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Nathanael Jared Makowski  
*Portland State University*

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Proposal and Analysis of Demagnetization Methods of High Voltage Power  
System Transformers and Design of an Instrument to Automate the  
Demagnetization Process

by

Nathanael Jared Makowski

A thesis submitted in partial fulfillment of the  
requirements for the degree of

Master of Science  
in  
Electrical and Computer Engineering

Thesis Committee:  
Martin Siderius, Chair  
Betsy Natter  
Branimir Pejcinovic

Portland State University  
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## ABSTRACT

Present demagnetization methods for large power system transformers are time consuming and can be dangerous to persons performing demagnetization. The work of this thesis was to develop improved demagnetization methods and to construct an automated instrument that would implement the methods developed.

One previously developed method was analyzed for effectiveness. Then, two new methods for demagnetization were developed and also analyzed for effectiveness. An automated test instrument prototype was redesigned to be able to accommodate these methods and to improve the safety of the user.

The previously developed method attempts demagnetization based on current flow behavior characteristics. The first new method is a magnetic flux estimation based on saturation time. The second new method is also based on measuring saturation time, modified to account for the variable voltage loss due to wire resistance.

The second of the two new methods developed proved to be the most effective for demagnetization and was able to demagnetize a transformer within an error margin of 2%. The instrument designed to perform the demagnetization with this new routine is now in early production stages for an expanded field trial with transformer maintenance teams.

## Acknowledgements

I am grateful to my advisor Dr. Martin Siderius for his guidance and encouragement to prepare this thesis with thorough attention to detail and professionalism.

It is an honor for me to have Dr. Branimir Pejcinovic and Prof. Betsy Natter participate on my thesis committee; my time working together with each was enjoyable and offered many of my most interesting learning experiences at PSU.

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Most of all, I thank God for bringing it all together.

## Table of Contents

	Abstract .....	i
	Acknowledgements .....	ii
	List of Figures .....	iv
1	Motivation .....	1
2	Introduction of Problem.....	4
2.1	Winding Resistance Test .....	4
2.1.1	IEEE Standard Procedure .....	4
2.1.2	Test Current Magnitude .....	5
2.3	Significance of Transformer Saturation .....	6
2.3.1	Transformer Health .....	7
2.3.2	Power System Protection .....	7
2.3.3	System Power Quality .....	9
3	Theory and Principals of Power Transformer Operation .....	10
3.1	History.....	10
3.2	Magnetic Properties .....	11
3.3	Electric Steel Magnetization & Hysteresis.....	13
3.4	Presently Used Demagnetization Methods .....	15
4	Previous Work.....	18
4.1	Instrument Design .....	18
4.2	Demagnetization Algorithm.....	20
5	Demagnetization Methods .....	23
5.1	Permeability Method .....	23
5.2	Time Based Method .....	24
5.3	Integration Method.....	26
6	Demagnetization Device Design Requirements .....	29
6.1	User Safety.....	29
6.2	Measurement System .....	33
6.3	System Reliability & Protection.....	34
6.4	Automation & Usability.....	35
7	Device Constructed for Demagnetization Testing.....	36
7.1	Controller.....	36
7.2	Device Power.....	37
7.3	Measurement Components .....	38
7.4	System & User Protection .....	40
8	Results .....	43
8.1	Methods for Determining the State of Residual Magnetization .....	43
8.2	Permeability Method .....	43
8.3	Time Based Method .....	44
8.4	Integration Method.....	46
9	Conclusions.....	47
10	Works Cited .....	49

## List of Figures

Figure 1 - IEEE Resistance Measurement Circuit.....	4
Figure 2 - Inrush Current example .....	6
Figure 3 - Magnetization Comparison of Silicon Steel to Iron.....	12
Figure 4 – Example of Current Magnitude During Demagnetization Routine.....	16
Figure 5 – Megger MTO210 Demagnetization Routine (16).....	17
Figure 6 - Prototype Test Instrument .....	18
Figure 7 - Device Design for Previous Work.....	18
Figure 8 - Present Winding Resistance and Demagnetization Test set.....	19
Figure 9 - Theoretical magnetizing Current and Magnetic Flux for one cycle .....	21
Figure 10 - Permeability Demagnetization Routine.....	24
Figure 11 – Core magnetization over time when a fixed voltage is applied to the winding...25	
Figure 12 - Time Integration Demagnetization Routine .....	26
Figure 13 - Modified Time Integration Demagnetization Routine .....	27
Figure 14 - Completed Test Set.....	40
Figure 15 - Test Instrument Internal Circuitry .....	41
Figure 16 - Test Instrument Schematic .....	42
Figure 17 - Example Current Flow Timeline after Voltage Polarity is Reversed.....	44
Figure 18 - Delta Transformer Magnetic Field during DC Energization .....	45
Figure 19 –Comparison of Demagnetization Methods: Maximum Error .....	47

## **1 MOTIVATION**

Present demagnetization methods for large power system transformers are time consuming and can be dangerous to persons performing demagnetization. Demagnetization after routine maintenance is an important practice for the health and long life of a transformer. High voltage power transformers are an essential part of any transmission system. At BPA (Bonneville Power Administration), with about 630 transformers representing approximately \$1 billion in assets, managing and prolonging the service life of transformers is critical. Towards this end, many new tools are being introduced for transformer testing and condition analysis including frequency response analysis and ultrasonic failure locating and prediction. Additionally, advancing technologies in other fields have helped reduce the stress and wear on transformer assets.

BPA's successful maintenance program helps to keep failure rates far below the average failure rate found in a major 10-year study (1). One of the tests that are performed is called a winding resistance test. This test measures the ohmic resistance of the winding material in high voltage transmission transformers. This is achieved by saturating the core with a DC voltage source in order to obtain a steady state current and then measuring the voltage drop across the winding. However, this test can leave the transformer in a state of heightened susceptibility to large inrush currents.

When a power transformer with residual magnetism left in the core is energized, inrush currents occur that can be potentially damaging to various portions of the power system. These currents can exceed the rated current by an order of magnitude and more. Studies have shown that the high mechanical forces and resulting vibrations due to these currents causes increased wear on the insulation of transformer windings (2). In a major 10-year study it was found that line surges, like that of inrush current, and Insulation degradation are the number one and two causes of transformer failures respectively; cumulatively these represented almost 35% of failures (1). Much effort has been made to reduce the likelihood and magnitude of inrush currents (3), (4), (5).

Existing guidelines and techniques (6) to restore a power transformer to a neutral magnetic state are time consuming and potentially dangerous to untrained personnel. Primary instruction texts make these methods even more problematic by giving instruction in a qualitative manner which adds a level of uncertainty to the accuracy of demagnetization and augments the associated dangers as well.

The work this thesis was to develop a demagnetization method that would decrease the time requirement for demagnetization and to develop a prototype test set that takes advantage of advanced technology in measurement and high speed digital processing to automate the demagnetization process. The innovative device automates the winding resistance test and leaves the transformer in a state that minimizes inrush currents upon energization. This prototype reduces the average



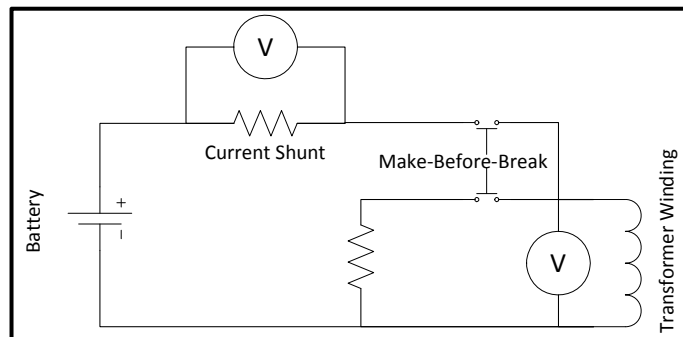
time needed to accurately prepare a transformer bank for energization by a full hour compared to some previous methods and provides an additional level of personnel safety when performing this transformer diagnostic test. Also, with further development, the flexibility of the advanced hardware could allow the integration of additional tests into the same unit and reduce the time necessary to set up the various tests that must be performed.

The deployment of this new test set will improve the accuracy and efficiency of routine transformer diagnostic tests. It will also extend the life of BPA's transformer assets thereby improving reliability and decreasing capital costs.

## 2 INTRODUCTION OF PROBLEM

### 2.1 WINDING RESISTANCE TEST

One of the many tests performed during routine maintenance of a power transformer is the winding resistance test. This test helps to gauge the health of internal connections within the transformer by comparing them to values measured by the manufacturer upon being constructed. This is an important benchmark; within a transformer there are often a number of different “tap” connections that can be made to adjust the ratio of the transformer by as little as a fraction of one percent. These tap positions on large power transformers are often controlled remotely by



**FIGURE 1 - IEEE RESISTANCE MEASUREMENT CIRCUIT**

dispatchers who monitor and make adjustments to maintain system balance. The reliability of these connections is critical to system operations.

#### 2.1.1 IEEE STANDARD PROCEDURE

This test is performed according to the directions given in IEEE 62-1995, (section 6.1.1.1) (6) by injecting a current into the winding of a transformer as displayed in Figure 1. Once the winding inductance has been overcome, ohms law can be used to calculate the resistance.

While the procedure is simple, the lasting effects of saturating the inductance of the winding can be significant. It is important that they be considered before

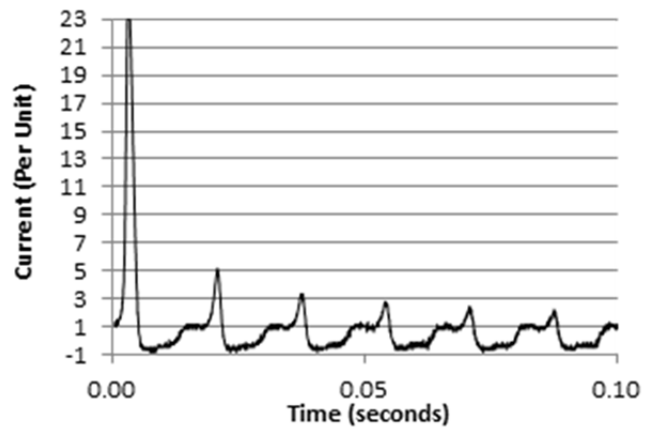
connecting the transformer to the power system, or performing other tests, and is specifically suggested in IEEE 62 before performing the 'Exciting Current' test (section 6.1.3.) The state of magnetization also affects the results of Frequency Response Analysis (FRA) tests, which is rapidly gaining popularity as a diagnostic tool. Saturation effects are discussed more in section 2.2

### **2.1.2 TEST CURRENT MAGNITUDE**

For the winding resistance test, the standard recommends using a current of less than 15% of the normal current rating for the transformer with no minimal or target current specified. A more specific target for measurement current, suggested by transformer manufacturers, is 1% of the transformers normal current rating. This recommendation seems to be a compromise with considerations of measurability and precision, testing time, and accuracy. They further suggest that exceeding 10% of the transformer's rated current for a winding resistance test may affect the temperature of the winding significantly enough to give erroneous readings. They also recommend no less than a minimum current of 0.1% of the transformer's rated current because of the difficulty in determining whether the current has reached a steady state or not.

### 2.3 SIGNIFICANCE OF TRANSFORMER SATURATION

As mentioned in the previous section, saturation of the transformer core is necessary for the winding resistance test. This is significant because of the resulting effects of residual magnetization due to saturation. This section will explain the significance and consequences of the residual magnetization and the physics of the residual magnetization will be considered in section 4.



**FIGURE 2 - INRUSH CURRENT EXAMPLE**

Figure 2 shows an example of the magnitude of current that can pass through the transformer windings when the core of the transformer goes into saturation due to the residual magnetization. TEST

In this graph the current is given in “Per Unit” quantities and is given by the relationship:  $P.U. \text{ Current} = \text{Actual Current} / \text{Normal Rated Current}$ . Thus, in this example, the current passing through the winding is more than 23 times the normal current for the first cycle and 5 times the normal current for the second cycle.

This transient inrush current can disturb the entire system with potentially damaging consequences. These consequences are generally grouped into one of

three main categories: Transformer Health, System Protection Planning, and Overall System Power Quality.

### ***2.3.1 TRANSFORMER HEALTH***

The first concern is with the effects on the transformer itself. Since the mechanical force on a winding is proportional to the square of the current, inrush currents cause a significant increase of mechanical stress forces on transformer windings as well as result in harmonic vibrations that increase degradation of insulation (1), (2). Transformer failure modes linked to insulation degradation are often very destructive in nature which can effect nearby components as well. Because of the significant investment each individual transformer represents, the adverse effect of inrush current on the internal components of a transformer with specific regard to service life reduction has led the power system industry to research and apply many procedural changes to the way that transformers are energized and de-energized including controlled closing (energizing the transformer at a specific point in time) and the use of surge suppression resistors (3).

### ***2.3.2 POWER SYSTEM PROTECTION***

The second issue that arises concerns power system protection plans. The high inrush currents can cause the power system protection and control circuitry that monitors system faults<sup>1</sup> to mistakenly operate (6) (7). Since transformers are taken out of service regularly for routine maintenance, if a protection relay system

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<sup>1</sup> line-to-ground or line-to-line short circuit condition

mistakenly recognizes a fault condition when attempting to bring the transformer back on-line the transformer may be automatically taken back offline. When this happens it is very difficult to determine whether the transformer was taken offline due to the effects of residual magnetism, due to a failure within the transformer, or because of a maintenance oversight. In some cases, attempting to energize the transformer a second time could have very damaging consequences, including case ruptures and fire. Before attempting to bring the transformer online a second time there is likely to be an investigation of the situation which will cause the loss of many hours of operation time as well as increased labor costs.

For example, a similar situation occurred after a transformer had undergone some extended maintenance and repair and was ready to be reinserted onto the power grid. The substation operator in charge tried to energize the transformer twice, however, the inrush currents were so great that the automated protection measures immediately disabled the transformer both times. Fearing there was internal problems there was hesitation to attempt a third time and were inclined to take the transformer apart to ensure that some aspect of repair wasn't overlooked. It was decided to contact the field services and testing department, which sent out an expert with experience in demagnetizing transformers. After performing the demagnetization, the transformer was successfully energized on the system upon the first attempt.

### **2.3.3 SYSTEM POWER QUALITY**

The third main issue deals with the effect on overall system power quality.

The effects observed include increases and decreases in the rms voltage called *resonant harmonic voltage swells* (8) and *voltage sags* (9). These events last 16ms to 60s in duration and are characterized by low frequency oscillation of rms voltage amplitudes that coincide with resonant points in the power transmission system. Also, since these effects unbalance the current flow of the power system, this can have a detrimental effect on distributed generation components (10): When generators are distributed across large service areas the power demand placed on an individual generator may be greater than others, this can result in high temperatures in a relatively short amount of time and high risk of failure, (11). Another consequence is that it can disturb the results of other routine maintenance tests. (12)

### **3 THEORY AND PRINCIPALS OF POWER TRANSFORMER OPERATION**

#### **3.1 HISTORY**

Silicon Steel, also known as Electrical Steel, is the standard for power transformer core material. More than 125 years ago, the effects of adding elements in various quantities to the steel alloy mixture were performed using systematic routines of experimentation by many entities. It was through this activity that the basis for modern electrical steel was discovered.

In 1886 Robert Hadfield filed for the patents on the alloy mixture for Silicon Steel because of its mechanical properties being useful for springs and some fine blades. The first transformer using this core material was not built until in 1913, almost 2 decades later.

The production of Silicon Steel for transformers was likely motivated by the increased industrialization and manufacturing required by the First World War. Hadfield's patents to produce the hard Manganese Steel as well as Silicon Steel allowed his business to flourish during this time. Employing as many as 15000 people by the end of the war, Hadfield was in a prime position to advance the expansion of the Electrical Power Grid.

Yet even now, the magnetization of Silicon Steel is not well understood (13). Because its magnetic permeability ( $\mu_r$ ) is both nonlinear and multivalued relative to the magnetic field strength applied, the qualities and characteristics of ferrous materials must be obtained for individual samples through experiment and testing.



Much in the same manner that Hadfield systematically used so many years ago when he first developed it.

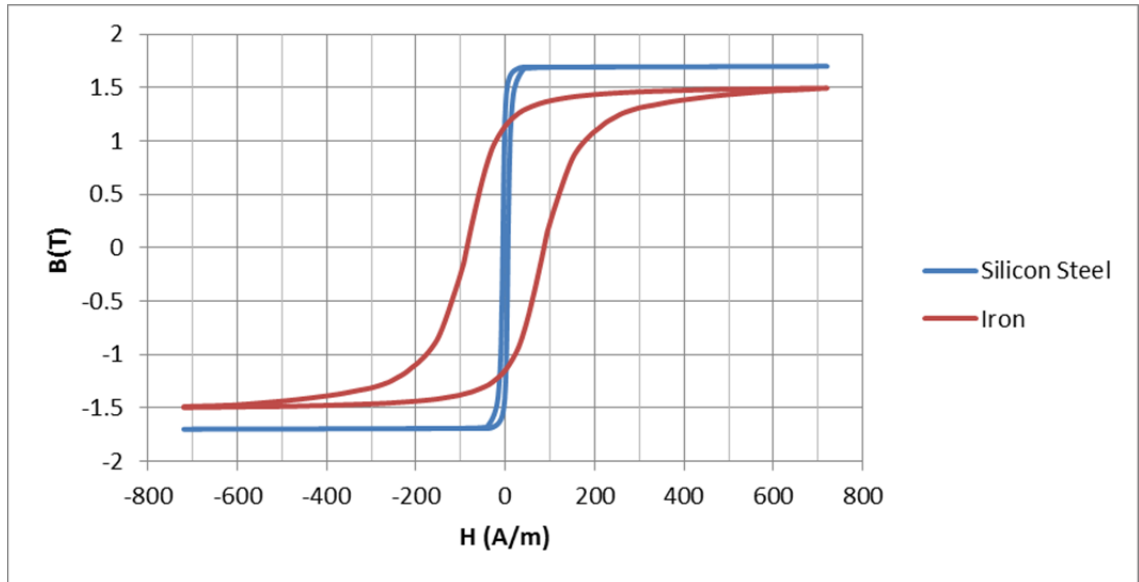
### **3.2 MAGNETIC PROPERTIES**

For the case of power transformer construction, core design has been highly optimized using materials with magnetic domains in the crystalline structure that align parallel to the edges of the crystal (the [001] vector). For Silicon Steel, this is achieved by the combination of approximately 4% Silicon to 96% Iron which results in a body centered cubic crystal lattice where the cube edges provide the easiest direction of magnetization.

The silicon infused steel is rolled into thin sheets and coated with a thin coating of insulation. A transformer core is constructed of many layers of this material being pressed together. This reinforces that the primary direction for easy magnetization will be along the desired path: in the direction that the windings around the transformer core will naturally drive the magnetic field when current passes through them.

With this type of core, transformers obtain an increased level of flux density with a lower magnetizing force (amp-turns per meter) than that of other ferrous materials. This is helpful for power transformers because this allows more energy to be transferred through the magnetic field for a specific amount of driving energy (loss). The efficiency difference between silicon steel and iron core materials is very

significant and is illustrated in Figure 3 where the area of the hysteresis loop is representative of the energy losses.



**FIGURE 3 - MAGNETIZATION COMPARISON OF SILICON STEEL TO IRON**

As you can see in Figure 3, the B-H relationship of transformer core materials is very linear until core saturation is reached, where the relationship changes very quickly. Because of this linearity and the dramatic change at saturation, power transformers can be designed to use a minimum amount of core material and operate close to these saturation points while still maintaining energy conversion efficiency. This factor also helps to simplify calculations in the analysis of magnetic saturation characteristics and will be used in the next section to estimate the maximum flux density of the core.

### **3.3 ELECTRIC STEEL MAGNETIZATION & HYSTERESIS**

As mentioned in the previous section, Silicon Steel functions at very high magnetic flux densities and exhibits highly directional magnetic domains.

Consequently, when considering how to demagnetize a transformer, this thesis proposes that taking these conditions into account can provide insight for the exploration of more efficient methods for demagnetization.

Conventional demagnetization methods employ the use of a diminishing alternating magnetic field which has the effect of randomizing the magnitude and direction of the magnetic domains within the crystal structure. This method is effective and has been used successfully in a broad range of applications in the history of electronics as well as other fields such as geology, paleontology, and archeology where it is utilized in date classification (14).

However, in the case of Silicon Steel, where the magnetic domains have a strong tendency to align, even if the magnetization direction vectors were able to be randomized, they would quickly and easily revert back to the primary axis of magnetization. This thesis proposes that the density of the magnetic flux along the primary magnetic path is the only remaining significant factor for demagnetization. By recognizing that this set of circumstances exists for power transformers, there is potential for improving the efficiency and safety of transformer demagnetization routines.

One method to test our ability to accurately estimate the magnetic flux density and the confidence of assumptions is to use a few known design values to predict measurable quantities. For example, it was useful to have an estimate for the saturation time of a transformer given a certain applied DC voltage.

Beginning with Faraday's Law, when applied to the geometries of a transformer, simplifies to:

$$V = N \frac{d\phi}{dt} \quad [1]^2$$

Where  $V$  represents the voltage across the transformer terminals and  $\phi$  represents the magnetic flux in Webers

Next, since transformers are usually designed to operate with a magnetic flux density just below the saturation point of the core (15), this condition can be used to estimate the total flux linkage, which is defined as  $N\phi$ . By integrating both sides of the equation for half of one cycle, the maximum amount of flux linkage delivered to the core can be found. Thus for a transformer with a specific voltage rating:

$$N\phi_{max} = \int_0^{\frac{1}{2}cycle} V dt \quad [2]$$

$$N\phi_{max} = \frac{1}{\sqrt{2}} V_{rated} \int_0^{\frac{.5}{60}} \sin(2\pi 60t) dt = V_{rated} \frac{\sqrt{2}}{120\pi} \quad [3]$$

Where  $V_{rated}$  represents the designed operating voltage of the specific individual transformer winding under test.

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<sup>2</sup> Fitzgerald, A.E. *Electric Machinery* (23)

In the case of the winding resistance test, the voltage applied to the winding is almost constant, such that the integration of the voltage over time simplifies to:

$$N\phi_{max} \approx V_{test}t_{sat} \quad [4]$$

By combining equations 3 and 4 an approximate time to reach saturation for a given test voltage can be found:

$$t_{sat} \approx \frac{V_{rated} \frac{\sqrt{2}}{120\pi}}{V_{test}} \quad [5]$$

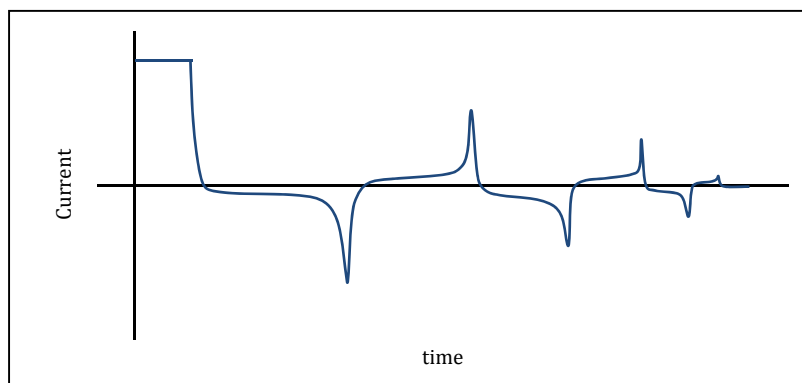
Where  $t_{sat}$  represents the time it takes to reach the magnetic flux saturation density of the transformer core and  $V_{test}$  represents the constant DC voltage applied to the winding during a resistance test.

As an example, for a transformer with a 230kV rating tested at 12V, the saturation time would be around 71 seconds according to this relationship.

### 3.4 PRESENTLY USED DEMAGNETIZATION METHODS

When performed, the present method most commonly used for demagnetization of a transformer is based on the standard found in IEEE 62-1995 (section 6.1.3.5) (6) which directs one to alternate the polarity of a fixed voltage with decreasing application time per alternation of polarity. With each alternation, the voltage is applied until the current flow has reversed and is “slightly lower” in absolute magnitude than the current in the previous application similar to the

method shown in Figure 5. This is continued until the next target current level is zero.



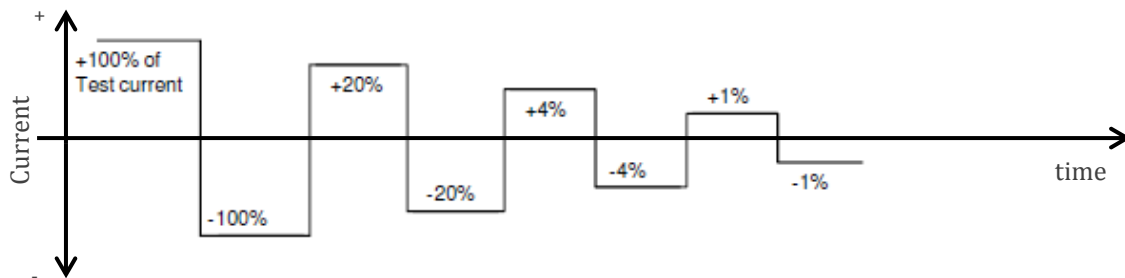
**FIGURE 4 – EXAMPLE OF CURRENT MAGNITUDE DURING DEMAGNETIZATION ROUTINE**

This method involves the manual, forced, interruption of the circuit while significant levels of current are passing through the transformer winding. This can create very high voltages and arcing discharges which is dangerous to both personnel and equipment. Additionally, depending on interpretation of the instructions, this process can take a significant amount of time.

Another method is used by the MT0210 Transformer Ohmmeter test utility produced by Megger®, a provider of electrical test equipment and measuring instruments for electrical power applications. This method is an automated method loosely based on the IEEE standard method.

The MT0210 also accomplishes demagnetization by applying an alternating DC potential to the windings (see Figure 5.) First, the application of the DC potential would be used for the initial winding resistance test. The voltage potential would

then be reversed until the current is equal in magnitude but in the opposite polarity. Once that magnitude of current is reached, the voltage potential is then reverted to the original polarity until the current is 20% of the original test current, at which time the voltage potential is reversed again until the current is 20% of the original test current in the opposite direction of the current than the first application of the voltage potential. This process is repeated for currents at 4% of the original test current and again for 1% of the original test current.



**FIGURE 5 – MEGGER MTO210 DEMAGNETIZATION ROUTINE (16)**

This unit was not available for evaluation so a detailed comparison will not be made. However, even assuming that the routine used by the MTO210 does sufficiently demagnetize the transformer, from the information presented, this demagnetization routine would appear to take significantly longer to execute than the routines proposed in this thesis.

Other methods of demagnetization have been proposed which involve the application of an ultra-low-frequency square-wave voltage source (17) can be used, however, they also require extensive demagnetization time.





Figure 1. The instrument design for that project was largely based on components that were already available on hand and established criteria for the following:

- Operating Voltage
- Current Limiting
- Protection Components

For the first criteria, an operating voltage of 12VDC was selected in the original design because vehicle batteries are readily available in the field. For many years, automotive batteries were the primary power source for winding resistance measurements in the field.

Originally, a single 12-volt battery was connected to the test instrument in Figure 8 and was always found adequate.



**FIGURE 8 - PRESENT WINDING RESISTANCE AND DEMAGNETIZATION TEST SET**

For the second criteria, the current limiting selection was decided by comparison and analysis of the readily available components with expected winding resistance values. In order to obtain accurate field voltage measurements and maintain quick saturation times, it was decided that the voltage across the current limiting resistor should not be much greater than the voltage drop across the winding resistance. Of the resistors that were available, two wire-wound  $0.2\Omega$  resistors were added in series to produce a limit of the short circuit current to 30A.

For the third criteria, protection from high voltages due to transformer inductance was accomplished with a combination of high power resistors. For this application a balance between the desires to limit the peak voltages that could appear across the analog-to-digital converter (ADC), yet also to quickly dissipate the energy in the transformer. Lower resistances allow for usage of resistors with a lower power rating, however, these take much longer to dissipate enough energy for the transformer to be disconnected. For this proof of concept a resistance of  $6\Omega$  with 600 watts of dissipation was selected since a current magnitude greater than 10 amps was not expected.

One component that was chosen based upon its capabilities rather than availability was the controller. The Q-screen, a single board computer with a built in touchscreen LCD interface was selected because of its ease of programming (C-based) and expandability through the addition of optional modules that were able to fulfill additional requirements of the test system.

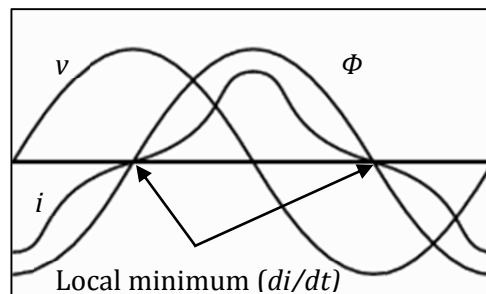
## 4.2 DEMAGNETIZATION ALGORITHM

In the previous work, attention was also given to the development of an algorithm for demagnetization. In that work, a theory was developed which showed that, by monitoring the change in current through the transformer windings, a neutral magnetization state of a transformer core may be extrapolated. The procedure attempted to identify the point of neutral magnetization by the

relationship of the magnetizing current to the relative permeability as well as to the total flux in the core.

Figure 9 illustrates the relationship of the current of a transformer to the magnetic flux in the core when powered by a sinusoidal voltage. In the graph, where the magnetic flux is zero, the current exhibits two distinguishable features. The first feature is that the change in current over time is a local minimum when the flux is zero. The second noticeable feature is that the current also passes through the zero when the flux does. However, this second feature is not as useful since this is only the case when powered by a sinusoidal voltage.

By monitoring the current and calculating the time derivative of the current after a constant voltage potential is applied, a local minimum in  $\frac{di}{dt}$  as the transformer magnetization swings between polarities can be identified. It was surmised that if the power source is removed at the appropriate time then the core should be left in a state of neutral magnetization.



**FIGURE 9 - THEORETICAL MAGNETIZING CURRENT AND MAGNETIC FLUX FOR ONE CYCLE**

The final circuit design for that project was successful in that it was capable of measuring the desired quantities and controlling the flow of current through the winding. However the accuracy of the measurements was ultimately found lacking once constructed. Also, after testing the proposed demagnetization method on a 115kV-230kV, single phase transformer, it was apparent that the demagnetization method needed improvement.

## **5 DEMAGNETIZATION METHODS**

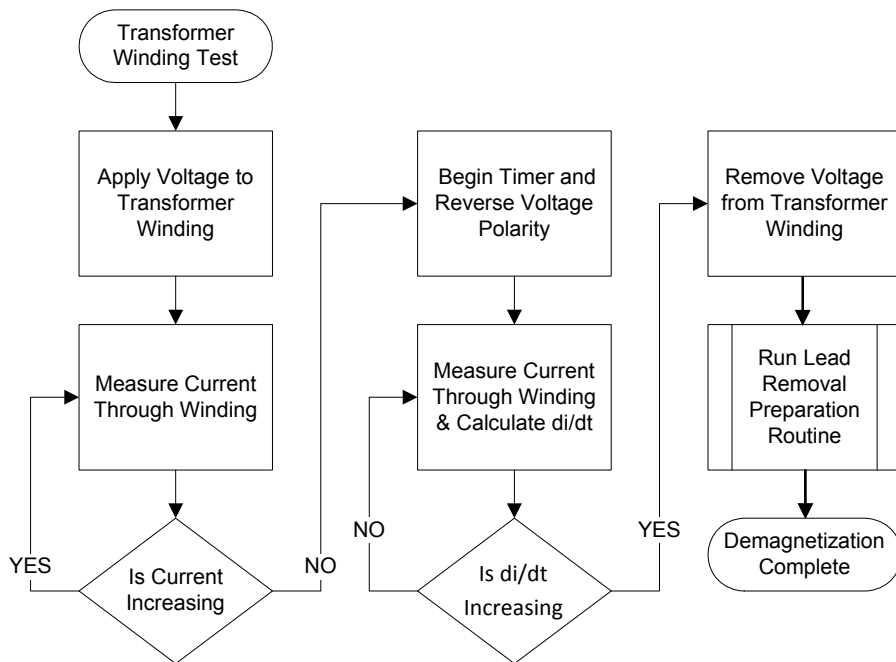
This thesis began with the intent to evaluate and improve upon the previous work in both demagnetization method and instrument operation. Weaknesses of the instrument and demagnetization method developed in previous work became apparent in preliminary testing, when evaluating the demagnetization of smaller distribution transformers (single phase, 13.8kV-240V) and one larger transmission transformer (single phase, 345kV-115kV).

The first step for this work was to identify alternate demagnetization methods. Then, since the prototype instrument failed to take into account certain transient voltages that were damaging to the sensors and electronics of the instrument, the second step would be the redesign of the instrument. Being second, this also provided opportunity to ensure that all the necessary design requirements were known when the instrument was re-designed.

### **5.1 PERMEABILITY METHOD**

Still needing evaluation at the start of this thesis, the demagnetization method developed in the previous work and introduced in section 4.2 will be discussed here first. This method was expected to be the most direct and quickest demagnetization method since it only required the voltage to be applied once for saturation and then reversed once for demagnetization. However, its accuracy and effectiveness regarding demagnetization is dependent on many assumptions about the properties of the transformer. For example, it requires that the magnetic hysteresis behave

similarly to that of an iron core inductor. Additional factors that could reduce the effectiveness of this method would be test environment conditions. Since the substations in which these measurements and tests are performed have large electromagnetic field interference, the ability to make the sensitive measurements necessary to identify the moment that  $\frac{di}{dt}$  begins to increase. This routine is illustrated in Figure 10 - Permeability Demagnetization Routine.



**FIGURE 10 - PERMEABILITY DEMAGNETIZATION ROUTINE**

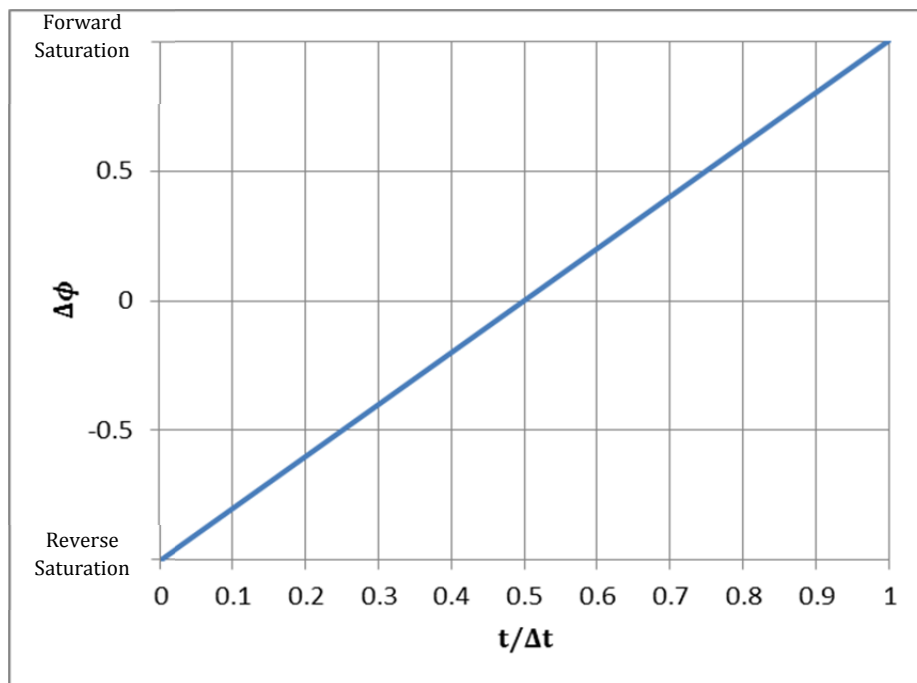
## 5.2 TIME BASED METHOD

The basis for second method of demagnetization comes from a proposal by the sponsor of the previous work. The method proposed is a time based method which estimates the magnetic flux in the transformer core via Faradays Law. Rearranging equation [1] for a constant voltage  $V$  gives:

$$\Delta t \propto \Delta \phi \quad [6]$$

Therefore, where the magnetic flux is directly proportional to the amount of time that a constant voltage is applied to the winding, by measuring the time needed for the magnetic state of the core to switch from being saturated in one direction to becoming saturated in the opposite direction we can determine how long a constant voltage needs to be applied to the winding that is saturated in order to reach the neutral point.

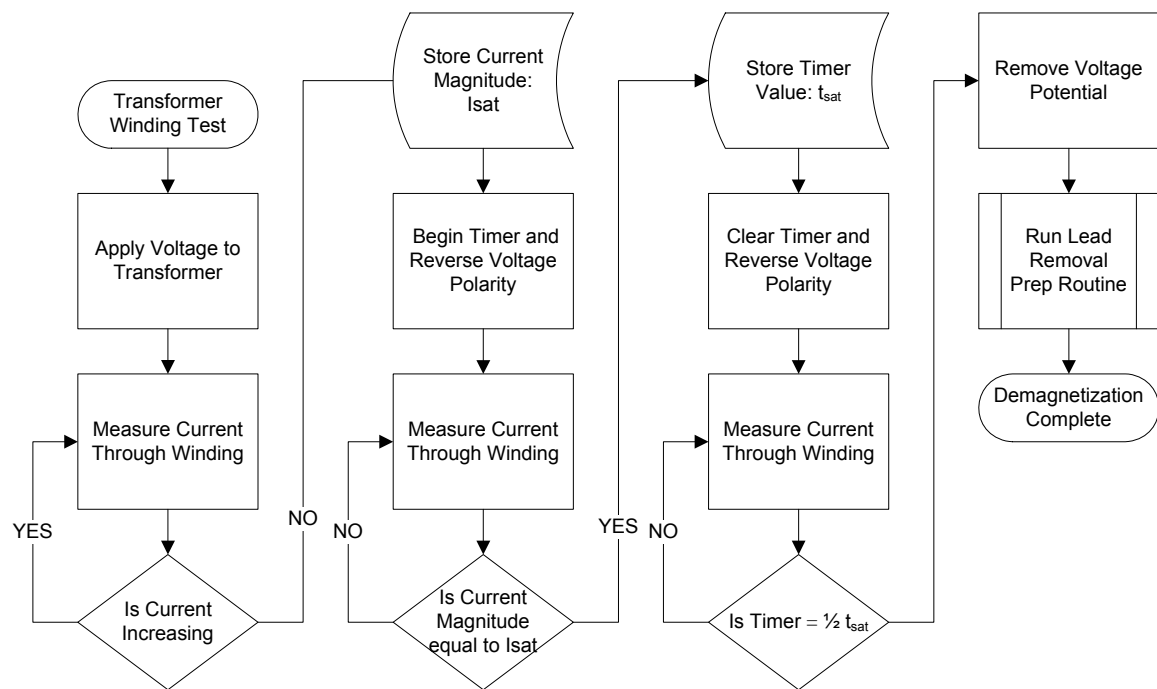
For example, the magnetic flux of a transformer shown in Figure 11 is saturated in a reverse polarity because of a current flowing through its winding. At



**FIGURE 11 – CORE MAGNETIZATION OVER TIME WHEN A FIXED VOLTAGE IS APPLIED TO THE WINDING**

$t=0$  a voltage is applied to the transformer winding that opposes the flow of current. Once the core has reached forward saturation, the voltage can then be reversed and applied for half the time required to reach the point of reverse saturation.

This method assumes that the energy loss due to winding resistance can be considered negligible compared to the energy that drives the magnetization of the core. The flowchart illustrating the steps for this method is shown in Figure 12



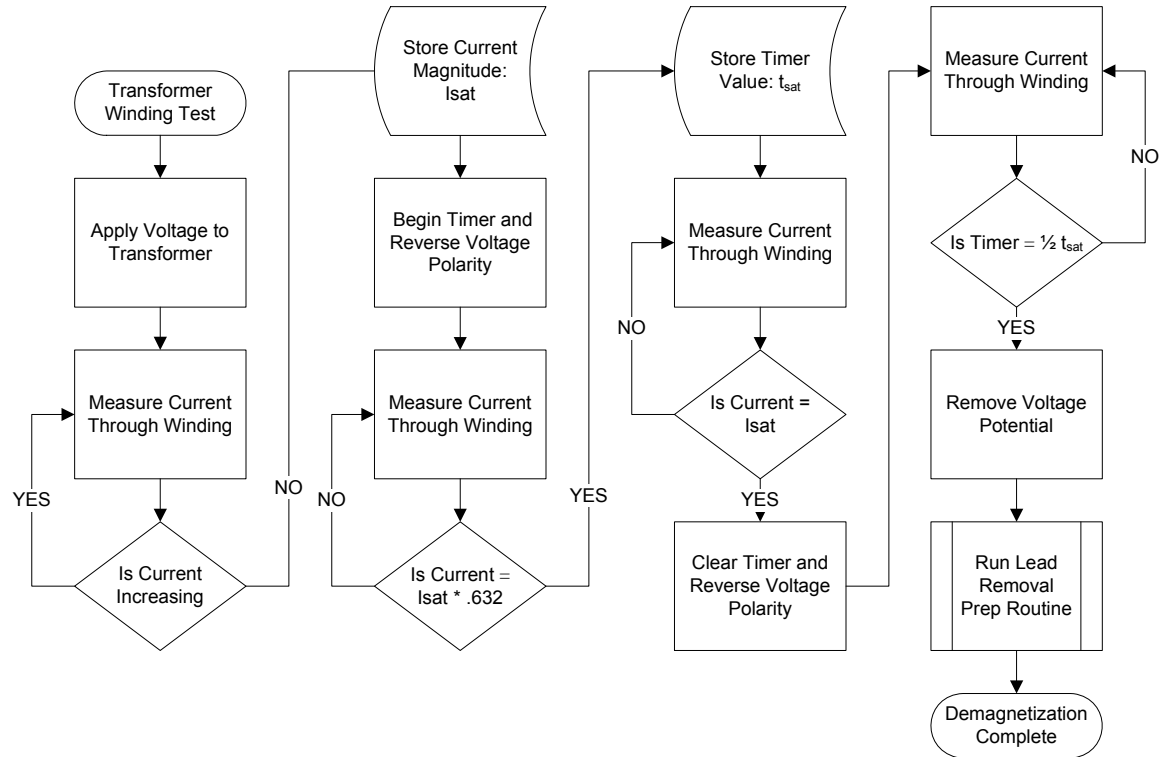
**FIGURE 12 - TIME INTEGRATION DEMAGNETIZATION ROUTINE**

### 5.3 INTEGRATION METHOD

The final method is similar to the second method; however, during testing it was found that the magnetization characteristics of transformer cores can greatly vary depending on transformer age and how the transformer is wound. Depending



on the sharpness of the transition to magnetic saturation as the magnetic field intensity increases, energy loss due to the winding resistance increases.



**FIGURE 13 - MODIFIED TIME INTEGRATION DEMAGNETIZATION ROUTINE**

Rather than assuming that the voltage driving the generation of magnetic flux within the transformer core remains constant at all times as in Equation [6], the accuracy of estimation can be increased by taking into account voltage losses due to the copper wire resistance as current increases. By evaluating the integral form of Faraday's Law with respect to form of the transformer windings gives:

$$N\Phi = \int V_L dt \quad [7]^3$$

<sup>3</sup> Fitzgerald, A.E. *Electric Machinery* (23)

where  $V_L$  represents the voltage drop across the winding due to self-inductance effects.

The voltage applied during the resistance test is a DC step of 12 volts and standard operating procedure is to allow the transformer winding to become saturated. Assuming that the voltage drop due to inductance decays with the natural time constant of the circuit, the integral of  $V_L$  can be reduced:

$$N\Phi = \int_0^{\infty} V_{L(t=0)} e^{-\frac{t}{\tau}} dt = \left[ -\tau V_{L(t=0)} e^{-\frac{t}{\tau}} \right]_0^{\infty} = 0 - (-\tau V_{L(t=0)}) = \tau V_{L(t=0)} \quad [8]$$

Where  $V_{L(t=0)}$  represents the initial voltage applied across the winding of the transformer. In the case of equation [8] in order to obtain the total change in magnetic flux, the time that it takes for the current to swing from 63.7% of the saturation value in the initial direction to 63.7% of the saturation value in the reverse direction can be substituted for  $\tau$ . Since the saturation current is already known from the winding resistance test, the time required to demagnetize the transformer using a constant applied voltage from magnetic saturation is easy to determine. The flowchart illustrating these changes is shown in Figure 13.

## 6 DEMAGNETIZATION DEVICE DESIGN REQUIREMENTS

A major component of this thesis was the redesign, construction, and programming of the automated control system capable of operating in a field environment. Four main design categories were identified from the analysis of the device's intended use and working environment:

- User Safety
- Measurement Accuracy
- System Reliability / Protection
- Usability / Automation

### 6.1 USER SAFETY

Large power transformers have the ability to obtain very high levels of magnetic flux density with cores that are of considerable volume. This results in an energy storage component of the transformer which is important to take into consideration. In order to ensure that this energy is safely controlled, reasonable estimates of the expected energy levels to be encountered are essential. Energy stored in a magnetic field is given by:

$$U = \frac{1}{2} \frac{B^2}{\mu} \nu \quad [9]^4$$

Where ( $\nu$ ) represents the volume of the core containing the magnetic field.

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<sup>4</sup> *Fundamentals of Applied Electromagnetics*, F. Ulaby

Unfortunately, there is no convenient way of measuring the magnetic field strength or determining the volume of the core without obtaining design information from the manufacturer. Thus, the value must be estimated by some combination of known or measureable values.

The most direct way to evaluate the energy stored in the inductor is to calculate it based on what power was delivered to the inductor over a specific period of time:

$$U = \int v_L i_L dt \quad [10]$$

While these values can be measured for a specific transformer, they can also be approximated based on equation [5] and utilizing two trends observed while performing experiments.

The first trend is due to the nature of the core material's permeability: for 80% of the time the current takes to reach saturation,  $v_L$  remains constant at approximately  $V_{Applied}$ . The second trend observed is that  $i_L$  is approximately 5% of  $I_{saturation}$ . Thus:

$$U_a = V_{applied} (.05 I_{saturation}) (.8 t_{saturation}) \quad [11]$$

The final 20% of the time it takes to saturate the winding  $v_L$  and  $i_L$  respond according to a natural curve associated with an air core inductance such that:

$$v_L = V_{applied} e^{-t/\tau} \quad [12]$$

$$i_L = I_{saturation} \left(1 - e^{-t/\tau}\right) \quad [13]$$

Experience has shown that on average, when a 230kV class transformer is energized with a 12V battery, it takes approximately 60 seconds to reach the saturation current of a transformer winding.

Thus integrating equation [10] using equations [12] and [13] for the final 20% of saturation time:

$$U_b = 0 - I_{saturation} V_{applied} \frac{-\tau}{2} \quad [14]$$

Where  $\tau$  represents the time it takes for the current to increase from its magnitude at 80% of the total saturation time to 63.2% of the saturation current magnitude.

Since winding resistance data can be found from the manufacturer's initial tests:

$$I_{saturation} = \frac{V_{applied}}{R_{winding}} \quad [15]$$

Then, the total energy stored is the addition of equations [11] and [14]

With these estimates (and the expected winding resistance values ranging between  $2\Omega$  to  $0.01\Omega$ ), the high voltage power transformers could store energy with a magnitude of hundreds of joules in the magnetic field when energized with a 12V source. During the testing of the work in this thesis, energy ranges as high as 530

joules were observed. For reference, the threshold for cardiac ventricular fibrillation (a fatal electric shock) is between 10-50 joules (19).

For this reason special care must be taken to ensure the operator knows not to attempt to disconnect the transformer leads while the test is in operation. While the battery can only deliver the energy at 12V of potential, if the transformer is interrupted while energized and at full saturation, the inductance of the winding is sufficient to generate extremely high voltages that are easily able to overcome the electrical resistance of a person's body.

Since voltage terminals must come directly through the test unit in order to connect the transformer to the relays that control the application and polarity of the voltage, the components must be properly selected to prevent failures which could lead to overheating and arcing.

Previous work had used a 600 Watt, 6 Ohm resistance for the discharge resistor on the basis of the continuous wattage rating. Additional analysis of the expected maximum energies above revealed that resistors classified with 600 Watts of dissipation would be sufficient for energy levels expected. Thus in regard to user safety, the value of resistance is somewhat flexible as long as the power rating is adequate.

Safety standards for DC voltage exposure were also considered. A standard commonly used by many industries for direct contact safety considerations requires voltages to be less than 60V (20). Other standards such as in ECMA-287 (21) allow

for voltages as high as 60V. In order to maintain voltages on the order of these magnitudes for winding currents of 30A maximum, the dissipation resistance should be less than 1.4 Ohms. However, due to the long time constant for the power dissipation at this value of resistance further considerations were taken.

Since contact with the system during the type of event where these high voltages would be generated is relatively small, the acceptability of contact with higher voltages was also considered. The National Institute for Occupational Safety and Health recognizes that bodily electrical resistance can be as high as 100,000 Ohms. The standard threshold of involuntary muscle contraction for DC current is 75mA (22). Thus, as long as the skin remains unbroken and dry, a potential of less than 7,500V may be sufficient, however, conditions in the field can vary greatly.

Before final selection of the dissipation resistance, voltage limitations of the control and measurement systems were taken into account. This is detailed in section 6.3.

## **6.2 MEASUREMENT SYSTEM**

The secondary concern pertains to the accuracy of measurements made by the system. The IEEE standard calls for field measurements that should be within 5% of the initial measurements made by the manufacturer when the transformer was first built. However, when BPA's field services team takes measurements on transformers in Bonneville's system, measurements are preferred to be within the factory error margin of 0.5%.

The winding resistance measurement system needs to be able to collect two fundamental measurements of the circuit: the voltage applied to the winding of the transformer and also the current passing through the windings of the transformer.

Due to the high standards for the error margin in resistance measurement for BPA's tests, it was desired to make measurements within a 0.1% margin. For data acquisition, this requires a resolution of 14 bits for a full scale measurement. However, for the voltage measurement, since the voltage will vary from 1 to 12 volts for reasons that will be covered in section 0, the resolution will need to be .005% of full scale, or 15 bits.

Characteristics of the measurement of current in the winding was more difficult to manage because the values could range anywhere from 0.5A to 30A. To obtain an accuracy of 0.1% at the lower bound, the measurement resolution must be no greater than 500 $\mu$ A/step. This results in a data acquisition resolution requirement of 19 bits.

Another consideration of the measurement system is the accuracy of the measurement. Thermal derating, thermal noise, component accuracy, and calibration uncertainty are a few of the factors that were also considered.

### **6.3 SYSTEM RELIABILITY & PROTECTION**

Protecting the sensitive data acquisition module also requires special consideration. There are many conditions, including operations of the control system, which could result in high voltages across various components of the test



unit. Specifically, when relay operations perform switching of polarities and disconnection of the voltage source from the large inductance of the transformer winding, high voltages could be generated across the voltage measurement terminals of the data acquisition component.

Another situation that may generate high voltages across the voltage measurement component leads is if the current carrying leads are removed when there is still current flowing through the transformer winding. Even a few milliamps of current can lead to thousands of volts if there is an attempt to abruptly interrupt the current.

#### **6.4 AUTOMATION & USABILITY**

In order to perform the automated tasks desired for this instrument, a suitable controller was necessary. This control system needed to be able to acquire and store the data associated with current and voltage measurements. The system would also need to perform high speed, real-time, calculation and manipulation operations. Additionally, the system would need to be able to provide control signals for relay operations to be directed by the specified routines and results of the calculations.

The ability for easy user interaction with the control system for operation of the test set was also desired. An ideal system would be able to prompt the user for input as well as be capable of presenting information, directions, and feedback both textually and graphically.

## **7 DEVICE CONSTRUCTED FOR DEMAGNETIZATION TESTING**

### **7.1 CONTROLLER**

Previous work had identified a single board computer manufactured by Mosaic industries, the Qscreen Controller™, to act as the control module for this system. This system was found to be flexible and robust for the purpose of this thesis project. The Qscreen is driven by a Motorola HC11 processor and provides the built in facility of a touch-screen display for a user-interface. Additionally, there are many optional and user-configurable components, termed “wildcard modules” by the manufacturer, designed to easily connect and communicate with the controller.

One of these wildcard modules is a 7 channel 24bit analog-to-digital converter data acquisition board. It is capable of 20 bits effective resolution with a 30Hz sample rate and has an input voltage range from -30mV to 5.03V as well as a precision 2.5V reference.

These two components provided the core for the instrument; incorporating these components required more than 3900 lines of code in order to take into account the unique conditions that the operating environment demands. While this is only given a passing mention here it represents a significant time component of this project.

## 7.2 DEVICE POWER

While a typical substation generally has numerous 110v outlets, this test set was intended to be a mobile unit. As such, it was decided that powering the set from a 12v battery would provide the most flexibility.

Another related consideration for device power is the voltage applied to the transformer windings in order to saturate the core. There are further time efficiency benefits that could be gained by stepping the voltage to higher potentials during the saturation phase of the test and then reducing the voltage to correspond with the desired current output. However, as experience has shown that using 12V generally keeps saturation within reasonable lengths of time, this method was not implemented.

While the use of a 12V battery to supply the power for the entire test set simplifies the power source needs, this increases the complexity for taking both voltage and current measurements. The challenge arises when the polarity of the applied voltage across the windings must be reversed: since the voltage of the ADC module is supplied by the Qscreen, the negative terminal of the battery is treated as the common terminal. In this case, there is a short circuit path for the battery through the ADC module when the polarity of the connections from battery to the transformer winding is switched.

To compensate for this situation, an isolated DC-DC converter was used to power the additional components of the test set which mainly consist of the Qscreen

and relay control lines. Using this modification, it was possible greatly simplify measurement offsets by connecting the appropriate end of the transformer winding to the built in 2.5 voltage reference of the ADC module.

Most power system transformers have rated currents in the hundreds or thousands of amperes (very few reaching greater than 2.5kA). Thus, in accordance with manufacturer suggestions of 1%-10% of rated current for core magnetization saturation, the selection of the target maximum current was 30A. Easily supplied with a car battery, this limit was regulated by a  $0.4\Omega$ , 600W, series resistance. This practical addition also changes the calculation for energy stored in the magnetic field of the core, since, as the current increases, the voltage applied to the windings is reduced. However, it is sufficient to be aware that regardless of this change, the energy stored in the magnetic field is still very large thus the protection circuitry detailed in section 7.4 was carefully selected.

### **7.3 MEASUREMENT COMPONENTS**

As mentioned in section 7.1, data acquisition is accomplished through the implementation of the 24 bit, seven channel, ADC designed for use with the Qscreen. Data acquisition was performed at a rate of 60 samples per second which reduced the effective resolution to 20 bits. This provided the foundation for measurements with the ability to produce measurements with a high level of precision.

Voltage measurements were made using the fully differential mode of the ADC. This mode allows for differential voltage measurements to be made anywhere

within  $\pm 2.5$  volts of the designated reference potential. As mentioned in section 0, the 2.5V reference of the Qscreen was connected to terminal 1 of the transformer output connections. The voltage was measured across a 4:1 voltage divider network in order to reduce the expected 12V difference between the two terminals of the output resulting in a 2.4V max input to the ADC. The resistors of this divider were chosen for low thermal drift and noise susception.

Two options were considered for current measurement. One method made use of Hall Effect current sensors, to isolate the potential differences of the circuit. This helped to reduce the complications of obtaining measurement signals within the voltage range limitations of the ADC. By using a  $\pm 30$ A range sensor and a  $\pm 5$ A range sensor, accuracy was expected to be better than 0.1%. In practice however, these devices proved prone to offset drift errors and a high susceptibility to external electromagnetic noise.

The second choice was to use a 50A current shunt, a precision  $1\text{m}\Omega$  resistor which provides an output of  $1\text{mV/A}$ . Utilizing an amplifier for this signal with a gain of 64, produced a signal that was 80% of the ADC input range at the full rated current of the test set. For this method, it is important that the resistance of the current carrying leads and connections be no greater than  $15\text{m}\Omega$ , since any greater resistance might shift the voltage reference too far from the voltages being measured across the shunt.

All calibration was programmed into the system using an RFL Industries AC/DC V-A Source Model 828 as a reference source.

#### 7.4 SYSTEM & USER PROTECTION

In order to safely discharge the applied current in the case of a test set or power source failure, a fixed protection resistor was added in parallel with the transformer windings at all times during the test. The value of this protection resistor was coordinated with the voltage divider network necessary to allow the ADC to measure voltages within the  $\pm 12\text{V}$  range as well as limit transformer discharge events to less than the continuous overvoltage protection of  $\pm 70\text{V}$  built into the ADC.

With consideration of the voltage divider network, the max voltage across the transformer winding terminals becomes 350V. Since the max current flowing through the winding will be 30A the largest resistance for this safety resistor should be about 12 Ohms. However, during testing it was found that the current decay was very slow. Since the discharge resistor did not reduce the current very quickly, it was found that there was still a high possibility for damage to be done to the ADC if the voltage measurement



FIGURE 14 - COMPLETED TEST SET

leads were not disconnected in the proper order.

Accordingly, to increase the rate of current decay, the resistance was increased to 24 Ohms. Also, a MOSFET switch with 1500V of isolation was added between the ADC and the voltage divider network. This provided the additional isolation needed for the increased voltage that would be seen on the transformer winding terminals. It also reduced the likelihood of damage to the ADC in the event of untimely lead disconnection.

With the addition of the MOSFET switch, the primary concern for failure was the protection resistor. Based on the expected energy calculated in section 6.1 and given the 5-second over-current ratings of the Ohmite 280 series resistors, a minimum of rating of 240 Watts would be necessary. To provide additional margin, two 300 Watt, 12 Ohm resistors were connected in series.



**FIGURE 15 - TEST INSTRUMENT INTERNAL CIRCUITRY**

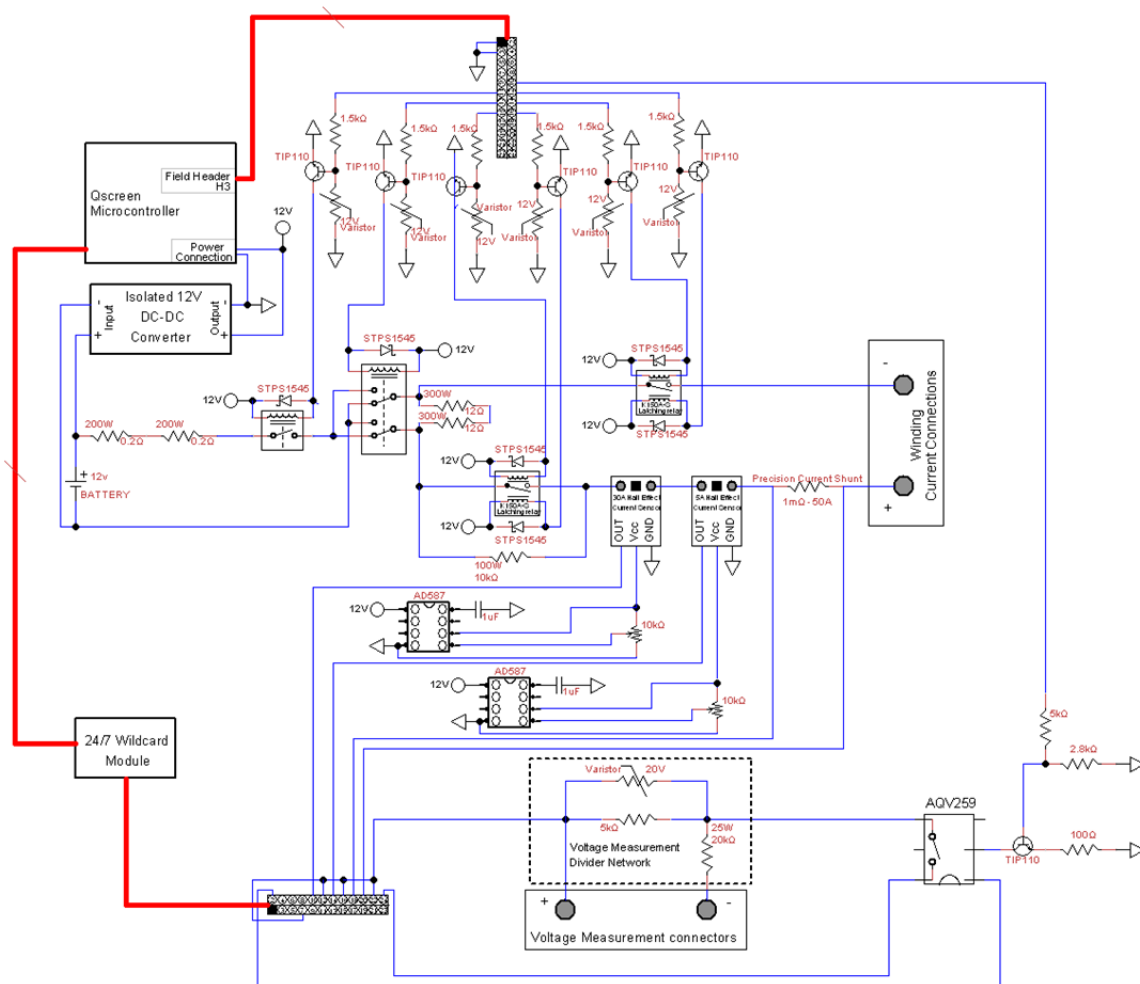


FIGURE 16 - TEST INSTRUMENT SCHEMATIC



## 8 RESULTS

### 8.1 METHODS FOR DETERMINING THE STATE OF RESIDUAL MAGNETIZATION

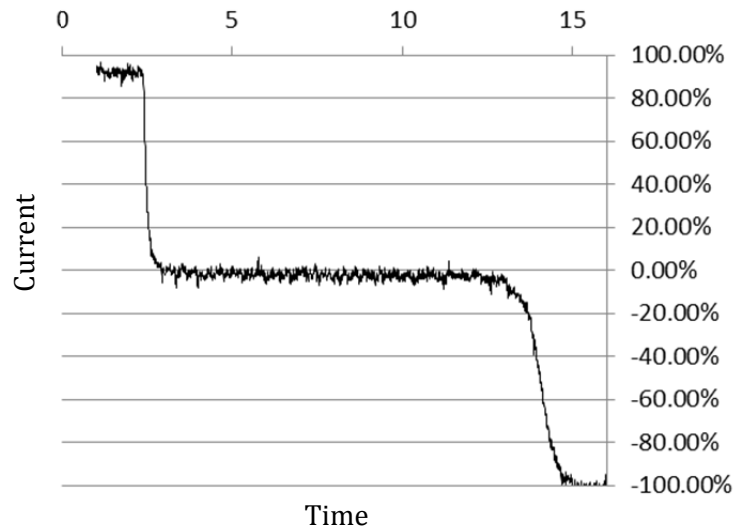
Of significant concern for these tests is the determination of the effectiveness of demagnetization. This state was attempted to be qualitatively determined in two ways, primarily by repeated comparison of the saturation time for a specific DC input voltage at both polarities after a demagnetization routine was completed.

The secondary method used was to energize an unloaded transformer and observe the magnitude of inrush current to the transformer. Unfortunately, this method was determined to be unreliable due to timing limitations and contact bouncing of the switching apparatus.

### 8.2 PERMEABILITY METHOD

This method used the relationship of the change in current over time to the amount of magnetic flux in the core in order to identify the neutral magnetization state. However, it proved to be much more complicated when dealing with real-world systems than the theoretical models. The reliability of the method in the previous work was difficult to implement because of the highly linear nature of silicon steel hysteresis characteristics. Additionally, it was suspected that losses due to magnetic flux leakage outside the core cause the local minimum of  $\frac{di}{dt}$  and the neutral magnetization point of the core to be out of phase.

When testing this method for demagnetization, it was found that the neutral magnetization state was overshoot by magnitudes of 20-30%.



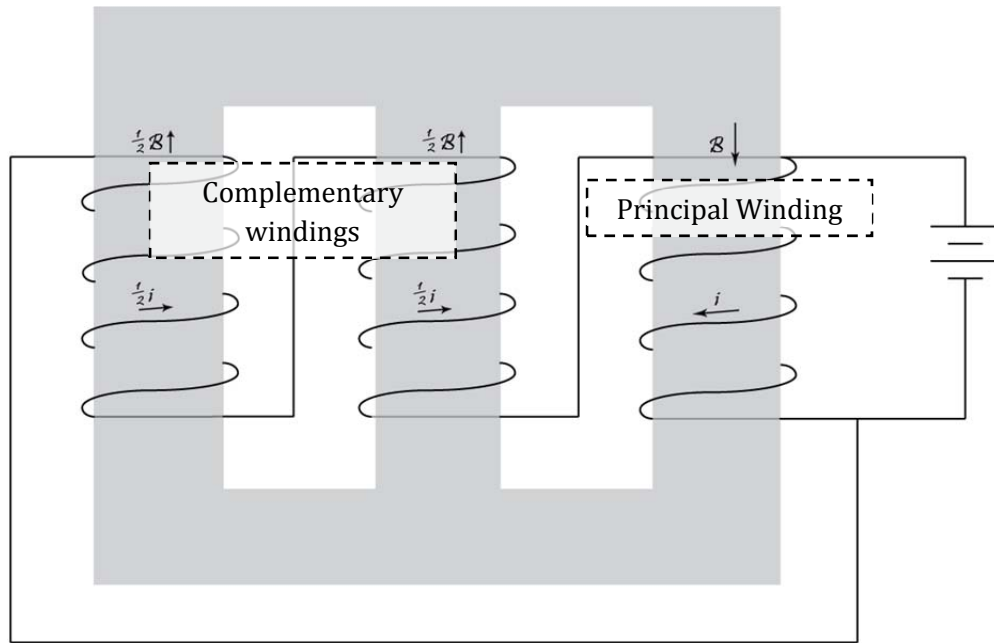
**FIGURE 17 - EXAMPLE CURRENT FLOW TIMELINE AFTER VOLTAGE POLARITY IS REVERSED**

### **8.3 TIME BASED METHOD**

Where isolated testing of a winding was possible (Wye-Wye & Delta-Wye), the integration method for demagnetization was much more effective than the previous method. For these types of transformers, this method was able to achieve a neutral magnetic state with a 7% maximum observed margin of error.

The area that proved an obstacle for this method was the demagnetization of transformers where the windings cannot be isolated. For transformer windings connected in a Delta configuration, when a potential voltage difference is applied between two of the three terminals the result is that while the primary winding builds flux according to the voltage applied, the other two windings will only see half the applied voltage. Thus, assuming the resistances of all three windings are comparable, the current flowing through the second and third windings is one half the current flowing through the principal winding under test. Due to the direction of the voltage polarity and the way that the windings are placed on the core, the

magnetic field due to this current works to reinforce the magnetic field generated by the current flowing in the primary winding as illustrated in Figure 18.



**FIGURE 18 - DELTA TRANSFORMER MAGNETIC FIELD DURING DC ENERGIZATION**

In addition to the previous factor, it appears that the reduced voltage across both complementary windings results in a longer saturation time for the complementary windings than the principal winding. This may occur because the permeability of the core (as well as the apparent change in inductance over time) depends on the amount of current. The end result is that the saturation time for the whole transformer is longer than the saturation time of the primary winding used in the previous calculations.

After implementing this routine, the residual magnetization of delta-wound transformers tested exhibited a 15%-25% overshoot of the neutral magnetization state.

#### **8.4 INTEGRATION METHOD**

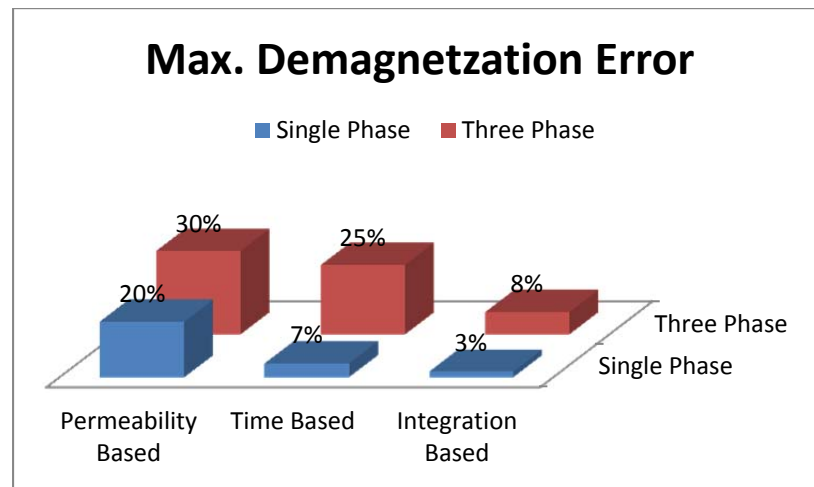
Modifying the target for the magnetic flux integration time not only helped to account for the effects of core magnetization but was also found to greatly increase the accuracy of demagnetizing transformers with Delta configuration windings.

Compensation of leakage losses was accomplished by adjusting the integration interval to begin the moment the voltage potential is reversed and to end when the current through the transformer reaches 63.2% of the saturation current in the opposite direction of current flow. This resulted in reaching a neutral magnetization state with a maximum observed error of 3% for transformers with isolated windings.

The reason for this increase in accuracy for Delta-wound transformers is due to the fact that the core material of the secondary windings saturates at a slower rate than the primary winding. It was found that, when the total current through the system is 63.2% of saturation current, the complementary windings have not yet gone into saturation and the principal winding is just reaching saturation. This gives an approximation for an integration interval that is reasonably effective. This demagnetization routine exhibited a 3%-8% overshoot of the neutral magnetization point for these types of transformers.

## 9 CONCLUSIONS

As expected from observations of transformer characteristics in the previous work, the permeability method for demagnetizing the transformer core was not very effective compared to the other two methods. The time base method for estimation of the magnetic state of a transformer core was found to be effective in predicting and attaining demagnetization of power transformers which only had a winding for a single phase.



**FIGURE 19 –COMPARISON OF DEMAGNETIZATION METHODS: MAXIMUM ERROR**

The integration based method was the method selected for future use. This method was found to have improved accuracy over the time based method when demagnetizing transformers with windings for all three phases. While not as fast as the Permeability method, this method considerably reduced the time required for demagnetization. The demagnetization method developed during this thesis is now going through the patent process by designated staff at BPA and the U.S. Department of Energy.

The instrument designed for the automation of this demagnetization routine was effective in improving the safety of the operator by automating many tasks where there was potential to come in to contact with high voltages. This instrument is now in early production stages for an expanded field trial with transformer maintenance teams.

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