Real-Time Circuit Breaker Health Diagnostics

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***Abstract*—Utilities have hundreds of circuit breakers that they plan to monitor for the purpose of accurately assessing health and performance. As circuit breakers age over time, improper operations can become more likely and cause problems on the power system. Utilities are making efforts to develop automated circuit breaker monitoring systems that diagnose the electrical and mechanical health of their circuit breakers in real time. This is a shift in the maintenance paradigm from time-based maintenance to as-needed maintenance. This shift comes with the benefit of maintaining adequate circuit breaker performance while reducing overall maintenance costs.**

This paper details a system developed at American Electric Power (AEP) for monitoring circuit breakers and presents an overview of the results of field trials that show the maintenance reductions gained by predicting required maintenance instead of scheduling it. The system collects data from deployed intelligent electronic devices (IEDs) to monitor circuit breaker conditions, including degrading performance, contact wear, SF6 gas integrity, gas pressure, compressor run times, compressor run currents, and much more. The system discussed in this paper also provides the ability to monitor real-time trip and close coil assembly performance by recording mechanical and electrical characteristics including trip coil current and operate time during circuit breaker operations. Recorded trip and close coil characteristics are used to diagnose armature misalignments, lubrication problems, interwinding short circuits, and so on to assist with maintenance and ensure future operations. Monitoring circuit breakers also allows for accurate price assessments of circuit breaker assets and aids in maintenance and replacement. Additionally, this paper presents an implemented monitoring solution that was used to demonstrate these capabilities and benefits.

I. Introduction

AEP has numerous circuit breakers installed that require regular testing to determine the health of each breaker and schedule maintenance or replacement as required. With such a large number of assets, AEP has an asset management group within their transmission department to manage all of the circuit breakers in addition to other substation equipment. Due to the large amount of time required to conduct tests on these assets, AEP's asset management group has undertaken a number of automated monitoring solutions for substation assets to reduce the cost of testing assets and gain real-time diagnostics capable of alerting them that a problem is likely to occur.

This paper focuses on the breaker monitoring portion of the Asset Health Center (AHC) software solution, including the data collected, how these data determine necessary maintenance, and an overview of collected test and field data.

II. Asset Health Center

The Asset Health Center (AHC) software solution is a collaborative effort between AEP and a third-party software company. The tool is a web-based interface that allows access from any AEP corporate connected laptop, mobile device, or PC. The software project was completed in December 2015. The software makes use of several available data sources, including equipment nameplate information, inspection and test results, supervisory control and data acquisition (SCADA) data, fault files, and real-time health-monitoring equipment. The tool includes algorithms that calculate the risk of failure, asset criticality, the need for maintenance, and the need for replacement [1].

AEP and third-party subject matter experts in substation equipment and asset management developed the algorithms to determine the health of each asset. Asset performance models (APMs) calculate the health of transformers, circuit breakers, and batteries. In general, these models calculate the probability of an asset failing to perform its intended function. The algorithms can also generate messages to inform users of abnormal conditions, recommend possible solutions, and provide a timeline to mitigate the conditions. For circuit breakers, the algorithms make use of parameterized models, which account for manufacturer design differences. These parameters provide thresholds to assess measurements and contrast with inspection data.

A maintain vs. replace algorithm assigns a replacement and health score to aid in justifying the need to replace or continue maintaining an aged asset. Operations and Maintenance (O&M) tasks (regulated, time-based, and condition-based) are prioritized based on safety, failure prevention, and asset criticality. Asset health, remaining useful life, and forecasted maintenance determine the priority of the asset replacement. The system provides alerts to AEP personnel that indicate when an asset is about to fail or needs maintenance. The number one consideration is ensuring safety. Ensuring personnel are not working near an asset that is about to fail is paramount. The next considerations are financial. Failure prevention is key to minimize the cost of replacement equipment, overtime to fix equipment failures, and any expedited costs.

The AHC software solution provides dashboards in a web browser interface that allow the user to sort through the health assessments and the suggested maintenance and renewal, filtering by asset type, organizational structure, voltage level, or age. An asset monitor dashboard summarizes the risk of failure for the entire population and allows the user to query by several filters and drill into specific assets. Equipment-specific dashboards visualize current measurements, trend value history, and how these data feed the asset health algorithm. The maintain vs. replace dashboard allows the user to see suggested maintenance tasks by area or by asset and visualize the pending cost of forecasted maintenance.

III. Testing and Maintenance

In AEP's transmission organization, the substation asset management group is responsible for the maintenance, replacement, and failure mitigation of substation equipment. Traditionally, time-based and regulatory-based maintenance guidelines drive the circuit breaker maintenance work plan. Each year, a preventative maintenance plan that includes routine inspections, equipment testing, and repairs is produced. In addition, a yearly capital rehabilitation work plan is developed for circuit breakers, with the goal of replacing the worst performers and obsolete models based on available funding. Finally, the substation asset management group assists field personnel with the repair or replacement of failed circuit breakers on an ongoing basis. The group provides decision support to field operations groups based on years of experience and past practices.

The replacement of existing circuit breakers is prioritized based on funding availability, equipment reliability, model obsolescence, and age. The substation asset management group has developed a ranking methodology specifically for circuit breaker replacement that pulls information from nameplates, inspections, test results, operational history, and trouble reports. The asset manager can use this ranking methodology, along with field experience, to prioritize a yearly rehabilitation plan.

Visual inspection of circuit breakers occurs on a routine basis. During these periodic checks, the breaker operations and loading are manually logged. The equipment is inspected for abnormal conditions inside the control cabinet and on the main units. The breaker remains in service during the inspection, but it does require a physical visit from trained personnel.

Circuit breaker preventative maintenance intervals are based on breaker model, voltage level, interrupting medium, and breaker application. For each category, AEP developed intervals based on manufacturer guidance and best practices for both external and internal maintenance. Additionally, AEP's guidance states that the breaker should operate at least once per year. Both external and internal maintenance require the breaker to be de-energized and isolated. External checks include the measurement of contact resistance, insulation resistance, oil quality, and maintaining the linkage, all where applicable. Internal tests include timing tests, replacing gaskets, and cleaning tanks, all where applicable. Circuit breaker corrective maintenance is performed on an as-needed basis. Corrective maintenance is event-driven based on inspections, operations, and failures.

Another key function of the substation asset management group is to advocate for breaker renewal initiative funding. Asset managers need to provide a business case stating the level of maintenance and replacement needed to keep the fleet of assets functioning reliably. To support replacement and maintenance decisions, the asset manager needs to combine the operational, inspection, testing, and failure data with financial information such as replacement cost, maintenance expense, and book value. Traditionally, both the data collection and analysis have been manual processes. AEP is starting to automate the data collection through the use of health monitoring and intelligent electronic device (IED) data.

Moving forward, AEP has decided to leverage extensive experience with digital relays for circuit breaker control in order to provide a better solution for breaker health monitoring and analysis. In general, the following parameters are important to record for breaker asset management: SF6 gas temperature, moisture, density, operating coil current, motor current, operation counts, load current, voltages, and contact timing. The following sections provide an overview of how these parameters are measured from both existing relay records and a new breaker control package.

AEP uses the AHC replacement score and asset health score for circuit breakers to determine which circuit breakers need replacement and how quickly it needs to happen. AEP uses these data for justification along with recovery time objectives (RTOs) on replacements. Monitoring these scores provides up-to-date data on circuit breakers to make better decisions and reduce O&M spending.

O&M spending is not desirable in the AEP business model. AEP has a yearly O&M budget that is limited. Presently, AEP performs inspections and maintenance on a time-based maintenance schedule. AEP can save on O&M costs and optimize the O&M dollars based on condition-based monitoring data and asset health scores. AEP wants to work on the right assets, at the right time, and with the right tools. The AHC system helps optimize the AEP O&M expenses in the following areas:

- Monthly—inspection time for circuit breaker SF6 gas readings
- Yearly—operational check for circuit breakers
- 6 years—external inspections
- 12 years—complete inspections

IV. Components of Breaker Monitor

Transmission circuit breakers range in operational voltages from 34.5 to 765 kV on the AEP system, which includes thousands of circuit breakers. Each circuit breaker is controlled and monitored using a microprocessor-based relay. This relay is responsible for functions such as control, automation, protection, data acquisition, disturbance monitoring, and asset health monitoring. An additional microprocessor-based relay supports the breaker monitoring and asset health monitoring requirements. This circuit breaker monitor (CBM) resides in close proximity to the asset to record data from various sensors.

Fig. 1 shows a diagram of the AHC design implementation that illustrates the system's overall monitoring and data collection architecture. The AHC collects real-time trend data and event-based data from IEDs, including the breaker relays and CBM devices. It then parses the data and applies various algorithms to provide asset details and maintenance through web-based dashboards and other human-machine interfaces (HMIs).

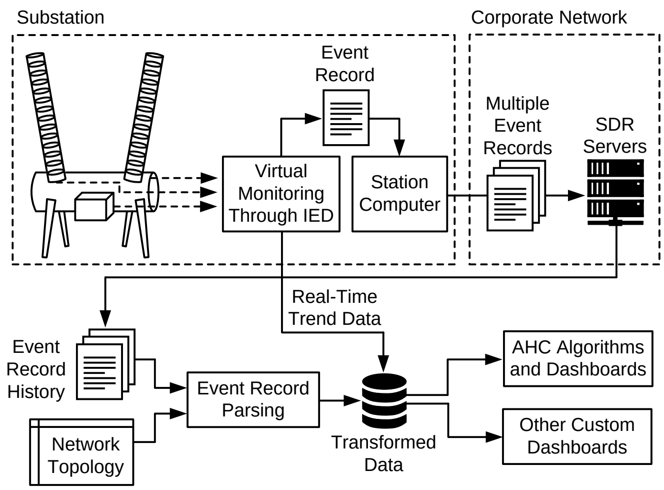

Fig. 1. Asset Health Center Architecture

For the AHC algorithm and health score calculation, the circuit breaker parameters are separated into five subsystems (dielectric, mechanical, wear, accessories, and other). More than 120 total parameters are used in the subsystems. The following list includes some examples for each of these categories:

- Accessories
  - Function of cabinet, mechanism, and tank heaters
  - Number of hydraulic pump starts
  - Total accumulated run hours of the air compressor
  - Total accumulated run hours of the SF6 compressor
- Dielectric
  - Insulating oil dielectric strength
  - Rated voltage vs. applied voltage
  - Rated current vs. applied current
  - SF6 moisture content, pressure, and purity
  - High-pressure SF6 moisture content, pressure, and purity
- Mechanical
  - Close time and velocity
  - Trip time and velocity
  - Interpole close time and trip time deltas
  - Resistor preinsertion time
  - Total interrupter travel
- Wear
  - Contact wear (switch operations)
  - Main nozzle wear
  - Auxiliary nozzle wear
  - Contact resistance
  - Interrupter wear
- Other
  - Mechanism stored energy state
  - Time elapsed since last inspection, maintenance, and overhaul
  - Breaker age

Each subsystem plays a vital role in the operational behavior of a breaker. The following subsections highlight some of the key features of the breaker monitoring system.

A. Breaker Relay

The primary function of the breaker relay is to provide control and protection for the breaker asset. In addition to these key functions, the breaker relay also provides oscillography data that are triggered for various disturbance monitors. These triggers include trip and close operations as well as system changes in voltage, current, and frequency. The records are automatically retrieved and sorted for the breaker asset. These event records also serve to meet AEP's protection and control (PRC) requirements for disturbance monitoring.

The oscillography records can be analyzed automatically for the important information they contain regarding the health of the breaker asset. When the AHC receives new COMTRADE records, the AHC algorithm automatically flags equipment operations that are out of specification and updates the overall asset health score. Evaluating the time it takes from trip coil energization to the elimination of current in each individual pole can indicate slow breaker trip operations. The AHC algorithm performs a similar calculation for closing breakers by looking at the time of close coil energization to current pickup.

Reference [1] discusses how AEP intends to demonstrate that contact wear over the life of a breaker can be evaluated by parsing such events, but the breaker relay is also capable of calculating the contact wear on a per-pole basis. When the breaker trips, the relay estimates the amount of contact wear based on an assumed arcing time. These values are stored in the relay, and breaker wear accumulates with each subsequent trip operation. Breaker relays have provided this information for years, but processes and procedures have limited the usefulness and confidence in the data.

To increase usefulness and improve confidence in the data, AEP sends the data back to the AHC for trending and monitoring in real time. The contact wear is stored at the remote server and is accessible for preloading when an asset is replaced. This is necessary, for example, when a relay fails or when capital projects change the breaker controls. Trending and archiving these data in the AHC makes the data available for the life of the asset, not the life of the monitoring equipment.

B. Circuit Breaker Monitor

The breaker relay and event analysis provide a tremendous amount of useful data regarding asset health. However, there are many failures that either cannot be detected or, if they are detectable, are not detected early enough to prevent a failure. This is why the CBM package is used to help detect these anomalies or sense failures at their initial stages and complement the breaker relay data. Breaker equipment specialists provided a list of important breaker characteristics, not currently measured by breaker relays, that they felt would provide useful data to help prevent failure and trigger a maintenance cycle. These monitoring parameters are measured by an array of sensors located at the breaker, collected and annunciated by the CBM, and then communicated back to the AHC for trending and maintenance triggers.

1) Trip Coil Currents

The CBM captures the coil signature during every breaker trip and close operation. The trip coil can be a noninvasive condition monitor sensor that provides valuable details of how the breaker is operating [2]. When the coil receives a trip or close operation, the coil energization indicates the breaker reaction, which contributes to the asset performance.

The breaker coil signature is captured using a Hall-effect current transducer with a frequency response that passes everything from dc to 350 kHz. The outputs of these signals are 0–5 Vdc and are measured using the CBM low-energy analog (LEA) inputs. The LEA inputs are sampled at 960 Hz, or 16 samples per power system cycle.

2) SF6 Density

The CBM continuously measures the SF6 gas density by fitting the circuit breaker with a gas density transmitter. The gas density transmitter provides a 4–20 mA signal as an input to the CBM, which also takes care of converting scaling and units. The particular gas density transmitter used is hermetically sealed and therefore not influenced by atmospheric pressure changes. The gas density transmitter is electrically compensated following the nonlinear behavior of SF6 gas according to the virial equation.

Gathering the gas density as an analog signal provides better SF6 awareness and tracking to comply with failure prevention and leakage tracking requirements. Traditional practices measure the SF6 density and alarm when the SF6 levels reach a low and lockout level. By tracking the SF6 density in real time, the AHC algorithm can anticipate the low and lockout SF6 levels and trigger maintenance activities to breakers with leaking gas.

3) Motor Current and Run Time

Circuit breakers use stored operating energy that typically comes from a compressed spring or hydraulic pressure. The operating energy is typically recharged following a circuit breaker operation so that the duty cycle of the breaker can be repeated. For a spring mechanism circuit breaker, some of the stored energy is released after a trip operation, and either an ac or dc motor begins to charge and recompress the operating mechanism spring.

Measuring not only how long the charging motor is running but when the motor is asked to recharge the operating mechanism can help identify a problem with the breaker if the value changes over time. Depending on the mechanism type, recharging the stored energy may be expected after a single trip operation. Further, prolonged charging operations may point to a charging system failure.

4) Cabinet Heaters

Circuit breakers are typically installed in an open-air switchyard environment and are subjected to a variety of weather conditions. AEP requires that all outdoor cabinets be equipped with a heater(s) for moisture control. Installing heaters in circuit breaker cabinets is a practice AEP equipment specialists advocate, but it is easy to overlook the health of these circuits.

To verify that the cabinet heaters are working, the current for the heater circuit is measured and monitored. If the measured current is above or below an expected operating range, that status is flagged and sent to the AHC to schedule maintenance.

V. Event-Based Field Data

The breaker monitoring system encompasses two categories of data collection: real-time and event-based. Breaker relays and CBMs supervise the breaker and trip coil statuses, charging motor conditions, SF6 gas quality, and heater integrity to provide continuous valuation of asset health. During operations, the relays also record concurrent event data that the AHC monitoring system uses to assess breaker performance and maintenance needs. These event-based data include transient recordings of breaker interrupt currents, breaker operation times, trip coil currents, battery voltages, mechanism charging currents, and mechanism charging times. This section includes analysis of various event-driven test data that demonstrate practical examples of assessing breaker performance after an operation.

A. Circuit Breaker

For every breaker operation, the breaker relay captures a recording of the interrupted current samples to accumulate a contact wear percentage that it continuously tracks over the breaker's lifetime. The AHC system parses through the breaker relay's COMTRADE records to assess the overall health of the breaker. It also examines symmetrical component data for voltages and currents that meet minimum and maximum criteria to distinguish between breaker test condition data and event data. An algorithm integrates arcing time with the interrupted root-mean-square (RMS) current. Traditionally, relay manufacturers provide breaker arc times as nameplate data. Trip coil current provides a closer estimate of this arc time that is a necessity for differing breaker types. Per-pole contact wear from these data accrues on every operation to provide historical context for the asset use.

In addition to contact wear, the AHC also collects other performance data, including operating time, operation count, and operation failure. These diagnostics assist with overall breaker life and maintenance needs. Slow operations indicate degradation, which creates a risk for breaker failures during future power system events. An accumulation of the operation time and operation counts provides means for predictive repairs or replacement.

B. Energization Test for 69 kV Bus

Fig. 2 shows a simplified one-line diagram of an AEP bus connection that is presently using the AHC. It includes a single, three-pole circuit breaker (CB-A) that connects between a 69 kV bus (Bus 1) and transmission line. The breaker relay measures the line current, line voltage, and bus voltage while providing processing logic and control to operate CB-A. Additionally, the breaker relay measures the trip bus dc voltage and records sample data during operations.

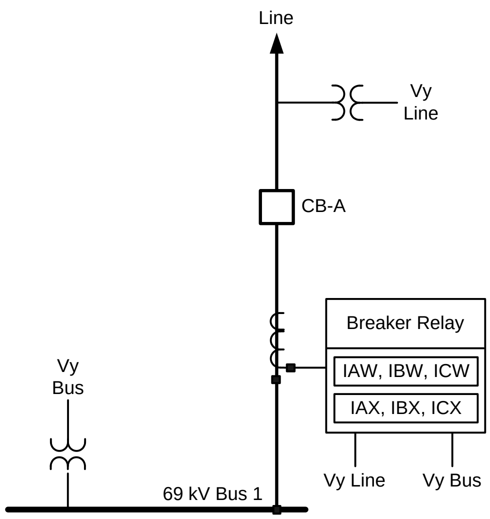

Fig. 2. One-Line Diagram of AEP Breaker Monitoring System

The example data in Fig. 3 include recorded bus voltage (VS1_kV), trip bus dc voltage (DC1), and trip circuit statuses during an energization test on the 69 kV bus.

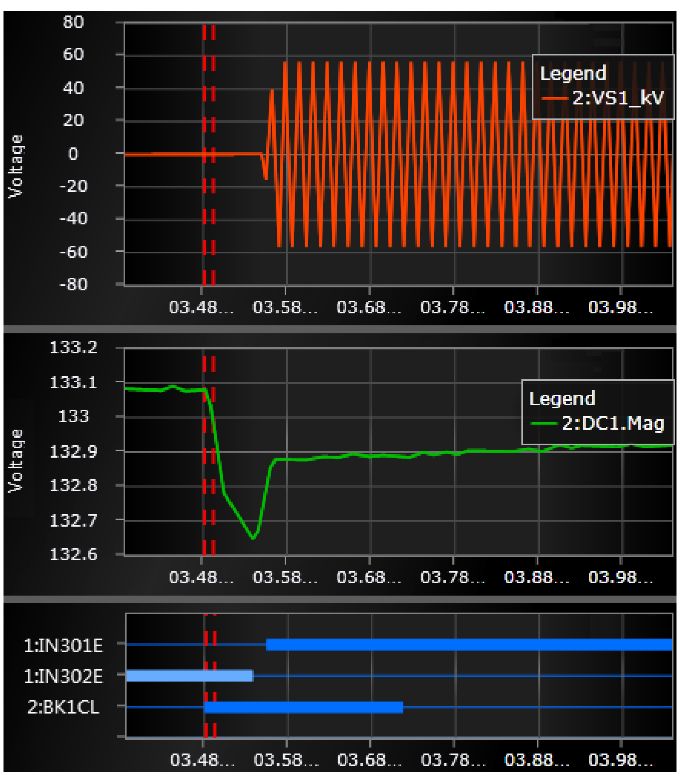

Fig. 3. Bus Energization Test Bus Voltage, Trip Bus Voltage, and Trip/Close Statuses

Using both the breaker relay and CBM, the AHC is able to capture bus energization voltage in tandem with trip bus dc voltage and trip circuit contact outputs. These data provide a more comprehensive view of breaker performance characteristics that are otherwise not available with traditional monitoring systems. Results from this test show that this system can characterize the performance of all of the breaker components that play vital roles in successful operations.

1) Trip/Close Circuit Performance

Fig. 4 includes an example of the trip circuit layout for CB-A. A 125 Vdc battery provides the necessary power to energize the trip coil and actuate tripping when the breaker relay initiates via its contact output. During each event, the CBM captures the close and open status values and times for the trip circuit while recording the trip coil current. The digital status values in Fig. 3 include the 52a (IN301E) and 52b (IN302E) auxiliary contacts and the relay close output (BK1CL) from the close circuit, which the CBM recorded during the breaker energization test. Observe that when the breaker output contact closes, the trip bus voltage immediately begins to drop as it energizes the trip coil to initiate a close operation on the breaker. As soon as the breaker closes and the trip coil disconnects from the battery (observable by 52a contact assertion, 52b contact de-assertion, and VS1_kV bus energization), the 125 Vdc bus voltage begins to recover to its initial operating range. These results exemplify the system's capability to capture the concurrent behavior of multiple trip circuit components during the close operation.

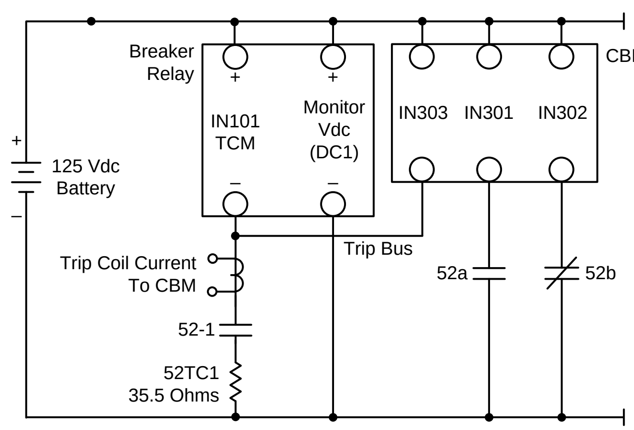

Fig. 4. CB-A Trip/Close Circuit With CBM

2) Charging Motor Time

In addition to trip circuit behavior, the CBM also records the recharging time immediately following breaker operations via motor run time. Fig. 5 includes a plot of the 52b (IN302E) trip circuit contact along with the auxiliary output contact for the breaker charging motor (IN305) for the bus energization test.

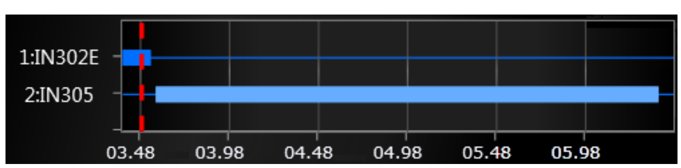

Fig. 5. Charging Motor Run Time

Observe that immediately after the breaker successfully closes (indicative of the 52b de-assertion), the charging motor starts and then runs continuously for approximately 3 seconds to recharge the CB-A breaker. These data provide the capability to track charging performance and alarm if the charge time exceeds a predetermined time limit or fails to charge. It also shows that the charging motor is behaving as expected after an operation.

C. Trip Coil Current

The CBM captures trip coil performance by recording coil current during operations. Current dynamics provide mechanical and electrical performance diagnostics. The AHC collects coil current data from the CBM and parses the data. Fig. 6 includes an example of a trip coil current from a laboratory test using a CBM to capture the data. The IED samples the current signal at a rate of 16 samples per cycle.

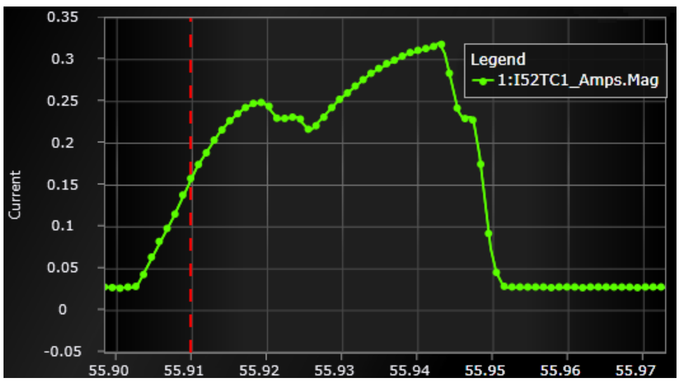

Fig. 6. Trip Coil Current Lab Test

Key transition points and peak amplitudes expose the trip coil performance and behavior. Mechanical prognosis includes armature alignment and lubrication, which increase armature travel times. Electrical prognosis includes interwinding shorts or insulation failures that demand larger current amplitude to provide adequate electromagnetic force for armature motion [3].

VI. Conclusion

Real-time asset health monitoring is an important strategy at AEP to help in safety, failure prevention, asset replacement prioritization, and maintenance optimization. Relays have vast amounts of data that can be used to help focus resources on the right equipment as needs arise. AEP's approach is to use as much relay data as possible, augmented with additional key measurements. Using highly reliable data from existing digital relays, helps reduce the cost and scale of the asset monitors.

Long-term, AEP will determine a standard for circuit breaker monitoring with both new and retrofit extra high-voltage (EHV) circuit breakers. AEP will also move toward monitoring lower voltage breakers when monitoring costs decrease. As new technologies emerge and new failure modes are discovered, AEP will continue to improve upon the AHC portfolio of monitoring capabilities.

VII. References

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VIII. Biography

Jason Byerly received his B.S.E.E. degree from The Ohio State University in Columbus, Ohio, in 2004. He has been an engineer at American Electric Power (AEP) since 2005, working on substation projects as a protection and control (P&C) engineer. He currently works on P&C standards for transmission and distribution substation design. Jason is a member of IEEE. He serves on the IEEE 1547 Working Group, is a professional engineer registered in Ohio, and was recently appointed as a U.S. representative in the IEC Technical Committee WG10.

Carey Schneider is currently a supervisor on the AEP transmission department's Asset Health Center (AHC) project. The AHC is a software and equipment monitoring effort aimed at increasing understanding of AEP substation equipment and assisting in asset management decisions. Carey has over 23 years of experience in manufacturing and business process improvement, technology project implementations, and project/engineering management. He has held numerous leadership positions that focused on process improvement projects and information technology project deployments in the utility industry, healthcare product distribution industry, and the telecommunication industry. Carey has a BS in mechanical engineering from The Ohio State University, a BS in management information science from Franklin University, and an MBA from Ohio Dominican University.

Robert Schloss is a development lead engineer in the R&D control and monitoring group at Schweitzer Engineering Laboratories, Inc. (SEL). He received his B.S.E.E. from the University of Idaho and has been with SEL since 2004. His experience includes research and development product engineering, as well as system design and commissioning of large-scale power system automation projects for critical assets. He is currently a member of IEEE.

Isaac West received his B.S.E.E. degree in 2011 and M.S.E.E. degree in 2013 from Montana Tech in Butte, Montana. He has been a power engineer at Schweitzer Engineering Laboratories, Inc. (SEL) since 2013, working in the R&D control and monitoring group.

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