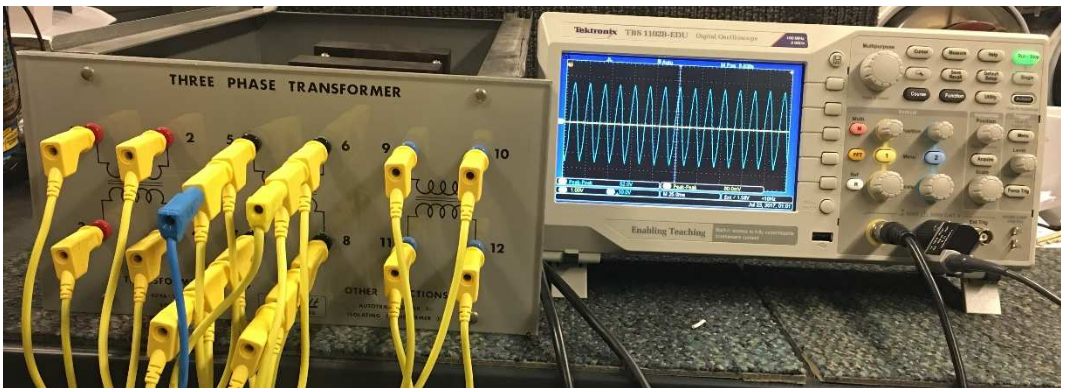

Figure 4-1: Isolation Transformer

Oscilloscope was measuring the readings with ground reference. The circuit used for experiment had its own ground. These two neutrals produced a common mode noise circuit and all the voltage was dropping in this neutral/ground loop. To eliminate this problem, we isolated the oscilloscope via an isolating transformer. The ground from the oscilloscope was isolated using three single phase transformers connected in parallel from which the oscilloscope was powered.

4.1.3 Holes in Transformer

Two holes in either limbs of the shell type transformer were drilled to hold the transverse probe of the Gaussmeter. One hole in each limb of the transformer would have been sufficient but, two are drilled so that the main flux coming from center limb will divide equally among the two limbs.

4.1.4 Stationary Probe

The transverse probe of the Gaussmeter is sensitive to the attack angle of the flux as shown in Figure 4-2.

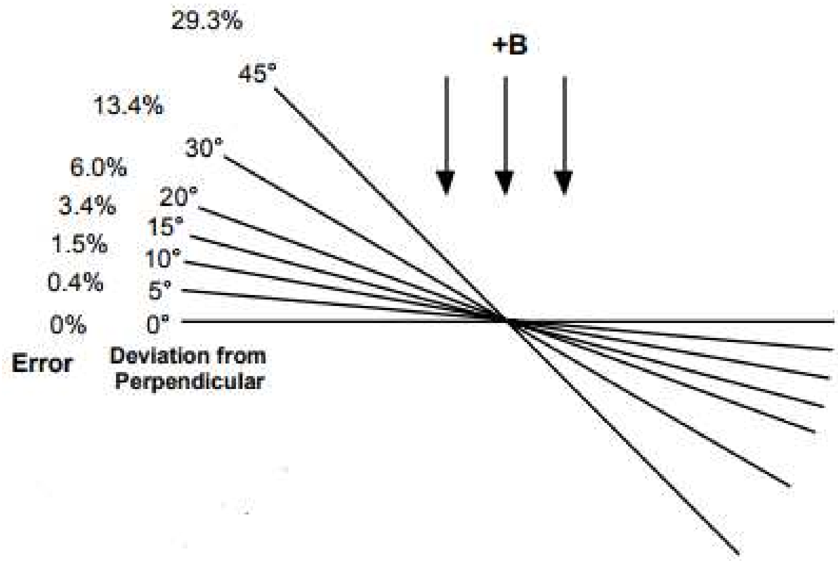

Figure 4-2: Effect of angle of probe on measurements

The probe was held perpendicular and stationary using wooden support, cement and tape to prevent rotation as seen in Figure 3-1.

4.2 Procedure

With all due precautions taken, the circuit was setup as shown in Figure 4-3 schematically and Figure 4-4 physically.

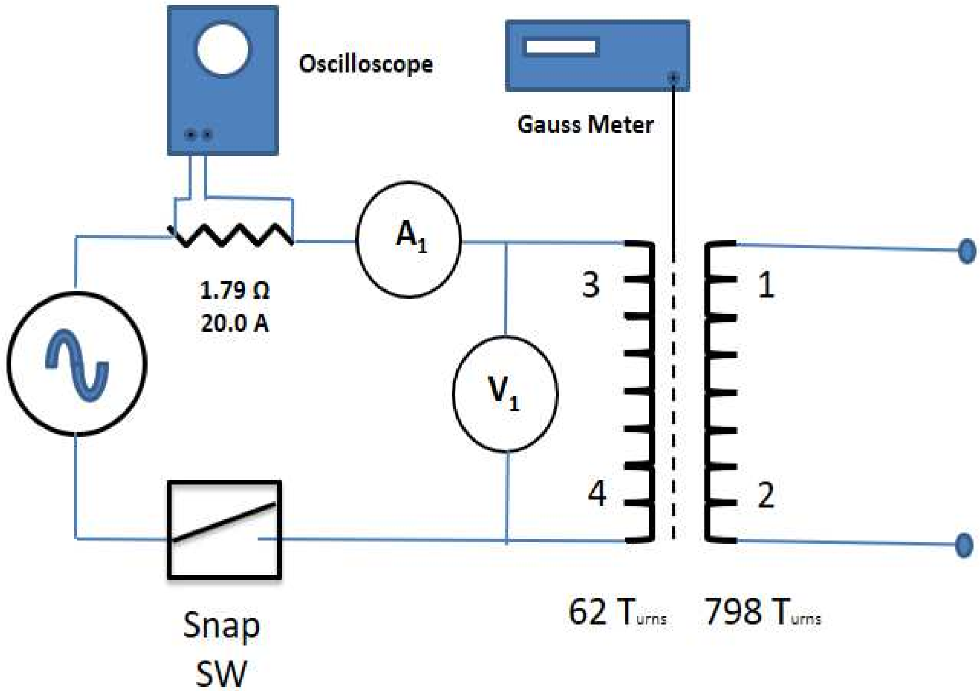

Figure 4-3: Circuit Schematic Diagram

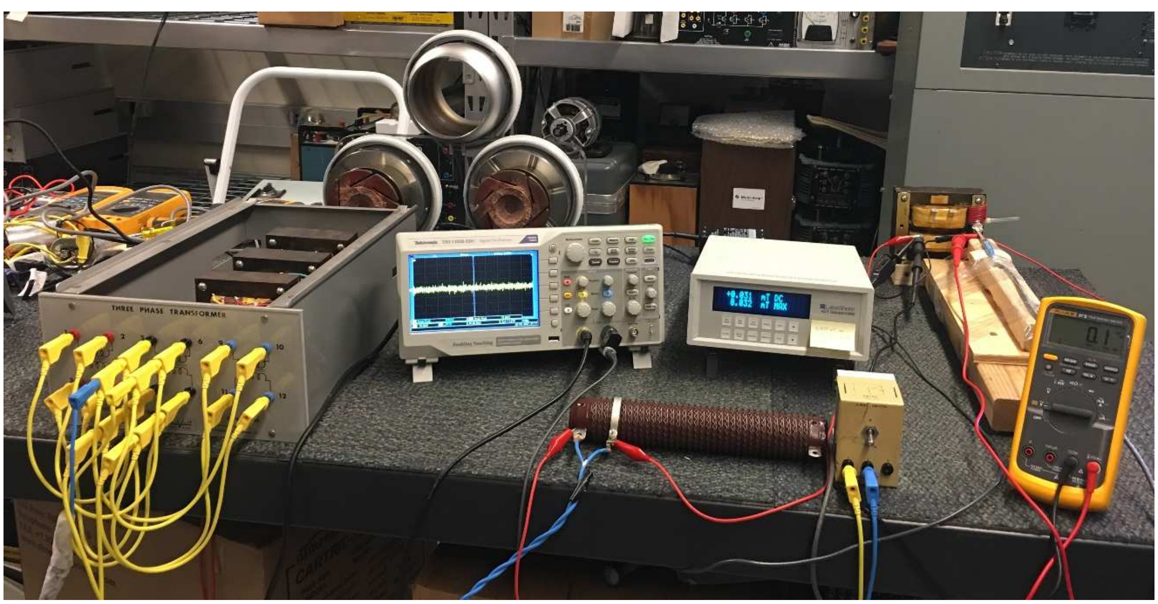

Figure 4-4: Physical Circuit Arrangement

- The supply voltage is set to 16.99V
- The transformer is energized by closing the snap action toggle switch.
- Current through the transformer is converted into voltage using 1.79Ω resistor connected in series.
- The voltage across the transformer is monitored on the oscilloscope.
- 2sec wait time is allowed for the flux in the transformer as well as the value on the Gaussmeter to stabilize.
- The waveforms are recorded on the scope as shown in Figure 4-4.

These steps were repeated several hundred times to obtain different values of remanence flux as a function of extinction current waveform. A short synopsis of these data points is illustrated on Table 3.

4.3 Results

Table 3. Results - A Synopsis of the Many Data Points where Current is Yellow and Voltage is Blue

Steady State Value of DC Flux (during Turn ON) (in mT)	Remanence Flux (after Turn OFF) (in mT)	Figure
27	0	4-5
-18	0	4-6
63	261	4-7
-54	-216	4-8
9	27	4-9
18	-9	4-10

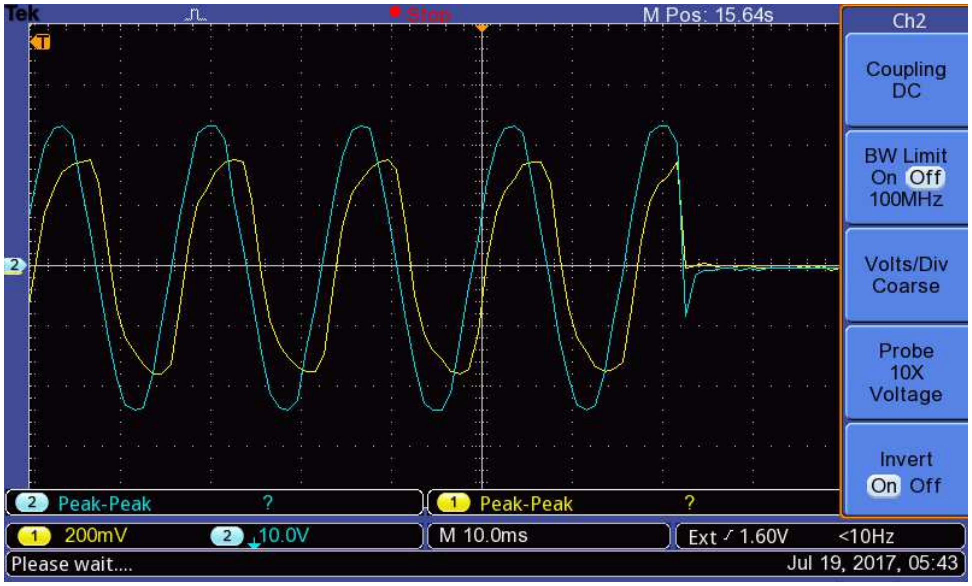

Figure 4-5: An Example of Current Cutoff at Maximum Positive with No Remanence

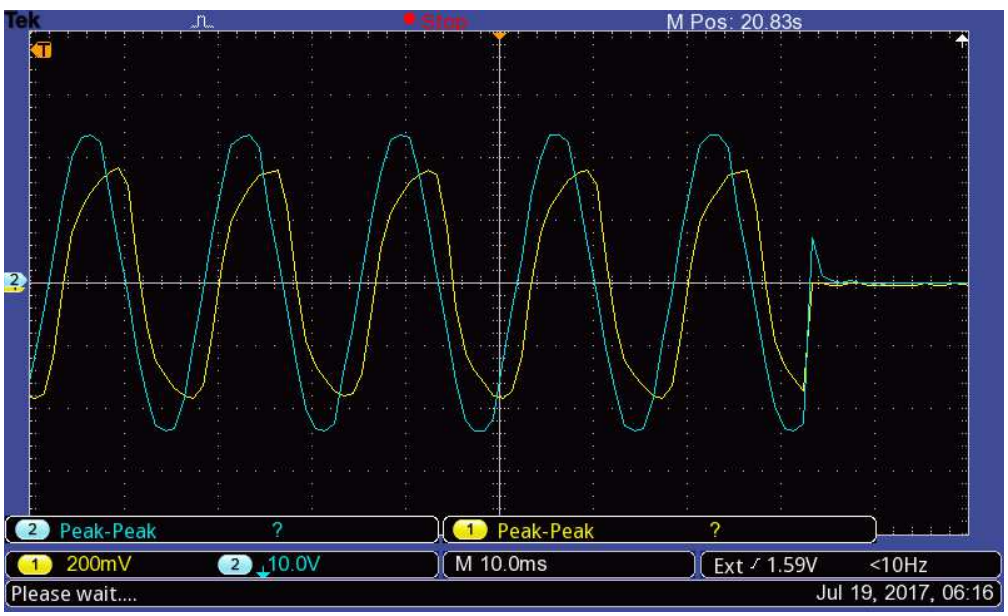

Figure 4-6: An Example of Current Cutoff at Maximum Negative with No Remanence

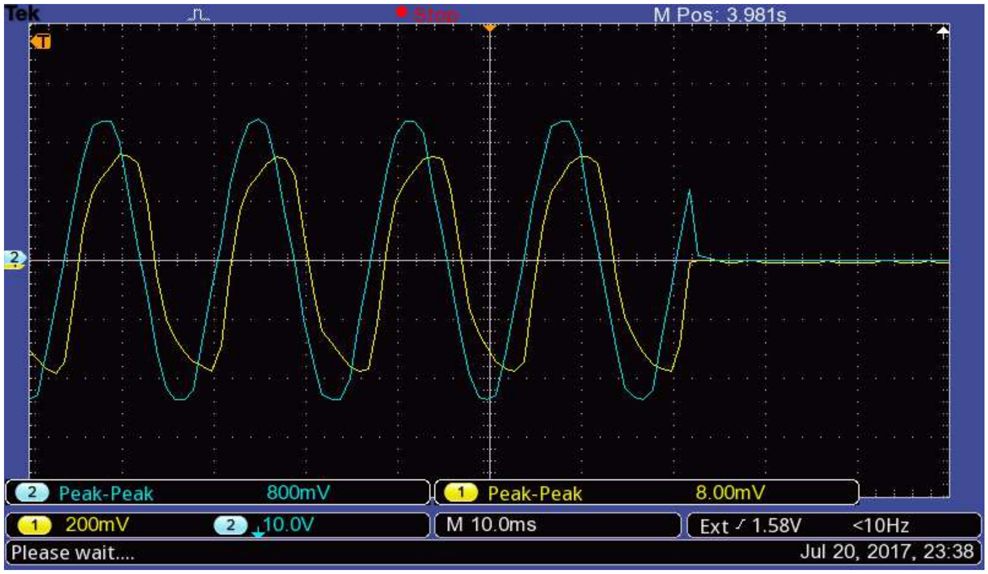

Figure 4-7: An Example of Current Cutoff long after Maximum Negative with a large value of Positive Remanence (261 mT)

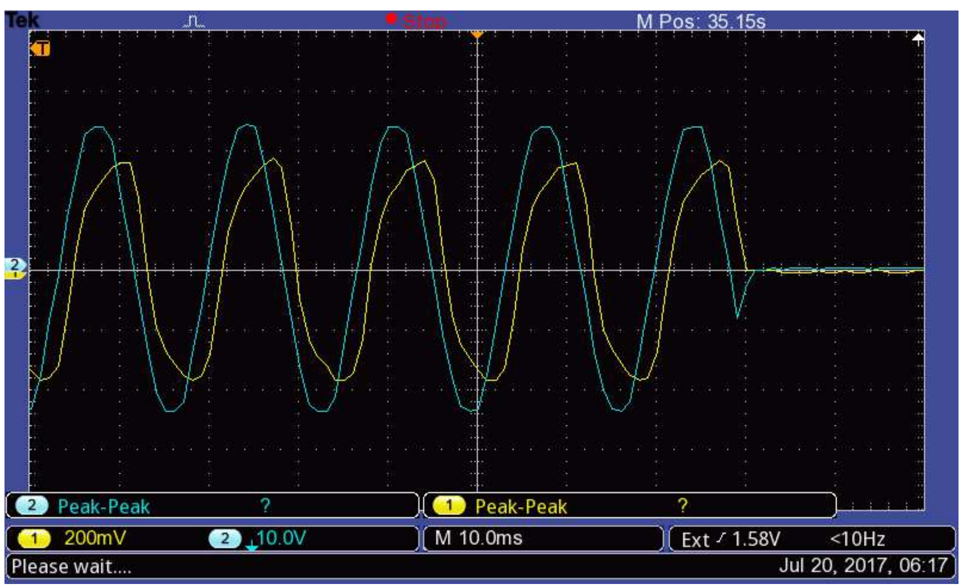

Figure 4-8: An Example of Current Cutoff long after Maximum Positive with a large value of Negative Remanence (-216 mT)

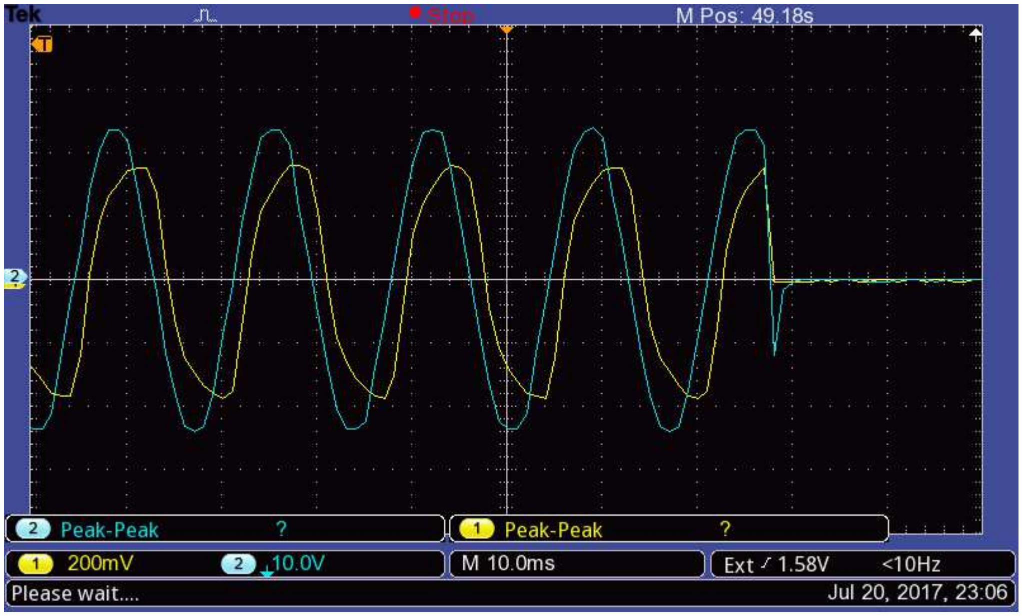

Figure 4-10: An Example of Current Cutoff shortly before Maximum Positive with a small value of Remanence (9 mT)

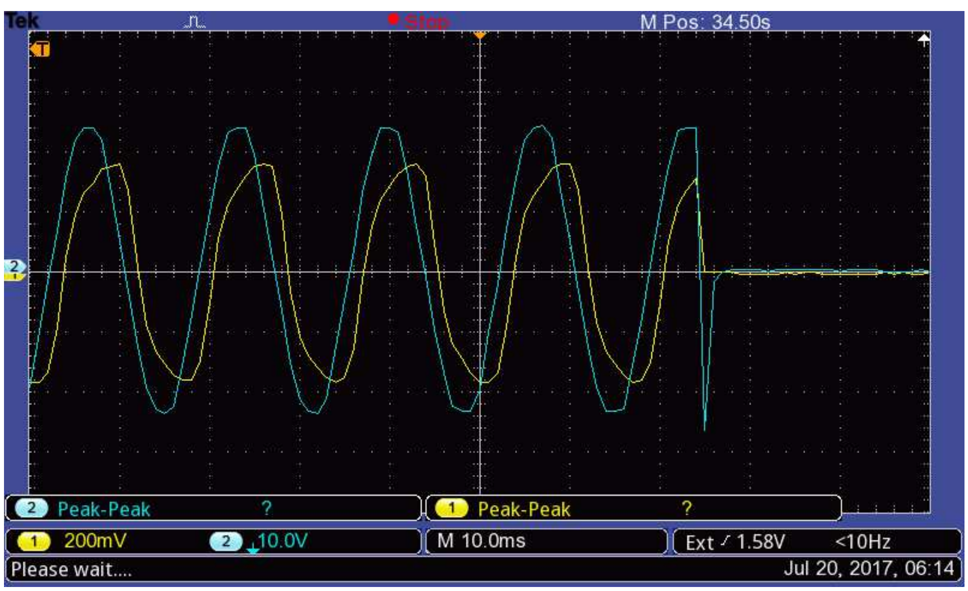

Figure 4-9: An Example of Current Cutoff shortly before Maximum Positive with a small value of Remanence (27 mT)

4.4 Observations

The following observations are made with the help of all the data recorded at the time of opening:

- Lower value of remanence in the transformer can be obtained by opening the switch at a point on the current waveform where it reaches the peak.
- If the transformer is de-energized when the current to the transformer is nowhere near the peak/at zero, it would leave higher values of remanence.

The transient recovery voltage observed in few measurements can be eliminated with the help of metal oxide surge arresters mounted on the transformer.

CHAPTER 5

IMPLEMENTATION OF THE CONCLUSIONS

5.1 Recap of the Conclusions

The conclusion stated de-energizing the power transformer at the effective current peak (without including the effects of saturation) would result in little to no remanence flux. Should the single-phase transformer be re-energized later, this lack of remanence would prevent this component of magnetizing current from appearing. Further, if the existing knowledge of point of wave breakers is implemented, via say a "Synchronous Close (Zero Voltage Close/Point on Wave) Circuit Breaker", then the inrush current attributed to energization of a transformer as a function of the voltage wave would also be zero. The transformer would now lack both components of magnetizing current assuming a solid-state breaker is used for the energization. Such would result in the transformer experiencing steady state current when energized prior to being loaded as illustrated below.

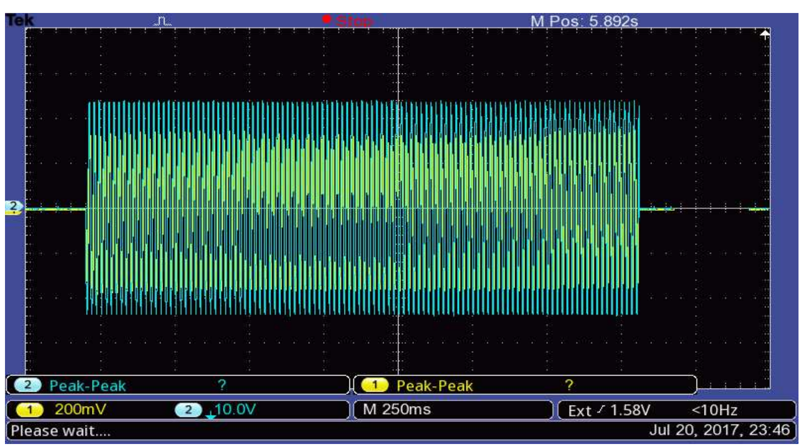

Figure 5-1: Anticipated Voltage & Current Waveforms Without Momentary Effects of initial voltage (Point of Wave) (Blue) or Remanence current (yellow)

5.2 Implementation

The implementation of the conclusion uses a Hall Effect transducer within the core of the power transformer, which may be realized by producing a punching in the laminations to form a very small void within which the transducer is mounted and the twisted shielded wiring may be placed and connected to the inside wall of the transformer (bulkhead) for external connection. The wiring of the transducer should be separated by a distance far more than the BIL of the transformer.

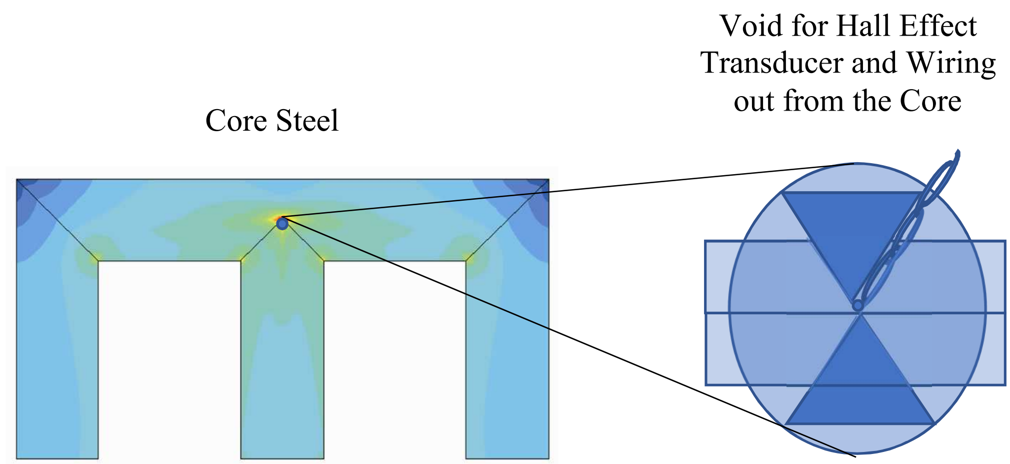

Figure 5-2: Implementation of Hall Effect Sensor in Core

The orientation is not critical so long as some of the transducer is facing the normal flux flow. Faults will not damage the transducer due to magnetic cancellation of all but magnetization. The transducer should be encapsulated in a material impervious to C-10 transformer oil. As with any small device, we would suggest five being connected and wired to the transformer bullhead for external connection.

5.3 Future Direction of Research

This research is entirely based upon the data collected by conducting experiment on single phase two winding shell type transformer. This method needs to be modified to apply to both three-phase core and shell type transformers, with and without nameplated loads and also under faulted conditions. In a single winding transformer, there would be only one flux to deal with however, this process must be modified for a three-phase transformer as there will be three fluxes (their sum and difference) to deal with.

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VITA

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