CHALMERS

Temperature Rise Testing of Current Transformers:

Improvement in Test Method

MASTER THESIS REPORT

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Abstract

The nature of electric power generation, transmission and distribution systems frequently faces high voltages, high currents, or a combination of both. Electric phenomena as well as material robustness requirements often mean that direct measurements using conventional voltmeters and ammeters are not cost effective, or even possible. For this reason, indirect measuring devices such as instrument transformers are employed in order to operate protective relays, thus preserving system stability and, as consequence, system reliability. Instrument transformers provide the only interface between high-power electric circuits and control electronics, thus becoming a key component of any power system. In order to verify that Current Transformers will be able to handle the stresses in the networks in which they will be installed, a series of so-called type tests are performed. Among these type tests is the Temperature Rise Testing, which is used to validate the Current Transformer's ability to withstand a rated temperature within an operating timeframe.

The temperature rise test is a standardized test. The aim of this thesis work is to evaluate the methodology being currently used in the industry and to propose improvements by applying concise analysis, electrical power engineering principles and optimization theories in order to increase measurement accuracy while also reducing test performance times. It has been suggested that the developed method should also ideally comprise modules for easy mounting, as well as flexibility to be used in other type of temperature rise tests, for an increased amount of CT Channels.

The ultimate goal is to get familiarized with the development of type testing procedures in order to provide insightful feedback and thus real improvement in the quality of the Temperature Rise Test, while at the same time developing a methodology which should be both simple and straightforward.

Throughout the testing development, one of the key findings was that a big percentage of the calculations were being performed by hand because of software incompatibilities. It was then proposed that time could be reduced significantly by creating a standardized software platform to collect data and perform automated calculations. Additionally, the process' predictability was also increased by means of the establishment of a baseline, calculated from experimental data. While this last feature did not reduce the time required to reach a steady state, it improved the system predictability and thus reliability.

Developments in reducing hardware setting times for testing were also explored, although some of them were ultimately deemed as not having a reasonable cost-benefit ratio, as well as providing a reduced overall test reliability.

Keywords: Current Transformer, Temperature Rise Test, Type Test, Optimization, Protection and Control

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Contents

Nomenclature

ANSI	American National Standards Institute
CT	Current Transformer
GIS	Gas Insulated Switchgear
IEC	International Electrotechnical Comission
ISO	International Organization for Standardization
SATS	Scandinavian Association for Testing of Electric Power Equipment
STC	Short Time Current
SWEDAC	Swedish Board for Accreditation and Conformity Assessment
TCF	Transformer Correction Factor
I_p	Current in Primary side
I_s	Current in Secondary side, 600/5 CT
I_2	Current in Secondary side, 1500/5 CT
I_{sDC}	(DC test) Current in Secondary side
N_p	Turns in Primary side
N_s	Turns in Secondary side
R_0	Winding resistance before the test
R_b	Burden resistance
R_{br}	(Equivalent) resistor across the primary terminals
R_{b2}	Burden resistance, 1500/5 CTs
R_{sh}	Current Shunt resistor
R_t	Winding resistance after the test
S	CT rating, 600/5

S_2	CT rating, 1500/5
T	Copper constant = 234.5
V_0	Winding voltage before the test
V_p	Voltage in Primary side
V_s	Voltage in Secondary side
V_t	Winding voltage after the test
θ_0	Ambient temperature before the test
θ	Ambient temperature after the test
θ_t	Equipment temperature
θ_{tr}	Temperature Rise

1. Introduction

Electric power generation, transmission and distribution requires indirect measuring devices such as instrument transformers in order to measure current flow and operate protective relays, thus preserving system stability and, therefore, system reliability. Instrument transformers provide the only interface between high power electric circuits and control electronics, therefore guaranteeing the operability of the measuring device is imperative because if a current transformer provides an inaccurate reading, protection coordination cannot be performed, which will lead to a systematic loss of control, and it will cascade into system breakdown if not corrected in a timely manner.

The High Power Laboratory in ABB Ludvika is accredited by SWEDAC in accordance with ISO/IEC 17025:2005, and it is also affiliated to SATS. It is one of few laboratories in Europe fully licensed to perform instrument transformer testing, as well other tests such as type tests (STC and Transient Recovery Test), dielectric testing as well as routine testing[1].

1.1. Aim

The aim of this project is to perform a temperature rise testing to a set of instrument transformers, in accordance with the current IEEE and IEC specification. Once the results have been obtained and validated against previous tests, we need to propose improvements in order to reduce the time required to calculate, process and present the information, thus reducing testing time while maintaining a high measurement accuracy. It has been suggested that the developed method should ideally be upgradeable to include as many CTs as possible. 40 CT channels is a reasonable number.

1.2. Problem

The main task in this problem consists of assembling a test experiment and performing a full temperature rise test to our test objects. The test requirements include a set of initial conditions which must be fulfilled, such as room temperature, humidity and adequate instrument pre-calibration. Parasitic currents, discharges and other related field current abnormalities when calibrating a test object must be taken into consideration and will be discussed. Each temperature rise testing can be regarded as a four-step process: Initial measuring; steady state; final measuring; and interpretation/validation of results.

Once results are obtained, a tool must be developed in order to minimize total testing time as well as to rearrange and interpret information in a simple, reliable manner, thus reducing the possibility for human error.

1.3. Method

Given the nature of the testing environment, the method applied involves both theoretical knowledge as well as laboratory setting up and field measurements. Relevant information about the equipment used is obtained directly from the equipment nameplate and manufacturers' data sheet, where available. Data acquisition was conducted by setting up digital readers (*dataloggers*), whereas data handling and interpretation required mathematical calculations following ANSI/IEC algorithms. In order to fulfill this project's aim of execution time reduction, the temperature rise testing will be conducted three times at first: A Simplified Preliminary Test, to test the equipment and methodology (using reference values from past testing); a Baseline Test to establish a starting baseline (using our own experimental values); and an Improvement Test where we will incorporate all the observations that have been noted once the process has been streamlined.

It is in our best interest to also perform further testing in order to confirm the repeatability of the improvement. Currently, there is a high demand for testing equipment in the diverse tests being performed in the laboratory, so we cannot guarantee that such testing could be performed with the exact same test equipment as the Improvement Test; therefore, while results with different testing equipment or software platforms should be very similar, little variations attributed to different equipment would invalidate any findings. It has been agreed that further verification testing will be conducted only if all the relevant equipment conditions are met.

1.4. Scope

The ABB High Power Laboratory in Ludvika is fully certified and can perform all the equipment tests performed, including standalone instrument transformers as well as those enclosed in GIS (further information in the next Chapter). The scope of this master thesis work will only be based on temperature rise tests, for standalone current (instrument) transformers. Current transformer calibration is not within our scope, however the problems associated with it will be discussed. The resulting model should be quicker to perform than the previous model, yet easy enough to be operated by a single person.

An additional goal is to witness and collaborate with several temperature-rise tests as well as other common type testing involving GIS, power transformers and Air/SF6 filled Circuit Breakers. The knowledge acquired in this matter will not be evaluated; however it will provide a strong foundation towards the formation of a Power Test Engineering profession.

2. Background

Temperature rise testing techniques on current transformers can be divided in two major groups, according to their technology: Instrument transformers as a standalone test object, and instrument transformers enclosed in a GIS. In the former, thermocouples are set along the current path, enclosure and bushings in the primary winding, whereas a so called *resistance method* is applied to determine the temperature increase in the secondary winding. In the latter technique, temperature increase is measured through thermocouples on the current path, enclosures and all other equipment except CT's, but the same *resistance method* is used to obtain the temperature increase in the secondary winding[2].

As stated in our scope, in this project we will focus on standalone current (instrument) transformers only. A fully detailed temperature rise testing will be performed to these test objects in compliance with IEEE and IEC standards.

2.1. Current Transformer Theory of Operation

A current transformer is defined as "an instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections"[3]. It can be initially regarded as an ideal transformer whose primary winding consists of one or few turns, thus having a comparatively bigger wire gauge than its secondary winding. For understanding purposes we can regard it as an ideal transformer that presents infinite no-load input impedance, no leakage inductance, zero winding resistance and no capacitance. It also presents no regulation drop, no core losses and therefore the output voltage is proportional to the primary voltage times the turns ratio (See Fig 1).

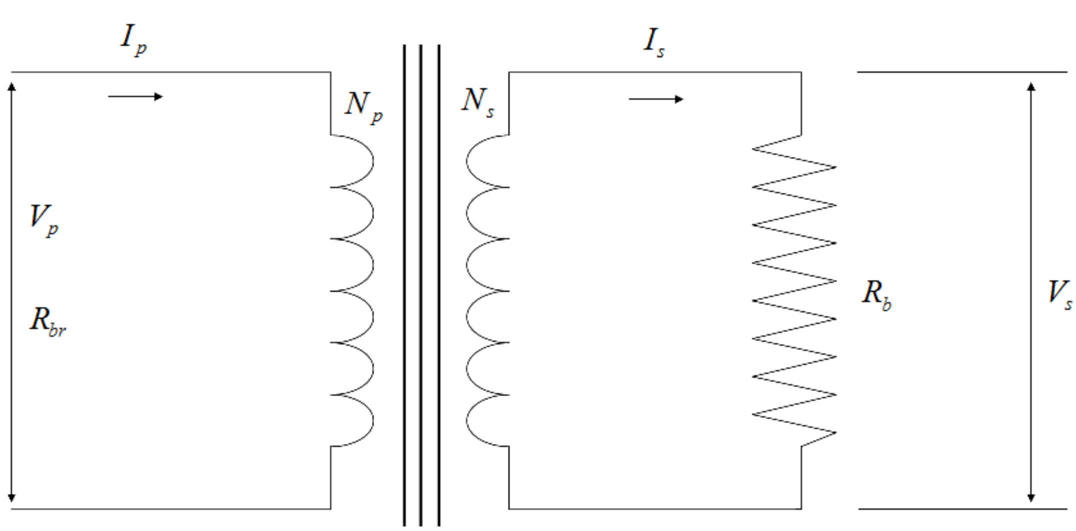

Figure 1. Ideal CT Theory of Operation

No core losses mean that 100% of the power is transferred from the primary winding to the secondary winding, as shown in (1).

$$V_p I_p = V_s I_s \tag{1}$$

Where V_p is the voltage in the primary side, V_s is the voltage in the secondary side, I_p is the current in the primary side and I_s is the current in the secondary side.

The current flowing through the circuit is an inverse function of the turns ratio of the device (2)

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} \tag{2}$$

Where N_p is the number of turns in the primary side, and N_s is the number of turns in the secondary side.

Therefore, the current in the primary side can be calculated if we know the current in the secondary side and the turns ratio (3).

$$I_p = I_s \frac{N_s}{N_p} \tag{3}$$

Current in the secondary winding will be determined by the voltage drop caused by the load impedance – the so-called *burden* resistance – (4).

$$I_s = \frac{V_s}{R_b} \tag{4}$$

Where R_b corresponds to this burden resistance.

We can therefore define the current in the primary winding as a function of this burden resistance and the turns ratio (5).

$$I_p = \frac{N_s V_s}{R_b N_p} \tag{5}$$

Sizing the burden resistance is especially important when evaluating high currents, because a voltage drop in the primary side is determined by this resistance. Therefore, a small turns ratio will translate to an even smaller resistor across the primary terminals (6).

$$R_{br} = R_b \left(\frac{N_p}{N_s} \right)^2 \qquad (6)$$

Where R_{br} is the (equivalent) resistor across the primary terminals.

For testing purposes, a burden resistance R_b is defined as $R_b + jX_b$, with a rated power factor of 0.8 inductive[4]. In reality, though, power factor is due to the mechanical or electrical design of the metering devices: Modern digital relays will usually have a power factor of 0.95 or even higher.

Current transformers can be included in two general categories: Metering service and relay service. Given their construction patterns, metering CTs should not be used for relay applications or system protection. Likewise, CTs designed for relay services should not be used for high accuracy metering.

CTs designed for metering service have smaller cores with small or negligible excitation currents, allowing the transformer to be highly accurate at normal load currents. However, this small core saturates at currents slightly above rated current. On the other hand, a CT designed for metering may not reliably operate protective devices during fault conditions. In order to prevent an incorrect reading due to non-linearity in the device, CT measuring characteristics are determined by their Accuracy Class. The standard accuracy classes for metering service and corresponding TCF limits for current and voltage transformers are shown in Table 1 (Our test CT's class is being highlighted).

Table 1. Standard Accuracy Class for Metering Service and Corresponding Limits (0.6 to 1.0 Power Factor) of Metered Load) [5]

Metering Accuracy Class	Current Transformers			
	At 100% rated current		At 10% rated current	
	Minimum	Maximum	Minimum	Maximum
0.3	0.997	1.003	0.994	1.006
0.6	0.994	1.006	0.988	1.012
1.2	0.988	1.012	0.976	1.024

Instrument transformers provide the only connection point between a power system and its protective relay equipment, depending on accurate CT readings to perform Protection & Control. CTs are therefore one of the most critical pieces of equipment in any power system.

2.2. Test Equipment

The test equipment consists of a Power Transformer, a set of CTs used as test objects, a reference CT with a shunt resistor to measure the current passing through the test objects, an adequately dimensioned cable, a matching burden resistance for each CT to be used as test objects, a digital data acquisition device and a CPU to process the information. For safety purposes, our data acquisition device is connected through a custom-made relay box. Additionally, a laser thermometer will be utilized to quickly validate the test[1] as it is being performed, without interfering with its development.

A thorough description of the test equipment is detailed below. Equipment images and test set up is shown in Appendix 1. Some of the methodologies and equipment used may be confidential; in such cases, data will be omitted according to ABB's Code of Conduct [6].

2.2.1. Power Transformer

The power transformer is a fully customizable 1 phase, 50 Hz ASEA, with a rated power of 30 kVA. It will be configured to adopt a 220 V (primary) – 5 V (secondary); 136 A (primary) – 6 kA (secondary); however, given the CT rating of the test object, only 600 A will pass through the secondary (see Below, CT Instrument Transformer).

2.2.2. CT Instrument Transformer

The CTs to be used as Test Objects for the preliminary test are 2 identical 600/5A, 80 VA Class 1.2, 50 Hz ASEA Type 1HDA 05C1. Power rating is 0.5 kV.

Under normal working conditions, at least six CTs are required: three on one side of a device and three on the other side, one CT for every phase. Based on customer's requirements on reliability and redundancy, two or more CT's may be used per phase, or tertiary winding measurements may even be included. Therefore, for our baseline and improvement tests, six CTs will be employed.

Four of them will be the same 600/5A, 80 VA Class 1.2, 50 Hz ASEA Type 1HDA 05C1 and two of them will be a 1500/5A, 60 VA Class 1.2, 50 Hz ASEA Type 1HDA 05C1. Ideally, we would test in sets of three (i.e. three CT in the high side and three CTs in the low side in the case of a power transformer, or 6 identical CTs in the case of a Circuit Breaker), but unfortunately we could not have such availability.

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[1] The temperature obtained by means of this laser thermometer is for reference purposes only. It will not be used in the test.

2.2.3. Burden Resistance

During regular operating mode, the burden resistance is “the impedance of the secondary circuit in ohms and power factor. The burden is usually expressed as the apparent power in volt-amperes absorbed at a specified power- factor and at the rated secondary current”[7]. In our test, the burden resistance applied is a variable resistor, *cucumber* styled 0 – 4Ω for the set of four 600/5 CTs and a 16Ω, *cucumber* styled resistor for our 1500/5 CT. We can calculate our burden by utilizing a variant of Joule’s law (7).

$$S = I_s \times V_s \tag{7}$$

Where S is the CT rating, in VA.

Additionally, Ohm’s law holds true for the Voltage in the secondary side (8).

$$V_s = R_b \times I_s \tag{8}$$

By combining both equations we obtain (9).

$$S = I_s^{\,2} \times R_b \tag{9}$$

And consequently, the burden resistance value (10).

$$R_b = \frac{S}{I_s^{\,2}} \tag{10}$$

Where I_s is the current in the secondary side, S is the CT rating (in VA) and R_b is the burden resistance.

2.2.4. Reference CT

In order to make sure that 600A are passing through the primary winding, We will use an additional 600/5 CT. Instead of a burden resistor, this reference CT has a 0.5 V/A shunt resistor to indirectly measure current through voltage drop by means of a true rms multimeter. The reason for using a voltmeter to indirectly measure current instead of measuring directly through the CT is because we would require a bigger cross section wire than what is currently available for the CT connections.

2.2.5. Data Acquisition

An Agilent® HP Data Acquisition Switch Unit 34970A (colloquially referred to as a *datalogger)* will be used for data collection. This device consists of a three slot mainframe with a built-in six ½ digit digital multimeter[8], and has a processing capacity of up to 60 simultaneous signals (30 channels). Corresponding Agilent® software will be used in the personal computer for data management.

Even though the device has a capability for 60 signals, currently the relay box can only connect 24 signals (12 channels) at a time, due to hardware limitations.

2.2.6. Relay Box

This consists of a custom built relay box with 24 inputs (12 pairs). It has been suggested that upgrading this device could provide for faster execution times. Even though designing a new relay box is not a part of the scope, it will also be discussed in due time.

2.2.7. Cable

The cable used for this testing is a 240 mm^2 copper cable. Voltage is minimal (5V) but current is 600A, so adequately gauging the cable is very important as the temperature rise test must run uninterrupted for a full day.

2.2.8. Thermocouples

A set of Type T copper-constantan thermocouples will be used for measuring the temperature variations thorough the test. These thermocouples are suited for a temperature range of -200°C to 350C, with no abrupt change in measuring characteristics[9].

3. Test Arrangement

As previously stated, a series of independent testing will be performed to validate our results. The first test to be performed is a preliminary test, followed by a baseline test and finally an improvement test. A verification test will follow, if conditions are adequate. The test procedure will be discussed in this chapter, and results will be presented and discussed in the next Chapter. The expected outcome as well as the scope of each test is described below.

3.1. Preliminary Test

Our preliminary test consists of a simplified two CT test version of the temperature rise test being perfomed at the laboratory, and its purpose is to determine if our test methods are adequate and the methodology is understood and applied correctly. Initial measuring, steady state and final measuring will be tested for the first time and the accuracy of the result is not so relevant; so long as they remain consistent and coherent. The equipment hardware will also be tested and expected values are taken from reference (historical) experiments. The internal switch to shift from measuring mode *mätläge* to operating mode *driftläge* will also be tested. Figure 2 shows the overall test arrangement diagram (only one CT shown in the diagram).

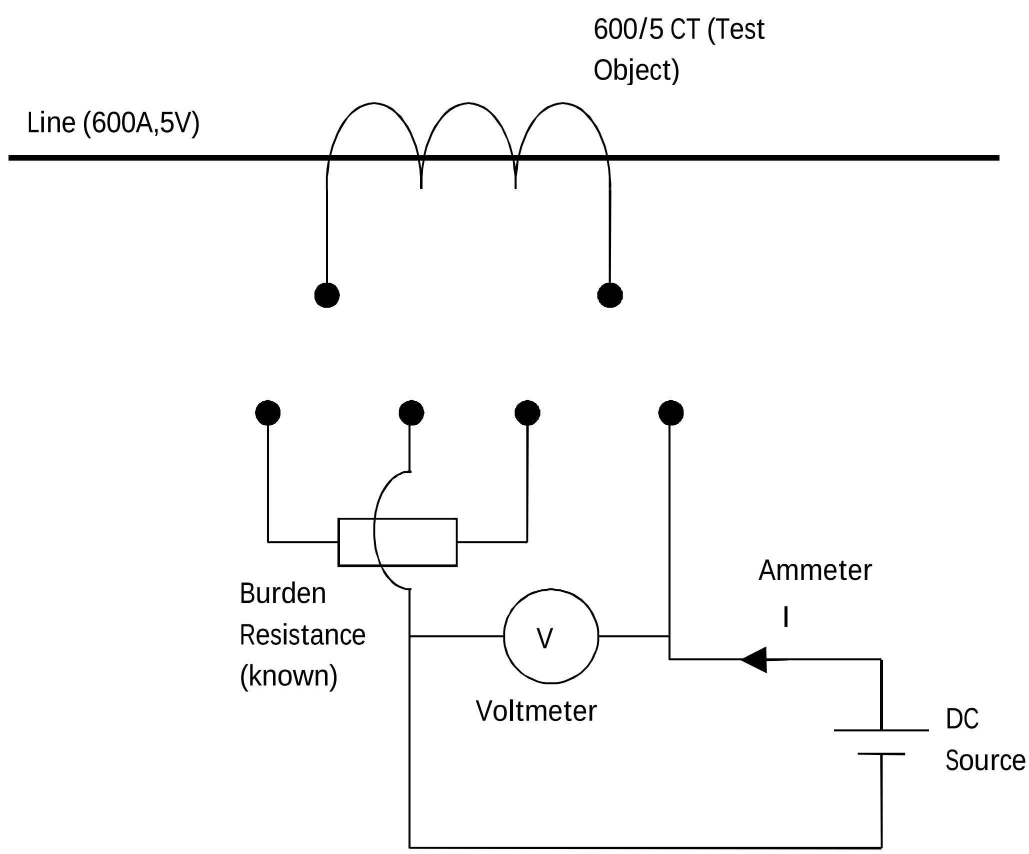

Figure 2. Overall Test Diagram

In order to evaluate the current methodology, the testing procedure can be further subdivided into four main processes, or blocks. Each testing block has been identified and can be subdivided according to Figure 3. We will therefore divide our work accordingly and study each block separately.

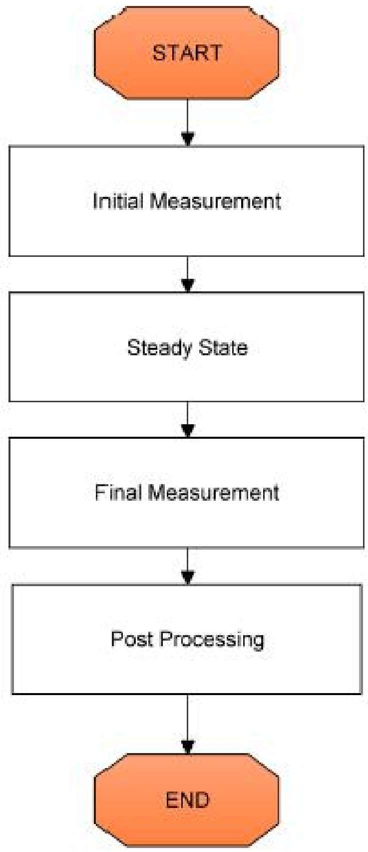

Figure 3. Four-Block Diagram Showcasing the Different Stages in the Test

3.1.1. Initial Measurement

The ABB High Power Laboratory follows a scheduled calibration scheme based on color labels for all their measuring equipment, which is currently the responsibility of the measuring department. For this testing, and following local best practices, we will rely on their expertise for our CT calibration.

In order to guarantee a reliable measurement, preliminary settings must be observed. The test current is measured by means of one CT equipped with a shunt resistor. Voltage drop across the shunt resistor is measured by means of a Fluke® true rms digital multimeter. In order to calculate the burden resistance, we will follow the burden resistance calculation and apply it to our CT (11).

$$R_b = \frac{S}{I_s^{\ 2}} \qquad (11)$$

Where I_s is the current in the secondary side, or 5A; S is the CT rating, or 80VA; and R_b is the Burden resistance, or 3.2Ω.

Each CT will be matched with its corresponding burden resistor, by means of a relay box. Once the test object and its burden are in place, and before any power is supplied, initial resistance in the secondary winding will be measured. Because of the winding sensitivity, resistance cannot be measured directly. Instead, it has to be calculated using the previously mentioned *resistance method*. An initial DC measurement is taken with 10% of its rated current, i.e. 0.5A. This is because 10% of the rated current does not influence the measurement through increased heating, resulting in an increased resistance reading. Using the *datalogger*, we will take five readings on preset intervals of ten seconds each. Ambient temperature is usually obtained from thermocouples, but for this preliminary experiment it will be taken from historical data in the Laboratory. The resistance can be then calculated (12).

$$R_0 = \frac{V_0}{I_{sDC}} \qquad (12)$$

Where R_0 is the winding resistance before the test, V_0 is the winding voltage before the test, I_{sDC} is the current at the secondary side (for our DC test), or 0,5A.

The corresponding schematic depicting the internal connection, set to *mätläge*, is shown below (Fig 4)

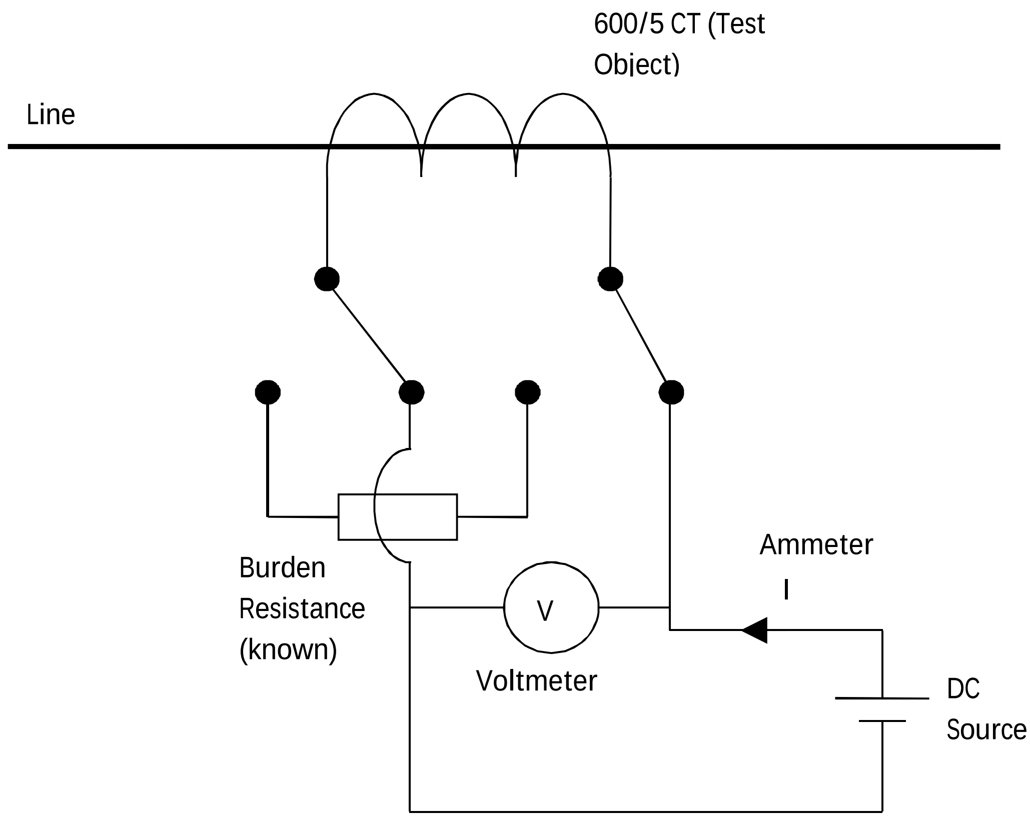

Figure 4. Initial Measurement Schematic Setup *(Mätläge)*

3.1.2. Steady State

Once initial measurements are taken, the switch is set on *driftläge*, effectively decoupling the DC source and the *datalogger*.

After it has been assessed that initial conditions are adequate, power is supplied to the transformer. Power is regulated by means of a varistor, using the Reference CT and a true rms digital multimeter. The shunt resistor has a 0.5V ratio so we will use the voltmeter to indirectly measure the 5A passing through the secondary winding, according to equation (13).

$$V = \frac{600}{600} \times I_s \times R_{sh} \qquad (13)$$

Where I_s is the current in the secondary side, or 5A; R_{sh} is the current circulating in the shunt resistor, or 0.5Ω. Therefore, V = 2.5V

Burden resistance should quickly increase in temperature; if this is negative, shut down immediately and check for faulty connections. A clear indication of a faulty connection is an incorrect reading in the reference CT. Once all connections have been checked, power is supplied by means of the varistor until 600A flow through the main line. Power must be supplied until steady state is reached, defined as a temperature increase of the current path (and all other parts such as tank and/or insulator) of less than 1 Kelvin per hour[10].

Given that components have varying degrees of heat coefficients, it is required for all elements of the test to reach a steady state. For this preliminary test, historical values suggest a timeframe of approximately 5 hours. The corresponding schematic depicting the internal connection is shown below in Fig 5.

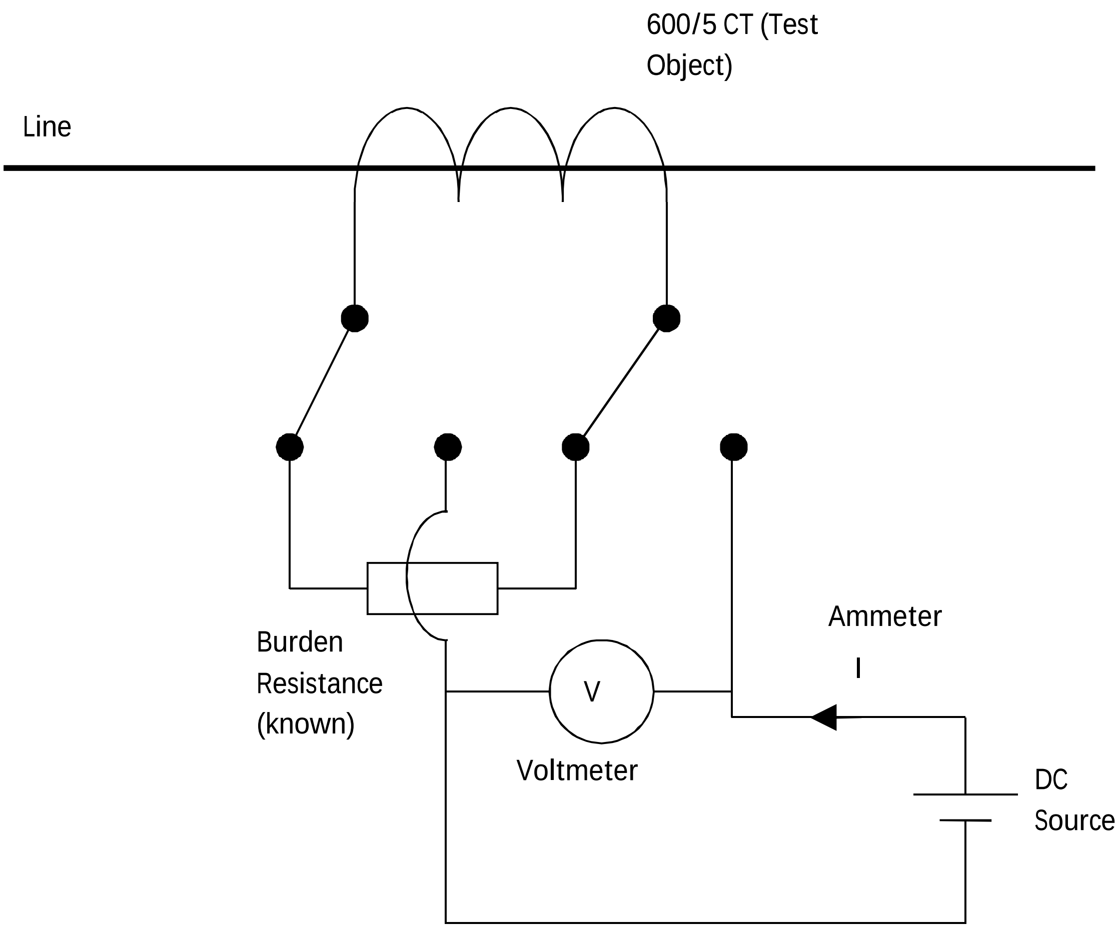

Figure 5. Schematic Diagram for a Steady State Condition *(Driftläge)*

3.1.3. Final Measurement

Once a steady state is reached, disconnect the power source, set the switch back to *mätläge*, and reconnect the DC source in the same way as the initial measurement. New voltage values are to be registered with the *datalogger*, following the same time interval and new resistance values are calculated, according to (14). The final ambient temperature measurement was taken from historical values.

$$R_t = \frac{V_t}{I_{sDC}} \tag{14}$$

Where V_t is the winding voltage after the test, I_{sDC} is the current in the secondary side (of our DC test), and R_t is the winding resistance after the test.

3.1.4. Post Processing

Further computing power is required to interpret results in order to calculate the final equipment temperature (15).

$$\theta_t = \left[\frac{R_t}{R_0} \times (T + \theta_0)\right] - T \tag{15}$$

Where θ_t is the equipment temperature; R_t is the winding resistance after the test; R_0 is the winding resistance before the test; T is the copper constant, or 234.5; and θ_0 is the ambient temperature before the test.

The final temperature rise then calculated by using the formula expressed in (16).

$$\theta_{tr} = \theta_t - \theta \tag{16}$$

Where θ is the ambient temperature after the test and θ_{tr} is the temperature rise.

Temperature rise must now be verified to be within acceptable limits. Results will be validated and discussed in the following Chapter 4.

3.2. Baseline Test

A full test was now carried out in order to establish a baseline. Six CTs were tested instead of two, because a CT measuring system typically involves at least one CT per phase and per side, such as when performing CT temperature rise testing on GIS switchgear[2]. For our temperature rise test, transformers shall be mounted in a manner representative to the mounting in service[11], therefore we will line the CT one after another, simulating a set of CTs for a Circuit Breaker protection relay.

The main goal in this project is to propose improvements in order to reduce the working time required to calculate, process and present the information. However, given the nature of the work being performed at the laboratory (i.e. one person working on several projects at the same time), it is virtually impossible to accurately measure the time required to set up the experiment from start to finish. Therefore the overall time required to physically set up the experiment can only be estimated, and efforts will be focused on the effectiveness of the new calculation tool.

For our baseline test, no improvements will be suggested or performed. The test will be conducted in the way it is currently being conducted, with supervision from ABB test engineers and responsible parties. We will subdivide the test in the same four blocks that we have identified from our preliminary test (see Figure 3 in section 3.1 for reference). We will discuss each block individually.

3.2.1. Initial Measurement

In order to establish an initial ambient temperature for our baseline test, room temperature was measured by means of oil-immersed thermocouples, and their signals were processed by means of a second *datalogger*. In order for the test to be valid, the thermocouples for measuring the ambient temperature shall be placed in a medium that will require not less than 2 hours for the indicated temperature to change[12]. Therefore, the temperature gradient properties of oil provide a solution to this requirement. IEC standard establishes at least a three-point temperature measurement, spread over a distance of 1 meter from the test object [13], while IEEE establishes that temperature should be measured at three different heights, at a horizontal distance adequate to prevent the transformer under test to influence the readings (1 m to 2 m, or 3 to 6 ft) [14]. Thermocouples were arranged in a triangular shape, at a distance of approximately 1 meter from the test objects and relatively equidistant from each other. They were placed at varying heights of roughly 3 feet from each other. Figure 6 shows the general arrangement, as well as all six CTs and the reference CT which will be used in the test[3].

[2] It is a preconceived idea that each phase must have one CT. In reality, each phase may have 2 or more CT's, depending on manufacturer design and reliability requirements.

[3] The *Datalogger* shown in this diagram corresponds to the one used to measure ambient temperature, and does not correspond to the one used for measuring CT winding resistance.

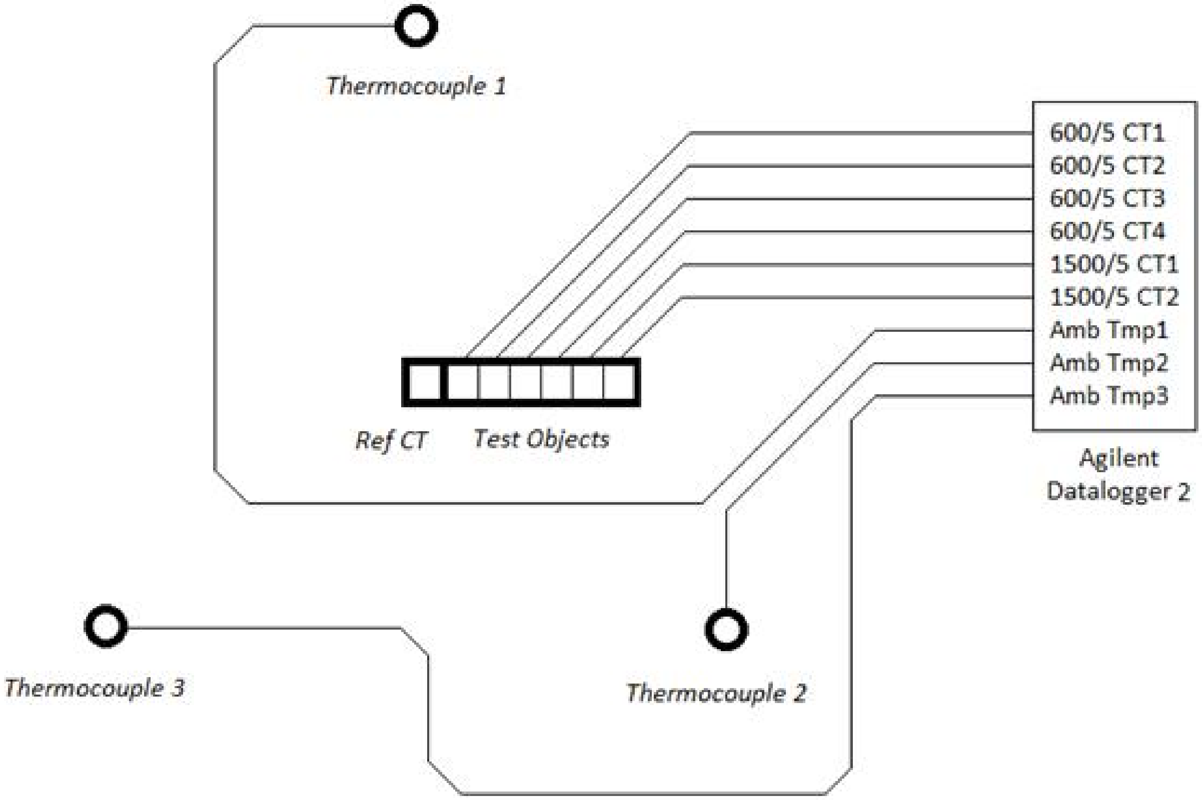

Figure 6. Thermocouple Placement and General Test Arrangement

In addition to the initial temperature reading by means of thermocouples, an initial CT winding resistance measurement is performed in the same manner as in the preliminary test. Because two CTs have a 1500/5 ratio and therefore a different burden rating, and since one of the 600/5 CTs also has a different burden resistance because of a technical issue with the equipment, it is expected that this test will yield three different temperature rise values: One for the set of three 600/5 CTs, one for the 600/5 CT connected to a different burden and one for the set of two 1500/5 CTs. We will therefore compare the results and the test will be considered valid if the results are proportional to their CT rating.

The burden resistance for the new 1500/5 CTs must be calculated, and because current in the primary side is still 600 A, a simple calculation establishes that the current in the secondary side should be 2A (17).

$$\begin{aligned}1500 &\rightarrow 5\\ 600 &\rightarrow I_2\\ I_2 &= \frac{600*5}{1500}\end{aligned} \quad (17)$$

Where I_2 corresponds to the current in the secondary side, or 2A.

The new burden resistance corresponds to (18).

$$R_{b2} = \frac{S_2}{I_2^{\ 2}} \quad (18)$$

Where S_2 corresponds to the CT rating, or 60VA; and R_{b2} is the burden resistance for the 1500/5 CTs, or 15Ω.

The process flowchart which was identified is described in Figure 7.

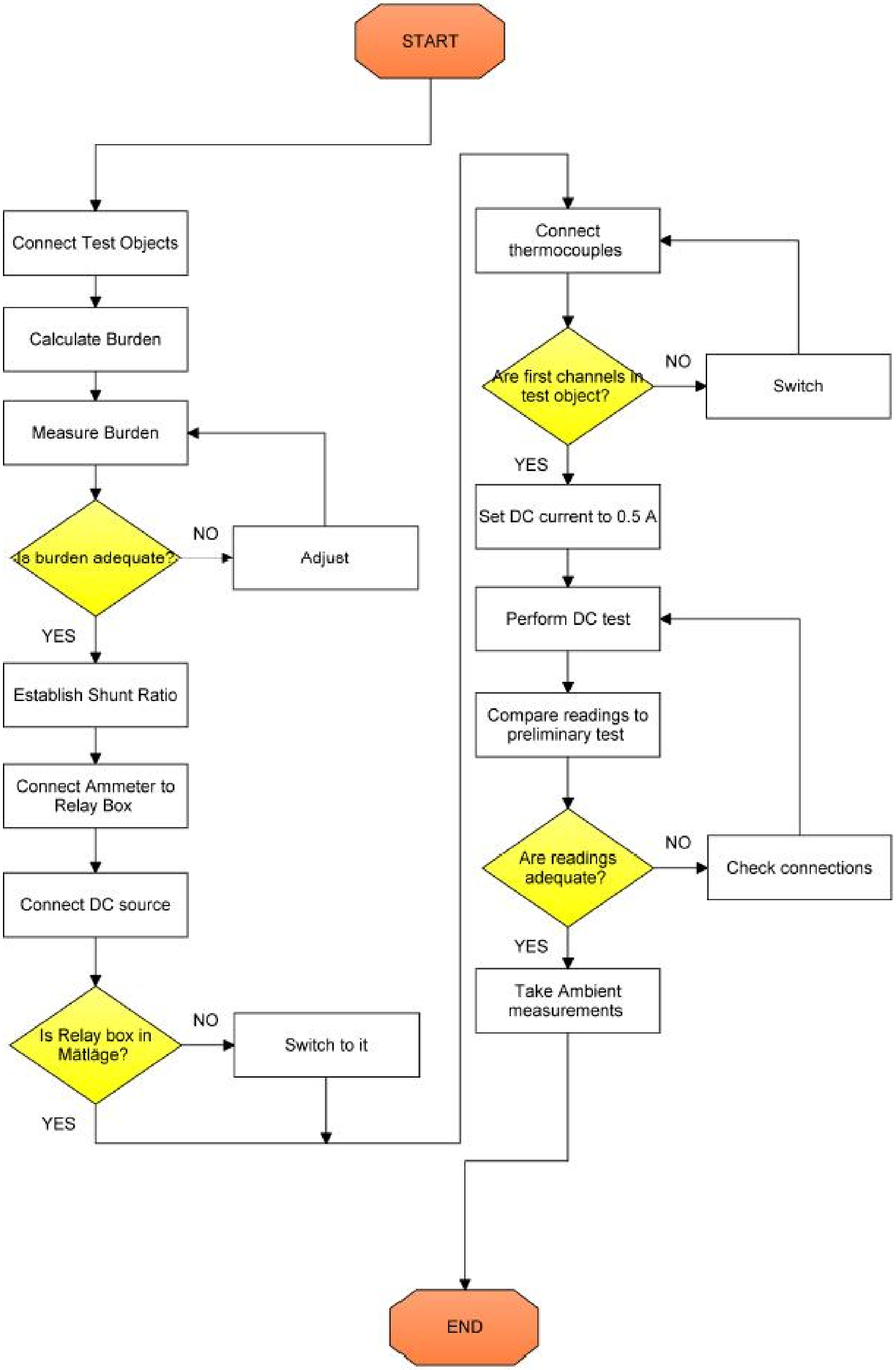

Figure 7. Flowchart for the Initial Measurement Experiment Setup

3.2.2. Steady State

Unlike the preliminary test, where the time required to reach steady state was estimated according to historical data, we will use the measurement from the thermocouples. Temperature measurement is conducted every 15 minutes, using dedicated software called MyVEETest®. In order to prevent common mode disturbances, current is interrupted during the scanning of the thermocouples. These current interruptions have a duration of 10 seconds each and are proven not to significantly affect the temperature[15]. As previously stated, steady state was defined as the point when temperature rise is less than 1 Kelvin/hour[10]. The process flowchart has been identified and is shown in Figure 8.

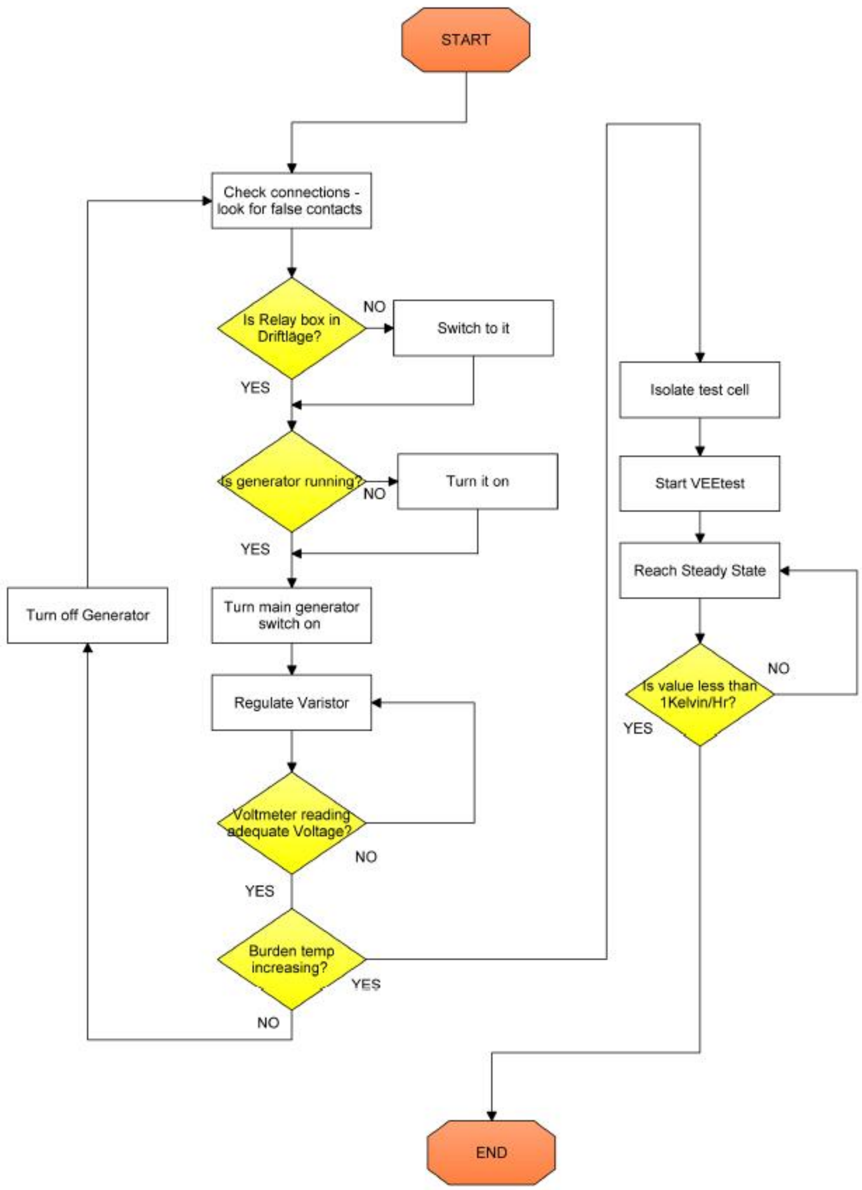

Figure 8. Flowchart for the Steady State Experiment Setup

3.2.3. Final Measurement

Once steady state has been reached, we will proceed to measure the temperature rise values in the secondary windings of the CTs by following the same procedure as with the preliminary test with the addition of the ambient temperature rise by means of the thermocouples, in the same manner as with the initial measurement in this baseline test. In case of misreading, likely causes for this error must be quickly identified and corrected in order to maintain a valid steady state condition. Figure 9 shows the identified flowchart.

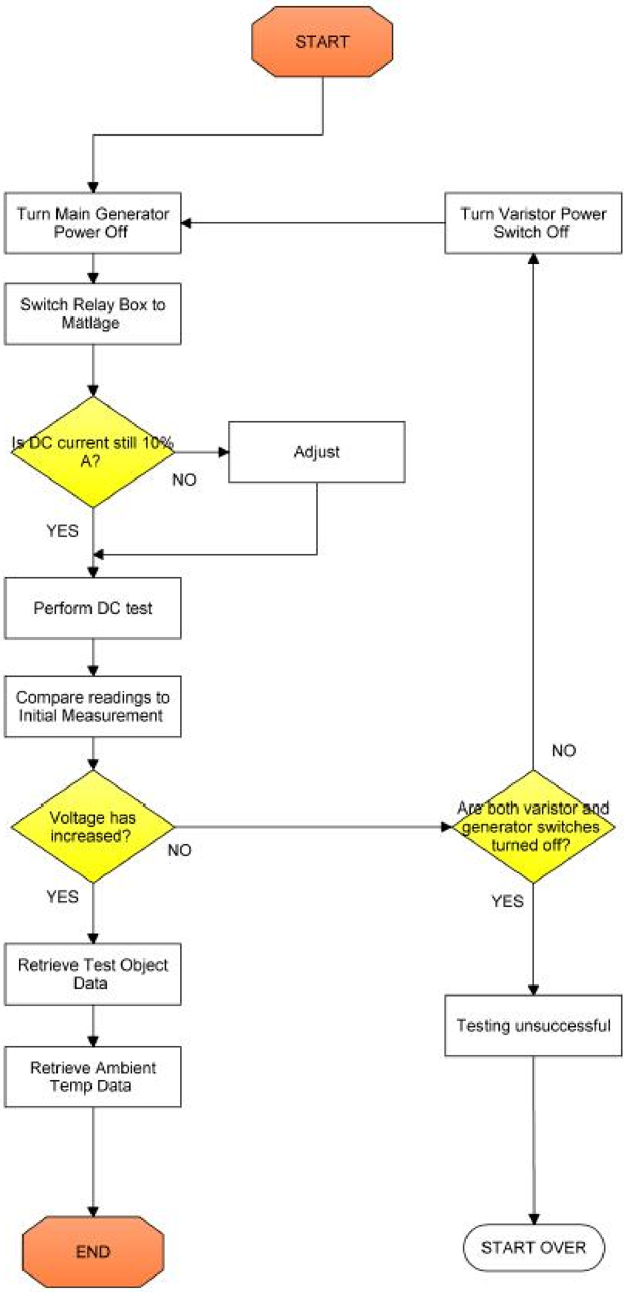

Figure 9. Flowchart for the Final Measurement Experiment Setup

3.2.4. Post Processing

Once the experiment is done, we must collect the results and perform calculations. The algorithms used were the same as with the baseline test, except that we measured six CTs instead of just two, and the ambient temperature was measured instead of estimated. Figure 10 shows the corresponding flowchart to this final part of the test.

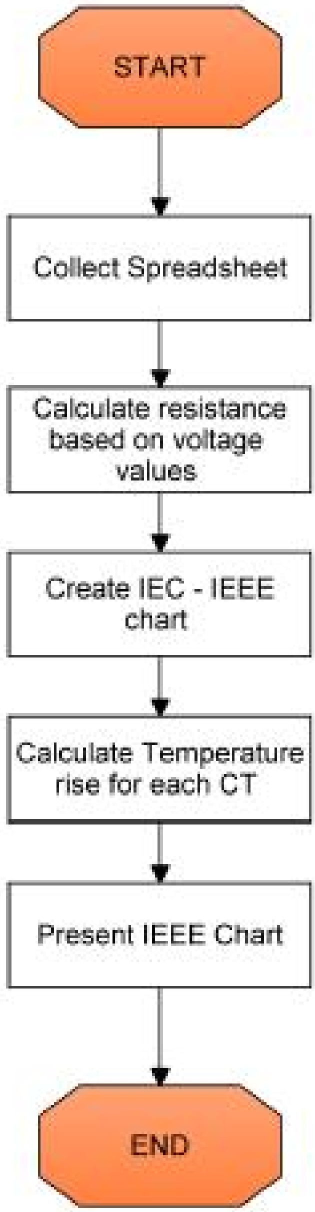

Figure 10. Flowchart for the Post Processing Experiment Setup

3.3. Improvement Test

Now that we have a sizable sample and enough information, improvement ideas will be proposed, implemented and a new test will be run. The findings as well as the proposal breakdown are explained in full detail below.

3.3.1. Initial Measurement

It was observed that a significant amount of time was being invested in the test setup, especially by first time test engineers, due to the lack of an adequate checklist. By providing a thorough flowchart, time can be reduced and human error can be minimized. Additionally, some tasks which could be improved were identified. These tasks included:

Burden calculation and mounting. It was suggested that using a clamp system as opposed to the traditional nut and bolt approach would expedite the burden measuring system. Several tests were performed and it was indeed faster; however, the clamp system was not sturdy enough to withstand several testing hours, and the probability of failure was not worth the time saved, so the idea was discarded because of reliability issues. It was also proposed that using a butterfly clamp would provide the best solution. This idea was discarded because there were no commercially available butterfly clamps with the required diameter and tension to provide a reliable connection. After further discussion with the engineer responsible for the test, it was decided that the burden calculation and mounting be left as it has been done before.

Data acquisition and handling. Data could be corrupted/lost in the acquisition and handling process due to the lack of a user interface. Initial values were hand written and hand calculated. Therefore, it was noted that this process can be easily streamlined with an automation tool.

3.3.2. Steady State

Since this is the actual time required for the experiment to reach a steady state, its time cannot be reduced. The wiring scheme, however, can be signaled in such a way as to prevent confusion between ambient temperature thermocouples and test objects. Even though it would be evident within the first hour if the wrong device is being measured, testing would have to stop, allow for cooling down and restart again.

3.3.3. Final Measurement

The ABB High Power Laboratory is already configured to provide data acquisition by means of a semi-automated system. The personnel working here is familiarized with this method and it provides the results in an efficient manner. Therefore, any change in this configuration would be unpractical.

3.3.4. Post Processing

It was observed that hand calculations, although very precise, could be optimized by means of an automated algorithm – Utilizing commercially available software, the problem being was that the file gathered from our datalogger was a .csv file, whereas the required format for an adequate calculation would preferably be a spreadsheet such as .xls or .xlsx.

In the following flowchart, the proposed algorithm will streamline the areas inside the rectangle, providing a reliable measurement that can be cross checked at any time. (See Figure 11). The test results are shown in the next chapter.

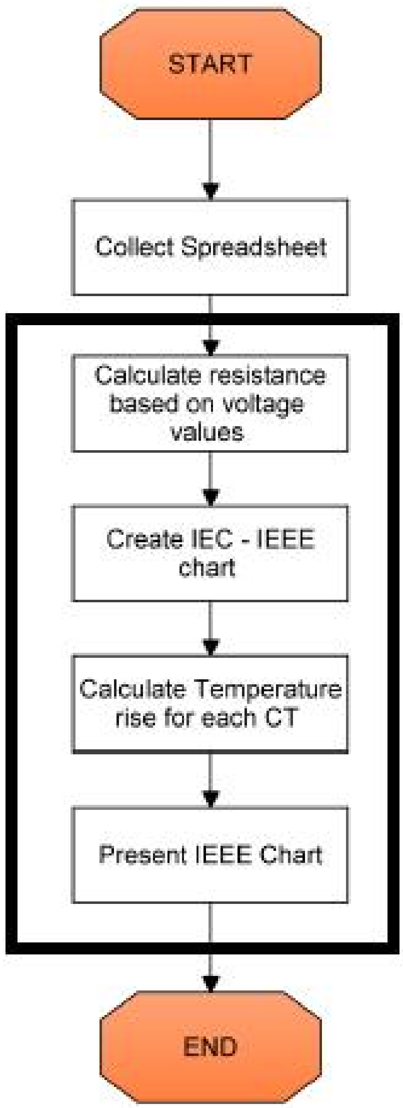

Figure 11. Proposed Improvement in the Flowchart for the Post Processing Experiment Setup

4. Results

In this chapter, the results of all the conducted tests will be presented and discussed. Findings and analysis regarding the current method are detailed below; whereas further discussion and proposals will be commented on Chapter 6: Future Work.

4.1. Preliminary Test

As previously mentioned, the scope of this test was to familiarize ourselves with the measuring equipment. Two CT's were tested, and both initial and final ambient temperature were taken from historical data in the laboratory, however burden resistance in one of the CTs was set at 3Ω instead of the calculated 3.2Ω, because of a hardware problem. The remainder of the test followed the procedure and values were calculated according to SATS Certification procedures [16]. The results are shown in Table 2.

Table 2. Temperature Rise Results of Preliminary Test with 2 Current Transformers

	Reference Value		Values at shut down			
	Resistance R0	Ambient Temp θ0	Resistance Rt	Ambient Temp θ	Temperature θt	Temperature rise θtr
V1	0.1734711	19	0.18019854	23.3	28.831067	5.53106697
	0.17342658	19	0.18007378	23.3	28.7163062	5.41630615
	0.17344766	19	0.18011056	23.3	28.7380742	5.4380742
	0.17345217	19	0.18011637	23.3	28.7397089	5.43970892
	0.17341754	19	0.18000924	23.3	28.635683	5.33568297
V2	0.21490094	18.9	0.23464622	23.3	42.1826062	18.8826062
	0.21496978	18.9	0.23466344	23.3	42.1143022	18.8143022
	0.21490094	18.9	0.23463762	23.3	42.1724655	18.8724655
	0.21489448	18.9	0.23457524	23.3	42.1072252	18.8072252
	0.21493536	18.9	0.23439238	23.3	41.8390309	18.5390309

Results show that, as expected, a different burden configuration yields a different terminal temperature rise. Because of technical problems, the test had to be interrupted and the DC source had to be replaced. This situation caused an adverse effect on the estimated time to reach a steady state condition, which explains the discrepancy between our expected value and our actual value (expected 23 Kelvin as opposed to the actual 18.8 Kelvin).

Nevertheless, the test was considered successful as it proves our measuring equipment to be working properly and data suggests that the test was converging adequately towards a steady state. Because of the several mishaps, the time required for testing amounted to over 2 days.

4.2. Baseline Test

The corresponding 6 CT test for our baseline calculation yielded the following results: As expected, temperature rise was higher in the 600/5 A (10,5 Kelvin) than in the 1500/5 A (5,9 Kelvin), given that the former CTs were used at rated current and the latter were purposely over dimensioned.

Figure 12 shows that the 600/5 CT (top graph) reached a Steady State[4] in a total time of 3 hours, whereas the 1500/5 CT (bottom graph) did so in 3 hours and 15 minutes. Nevertheless, since both CT types are part of the system, we took into consideration the time from the latter CTs. Additionally, the test was left running longer to check for any abnormalities.

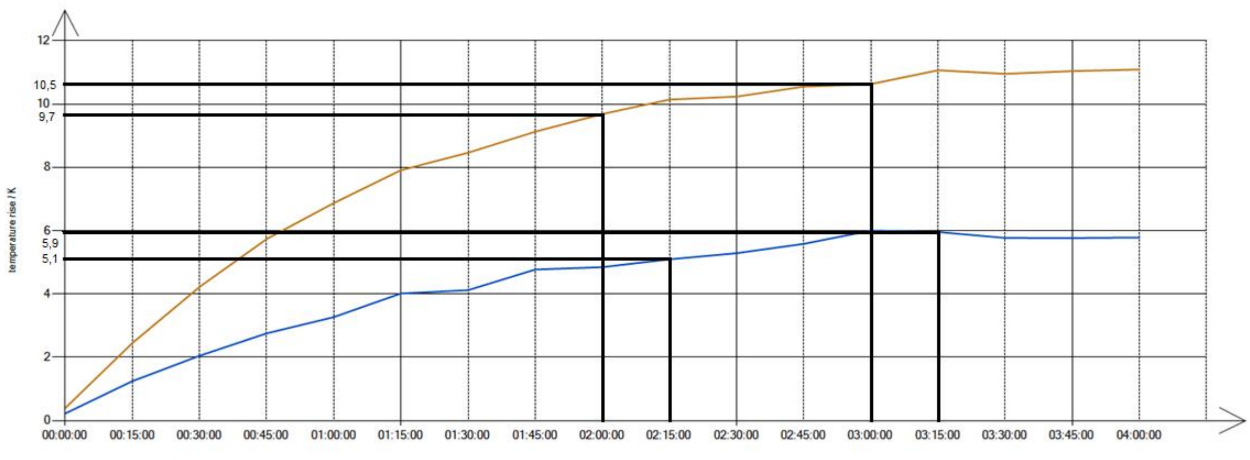

Figure 12. 600/5 (Top) and 1500/5 (Bottom) CT Test Object Performances while reaching Steady State

The system, as a whole, required less time to reach a steady state condition: 3 hours and 15 minutes, instead of 5 hours[5]. The temperature rise was also smaller than expected. This can be attributed to the test cell being bigger (and therefore the temperature rise was *spread* over a larger volume), and possibly because CTs had different ratings, which contributed to uneven temperature increases.

The measured temperature rise was 13,10 Kelvin at its most critical and 8,17 Kelvin at its lowest value. Ambient temperature increased by 1,33 Kelvin, from 20,71 to 22,046 Kelvin. Table 3 shows the entire results for the 6 CTs tested.

[4] Previously defined as a temperature increase of 1 Kelvin/Hour

[5] Average time for Current Transformer temperature Rise Testing.

Table 3. Temperature Rise Results of Baseline Test with 6 Current Transformers

	Reference Value		Values at shut down			
	Resistance R0	Ambient Temp θ0	Resistance Rt	Ambient Temp θ	Temperature θt	Temperature rise θtr
V1	0,17438619	20,7146	0,18345943	22,046	33,9933143	11,9473143
	0,17442426	20,7146	0,18328304	22,046	33,6766098	11,6306098
	0,17447955	20,7146	0,18333359	22,046	33,6655781	11,6195781
	0,17438619	20,7146	0,18320818	22,046	33,6256034	11,5796034
	0,17441824	20,7146	0,18320646	22,046	33,5738145	11,5278145
V2	0,2135242	20,7146	0,22306666	22,046	32,1202164	10,0742164
	0,21357584	20,7146	0,22302578	22,046	32,0069009	9,96090093
	0,21350484	20,7146	0,22294618	22,046	32,0003761	9,95437606
	0,21356508	20,7146	0,22289456	22,046	31,8635177	9,81751773
	0,2135113	20,7146	0,22273538	22,046	31,7403391	9,69433909
V3	0,17263754	20,7146	0,18240257	22,046	35,1505088	13,1045088
	0,17264507	20,7146	0,18227417	22,046	34,9489304	12,9029304
	0,17271046	20,7146	0,18223372	22,046	34,7871436	12,7411436
	0,17264593	20,7146	0,18215177	22,046	34,7666498	12,7206498
	0,17265518	20,7146	0,18213542	22,046	34,7280557	12,6820557
V4	0,17188227	20,7146	0,18039751	22,046	33,3582138	11,3122138
	0,17192874	20,7146	0,18032179	22,046	33,1734243	11,1274243
	0,17189841	20,7146	0,18026608	22,046	33,1379354	11,0919354
	0,17187345	20,7146	0,18025209	22,046	33,1560314	11,1100314
	0,17191239	20,7146	0,18015466	22,046	32,9507639	10,9047639
V5	0,29644198	20,7146	0,31054698	22,046	32,8579608	10,8119608
	0,29635164	20,7146	0,3105771	22,046	32,9654014	10,9194014
	0,29633228	20,7146	0,31058356	22,046	32,9884391	10,9424391
	0,29640326	20,7146	0,3104803	22,046	32,8354725	10,7894725
	0,29631076	20,7146	0,31045018	22,046	32,8929847	10,8469847
V6	0,2922193	20,7146	0,30335144	22,046	30,4370402	8,39104016
	0,29215476	20,7146	0,30329766	22,046	30,4485874	8,40258745
	0,29224942	20,7146	0,30320946	22,046	30,2857472	8,23974722
	0,2921354	20,7146	0,30314708	22,046	30,3345964	8,28859643
	0,29227952	20,7146	0,30316858	22,046	30,2227828	8,17678276

In general terms, results show a low temperature increase as compared to previous tests, but was validated with ABB test engineers and they approved these values. Test was successful as the steady state temperature rise time was observed within an expected timeframe.

Likewise, the time used for data processing was also being measured. Five tasks in particular took a long time to process, which are shown in Figure 13.

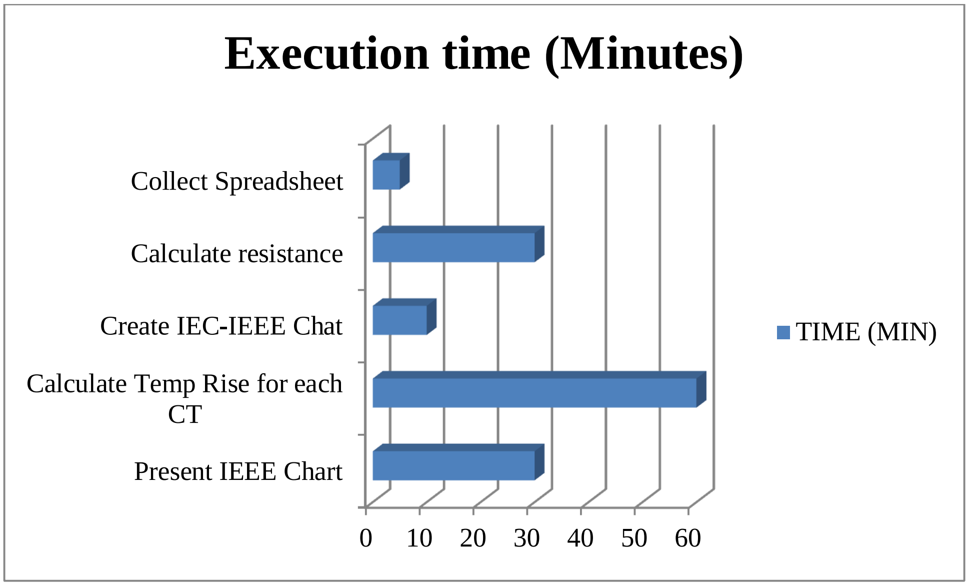

Figure 13. Time Required to Hand-Calculate Post Processing Values (Current Method)

The total time used for the test is shown in the Table 4 below:

Table 4. Observed Total Time Required to perform a Full CT Temperature Rise Test

TASK	BASELINE
1) Initial Preparation	Circa 5 Hours
2) Steady State	Circa 4 Hours[6]
3) Final Measurement	5 min
4) Collect spreadsheet	5 min
5) Calculate resistance	30 times – 30 min
6) Create IEC-IEEE chart	10 min
7) Calculate temp-rise for each	30X2 times – 60 minutes
8) Present a new IEEE Chart	30 min
TOTAL	11 Hours and 20 minutes

[6] Standalone Current Transformer Temperature Rise only. This time can vary considerably depending on the equipment to be tested as well as the insulation medium.

4.3. Improvement Test

A further analysis revealed that only a handful of all the information that is generated needs to be presented to the customer, allowing for a simplification in the IEEE/IEC chart. Once all the relevant information was identified, it was possible to create a VBA routine to sort and operate the information into a desired shape. The VBA routine can be revised under Appendix 2. The test was conducted again and the results are shown in Table 5 (Same data was used because this is a post-processing algorithm).

Table 5. Temperature Rise Results of the Improvement Test - Automated Table

	Reference Value		Values at shut down			-
	Resistance R0	Ambient Temp θ0	Resistance Rt	Ambient Temp θ	Temperature θt	Temperature rise θtr
201 (VDC)	0,17438619	20,7146	0,18345943	22,046	33,9933143	11,9473143
202 (VDC)	0,2135242	20,7146	0,22306666	22,046	32,1202164	10,0742164
203 (VDC)	0,17263754	20,7146	0,18240257	22,046	35,1505088	13,1045088
204 (VDC)	0,17188227	20,7146	0,18039751	22,046	33,3582138	11,3122138
205 (VDC)	0,29644198	20,7146	0,31054698	22,046	32,8579608	10,8119608
206 (VDC)	0,2922193	20,7146	0,30335144	22,046	30,4370402	8,39104016

Execution times were measured. Table 6 shows that this improvement can be seen in the following stages of the post processing block:

Table 6. Observed Time Reduction in Post Processing with respect to Baseline Test

TASK	BASELINE	IMPROVEMENT
4) Collect spreadsheet	5 min	SAME
5) Calculate resistance	30 times – 30 min	ONE CLICK
6) Create IEC-IEEE chart	10 min	
7) Calculate temp-rise for each	30X2 times – 60 minutes	
8) Present a new IEEE Chart	30 min	
TOTAL	2 Hours and 15 minutes	5 minutes

Therefore, the overall time reduction with this new tool is 8 Hours and 50 minutes, which represents a time saving of 22%. In addition to the execution time being reduced, this automation tool organized data in a way that is much more useful to the ABB engineering team: By sorting all the information in a useful manner, it was possible to quickly perform time consuming secondary tasks, such as plotting resistance charts[7], immediately comparing new with existing results and therefore streamlined information storage best practices.

After a discussion with the ABB team, it was concluded that setting up a verification test was not needed. This was due to the fact that the optimization tool only handled the software part of the testing, and thus validating the test results did not require a physical reconstruction of the 6 channel, 5 measurement test arrangement. Instead, a much more relevant experiment was to use data from a longer (SF6 Circuit Breaker) temperature test performed in parallel with a 9 channel and a 253 measurement arrangement. The tool was modified to adapt to this setup, handled the information and provided the expected results. ABB was shown the results as they were being developed and were pleased with the results.

[7] Not required by ANSI/IEC, however some internal clients have requested this information along with the test report.

4.4.Further Analysis

In addition to the time reduction, a system was proposed to mathematically estimate the total test time required for both the 600/5 CT and the 1500/5 CT. By having an estimated value, the test engineering team is able to perform additional tasks while the system accurately predicts (within (an error margin of only 2.15%) the time that will be required for the test object to reach a steady state.

In order to develop this model, empirical data was obtained from our baseline test. This data corresponds to the value of the 600/5 CT (See Figure 14 and Table 7).

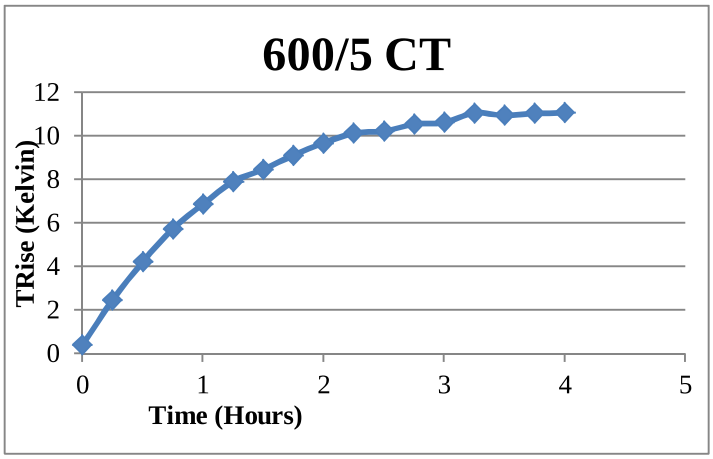

Figure 14. Time Required to reach a Steady State (600/5)

Table 7. Time required (detail)

TIME (Hours)	Temp Rise (600/5 CT)
0	0,399333
0,25	2,452
0,5	4,223667
0,75	5,738
1	6,873667
1,25	7,911
1,5	8,463
1,75	9,127
2	9,685667
2,25	10,142
2,5	10,23533
2,75	10,55133
3	10,63067
3,25	11,068
3,5	10,95567
3,75	11,04133
4	11,092

The time was then determined by a simple algorithm: by substracting the final temperature to the initial temperature one hour after the test began, we can know the temperature change (Delta T). The algorithm then continues by performing this evaluation in every 15 minute interval (shown here as a 0.25, or one quarter hour). Once this temperature difference was less than one Kelvin, a steady state condition was reached (Table 8).

Table 8. Observed Time Reduction in Post Processing with respect to Baseline Test

TIME (Hours)	DELTA T	RESULT
0		
0,25		
0,5		
0,75		
1	6,474333	
1,25	5,459	
1,5	4,239333	
1,75	3,389	
2	2,812	
2,25	2,231	
2,5	1,772333	
2,75	1,424333	
3	0,945	Steady State
3,25	0,926	Steady State
3,5	0,720333	Steady State
3,75		
4		

By applying a third degree logarithmic regression, it is possible to establish a *trendline*, with an established formula and an acceptable accuracy level. The equation that best matches our expected curve is (19).

$$y = 0.2471x^3 - 2.454x^2 + 8.5417x + 0.4828 \quad (19)$$

Where y is the temperature rise in Kelvin, and x corresponds to the time in Hours. The proposed fit is shown in figure 15:

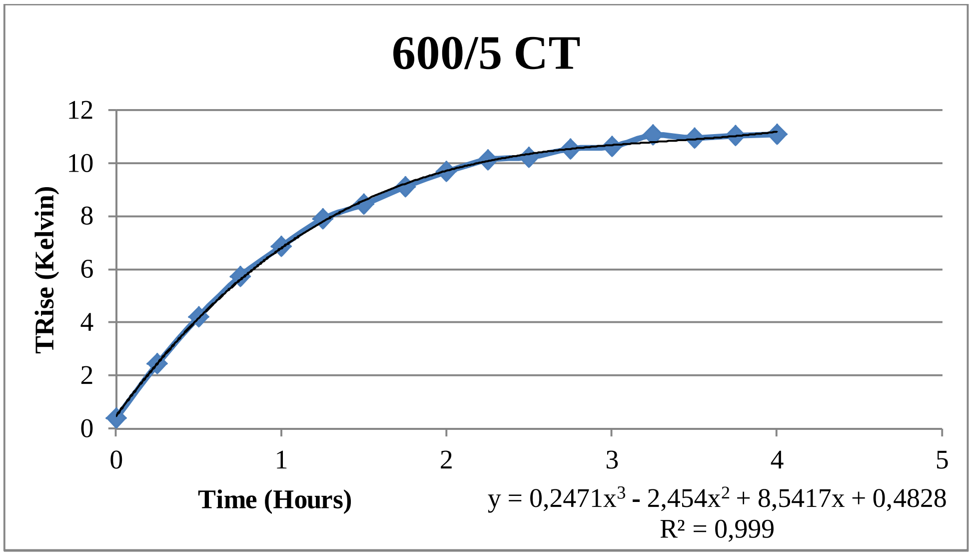

Figure 15. Proposed logarithmic regression of 600/5 CT

The formulation will then be validated by comparing the laboratory results (Table 9) with the theoretical results (Table 10).

Table 9. 600/5 Baseline test laboratory results

TIME (Hours)	600/5 CT (Laboratory)	DELTA T	RESULT
0	0,399333		
0,25	2,452		
0,5	4,223667		
0,75	5,738		
1	6,873667	6,474333	
1,25	7,911	5,459	
1,5	8,463	4,239333	
1,75	9,127	3,389	
2	9,685667	2,812	
2,25	10,142	2,231	
2,5	10,23533	1,772333	
2,75	10,55133	1,424333	
3	10,63067	0,945	Steady State
3,25	11,068	0,926	Steady State
3,5	10,95567	0,720333	Steady State
3,75	11,04133		
4	11,092		

Table 10. 600/5 Theroetical (Calculated) results

TIME (Hours)	600/5 CT (Theoretical)	DELTA T	RESULT
0	0,4828		
0,25	2,468711		
0,5	4,171038		
0,75	5,612945		
1	6,8176	6,3348	
1,25	7,808167	5,339456	
1,5	8,607813	4,436775	
1,75	9,239702	3,626756	
2	9,727	2,9094	
2,25	10,09287	2,284706	
2,5	10,36049	1,752675	
2,75	10,55301	1,313306	
3	10,6936	0,9666	Steady State
3,25	10,80543	0,712556	Steady State
3,5	10,91166	0,551175	Steady State
3,75	11,03546		
4	11,2		

It can be thus appreciated that the proposed curve matches the steady state behavior that was observed in the Steady State Test. As previously stated, the margin of error is only 2.15% (600/5 CT Laboratory vs Theoretical values). Therefore, it can be validated that this proposal can adequately predict the behavior of our 600/5 CT temperature rise test.

A similar approach was taken for the 1500/5 CT, for which the results were slightly different than for those obtained in our baseline test (Figure 16 and Table 11):

Table 11. Time Required (detail)

TIME	1500/5 CT
0	0,226333
0,25	1,248
0,5	2,049667
0,75	2,758
1	3,270667
1,25	4,018
1,5	4,122
1,75	4,773
2	4,849667
2,25	5,097
2,5	5,289333
2,75	5,584333
3	6,003667
3,25	5,961
3,5	5,771667
3,75	5,767333
4	5,784

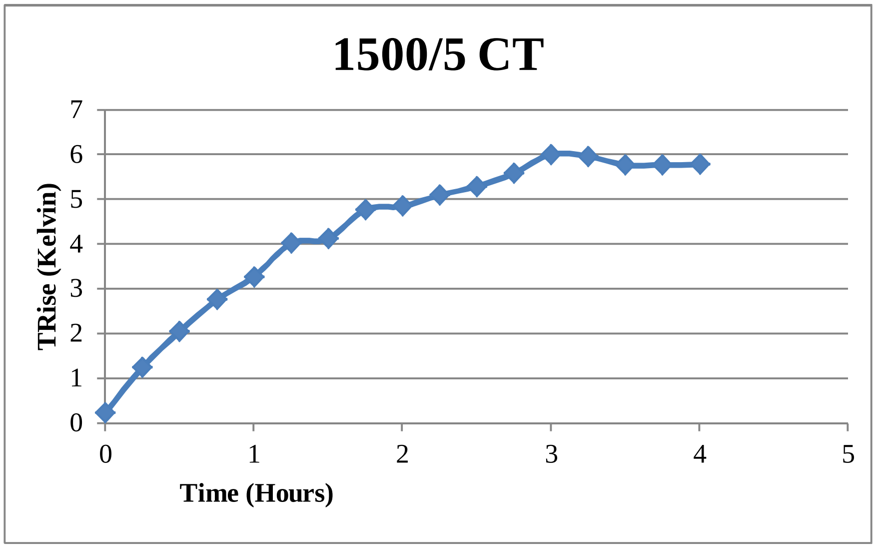

Figure 16. Time Required to reach a Steady State (1500/5)

The logarithmic regression is shown in Equation (20).

$$y = 0.0547x^3 - 0.8061x^2 + 3.7221x + 0.3283 \qquad (20)$$

Also where y is the temperature rise in Kelvin, and x corresponds to the time in Hours. The fit curve is superimposed in Figure 17:

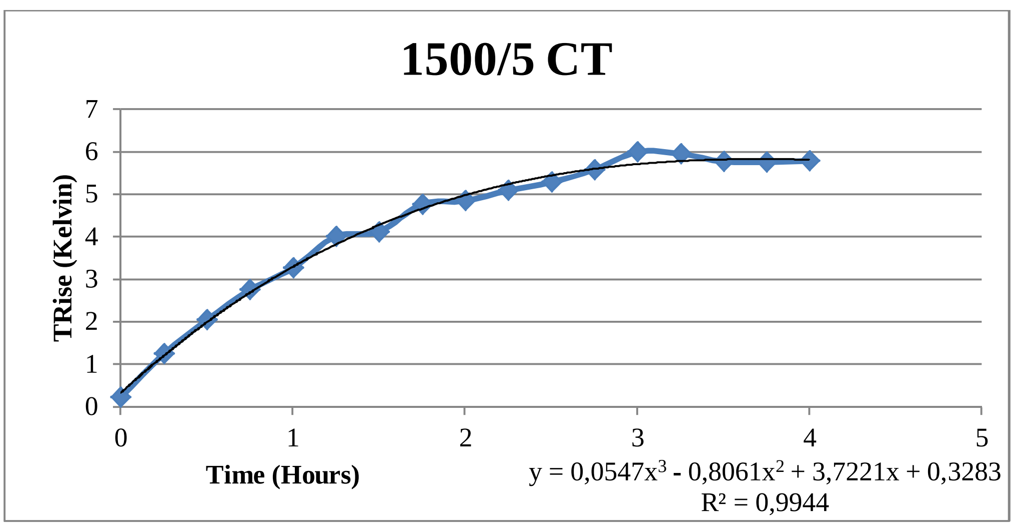

Figure 17. Proposed logarithmic regression of 1500/5 CT

The comparison between the laboratory results and the theoretical results are shown in Table 12 and Table 13, respectively.

Table 12. 1500/5 Baseline test laboratory results

TIME (Hours)	1500/5 CT (Laboratory)	DELTA T	RESULT
0	0,226333		
0,25	1,248		
0,5	2,049667		
0,75	2,758		
1	3,270667	3,044333	
1,25	4,018	2,77	
1,5	4,122	2,072333	
1,75	4,773	2,015	
2	4,849667	1,579	
2,25	5,097	1,079	
2,5	5,289333	1,167333	
2,75	5,584333	0,811333	Steady State
3	6,003667	1,154	
3,25	5,961	0,864	Steady State
3,5	5,771667	0,482333	Steady State
3,75	5,767333		
4	5,784		

Table 13. 1500/5 Theroetical (Calculated) results

TIME (Hours)	1500/5 CT (Theoretical)	DELTA T	RESULT
0	0,3283		
0,25	1,209298		
0,5	1,994663		
0,75	2,68952		
1	3,299	2,9707	
1,25	3,82823	2,618931	
1,5	4,282338	2,287675	
1,75	4,666452	1,976931	
2	4,9857	1,6867	
2,25	5,245211	1,416981	
2,5	5,450113	1,167775	
2,75	5,605533	0,939081	Steady State
3	5,7166	0,7309	Steady State
3,25	5,788442	0,543231	Steady State
3,5	5,826188	0,376075	Steady State
3,75	5,834964		
4	5,8199		

From the above tables it can be seen that the linear regression “predicts” a steady state at T = 3 hours, whereas the test experiment reaches such a state in 3 hours *and* 15 minutes – even though it briefly reaches a state in under 3 hours, at 2 hours and 45 minutes. It is important to note that this reading cannot be used as IEEE establishes that the temperature shall not change by more than 1 kelvin/hour in the following three successive intervals.

Nevertheless, our proposed system is within 15 minutes of emulating real test conditions, with a cumulative margin of error of just 4.17% (1500/5 CT Laboratory vs Theoretical values) with respect to the original curve. It is therefore a valid reference to estimate the time required to reach a steady state.

5. Conclusion

The challenge of this thesis work was to propose, design and develop a temperature rise testing method that is robust, yet simple enough to be operated by a single person – and most importantly, to be developed using only readily available infrastructure.

Aside from a thorough theoretical understanding of instrument transformer measuring, interpretation and operation, the development of this project required actual physical wiring, assembly and interaction with the equipment, in addition to some programming skills. The basic premise was for the resulting tool to perform the task as intended, using readily available infrastructure. The requirement of the task was to handle at least the 40 CT channels available; the end tool was able to process a virtually infinite number of CT channels. The only physical limitation is currently due to the existing relay box as well as the *datalogger*. Morevoer, the tool is flexible enough to be modified and used in any temperature rise testing involving the resistance method, be it Current Transformers, GIS Switchgear or Circuit Breakers, as it was demonstrated.

The designed data collection platform was able to synchronize data logs from tests of varying configurations. The improvement with this implementation will be even more evident when a data intensive project such as a GIS bay temperature rise testing will be performed. The data validation experiment performed on the 9 channel, 253 measurement test object is proof of this data collection tool being effective in reducing working time. Therefore, the upcoming GIS bay test at ABB Ludvika, as well as any other data intensive test, is guaranteed to present the same outcome.

Additionally, the baseline estimation tool will equip the test engineers with an average time estimation required to reach an established temperature rise, with information based solely on the test object characteristics. The mathematical model developed to estimate the time required for the test object to reach a steady state was also validated against real test values. The variation between both can be considered negligible for practical applications. Even though the development of this model would not equate to shorter testing times, it provides an acceptable time framework so that the testing responsible parties can focus on diverse activities rather than focus on one single test. The result is an improved test confidence and controllability.

Finally, the knowledge gained from individually developing each stage of the test represents a very valuable experience, because it provided a balanced combination of theoretical and practical work.

6. Future Work

Upon presenting the work at ABB in Ludvika, I had suggested that testing time can be reduced further (if desired) if a permanent link is created between the automated tool, the *Datalogger*, and the CPU in charge of performing the DC measurement. This was not done because there is currently a high demand for both the *Datalogger* and the CPU. Thus, linking all three devices to perform just one task is not a viable solution at the moment. Further research should be focused on developing a HMI to enable multiple parallel configurations, although this improvement must ideally originate from the IT Department in conjunction with the Measuring Department.

The user interface of the calculation tool can be improved by eliminating redundant algorithms. Further communication with the IT Department should provide an acceptable solution – however constant feedback from the engineering department is required at all times in order to keep the tool simple, useful and user friendly. On a global scale, a further revision must be performed as this tool was developed for the European market, using standard European math expressions and symbology.

A slight improvement is possible if a process flowchart is always visible. The possibility of human error can be reduced if the process flowchart can be embedded into the software. This would allow for faster checklists, although this improvement can be considered negligible as the testing process has a quick learning curve. Finally, a document template can be created to be automatically populated with data from our improvement tool. This step, although feasible, must be discussed with the engineering team, as a completely automated report may be counterproductive.

7. References

[1] ABB Website / High Power Laboratory, Ludvika Sweden.

[2] IEC Std 60044-1-2003. “Instrument Transformers” Page 51. Clause 7.2, Paragraph 4.

[3] IEC Std 60044-1-2003. “Instrument Transformers” Page 13. Clause 2.1.2, Paragraph 1.

[4] IEC Std 60044-1-2003. “Instrument Transformers” Page 77. Clause 12.3, Paragraph 2.

[5] ANSI/IEEE Std C57.13-2008 (Redline) “IEEE Standard Requirements for Instrument Transformers”. Page 31. Clause 5.3, Paragraph 1.

[6] ABB Code of conduct, page 12 “Confidential Information”. ABB Ltd, CH – 8050 Zurich Switzerland, 2009

[7] IEC Std 60044-1-2003. “Instrument Transformers” Page 17. Clause 2.1.13, Paragraph 1

[8] AGILENT Website / agilent.com

[9] TEMPSENS Website / Tempsens.com Type T (copper – constantan) thermocouple properties.

[10] IEC Std 60044-1-2003. “Instrument Transformers” Page 51. Clause 7.2, Paragraph 1.

[11] IEC Std 60044-1-2003. “Instrument Transformers” Page 51. Clause 7.2, Paragraph 3.

[12] ANSI/IEEE Std C57.122-2008 (Redline) “IEEE Standard Requirements for Instrument Transformers”. Page 87. Paragraph 3.

[13] IEC Std 62271-1-2007. “High Voltage Switchgear and Controlgear” Page 70. Clause 6.5.4, Paragraph 1.

[14] ANSI/IEEE Std C57.122-2008 (Redline) “IEEE Standard Requirements for Instrument Transformers”. Page 87. Paragraph 2.

[15] SATS Certification RoP No 01-A27 (Rev1) “Temperature rise on a Gas Insulated Switchgear bay, type ELK 0 (range 4)” Page 4. Trondheim, October 10, 2001.

[16] SATS Certification RoP No 01-A27, adapted from IEEE Std C37.122-2010 “IEEE Std for High Voltage GIS rated above 52 kV”. Subclause 5.8.1.1 – 5.8.1.5.

Appendix 1 Instruments and Test Arrangement

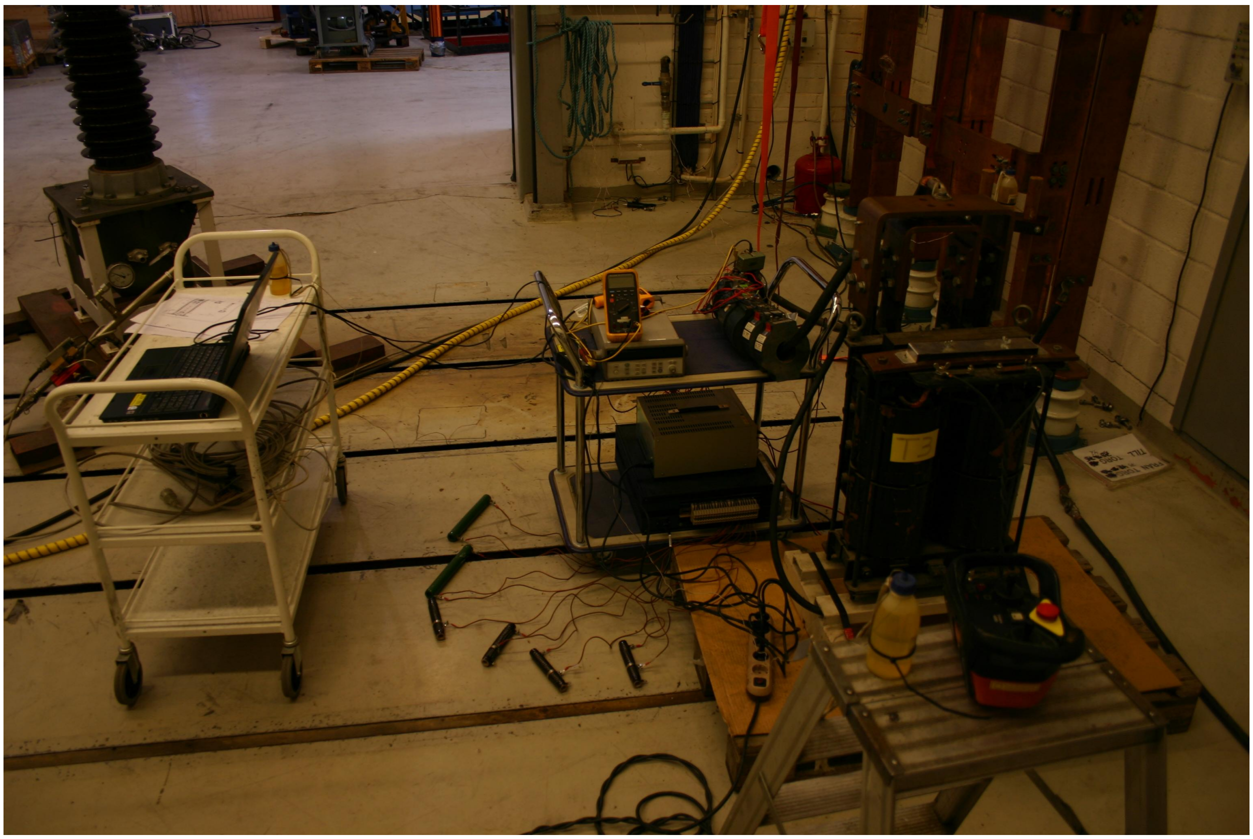

Figure 18. General Test Arrangement with Thermocouples as a Temperature Measuring Device

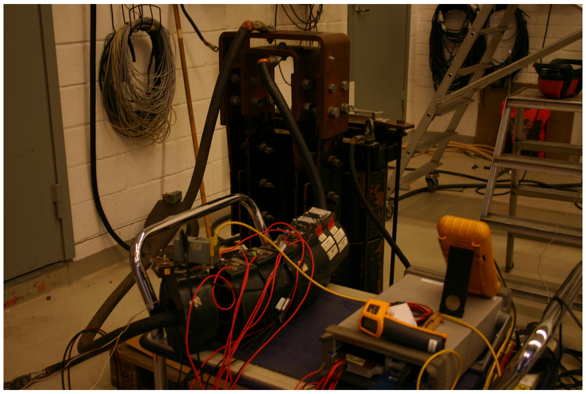

Figure 19. Power Transformer (Background), Current Transformers (Left) and Laser Thermometer (Foreground)

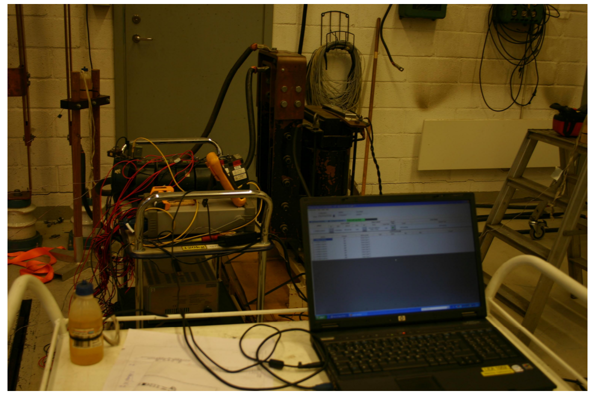

Figure 20. Agilent© HP Data Acquisition HMI

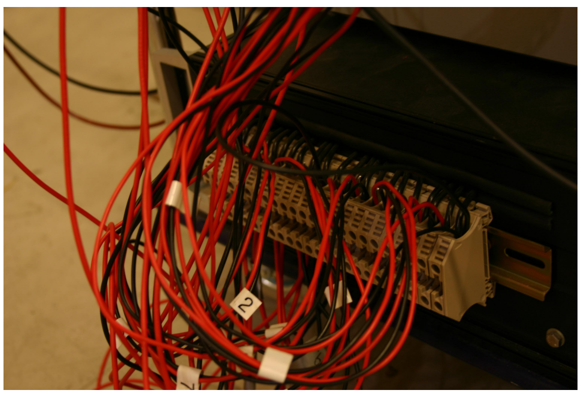

Figure 21. Relay Box (Detail)

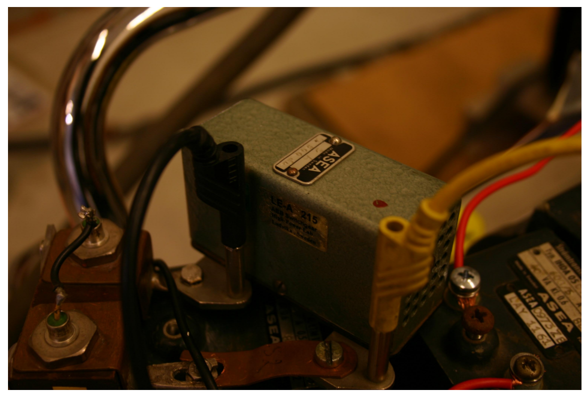

Figure 22. 0,5 V/A Shunt Resistor

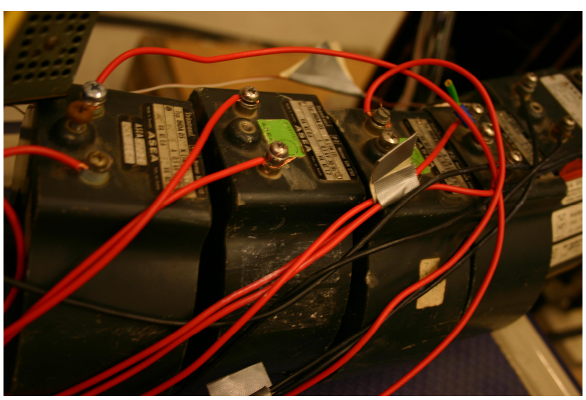

Figure 23. Current Transformers as Test Object (Detail)

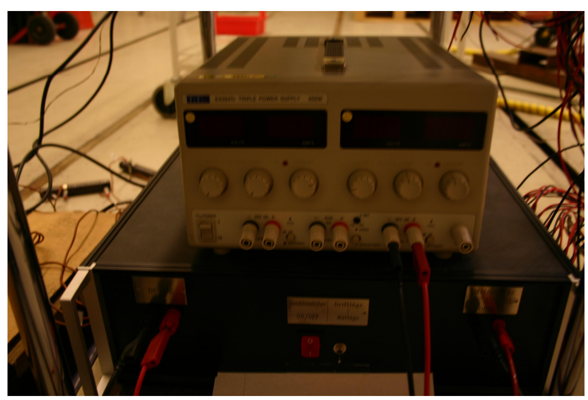

Figure 24. DC Power Source (Top) and Relay Box with *Mätläge/Driftläge* Switch (Bottom)

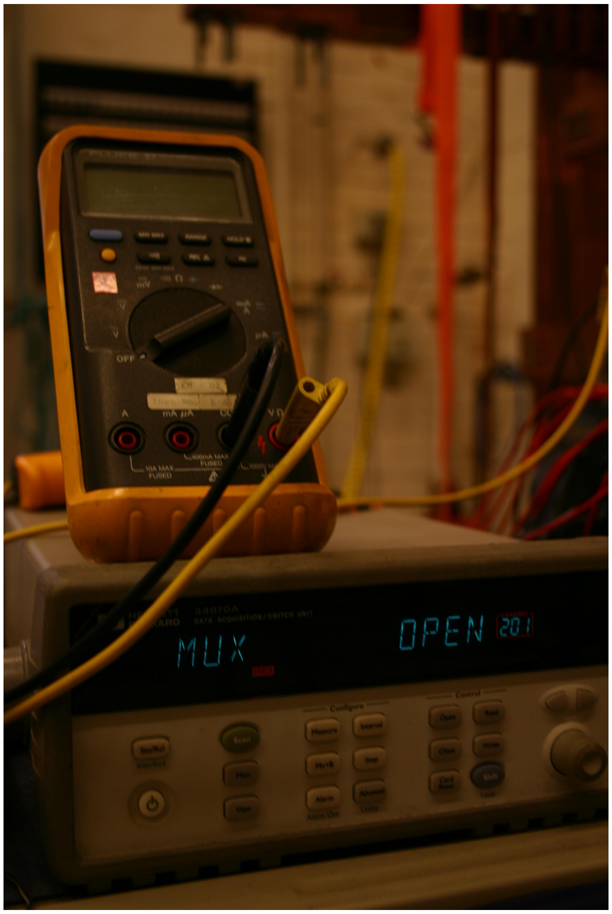

Figure 25. Fluke Multimeter for measuring DC Current (Top) and Agilent© HP Data Acquisition (Bottom)

Appendix 2 VBA Process Automation Routine

```
Sub Macro1()
'' Macro1 Macro
'    Sheets("Paste BEFORE data
here").Select
   Columns("A:A").Select
   Selection.TextToColumns
Destination:=Range("A1"),
DataType:=xlDelimited, _
       TextQualifier:=xlDoubleQuote,
ConsecutiveDelimiter:=False, Tab:=True, _
       Semicolon:=True, Comma:=False,
Space:=False, Other:=False, FieldInfo _
       :=Array(Array(1, 1), Array(2, 1),
Array(3, 1), Array(4, 1), Array(5, 1), Array(6,
1), _
       Array(7, 1), Array(8, 1)),
TrailingMinusNumbers:=True
   Sheets("Paste AFTER data here").Select
   Columns("A:A").Select
   Selection.TextToColumns
Destination:=Range("A1"),
DataType:=xlDelimited, _
       TextQualifier:=xlDoubleQuote,
ConsecutiveDelimiter:=False, Tab:=True, _
       Semicolon:=True, Comma:=False,
Space:=False, Other:=False, FieldInfo _
       :=Array(Array(1, 1), Array(2, 1),
Array(3, 1), Array(4, 1), Array(5, 1), Array(6,
1), _
       Array(7, 1), Array(8, 1)),
TrailingMinusNumbers:=True
   Sheets("Paste BEFORE data
here").Select
   Range("A1").Select
End Sub
Sub Macro2()
' Macro2 Macro
   Sheets("Resistance BEFORE").Select
   Range("G1").Select
   ActiveCell.FormulaR1C1 = "I ="
   Range("H1").Select
   ActiveCell.FormulaR1C1 = "0,5"
   Range("H2").Select
   Sheets("Resistance AFTER").Select
   Range("G1").Select
   ActiveCell.FormulaR1C1 = "I ="
   Range("H1").Select
   ActiveCell.FormulaR1C1 = "0,5"
   Range("H2").Select
   Sheets("Paste BEFORE data
here").Select
End Sub
Sub Macro3()
' Macro3 Macro
   Range("A5").Select
   Range(Selection,
Selection.End(xlDown)).Select
   Range(Selection,
Selection.End(xlToRight)).Select
   Selection.Copy
   Sheets("VoltageBEFORE").Select
   Selection.PasteSpecial
Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
       False, Transpose:=True
   Range("A1").Select
   Sheets("Paste AFTER data here").Select
   Range("A5").Select
   Range(Selection,
Selection.End(xlDown)).Select
   Range(Selection,
Selection.End(xlToRight)).Select
   Application.CutCopyMode = False
   Selection.Copy
   Sheets("VoltageAFTER").Select
   Range("A5").Select
   Selection.PasteSpecial
Paste:=xlPasteAll, Operation:=xlNone,
SkipBlanks:= _
       False, Transpose:=True
   Range("A1").Select
   Sheets("Paste BEFORE data
here").Select
End Sub
Sub Macro4()
' Macro4 Macro
   Sheets("Resistance BEFORE").Select
   Range("B7").Select
```

```
    ActiveCell.FormulaR1C1 = _
"=IF((VoltageBEFORE!RC=0),"""",ABS(Volt
ageBEFORE!RC/'Resistance
BEFORE'!R1C8))"
    Selection.AutoFill
Destination:=Range("B7:AA7"),
Type:=xlFillDefault
    Range("B7:AA7").Select
    Selection.AutoFill
Destination:=Range("B7:AA107"),
Type:=xlFillDefault
    Range("B7:AA107").Select
    Sheets("Resistance AFTER").Select
    Range("B7").Select
    ActiveCell.FormulaR1C1 = _
"=IF((VoltageAFTER!RC=0),"""",ABS(Voltag
eAFTER!RC/'Resistance AFTER'!R1C8))"
    Range("B7").Select
    Selection.AutoFill
Destination:=Range("B7:AA7"),
Type:=xlFillDefault
    Range("B7:AA7").Select
    Selection.AutoFill
Destination:=Range("B7:AA107"),
Type:=xlFillDefault
    Range("B7:AA107").Select
    Range("E30").Select
    Sheets("Paste BEFORE data
here").Select
    Range("A1").Select
End Sub
Sub Macro5()
' Macro5 Macro
    Sheets("VoltageBEFORE").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Selection.Copy
    Sheets("Resistance BEFORE").Select
    Range("A6").Select
    ActiveSheet.Paste
    Sheets("Resistance AFTER").Select
    Range("A6").Select
    ActiveSheet.Paste
    Sheets("Paste BEFORE data
here").Select
End Sub
Sub Macro6()
' Macro6 Macro
    Sheets("VoltageBEFORE").Select
    Range("A7").Select
    Range(Selection,
Selection.End(xlDown)).Select
    Selection.Copy
    Sheets("Resistance BEFORE").Select
    Range("A7").Select
    ActiveSheet.Paste
    Sheets("Resistance AFTER").Select
    Range("A7").Select
    ActiveSheet.Paste
    ActiveWindow.ScrollWorkbookTabs
Position:=xlFirst
    Sheets("Paste BEFORE data
here").Select
End Sub
Sub Macro7()
' Macro7 Macro
    Sheets("VoltageBEFORE").Select
    Range("A7").Select
    Range(Selection,
Selection.End(xlDown)).Select
    Selection.Copy
    ActiveWindow.ScrollWorkbookTabs
Sheets:=1
    Sheets("Temp rise Calculation").Select
    Range("A3").Select
    ActiveSheet.Paste
    Range("B3").Select
    Application.CutCopyMode = False
    ActiveCell.FormulaR1C1 = "=IF(RC[-
1]="""","""",('Resistance BEFORE'!R[4]C))"
    Range("B3").Select
    Selection.AutoFill
Destination:=Range("B3:B40"),
Type:=xlFillDefault
    Range("B3:B40").Select
    Range("D3").Select
    ActiveCell.FormulaR1C1 = "=IF(RC[-
3]="""","""",('Resistance AFTER'!R[4]C[-2]))"
    Range("D3").Select
    Selection.AutoFill
Destination:=Range("D3:D40"),
Type:=xlFillDefault
    Range("D3:D40").Select
    Range("F3").Select
    Selection.AutoFill
Destination:=Range("F3:F40"),
Type:=xlFillDefault
    Range("F3:F40").Select
    Range("G3").Select
```

```
    Selection.AutoFill
Destination:=Range("G3:G40"),
Type:=xlFillDefault
    Range("G3:G40").Select
End Sub
Sub Macro8()
' Macro8 Macro
    Range("C3,E3").Select
    Range("E3").Activate
    With Selection.Interior
        .Pattern = xlNone
        .TintAndShade = 0
        .PatternTintAndShade = 0
    End With
    Range("A1").Select
End Sub
Sub FORMAT()
' FORMAT Macro
    ActiveWindow.ScrollWorkbookTabs
Position:=xlFirst
    ActiveWindow.ScrollWorkbookTabs
Position:=xlFirst
    Sheets("Paste BEFORE data
here").Select
    Range("A5").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Sheets("Paste AFTER data here").Select
    Range("A5").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
```

```
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Sheets("VoltageBEFORE").Select
    Range("A5").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Sheets("VoltageAFTER").Select
    Range("A5").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
```

```
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Sheets("Resistance BEFORE").Select
    Range("A6").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Range("A1").Select
    Sheets("Resistance AFTER").Select
    Range("A6").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlDown)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
```

```
    Range("A1").Select
    ActiveWindow.ScrollWorkbookTabs
Position:=xlLast
    Sheets("Temp rise Calculation").Select
End Sub
Sub FORMAT2()
' FORMAT2 Macro
    ActiveWindow.ScrollWorkbookTabs
Position:=xlFirst
    Sheets("Paste BEFORE data
here").Select
    Cells.Select
    Cells.EntireColumn.AutoFit
    Sheets("Paste AFTER data here").Select
    Cells.Select
    Cells.EntireColumn.AutoFit
    Sheets("Paste BEFORE data
here").Select
    Range("A1").Select
    Sheets("Paste AFTER data here").Select
    Range("A1").Select
    Sheets("VoltageBEFORE").Select
    Cells.Select
    Cells.EntireColumn.AutoFit
    Sheets("VoltageAFTER").Select
    Cells.Select
    Cells.EntireColumn.AutoFit
    Range("A1").Select
    Sheets("Resistance BEFORE").Select
    Cells.Select
    Cells.EntireColumn.AutoFit
    Range("A1").Select
    Sheets("Resistance AFTER").Select
    Cells.Select
    Cells.EntireColumn.AutoFit
    Range("A1").Select
    ActiveWindow.ScrollWorkbookTabs
Position:=xlLast
    Sheets("Temp rise Calculation").Select
    Range("A1").Select
End Sub
Sub FORMAT3()
' FORMAT3 Macro
    Range("A3").Select
    Range(Selection,
Selection.End(xlToRight)).Select
    Range(Selection,
Selection.End(xlUp)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With
Selection.Borders(xlInsideHorizontal)
        .LineStyle = xlContinuous
        .ColorIndex = xlAutomatic
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Range("A3").Select
    Range(Selection,
Selection.End(xlDown)).Select
    Range(Selection,
Selection.End(xlToRight)).Select
Selection.Borders(xlDiagonalDown).LineStyl
e = xlNone
Selection.Borders(xlDiagonalUp).LineStyle
= xlNone
    With Selection.Borders(xlEdgeLeft)
        .LineStyle = xlContinuous
        .ColorIndex = 0
```

```
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeTop)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    With Selection.Borders(xlEdgeBottom)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlEdgeRight)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThick
    End With
    With Selection.Borders(xlInsideVertical)
        .LineStyle = xlContinuous
        .ColorIndex = 0
        .TintAndShade = 0
        .Weight = xlThin
    End With
    Range("A1").Select
End Sub
```

```
Sub MAIN()
    Call Macro1
    Call Macro2
    Call Macro3
    Call Macro4
    Call Macro5
    Call Macro6
    Call Macro7
    Call Macro8
    Call FORMAT
    Call FORMAT2
    Call FORMAT3
End Sub
```