High Voltage and High Current Testing of Non-Conventional Instrument Transformers for Digitalized Protection of Power Systems

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***Abstract*—This paper bridges the gap between the existing knowledge of low power instrument transformers (LPITs) as a subset of non-conventional instrument transformers (NCITs) and the utility needs by conducting accurate and thorough testing in a well-equipped, high-voltage lab. The LPITs are tested under high voltage and high current quantities based on general testing requirements defined in the IEEE/ANSI C57.13 and the IEC 61869 standards. A traceable primary current or voltage is injected into the sensors, and the output current and voltage are captured to depict the accuracy and linearity of the sensors. Step change tests are performed to understand the sensor's performance under a simulated fault event. Nominal current and voltage quantities are supplied to the sensors. Then, the current and voltage values are changed to simulate a fault. The sensor output is compared to the primary values to identify the linearity and accuracy of the sensors. The test results are analyzed to demonstrate how they operate. Various test cases are considered, including the linearity and accuracy, withstand capability, temperature effect across a wide range, impact of frequency, impact of electromagnetic interference, and impact of dynamic changes of primary currents and voltages. The results of this paper will benefit many utilities and stakeholders considering the deployment of digital substations and looking for optimal and cost-efficient approaches.**

Keywords—HV Testing, NCITs, LPITs, IEDs, Power System Protection, Digitalized Systems.

I. Introduction

Technology advancements have inspired many utilities to invest more in the latest technologies to deploy fully digitalized substations. Non-conventional instrument transformers (NCITs) can be important in optimizing the substation footprint, minimizing the deployment cost and data management. NCITs act as measurement transducers using a measurement technique different from what is being used by traditional instrument transformers (ITs). They can easily be integrated with merging units and communicate low-power signals via the protocol defined by the IEC 61850 standard. Due to their advantages over traditional ITs, many utilities consider NCITs valuable assets for optimal deployment of advanced digital substations. NCITs also provide utilities with conventional substations as an alternative solution to address the challenges associated with the design and equipment rating that come with conventional ITs.

Low power instrument transformers (LPITs), as a subset of NCITs, are based on passive technologies without any active components. They produce relatively low magnitude analog voltage signals which are proportional to their primary voltages or currents. They can be connected to intelligent electronic devices (IEDs) without any conversion if the IED can accept the LPIT output signals. However full-scale utilization of LPITs in utility grade applications still needs some basic experimentation and testing before they can be rolled out as a viable alternative for conventional instrument transformers. This is to verify that they meet the expected requirements.

This paper describes the details of testing the LPITs in a well-equipped, high-voltage lab. The LPITs are tested under high voltage (HV) and high current quantities based on the testing requirements defined in IEEE/ANSI C57.13 and the IEC 61869 standards [1]-[3].

The sensors that are chosen for the tests are Rogowski coil type LPITs for current measurements and resistance divider type LPITs for voltage measurements. These sensors use twisted pair cables for the secondary connections and therefore some tests involve using these cables as well.

A traceable primary current or voltage is injected into the sensor, and the output current and voltage are captured to depict accuracy and linearity. Step change tests are performed to understand the sensor's performance under a simulated fault event. Nominal current and voltage quantities are supplied to the sensors. Then, the current and voltage values are changed to simulate a fault. The sensor output is compared to the primary values to identify accuracy and linearity. The test results are analyzed and discussed, and the data to support the discussions are provided.

II. Problem Description and Methodology

A. *Test Setup*

Fig. 1 shows the high-level setup for testing an LPIT current sensor, and Fig. 2 shows the corresponding physical setup in the lab. In the setup, the sensor is fitted around a current-carrying cable. This current measured by the sensor comes from a regulator attached to a CT driver with both ends of the cable connected. The CT driver steps the current up and down to allow testing of input current. A current meter is connected to the cable to measure the input current observed by the current sensor. A waveform recorder is connected to the current sensor output port to monitor the resulting output voltage waveform.

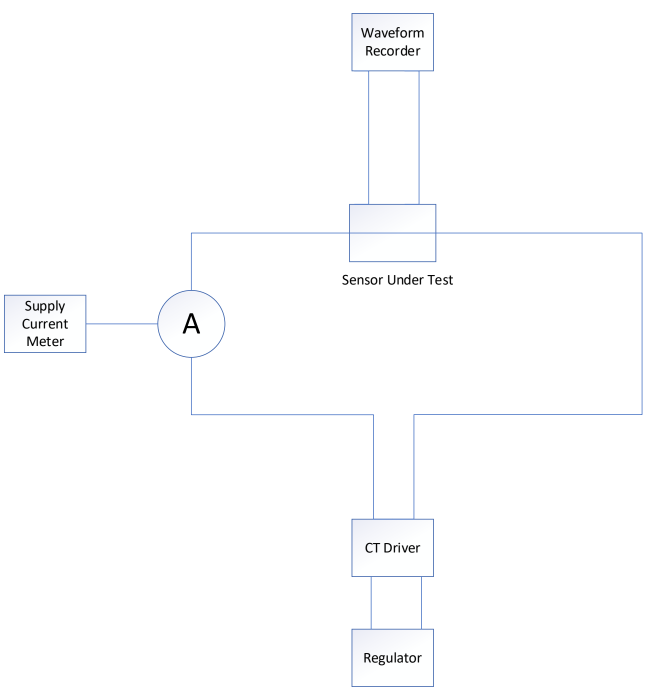

Fig. 1. High-Level Layout of Test Setup for Testing the LPIT Current Sensors

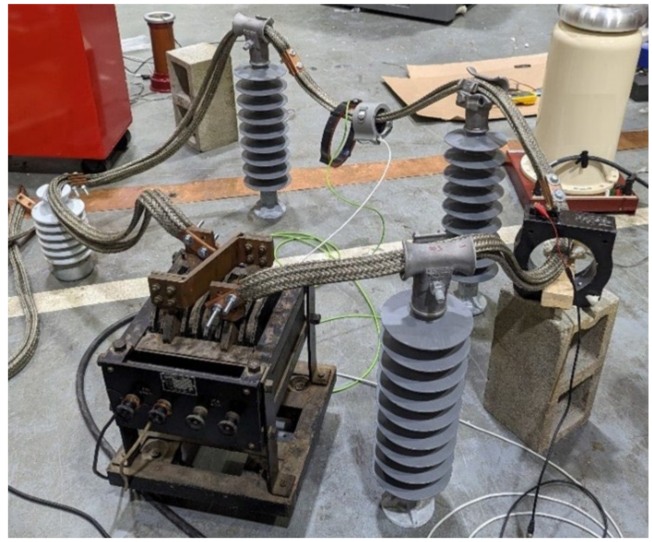

Fig. 2. Current Sensor Test Setup in the Lab

The voltage sensor test setup shown in Fig. 3 consists of the LPIT voltage sensor and a supply voltage meter attached to a voltage supply. The voltage supply available during testing can provide up to 130 kV. The supply voltage meter measures input voltage, so an expected output voltage value can be calculated based on the rated voltage sensor transformation ratio. The waveform recorder is connected to the voltage sensor to record the output voltage waveform.

Fig. 3. Voltage Sensor Test Setup in the Lab

Beyond the basic setup for the current and voltage sensor testing, additional HV lab equipment and setup modifications are used for specific tests. This includes a temperature chamber integrated into the test setup (see Fig. 4). The sensors can be placed into the chamber and subjected to temperatures between -75°C and 175°C. Another piece of equipment available in the HV lab is a signal generator for modulating voltage frequency. In the case of electromagnetic interference effects on the data, the original current and voltage sensor setups are moved close together, as per Fig. 5.

Fig. 4. Setup for Testing Temperature Impact Using the Temperature Chamber

Fig. 5. Setup for Impact of Electromagnetic Interference Testing

B. Test Cases

Following a survey of available LPIT current sensors and voltage sensors, two manufacturers (Manufacturer A and Manufacturer B) were chosen to supply both a current sensor and a voltage sensor, for a total of four sensors to be evaluated during testing. The basis of LPIT sensor testing is step-by-step change testing, where current and voltage values supplied to the sensors are changed incrementally to observe the impacts of fault-like conditions. Comparing the input values and the sensor output allows errors to be observed in sensor measurement. Type testing is done to evaluate the performance of the selected current and voltage sensors. The following tests were executed:

1) Linearity, accuracy, and withstand capability: The linearity and accuracy tests are conducted by injecting a traceable amount of primary current or voltage into the sensor in 10% steps, and the output current and voltage are captured. The primary current range for current sensor testing is specified as 0A to 1000A to simulate the use of the sensors on 1000A switchgear. Linearity and accuracy testing is conducted with two additional CAT-6 ethernet cable lengths (50 and 100 meters) to observe impacts on current sensor output. The measurement range of 0 primary volts to 110% of the sensor's primary voltage rating is used for voltage sensors. Withstand capability testing is done on the voltage sensors at the overvoltage test points of 150% and 190% of the primary voltage rating.

2) Temperature impact: The effect of temperature on sensor performance is evaluated by repeating the linearity and accuracy test at various temperatures. The temperatures selected for testing are -75°C, -25°C, -5°C, 40°C, 60°C, and 85°C. Negative 75°C is the lowest possible temperature that can be reached with the temperature chamber in the lab, and 85°C is the highest temperature an LPIT sensor must withstand according to IEC 61869.

3) The impact of frequency changes on sensors: Testing the impact of frequency changes on sensor performance is conducted by repeating the linearity and accuracy tests at two frequency values (55 Hz and 65 Hz) other than the nominal frequency of 60 Hz. This type of test is only available for voltage sensors. The equipment available in the lab cannot modify the current frequency.

4) The impact of electromagnetic interference (EMI) on the sensors: To determine the effect of EMI, the linearity and accuracy tests are repeated with the presence of a current or voltage source close to the test setup. A 17-kV voltage source is used for current sensor testing, and a 1000-A current source is used for voltage sensor testing. The sensors for both manufacturers are located beside one another to observe any changes to measured values due to sensor proximity.

5) The impact of dynamic changes of primary current and voltage values on the sensor output: This test is performed by drastically changing the current or voltage supplied to the sensor and monitoring the output waveform for differences compared to normal operation. Current sensor testing involves changing the primary current from 0A to 1000A, then 0A to 500A. The immediate change from 0% to 100% of primary voltage is tested for the voltage sensors.

The data collected in the tests includes input current or voltage, output voltage, and phase shift. Calculations were performed to determine the expected output voltage value based on the sensor's input value and transformation ratio and find the subsequent error between the expected and actual output value.

III. Test Results

A. Linearity, Accuracy, and Withstand Capability

Fig. 6 contains the linearity testing results for the current sensor from Manufacturer A (Current Sensor A), including the data for testing the sensor with 50- and 100-meter Cat-6 ethernet cables, respectively. The magnitude of the error for linearity testing results for all cable lengths remained below 0.62%. The observed phase shifts during testing of all cable lengths were a maximum of 2° off the ideal 90° phase shift. The error and difference in phase shifts can be attributed to oscillations in the input and output values during recording. Overall, these results show Current Sensor A measures the current accurately and maintains linearity. Modifying the cable length does not have a noticeable impact on linearity and accuracy for this sensor.

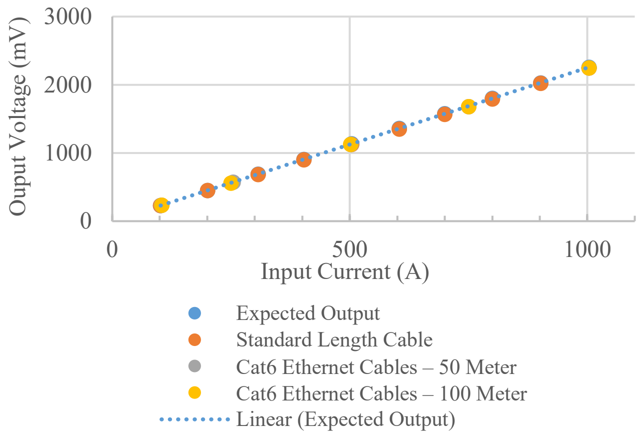

Fig. 6. Linearity and Accuracy Test Results for Current Sensor A

Manufacturer B's current sensor (Current Sensor B) waveform shown through the oscilloscope in the lab contained significant noise. The distortions in the waveform from the noise prevented the oscilloscope from determining phase shift. As a result, phase shift values were not recorded for Manufacturer B's current sensor. Fig. 7 contains the linearity testing results for Current Sensor B for all cable lengths tested. For the lowest primary current applied, the magnitude of the error for the measured output reached a peak of 10.25%. This could be a result of the observed noise interfering with the low voltage output signal enough to cause significant error. The error observed for linearity testing for the 50- and 100-meter cables was lower on average than for the linearity test with the standard-length cable, indicating that the cable's length does not negatively impact this sensor's linearity and accuracy.

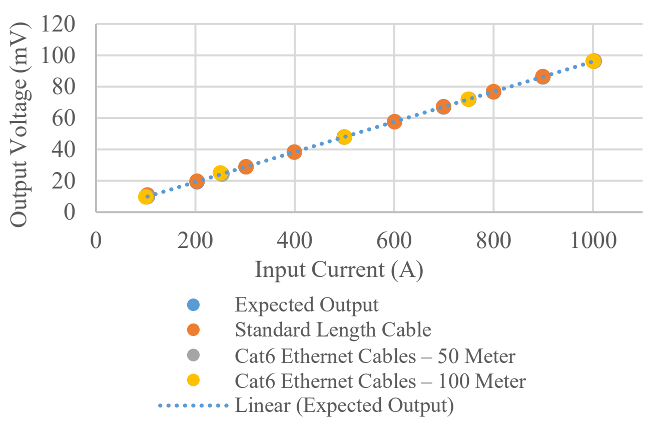

Fig. 7. Linearity and Accuracy Test Results for Current Sensor B

Fig. 8 shows the results for linearity, accuracy, and withstand capability testing for Manufacturer A's voltage sensor (Voltage Sensor A). The average error between the expected and actual voltage output for the sensor was 1.9681%. The scope measuring phase shift oscillated through several values close to 0° and could not be measured precisely. The phase shift can be estimated as 0°. The over-voltage data points did not have noticeably higher errors than the linearity testing results.

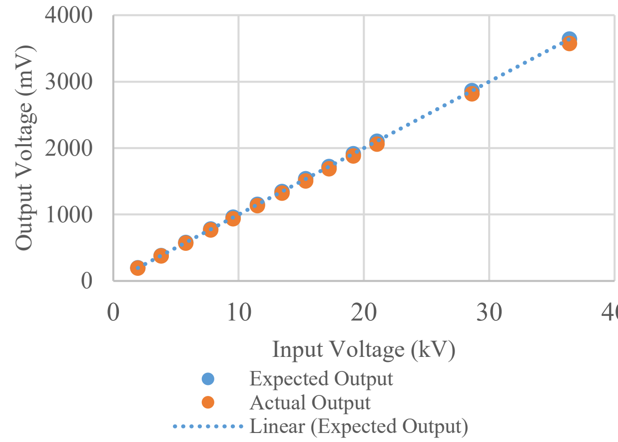

Fig. 8. Linearity, Accuracy, and Withstand Capability Test Results For Voltage Sensor A

Fig. 9 shows the results for linearity, accuracy, and withstand capability testing for Manufacturer B's voltage sensor (Voltage Sensor B). The average error between the expected and actual voltage output was lower than that of Manufacturer A's voltage sensor, at –0.5713%. The phase shift measured by the scope varied around 0°. The over-voltage data points had slightly higher errors than the linearity testing results.

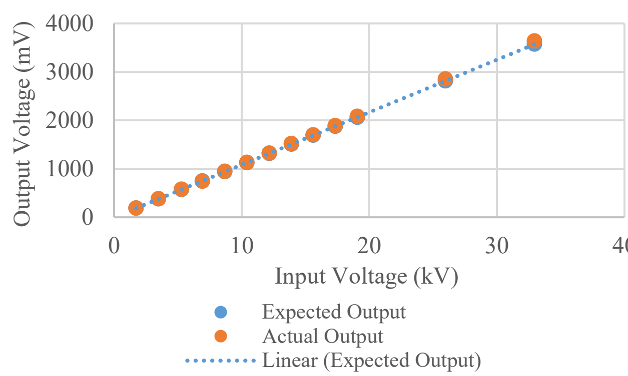

Fig. 9. Linearity, Accuracy, and Withstand Capability Test Results for Voltage Sensor B

B. Temperature Impact

The primary current values of 100A, 300A, and 500A were applied to the sensor at each temperature to test the impact of temperature on the current sensors. The setup for this test involves placing the sensor in the temperature chamber, which uses cables that can safely withstand a maximum of 500A for extended periods, making this the upper limit for primary current. For voltage sensor testing, the same input primary voltage as the one for linearity and accuracy testing is used.

In the data collected for Current Sensor A, the error ranged from –2.018% to 0.774% across all tested current values and temperatures (see Fig. 10). At lower primary current values, the error magnitude was slightly larger than at higher primary current values. There was no significant difference between the error observed in this test and the linearity and accuracy test, indicating that temperature does not greatly impact the sensor's performance.

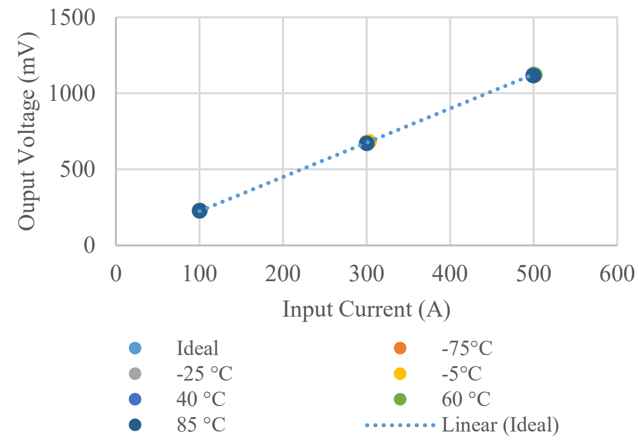

Fig. 10. Temperature Impact Test Results for Current Sensor A

Fig. 11 shows the results from the temperature test for the Current Sensor B. Error ranged from –37.852% to –0.833% for the test. This range is much wider than that of Current Sensor A and is larger than the error range observed during the initial linearity test for Current Sensor B. At lower primary current values, the error magnitude was significantly larger than for higher primary current values. Compared to the linearity and accuracy test results, the error magnitude was generally larger under non-ideal temperatures, indicating this sensor does not have the same accuracy when exposed to extreme temperatures.

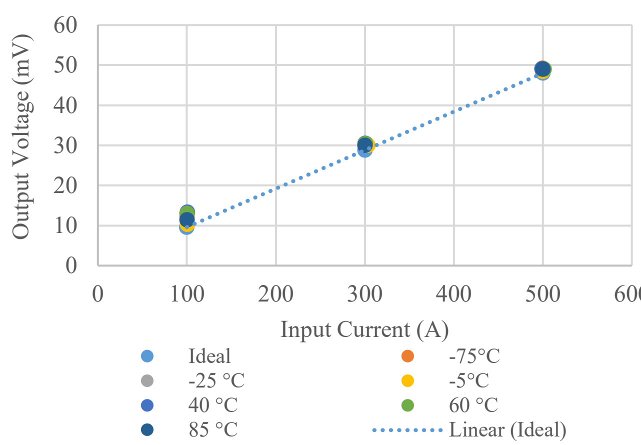

Fig. 11. Temperature Impact Test Results for Current Sensor B

The two voltage sensors were subjected to the same voltages for their tests. Voltages of 10%, 50%, and 100% of the primary voltage rating of Voltage Sensor B, in addition to 100% of the primary voltage rating of Voltage Sensor A, were used.

Fig. 12 demonstrates the results of temperature impact testing for Voltage Sensor A. The error in the results ranged from 1.792% to 5.782%. The highest error came from test cases with higher applied temperatures. Considering this and that the largest error observed in the linearity and accuracy test was 2.356%, temperature appears to impact the ability of the sensor to measure the voltage accurately and linearly.

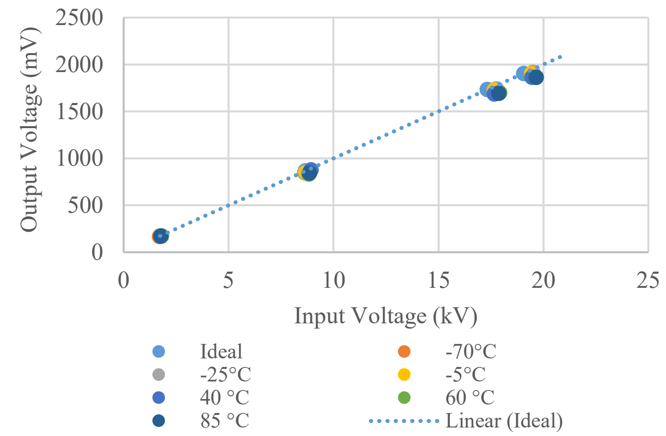

Fig. 12. Temperature Impact Test Results for Voltage Sensor A

Fig. 13 shows the data from the temperature impact testing for Voltage Sensor B. The error range was from -0.3923% to 3.8451%, which is higher than during linearity and accuracy testing of –1.0135% to 0.4786%. Test cases with higher applied temperatures had higher errors, similar to Voltage Sensor A. This indicates temperature reduces the linearity and accuracy of this voltage sensor.

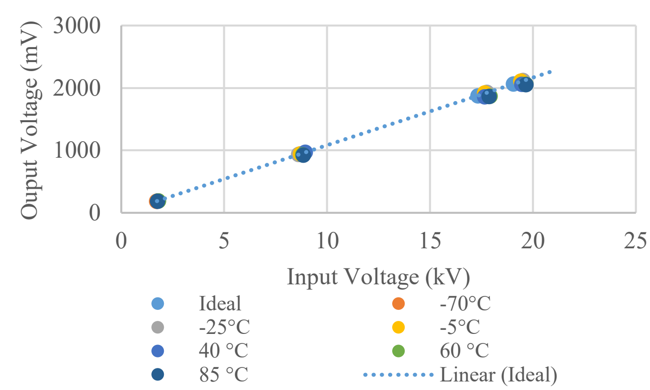

Fig. 13. Temperature Impact Test Results for Voltage Sensor B

C. *Frequency Impact*

Frequency testing was conducted on the voltage sensors at test points of 10% of primary voltage rating, 50% of primary voltage rating, and 100% of available voltage without distortion. The highest voltage available from the signal generator is 13.82 kV, but the maximum voltage of 12.078 kV was used, since distortions were observed on the peaks of the waveforms for voltage values above this.

Fig. 14 and Fig. 15 show Voltage Sensors A and B test results at different frequencies, respectively. The data do not show any significant differences in the measurement error between 55 Hz, 60 Hz, and 65 Hz. The error magnitude for values for 65 Hz is lower than the values for other frequencies for both sensors, but not by a large margin. The phase shift measured on the scope oscillated around 0° and can be estimated as 0° for both sensors.

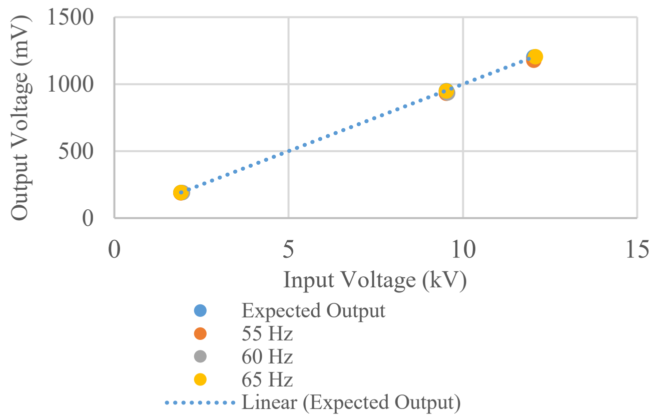

Fig. 14. Frequency Impact Test Results for Voltage Sensor A

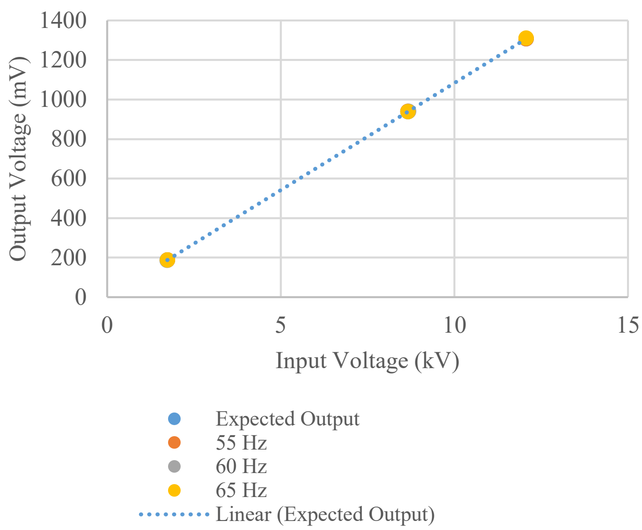

Fig. 15. Frequency Impact Test Results for Voltage Sensor B

D. *Electromagnetic Interference Impact*

The test points used for the sensors were 10%, 50%, and 100% of the rated primary current or voltage. The linearity and accuracy test output for these test points is adjusted based on a ratio between the input current from the linearity test and the input current from the EMI test. The calculated error is a comparison of the adjusted linearity and accuracy test output and the EMI test output.

The results for Current Sensors A and B, shown in Fig. 16 and Fig. 17, respectively, demonstrate a difference between the adjusted linearity and accuracy test output and the EMI test output for both sensors. Applying 10% of the rated primary current results in the highest error magnitude in both tables. For Current Sensor A, the error for this primary current is –3.068%, compared to –6.668% for Current Sensor B. For 100% of the primary current, the error is much closer to 0 for both sensors, with the error being –0.015% and –0.793% for Current Sensors A and B, respectively. Overall, while EMI impacts both current sensors from the voltage source, this impact is small.

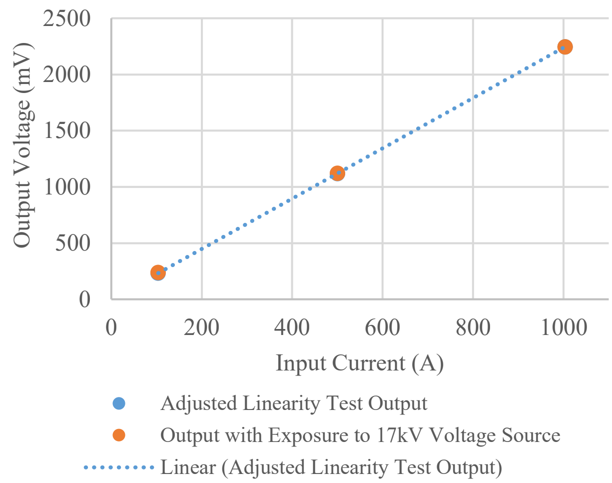

Fig. 16. EMI Impact Test Results for Current Sensor A

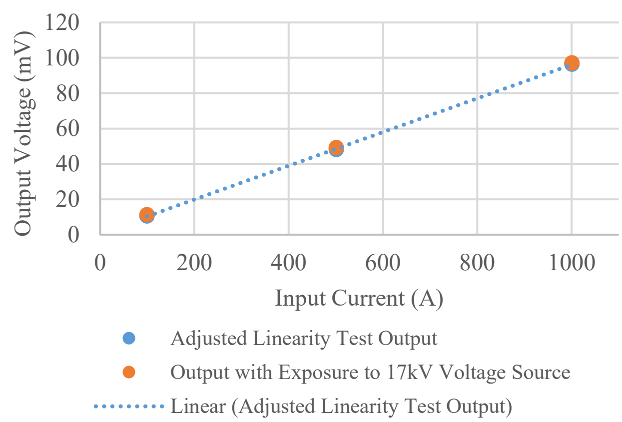

Fig. 17. EMI Impact Test Results for Current Sensor B

0 and Fig. 19 contain the results for Voltage Sensors A and B, respectively. The magnitude of the error between the adjusted linearity and accuracy test output and the EMI test output remained below 0.6% for both sensors. The average error was 0.224% for Voltage Sensor A and 0.259% for Voltage Sensor B. This indicates that the presence of the current source has minimal effect on the voltage sensor performance.

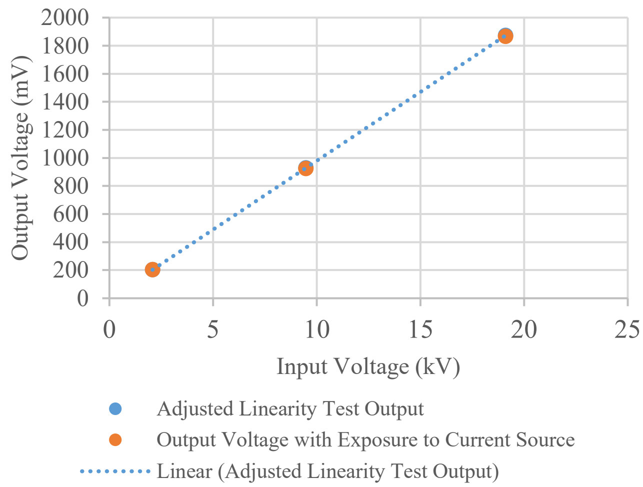

Fig. 18. EMI Impact Test Results for Voltage Sensor A

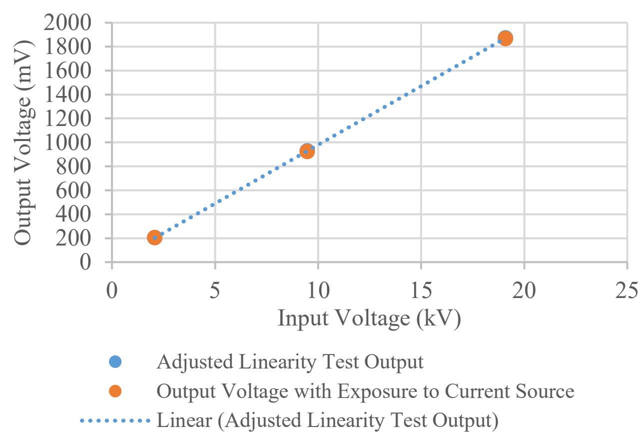

Fig. 19. EMI Impact Test Results for Voltage Sensor B

E. Impact of Dynamic Changes of Primary Current and Voltage Values

The results of the impact of dynamic changes of primary current and voltage testing for Current Sensor A and Voltage Sensors A and B are found in TABLE I. through TABLE III. The waveforms for Current Sensor B contained excessive distortions during linearity testing, thus the impact of dynamic changes testing was not conducted. For all sensors tested, the observed output waveforms during the dynamic changes test showed no noticeable differences in response compared to the linearity and accuracy test waveforms.

TABLE I. IMPACT OF DYNAMIC CHANGES OF PRIMARY CURRENT TEST RESULTS FOR CURRENT SENSOR A

Step	Input (A)	Observations
Change primary current from 0% to 100%	1000	Same response as normal operation
Change primary current from 0% to 50%	500	Same response as normal operation

TABLE II. IMPACT OF DYNAMIC CHANGES OF PRIMARY CURRENT TEST RESULTS FOR VOLTAGE SENSOR A

Step	Input (kV)	Observations
Change primary voltage from 0% to 100%	19.2	Same response as normal operation

TABLE III. IMPACT OF DYNAMIC CHANGES OF PRIMARY CURRENT TEST RESULTS FOR VOLTAGE SENSOR B

Step	Input (kV)	Observations
Change primary voltage from 0% to 100%	19.6	Same response as normal operation

IV. CONCLUSION

In this paper, the results of LPIT testing in a well-equipped, high-voltage lab are given and discussed. Various test cases are considered, and two sets of current and voltage sensors from two manufacturers were tested, Manufacture A and Manufacture B.

The two sensors' linearity, accuracy, and withstand capability were tested. For Current Sensor A, the magnitude of the error for linearity testing results for all cable lengths remained below 0.62%. Overall, these results show Current Sensor A measures current accurately and maintains linearity. Modifying the cable length does not have a noticeable impact on linearity and accuracy for this sensor. The Current Sensor B waveform shown through the lab's oscilloscope contained significant noise. The distortions in the waveform from the noise prevented the oscilloscope from determining phase shift. For the lowest primary current applied, the magnitude of the error for the measured output reached a peak of 10.25%. This could be the result of the observed noise interfering with the low voltage output signal enough to cause significant error. It is indicated that the cable length at the sensor output does not negatively impact linearity and accuracy for this sensor. For Voltage Sensor A, the average error between the expected and actual voltage output for the sensor was 1.9681%. For Voltage Sensor B, the average error between the expected and actual voltage output was lower than that of the Manufacturer A voltage sensor, at –0.5713%

The impact of the temperature on the accuracy of the sensors was evaluated. For Current Sensor A, there was no significant difference between the error observed in this test compared to the linearity and accuracy test, indicating that the temperature does not greatly impact the sensor's performance. Compared to the linearity and accuracy test results for Current Sensor B, the error magnitude was generally larger under non-ideal temperatures, indicating this sensor does not have the same accuracy when exposed to extreme temperatures.

For Voltage Sensors A and B, the highest error came from test cases with higher applied temperatures. Considering this and that the largest error observed in the linearity and accuracy test was 2.356% and 3.8451% for Sensors A and B, respectively, temperature appears to impact the ability of the sensor to measure the voltage accurately and linearly.

Frequency testing was conducted on the voltage sensors, and the results show that the error magnitude for 65 Hz is lower than those for the other frequencies for both sensors, but not by a large margin.

The impact of EMI on the current and voltage sensors was evaluated. Overall, while EMI impacts both current sensors from the voltage source, this impact is small. In addition, it is indicated that the presence of the current source has a minimal effect on voltage sensor performance.

The results of the impact of dynamic changes of primary current and voltage testing were evaluated. For all sensors tested, the observed output waveforms during the dynamic changes test showed no noticeable differences in response compared to the linearity and accuracy test results.

References

[1] IEEE Standard Requirements for Instrument Transformers, IEEE C57.13-2016.

[2] IEEE Guide for the Application of Rogowski Coils, IEEE C37-235-2021.

[3] Additional General Requirements for LPITs- IEC 61869 standards Parts 1, 6, 10 & 11.