

TESTING OF OPEN SECONDARY WINDOW-TYPE CURRENT TRANSFORMERS – TEST PLAN

1.1 INTRODUCTION

1.1.1 Basic Principles of Current Transformer

The design and construction of a window-type (or donut-type) current transformer (CT) consist of two separate windings on a common laminated iron or steel core [Refs. 1, 2]. The primary winding is made out of more than one turn of heavy gauge wire capable of carrying a large primary current from a power distribution system, where the secondary winding uses many turns of smaller gauge wire with a current carrying capacity of 1 amp or 5 amps depending on the instrumentation design. Under normal operation, the alternating current (AC) in the primary winding (known as excitation current) produces an alternating magnetic field in the core, which then induces an alternating current in the secondary winding circuit. The primary and secondary circuits are magnetically coupled so that the secondary current is linearly proportional to the primary current over the intended range of the CT.

The linear proportionality between the primary and secondary currents ceases when the excitation current increases to a certain level, depending on the magnetic saturation in the CT's iron core. At this point, an increase in the excitation current produces a significantly smaller increase in the secondary current.

A CT rated 1200:5 current ratio will produce 5 amps secondary current when 1,200 amps of current flow in the primary. The relationship between primary current and secondary current is based on the ratio of their turns in the windings of the CT's core. In fact, the Amperes-Turns (i.e., current multiplied by number of turns) in the primary winding is maintained equal to the Amperes-Turns in the secondary. Theoretically, the secondary voltage increases or decreases as required for maintaining a constant primary-to-secondary current ratio.

CTs, a specific type of instrument transformers, are widely used in the electric power industry, including nuclear power plants (NPPs), to monitor the current at strategic locations in electrical power distribution systems. These CTs provide isolation from the high voltage primary, and step-down the magnitude of the measured current to a value that can be safely handled by the monitoring instruments. Thus, they are designed to measure the current in AC power systems (generally three-phase systems) in their primary winding and transform this current into a representative low secondary current for instrumentation used for remote readout of the current.

1.1.2 Potential Fire Due to Open-Circuited Secondary

In a letter to the NRC dated July 21, 1983, Brookhaven National Laboratory (BNL) raised a potential concern for fire-induced open circuits on a CT's secondary [Ref. 3]. The BNL letter postulated the scenario in which potentially high voltages induced on the secondary winding of a CT as a result of open circuiting the CT secondary due to fire-induced failure of the CT or its connected components. The postulated failure mode could potentially start a secondary fire at a location remote from the initiating fire area.

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It has been recognized that as long as current is flowing in the primary winding of a CT, an open-circuit in a CT's secondary can cause high voltages on the secondary circuit as the CT attempts to maintain the current relationship dictated by the transformer's winding turns ratio [Ref. 4]. This condition can result in CT damage and potentially generate voltages that may exceed the dielectric strength of the current transformer insulating materials or other CT circuit conductors, which may cause arcing to connected components.

The resulting high voltage condition in the secondary circuit from an open-circuited CT introduces a potential failure mode that warrants further investigation as part of the final resolution of circuit failure issues associated with the fire protection strategies at nuclear power plants. The secondary circuit from the CT location in the plant to the main control room instrument indications may consist of long (e.g., hundreds of feet) instrument wires, whose insulations are susceptible to secondary fires. Since the safe shutdown analysis and the fire probability risk assessment (Fire PRA) are based on one fire area (safe shutdown) or one scenario at a time, the possibility of a second fire in a separate location fire area can significantly impact the final outcome of the analysis results, and subsequent fire protection strategies.

1.2 OBJECTIVE

1.2.1 Purpose and Scope

The purpose of this test program is to better understand the following scenario: Will fire-induced open circuiting of the secondary circuit of a CT, which is operating within its rated continuous primary current limits, result in an excessively high voltage in the secondary circuit sufficient to start a fire in the form of explosion or arcing in the circuit's insulation at the location of the CT itself or at some other location in the secondary circuit?

Because the secondary open-circuit voltage is limited by saturation of the CT's iron core, the root-mean-square (RMS) value measured by a voltmeter may not appear to be dangerous. However, as the current cyclically passes through zero (e.g., a sinusoidal AC current at a power frequency of 60 Hz), the rate of change of flux at current zero is not limited by saturation, and is raised to a higher than normal magnitude. This induces high peaks or pulses of voltage in the secondary circuit. These high peaks can exceed the rated dielectric strength of the instrumentation cable insulation, potentially causing break down of the insulation and arcing to adjacent electrical components.

1.2.2 Recent CT Test Results

Based on a presentation given by Steve Laslo of the Bonneville Power Administration in March 2012, the response of a 3000:5 CT¹ to an open secondary can be illustrated in Figures 1 and 2 below [Ref. 5]. Figure 1 is a composite summary of the CT's response in terms of flux in the core, primary current, and induced secondary voltage (E_s) changes under open secondary condition.

¹ CT used was from a retired 500kV ITE SF6 PCB – BCT 3000/5 (Full Winding). CTs used in nuclear safety systems are smaller and typically at low voltage ratings (600V-6kV).

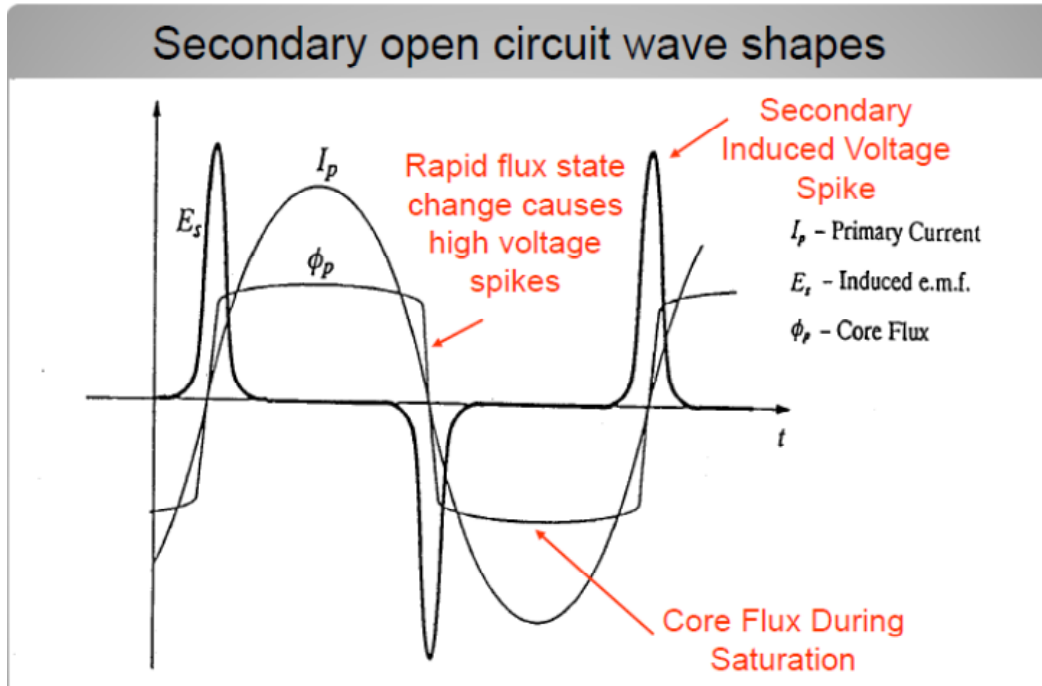


Figure 1: CT Response - Open Secondary Circuit [Ref. 5]

Of interest to this program is the ability to measure the magnitude and duration of the secondary voltage spike that is induced by opening the secondary side of an energized CT. In the same presentation, the secondary "peak" voltage is plotted as a function of the magnitude of the primary current for the 3000:5 CT (see Figure 2). In the test program, this simplified response will be more accurately quantified in magnitude and time response using high-speed data acquisition equipment described in Section 1.3.1.

The presentation also indicates that moderate to high voltage spikes up to 2,220 volts in the secondary were observed for the low primary current flow below 813 amps and the CT flux behaved sinusoidal with some minor distortions at higher current levels. Above 813 amps up to 2,337 amps (i.e., 80% of the 3,000 amps) of primary current the CT started making significant noise and the flux reached to a fully saturated waveform with 3,600 volts secondary voltage spikes. The testing continued to a primary current level of 6,487 amps for the 3000:5 CT, the secondary voltage spikes became progressively higher and narrower, and the extremely high secondary voltage spikes of 8,000 volts were observed with excessively high CT noise levels.

Since the presentation was intended for training purposes it does not provide any test data or photos of arcing or damage to the secondary circuit or its components. However, it concluded that CTs with very high turn ratios can produce very high voltages on the open-circuited secondary even at low levels of primary current flow.

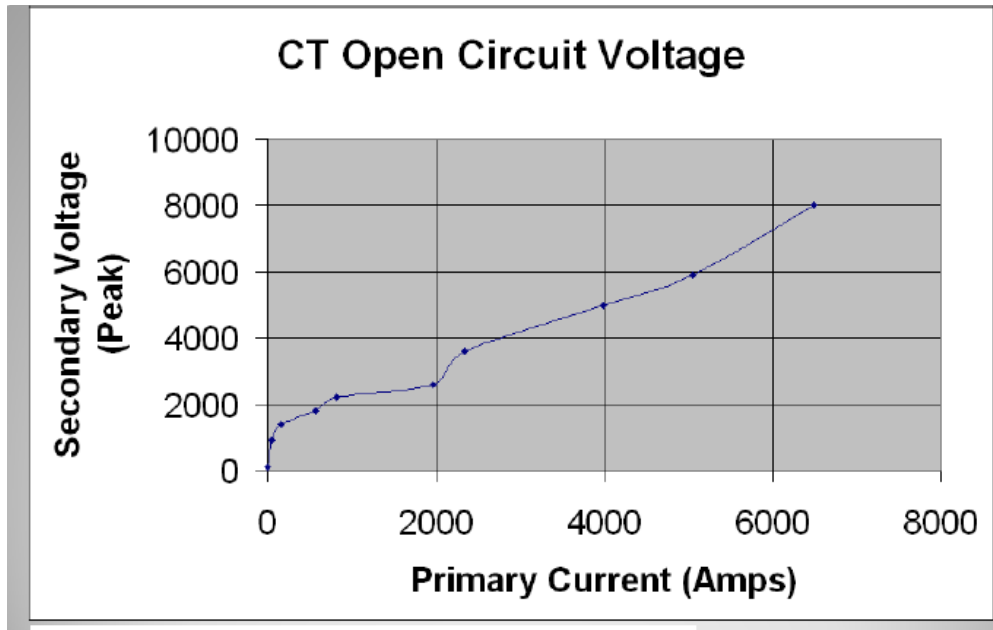


Figure 2: Secondary Peak Voltage Achieved During Open Circuit on the Secondary of a CT [Ref. 5]

References 6 and 7 present similar open secondary CT testing. Unlike Reference 5 presentation, no specific test data are available from these programs, just videos showing the test profiles. Both indicated no secondary wiring failure with some explanations given in Reference 6. Reference 7 showed that with intermittent shorting of the secondary terminals its insulation could be compromised with arcing at the CT connecting location. It appears that the size and application of CTs under the purview of nuclear power plant's fire safety are smaller (i.e., typically for a line voltage up to 6 kV or less) from those used in these test programs.

Based on the above test characteristics and many other similar test videos seen on the internet, high secondary voltage spikes are expected during the testing in the form of arcing or insulation damage in the secondary circuit. Since the insulation of the CT's secondary is typically designed to withstand voltages between 2,500 – 4,000 Volts [Ref. 8], it is unlikely that we will observe any such damage scenarios without exceeding this voltage threshold or inducing a failure by some other means. However, it should be noted that the sole purpose of this testing is to obtain adequate information that would form the technical basis for assessing the propensity of a secondary fire or damage to the secondary side circuit or components under an open-circuited CT secondary [Ref. 9].

1.3 TESTING APPROACH

For this test program, we will simulate the effects of a fire that damage the secondary side conductors of an energized CT that are typically used in the safety systems in nuclear power plants, causing an open circuit on the secondary windings. As discussed earlier, the open circuit is expected to cause abnormally high secondary voltages when primary current flow is present. This testing will evaluate the potential effects of these high voltage spikes on an open-circuited CT secondary circuit. Specifically considered is whether the possibility exists for the high voltage to cause sustained arcing or a catastrophic failure of the CT (or other secondary circuit elements) that is sufficiently energetic to initiate a secondary fire that damages components or

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equipment beyond the CT's circuit and its components. A secondary fire here is a fire at a location remote from the original fire that is responsible for the initial open-circuit in the CT secondary circuitry.

A series of tests will be conducted to demonstrate the impact of the primary current values on the secondary peak voltage. This is important in determining if the peak voltages on the secondary are high enough to damage the insulation and create a potential fire source.

1.3.1 BNL Superconducting Magnet Test Facility

The Superconducting Magnet Division at BNL has been involved in testing various superconducting magnets for use in both particle accelerators and experimental facilities. Capabilities include:

- Superconductor materials development/test facility
- Magnetic structure design
- Superconducting magnet fabrication
- Vertical and horizontal cryogenic testing
- Magnetic field measurements.

The CT testing will be carried out in the high bay area of the Superconducting Magnet Division test facility. Magnet Division routinely assembles and tests very high current, high field superconducting electromagnets for particle accelerators like Relativistic Heavy Ion Collider (RHIC) at BNL and Large Hardon Collider (LHC) at the European Organization for Nuclear Research (CERN). The test facility has various AC- and DC-controlled power sources ranging from 480 Volts, 1,600 Amps (AC) to 30 Volts, 30,000 Amps (DC). Associated with these power sources, each test facility has a state-of-the-art high speed multi-channel data acquisition system with the sampling frequency of up to 1 MHz and 16 bit resolution. Many other monitoring systems, sensors and equipment required to do such specialized measurements are also available for this test program. Available equipment includes isolation and buffer amplifiers for high voltage measurement, voltage and current transformers, high current controlled switches and circuit breakers, and deionized water supply for cooling the load banks.

Laboratory Space

Figure 3 shows an aerial view of the high bay area at the BNL Superconducting Magnet test facility. All CT tests will be carried out at the barricaded area (right).

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Figure 3: Areal View of the Test Facility

As shown in a close-up photo in Figure 4, its present configuration has the required AC current source and the spacing around it to set up an enclosed cabinet with each CT under test and to locate the data acquisition racks.

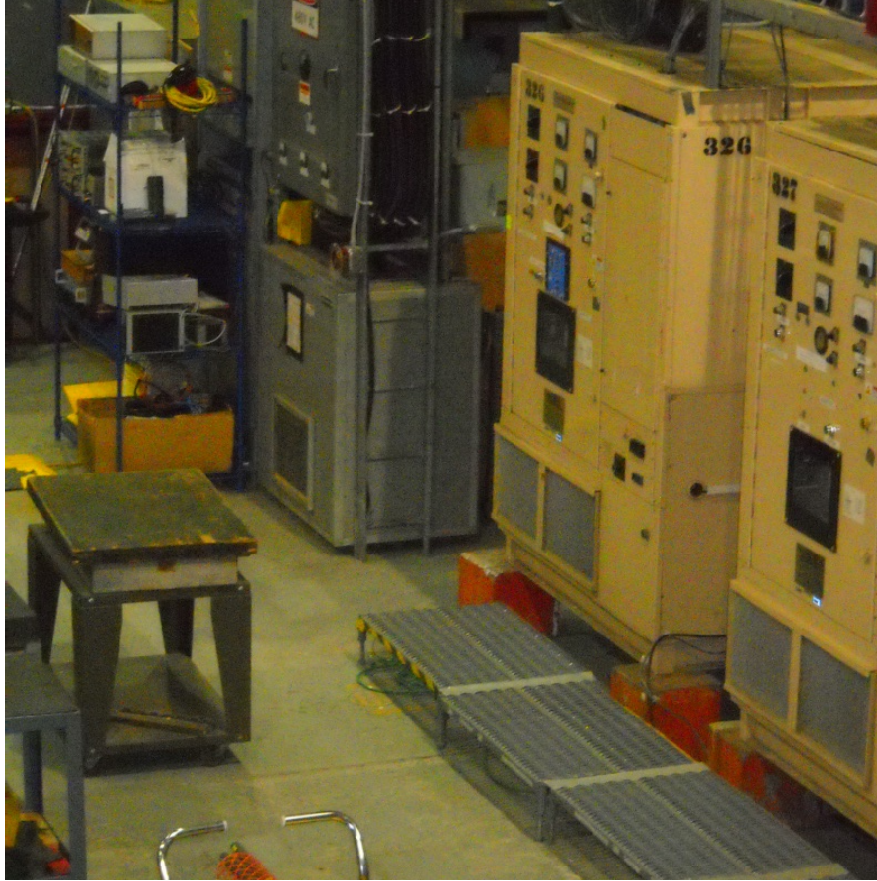


Figure 4: Close-up Photo of the Proposed CT Test Area

CT Test Setup

At this time six CTs with 2000:5 and six other CTs with 4000:5 current ratios, as shown in Figure 5 below, are available to BNL for testing. These twelve CTs have been supplied by the NRC and if needed, additional units with different current ratios will be acquired for testing. Some of these new ones may include different CT manufacturers.

The 4000:5 CTs have secondary terminals for eight different turn ratios from 100 through 800. They include 500:5 (X1-X2), 1000:5 (X3-X4), 1500:5 (X2-X3), 2000:5 (X1-X3), 2500:5 (X2-X4), 3000:5 (X1-X4), 3500:5 (X2-X5), and 4000:5 (X1-X5) current ratio ratings, where X's are secondary taps of the CT.

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Current Ratio: 2000:5



Multi-Ratio Design: (500, 1000, 1500, 2000, 2500, 3000, 3500, and 4000):5

Figure 5: Amran Current Transformers

Figure 6 shows the power supply circuit for the proposed CT tests. The primary current for the CT under test will be set up from a three-phase delta connected water-cooled load bank of 0.78 ohms each leg connected to a 480V, AC power source through 700 Amps circuit breaker and remotely controlled contactor. These will give about 600 Amps in each phase of the circuit which will be measured by three 800:5 CTs. The supply current to the primary circuit can be adjusted to get the required value by manipulating the resistance of the load bank. As shown in

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Figure 6, current in one phase will be used to generate the necessary Ampere-Turns in the primary of the CT under test. For example, to test a 4000:5 CT, seven (7) turns of Ultraflex 500MCM cable will be wrapped around the core of the CT. Exact current in that phase will be measured and recorded using three in-house 800:5 CTs.

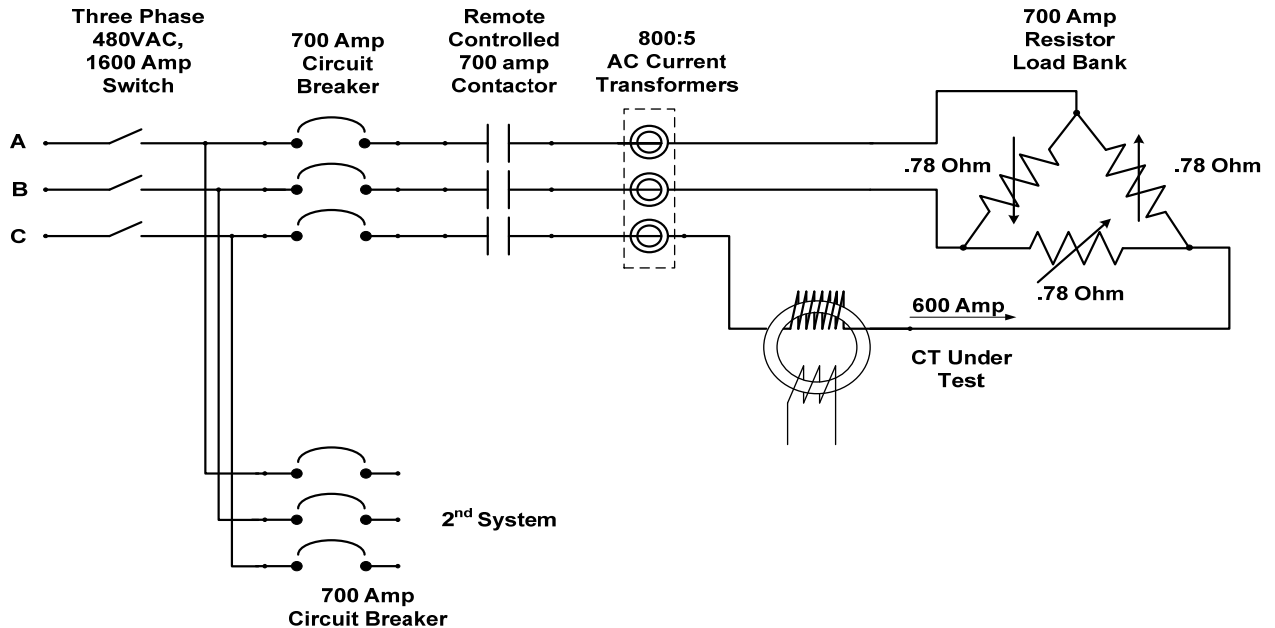


Figure 6: Test Power Supply Setup

The circuit diagram in Figure 7 illustrates the test setup for obtaining the characteristics of an open-circuited CT. As stated above, a test current source feeds the CT's primary side to represent the normal current flow in a power circuit. Approximately 100 feet of secondary cable with a burden resistor (or ammeter) will be used to simulate an actual plant's normal configuration. The CT secondary side will be instrumented with a relay for intermittently opening the circuit or a very low current fuse link (e.g. 1 amp) for an instantaneous circuit break. The increase in the secondary voltage and decrease in secondary current will be recorded via high voltage isolation modules. A computerized high speed data acquisition system will be used to capture the CT secondary voltage and current. Other parameters to be monitored during testing include primary current and voltage, magnetic flux, and the temperature of the CT magnetic elements. A high speed video camera and a thermal imaging infra-red camera will also be used to capture the arcing and fire formation (if any) at several strategic locations. These cameras will be synchronized with the high speed data acquisition system to get secondary circuit characteristics during the arcing process.

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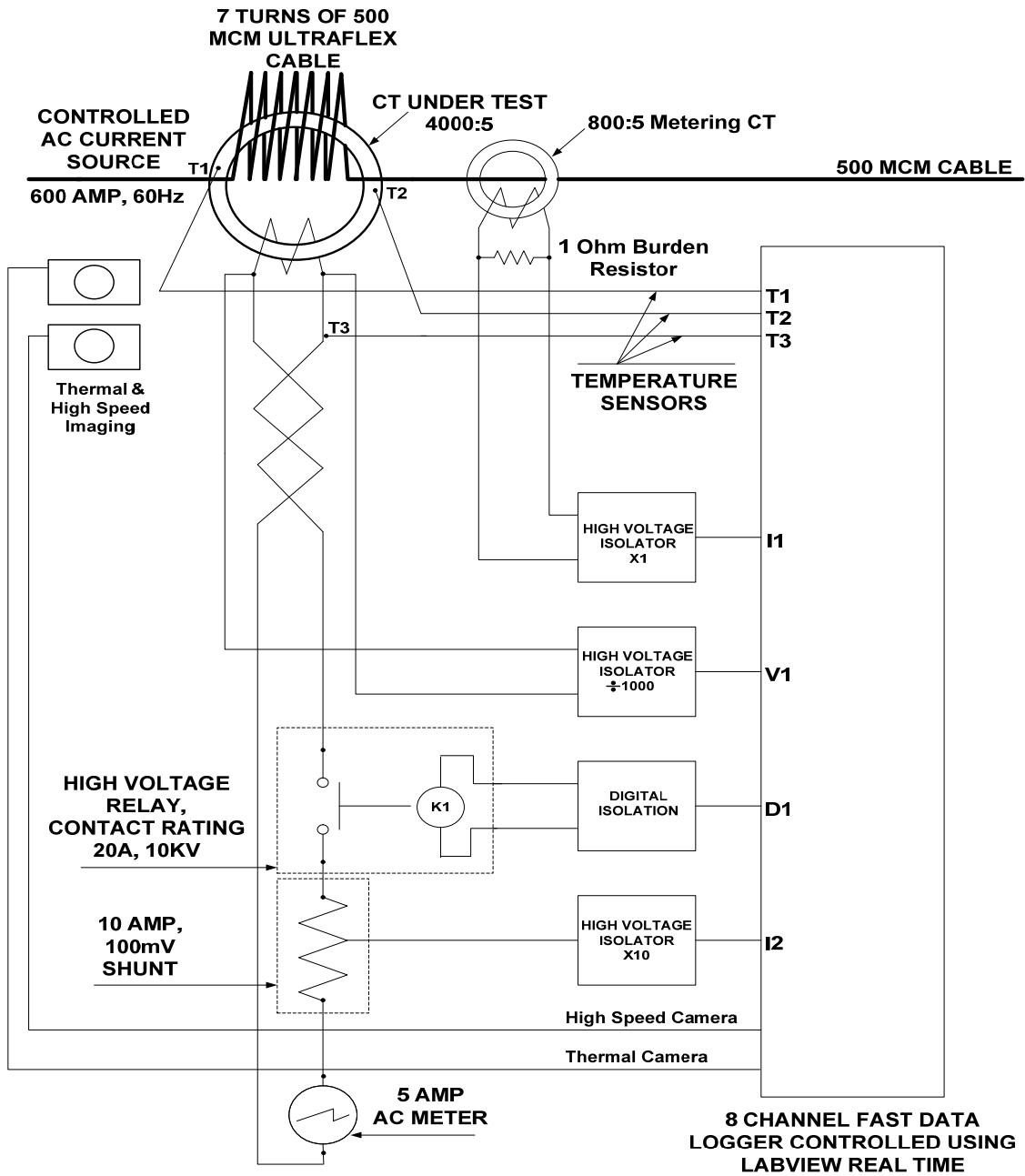


Figure 7: Proposed Secondary Circuit Layout of the CT Testing

Data Acquisition Equipment

Figure 7 above shows the instrumentation and data acquisition connections on secondary side of the CT under test. This setup will capture the high secondary voltage spikes and the profile of arcing current at the instance of opening of the secondary of a CT along with images from high speed and thermal cameras. Opening of the secondary of CT will also be simulated. Details of the instrumentation are as follows:

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High Speed Data Logger: The 8 channel high speed data logger has a sampling rate of 100K Samples/sec per channel, sampled simultaneously. This logger is programmed using LabView Real Time graphical programming software and uses digital to analog converter hardware from National Instruments.

HV Isolators: These isolator modules manufactured by VeriVolt Inc. provide fast response and isolation between channel to channel and channel to ground in excess of 10,000V. They have programmable gain to maintain output voltage within +/- 10V range for data logger.

High Voltage Relay: A high voltage (HV) relay is used to provide clean opening (or instantaneous break) of the secondary circuit of the CT under test. It has contact ratings of 20 Amps at 10 kV. The relay ratings are intended to prevent contact fusing and excessive arcing during high voltages generated when the circuit is opened.

Shunt-10A, 100mV: The voltage signal across this shunt will be used to capture the characteristic and duration of the arcing current at the instant of opening of the secondary of CT under test. Arcing current can last up to few AC cycles and its profile can give good correlation between arcing duration and igniting of a fire.

The following parameters will be measured and logged using high speed data logger:

- T1, T2: Temperature of the CT's magnetic core at two opposite ends.
- T3: Temperature of the twisted pair cable connecting CT's secondary to the meter.
- I1: Primary current of the CT under test by measuring voltage across 1ohm burden resistor.
- I2: Secondary current of the CT under test by measuring voltage across 10A, 100mV shunt. Isolator for this signal provides the gain of 10 so that with 5A RMS flowing in the circuit, data logger sees 500mV rms.
- V1: Voltage across secondary of the CT under test. Because of the high voltage generated during opening of the secondary, this voltage is isolated and divided by 1000 before being fed to the data logger.

All the above parameters will be captured for duration of 10 seconds, 5 sec before trigger and 5 sec after trigger. Data capture trigger and the opening of secondary through high voltage relay is done using isolated digital output D1 of the data logger.

Captured data will be logged as an excel file and its time stamp will be synchronized with that of camera images.

1.3.2 Quality Control and Safety

Existing BNL quality control procedures will be used to ensure all results are reproducible and accurate. Instruments will be calibrated using standards that are traceable to a national standard. Any new equipment will be field tested and calibrated as needed to ensure it is operating properly.

Since the CT testing involves high voltage and potential for high energy arcing and/or explosion of insulations, approval (if required) from the BNL safety committee after reviewing the test plan and all safety requirements will be obtained.

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Project reports will receive a BNL technical review and will be reviewed and approved by the NRC/RES Project Manager.

1.4 TEST MATRIX

1.4.1 Test Configurations

CTs to be Tested: Amran 2000:5 and 4000:5 (with multiple turn ratios from 100, 200, 300, 400, 500, 600, 700, 800) shown in Figure 5

Primary Voltages: 120V, 240V, 480V

Primary Current Levels: 500A, 1000A, 1500A, 2000A, 2500A, 3000A, 3500A, 4000A

Open Secondary Simulations: Open Secondary (Base Line); Fast Open using Fuse Link (for Open Circuit Fault); Intermediate Open using a Relay (for Arcing Fault)

Maximum Duration of Test: 10 minutes (subject to change based on test results)

Secondary Cable: 100 feet of AWG 12/14/16, 2 conductor 600V (no drain or ground wire) for instrument wiring application

Insulation Resistance (Megger Test) of the secondary cable will be monitored at the beginning and ending of each test set up for its insulation integrity

Locations Subject to Visual Monitoring (Camera and Thermal Imaging) for Secondary Fire (or Arcing): CT, 50 feet from the CT (Another Fire Area) including the open circuit simulations, and 100 feet from the CT (Ammeter or Protective Relay Location)

For each test set up, the following data will be obtained:

- Primary Voltage
- Primary Current
- Secondary Voltage
- Secondary Current (Prior to Open Circuit Fault)
- Temperatures at three locations (see Figure B-7)
- Magnetic flux density

For each test set up, the following locations will have Visual and Thermal Imaging:

- CT Location
- Open Secondary Fault Location
- Ammeter Location

High Speed data will be obtained for the first couple of minutes, followed by slower speed data acquisition for remaining of test duration for capturing any arcing fault in the secondary cable.

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1.4.2 CT Preliminary Tests

The following tests are planned to be performed first:

- a. Baseline Performance
Prior to conducting the open circuit testing of the CT, it will be operated to obtain baseline performance information including core temperature, and primary to secondary current and voltage response between 1000 and 4000 amps (primary). For this, one of the 2000:5 CTs will be tested.
- b. Fast Open Secondary Response
Using a time delay fuse link (not shown in Figure B-7) on the secondary circuit, the secondary voltage response will be obtained with primary current values ranging from 1000 to 4000 amps. The results of this series of tests will yield information on the CT's voltage response to a single initiating open circuit event as a function of primary current values.
- c. Intermittent Open Secondary Response
Using a mechanical switch or relay that interrupts the secondary circuit at 1 second intervals for 10 seconds (10 circuit interruptions), the CT's response will be recorded to determine the repeatability of its response and the potential additional degradation that results to the secondary side cable insulation.

Repeat this with modifications as necessary for the different sizes of CTs to be tested.

1.4.3 CT Subsequent Tests

Depending on the results of the above preliminary tests, additional tests will be performed to meet the objectives of this test program.

- a. If the secondary voltage spikes demonstrate secondary fire or arcing in the secondary cabling, then additional tests will be performed to evaluate all influencing parameters that are important to this scenario.
- b. If the secondary voltage spikes indicate no secondary fire or arcing, then the testing will be extended to determine the threshold condition at which arcing in the secondary circuit could be observed.
- c. Ammeters or protective relays will be added to the secondary circuit. Failures will be assessed based on the following: CT fails or ammeter/relay fails or cable fails. A technical basis will be derived from the test for developing guidelines for open secondary CT scenarios.

If necessary, other tests will be carried out on CTs from several manufacturers and at higher voltage levels up to 4.1 kV. Some of these tests will require support from the NRC COR.

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1.5 DATA EVALUATION

The testing will indicate the potential for a secondary fire occurring away from the CT location in a nuclear power plant set up. All test data will be collected directly from the Data Logger as shown in Table 1.

If the open circuited CT secondary is considered to be incapable of starting a secondary fire, this testing will provide the technical basis for the JACQUE-FIRE Volume 3 Working Group for assessing the following conditions:

- Neither the CT nor its secondary circuit shows any signs of arcing or explosive failure.
- Either the CT or its secondary circuit does show signs of arcing, but the duration is short and near the CT, or the arc is of insufficient intensity to ignite surrounding materials farther from the CT.
- The CT does exhibit explosive failure, but the explosive behavior is near the CT and insufficient to damage surrounding materials. The explosive failure is not accompanied by subsequent arcing of the CT or its secondary circuit.

If the testing does accompany the explosion or arcing failure, it will be evaluated further by the working group for further testing or studies.

1.6 DOCUMENTATION

A technical test report (or NUREG/CR) will document the test procedures and details of the testing that will include all assumptions and limitations. The test results will be summarized for the working group so that the CT's secondary fire issue can be technically assessed and appropriate guidelines are developed for circuit analysis in the fire protection program.

1.7 REFERENCES

- 1 "Instrument Transformer Basic Technical Information and Application," GE Digital Energy – ITI, www.gedigitalenergy.com/products/manuals/geh-230af.pdf
- 2 "Instrument Transformers – Technical Information and application Guide," ABB Field Engineering Services Instrument Transformers On-site Testing.
- 3 BNL Letter from Mr. E. A. MacDougall to Nicholas S. Fiorante of NRC, dated July 21, 1983.
- 4 Kaufmann, R. H. and Camilli, G., "Overvoltage Protection of Current Transformer Secondary Windings and Associated Circuits," Transactions of the AIEE, Vol. 62, July 1943, pp. 467-472.
- 5 Bonneville Power Administration Presentation of CT's Safety Hazards for Class Room Lecture by Steve Leslo (2/20/2013): https://www.eiseverywhere.com/file_uploads/dbb5ba3a17812e8cea24ddf2aeebfa2d_Current_Transformers_for_HORS_2013-2.pdf

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- 6 NGK (a Japanese Manufacturer) CT Open Circuit Test:
<https://www.youtube.com/watch?v=TGEcBCR4DV0>
- 7 CT Fails When Leads Open Circuited: <https://www.youtube.com/watch?v=j6v0ybdhGk0>
- 8 UL 61010B-1, "Electrical Measuring and Test Equipment; Part 1: General Requirements.
- 9 "Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE) – Phenomena Identification and Ranking Table (PIRT) Exercise for Nuclear Power Plant Fire-Induced Electrical Circuit Failure," Volume 1, NUREG/CR-7150, EPRI 1026424, October 2012.

Table 1: Test Data Acquisition

[illegible]