ONLINE MONITORING OF ROD CONTROL SYSTEMS IN COMBUSTION ENGINEERING PRESSURIZED WATER REACTORS

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ABSTRACT

Current designs of Pressurized Water Reactors (PWRs) are equipped with control and shutdown rods that are inserted and withdrawn from the reactor core to control reactivity. In Combustion Engineering (CE) plants, these rods are moved using the Control Element Drive Mechanism (CEDM) and controlled by the CEDM Control System (CEDMCS). In the event of system failure, troubleshooting activities can have a substantial impact on plant resources. Furthermore, CEDM component failures have occurred without warning, which has led to increased costs for the plants. These issues, combined with the inherently complex design of the CEDMCS, create a need for an online diagnostics system that can improve system health monitoring, increase diagnostic capabilities, and decrease troubleshooting time.

This paper describes an advanced analysis and diagnostics system that monitors the CEDMCS during plant operation and provides critical information to onsite personnel to help detect and prevent problems before they impact normal plant operation. This system uses existing CEDMCS test points to acquire data and needs no modifications to the CEDMCS for implementation. The online monitoring capabilities automatically collect data during normal operation and diagnose failure events, reduce troubleshooting time and provide plant personnel with valuable information which is not currently available. Additionally, the system has built-in features used to streamline routine surveillance testing, collect stationary and movement data on multiple rods simultaneously, automate analysis, and generate reports.

This system was developed with input from industry CEDMCS engineers at existing commercial facilities and has been deployed in multiple operating nuclear plants. The system has demonstrated itself to be a valuable tool for CEDMCS health monitoring, not only in reducing required man-power for routine system testing, but also in detected impending coil faults and allowing plant engineers to mitigate system component failures to prevent impending plant shut downs.

Key Words: CEDM, CEDMCS, Rod Control Diagnostics

1 INTRODUCTION

Conventional light water reactors (LWR) use specially designed rods that are moved into and out of the reactor core to control the rate of nuclear fission. In plants designed by Combustion Engineering (CE), this is accomplished using an electromechanical device known as a Control Element Drive Mechanism (CEDM) that is controlled by the CEDM Control System (CEDMCS). Although these systems have operated very reliably in commercial nuclear plants for decades, the lack of any substantial built-in monitoring and diagnostics can result in lost revenue and wasted resources when unexpected problems arise. This is compounded by the fact that aging and obsolescence is causing problems to occur more often [1]. One area of industry concern is CEDM coil failure resulting in a dropped rod. This has created an opportunity for an online diagnostics system that can improve system health monitoring, troubleshooting, and trending capabilities of the CEDMCS.

This paper describes the results of a research and development (R&D) effort resulting in a diagnostic system that performs monitoring of CEDMCS health and identifies coil degradation, and discusses some of the data analysis techniques used to predict system health. In addition to providing diagnostics information, the system automates field testing of CEDM timing and sequencing, coil voltage and current levels, coil voltage calibrations, and hold bus surveillances. The combination of diagnostics capabilities and test automation provided by this system facilitates efficient condition-based maintenance of control element drive mechanism systems.

2 BACKGROUND

The CEDM is an electromechanical system that provides precise vertical movement to each of the Control Element Assemblies (CEAs) located within the fuel bundles of a reactor core. The CEDMs, shown in Figure 1, are located on top of the reactor vessel head and vary in number from 37 to 91 depending on the specific plant. Reactivity control is accomplished by moving the CEAs in groups which are symmetrically distributed throughout the reactor core to achieve reactivity control. Regulating control groups typically consist of 4-8 CEAs, and are used to provide precise reactivity control. Shutdown control groups, containing up to 20 CEAs per group, are used for the sole purpose of providing a rapid decrease in reactivity during the instance of a reactor trip.

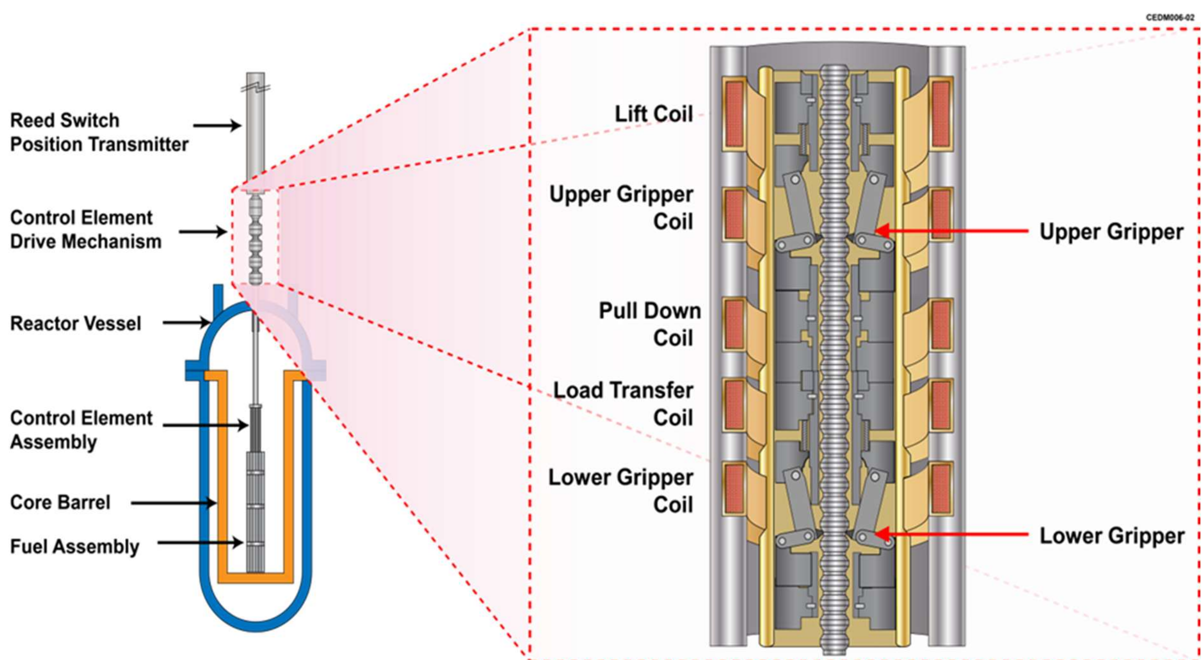

Figure 1. CEDM Internal Components

Each CEDM consists of five coils and two gripping mechanisms. Linear movement of the CEA is accomplished by sequentially inducing a magnetic field in the coils to operate the mechanical parts of the system. The magnetic flux provides the energy needed to hold, insert, or withdraw the CEA from the reactor core in ¾ inch steps. The standard CE CEDM design consists of five electric coils [Lift (L), Upper Gripper (UG), Pull Down (PD), Load Transfer (LT), and Lower Gripper (LG)] and two electromagnetic jacks with grippers (Upper and Lower). A detailed view is shown in the cross section of the CEDM coil assembly in Figure 1. The PD coil has been eliminated in some plants.

The CEDM system block diagram, shown in Figure 2, includes control inputs from the control room panel and reactor protection system, CEDM power switching circuitry, subgroup logic, common logic, power distribution from the motor generator (MG) sets, and the CEDM. The CEDMCS, located outside of containment, provides control signals to the CEDM by supplying the proper power sequencing for desired CEA movement. Control is accomplished through use of the power switching modules, subgroup logic cards, and common logic cards. Electronic components associated with each of these items can cause major system failures, making up almost half of all CEDM failures [2].

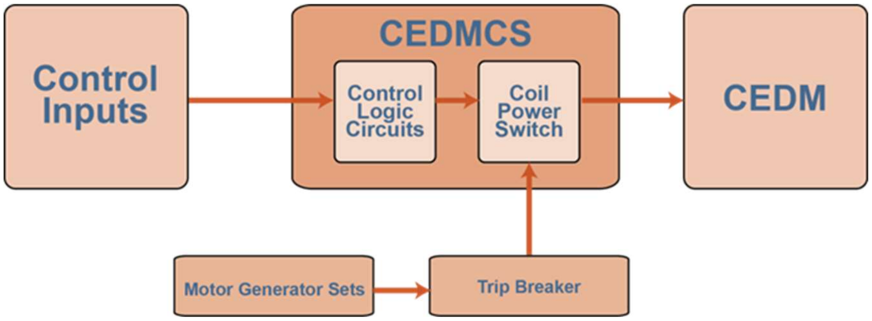

Figure 2. Major Components of the CEDMCS

3 DESCRIPTION OF THE CEDMCS DIAGNOSTICS SYSTEM

AMS, along with collaboration with engineers at Palo Verde Nuclear Generating Station (PVNGS), designed and developed a comprehensive CEDM Monitoring and Diagnostics (CMD) system. The CMD system is designed to make non-intrusive measurements of existing test point signals during all modes of plant operation to provide automated monitoring, fault detection, and diagnostics to classify system failures, trend important parameters, log abnormal events, and localize faults. Inputs from existing test points which can be acquired without affecting normal plant operation, are used as inputs to the CMD system. The CMD system uses this data to perform monitoring, fault detection, and diagnostics. By using data algorithms to extract and calculate important parameters, diagnostic information can be obtained.

The CMD system consists of a CEDM data acquisition (CDA) hardware unit, a control computer, associated cables, and software. Figure 3 shows a block diagram of the main components of the CDA hardware. The control computer connects to the CDA equipment over a standard TCP/IP network connection. The plant CEA test signals are connected to the rear panel of the CDA equipment using custom made, low-noise cables, and plant-specific connectors at the field-end that connect to the plant's CEDMCS test points. Two versions of the data acquisition system hardware, CDA-1 and CDA-2, were developed as shown in Figure 4. The CDA-1 is capable of data acquisition of 24 CEAs simultaneously (1 Group with 6 subgroups) whereas the CDA-2 can acquire data on 6 CEAs simultaneously (1 subgroup).

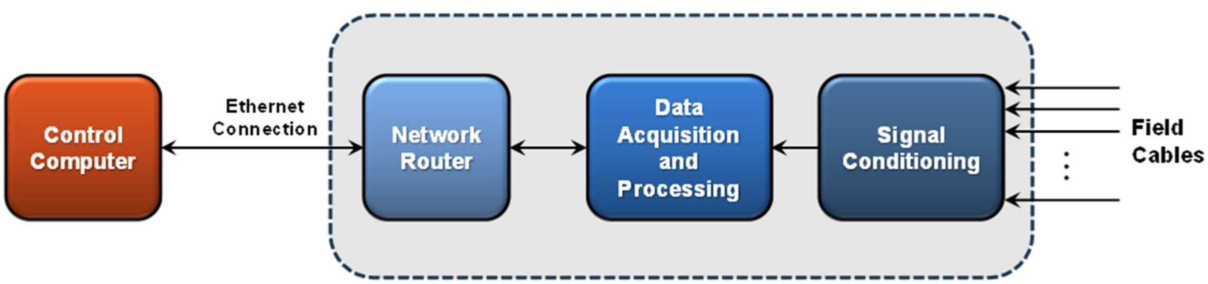

Figure 3. Block Diagram of CDA Equipment Components

Figure 4 Size Comparison Between CDA-1 (Left) and CDA-2 (Right)

In addition to custom hardware, a custom software package was developed to perform control of the hardware, analysis of collected data, and rapid report generation. Figure 5 shows three user interface screens used for data acquisition. This includes a configuration screen where data acquisition parameters are controlled, a main data acquisition screen used to collect CEDM coil currents and voltages, and a CEDM voltage calibration screen that can be used during adjustment of the individual phases of a CEDM coil. Figure 6 shows the software's various analysis screens. DC Hold analysis is used to test the CEDMCS hold bus which applies an alternate voltage for maintenance of the main power switch, a timing analysis screen used to calculate the times and transitions between the various electrical events during CEDM movement, and a data overlay screen which is useful for comparison of various data sets. A more in-depth discussion of the analysis features can be found in [3].

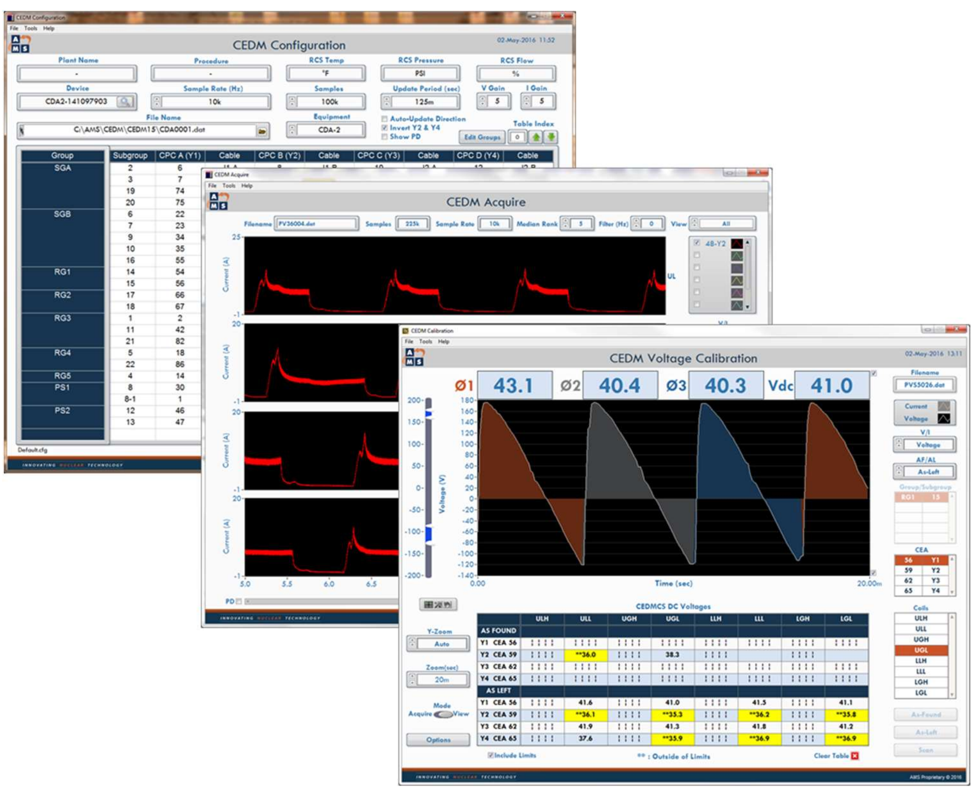

Figure 5. CDA Software Data Acquisition Screens

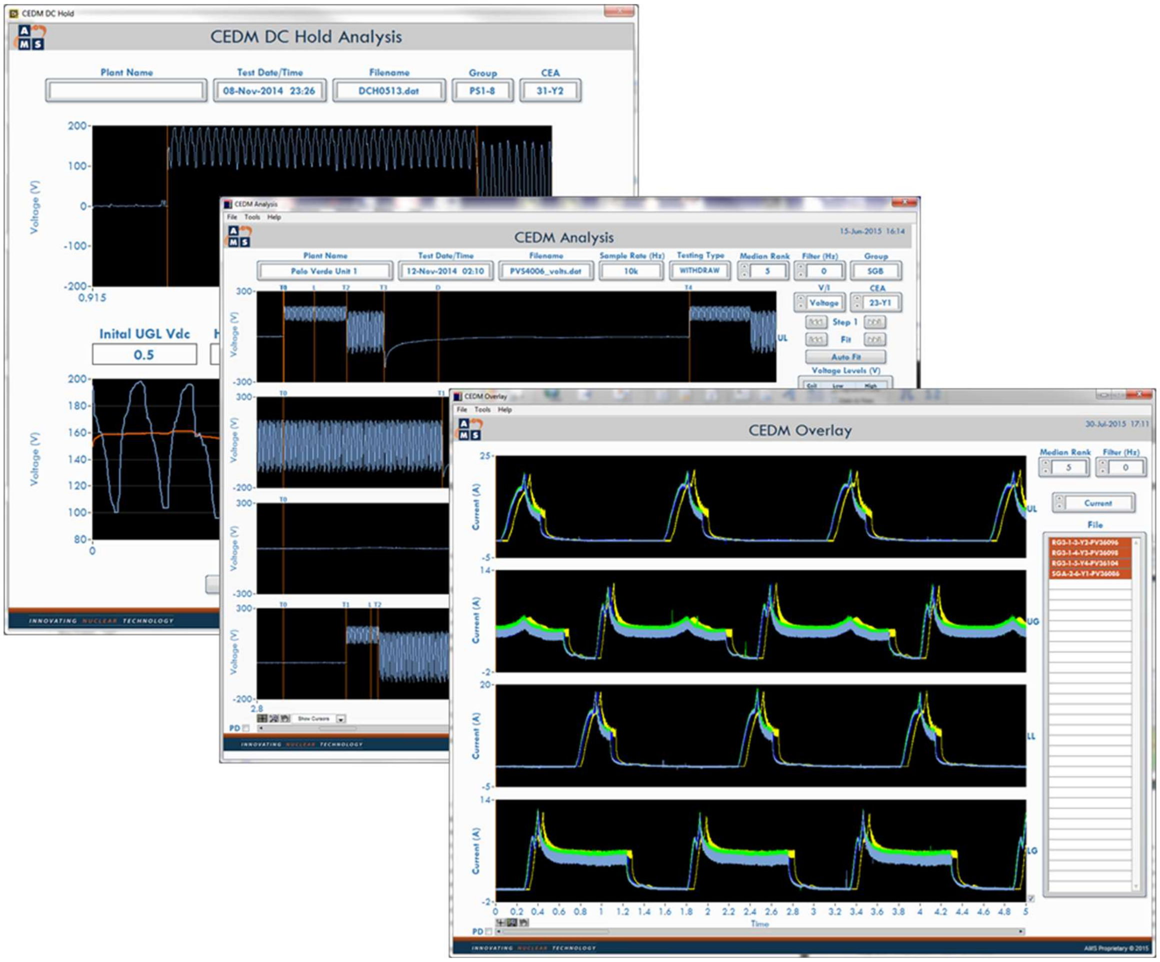

Figure 6. CDA Data Analysis Screens

4 DIAGNOSTIC TECHNIQUES USED TO DETERMINE CEDMCS HEALTH

During development of the CMD system, various techniques were investigated for their usefulness in detecting CEDMCS problems. Of these it was found that coil resistance and temperature, as well as stationary coil current peak-to-peak amplitude was the best indicator of developing problems. These techniques and the details of the implementation are discussed in the following sections.

4.1 Coil Resistance and Temperature

A major concern with CEDM coils is their ability to withstand elevated temperatures for extended periods of time, especially during operation where a single coil is continuously energized for an entire fuel cycle (18-24 months). Discussions with engineers at supporting nuclear sites have indicated that premature coil failure resulting from thermal degradation is becoming an industry-wide issue for CE-style coils. Not only is there residual heat from the reactor, but since current is continuously flowing through the Upper Gripper coil when the reactor is at power, a non-negligible amount of heat is being generated by the coil itself. Remotely being able to determine the temperature of a CEDM coil was an important milestone during the development of the CMD system. Figure 7 shows a lower gripper coil placed inside an industrial temperature chamber with a thin film RTD attached to record the ambient temperature surrounding the coil. Figure 8 shows the surface temperature as a function of DC resistance.

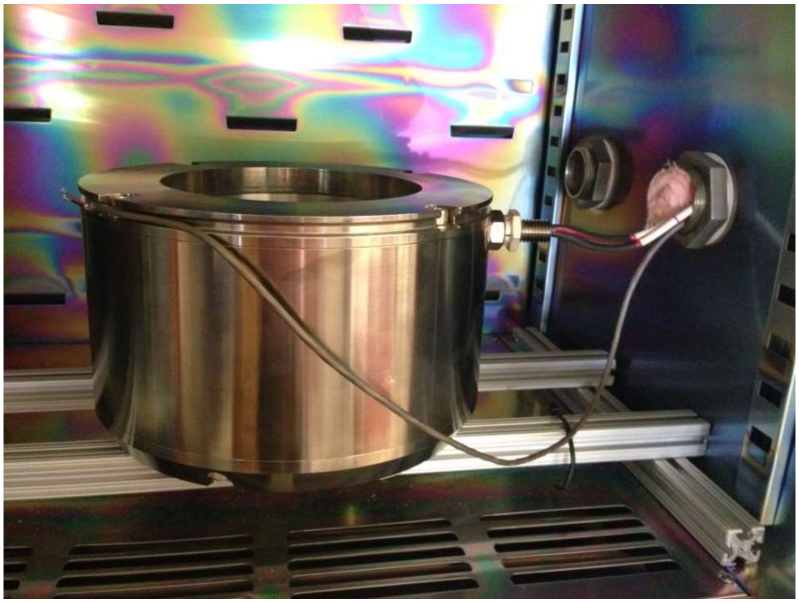

Figure 7. Lower Gripper Coil Temperature Testing

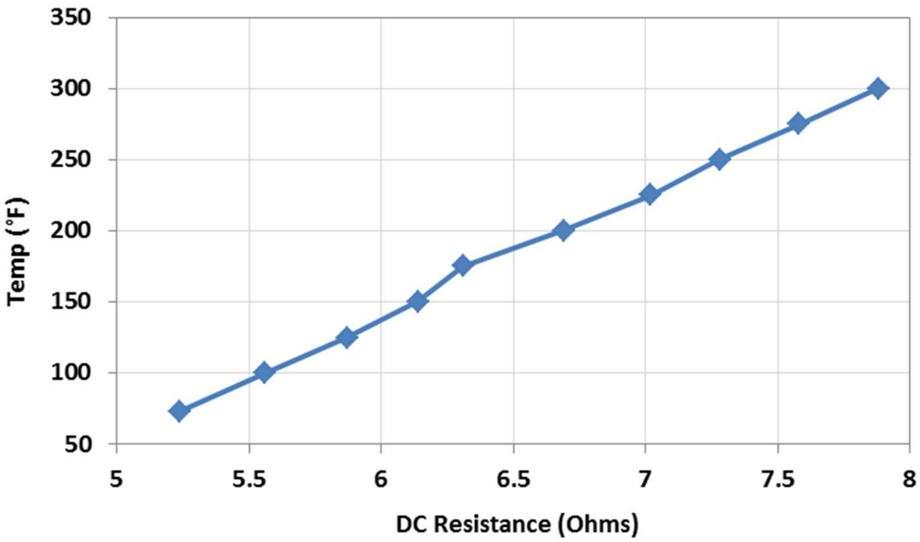

Figure 8. Lower Gripper Temperature as a Function of DC Resistance

This relationship is linear, and of the form:

$$T_{coil} = R_{coil} \cdot m + b \tag{1}$$

where R_{coil} is the measured resistance of the coil, and m and b are constant linear slope and offset parameters. The linear parameters can then be calculated using the collected laboratory data, which are unique for each type of coil (upper lift, upper gripper, pull down, lower lift, lower gripper). In the field, the coil temperature is calculated using:

$$T_{coil} = \left[\left(\frac{V_{avg}}{I_{avg}}\right) - R_{cab}\right] \cdot m + b \tag{2}$$

where V_{avg} and I_{avg} are the steady state average voltage and current, R_{cab} is the resistance of the cable from the CEDMCS cabinet to the CEDM coil, and m and b are the slope and offset parameter of the particular coil. Note that the terms within the brackets of Eq. 2 are equivalent to R_{coil} in Eq. 1.

The research above was used to integrate resistance and temperature calculations into the CMD data analysis tools, and several reporting and analysis tools were built into the CMD software. Figure 9 shows two user interface screens for reporting functions. The main report screen can be used to calculate various parameters of collected data including voltage and current levels, coil resistances, temperature, movement event timing, and others. Additionally, a Core Map Data View screen was developed, providing a visual representation of collected data, mapped to each CEA and its position in the reactor core.

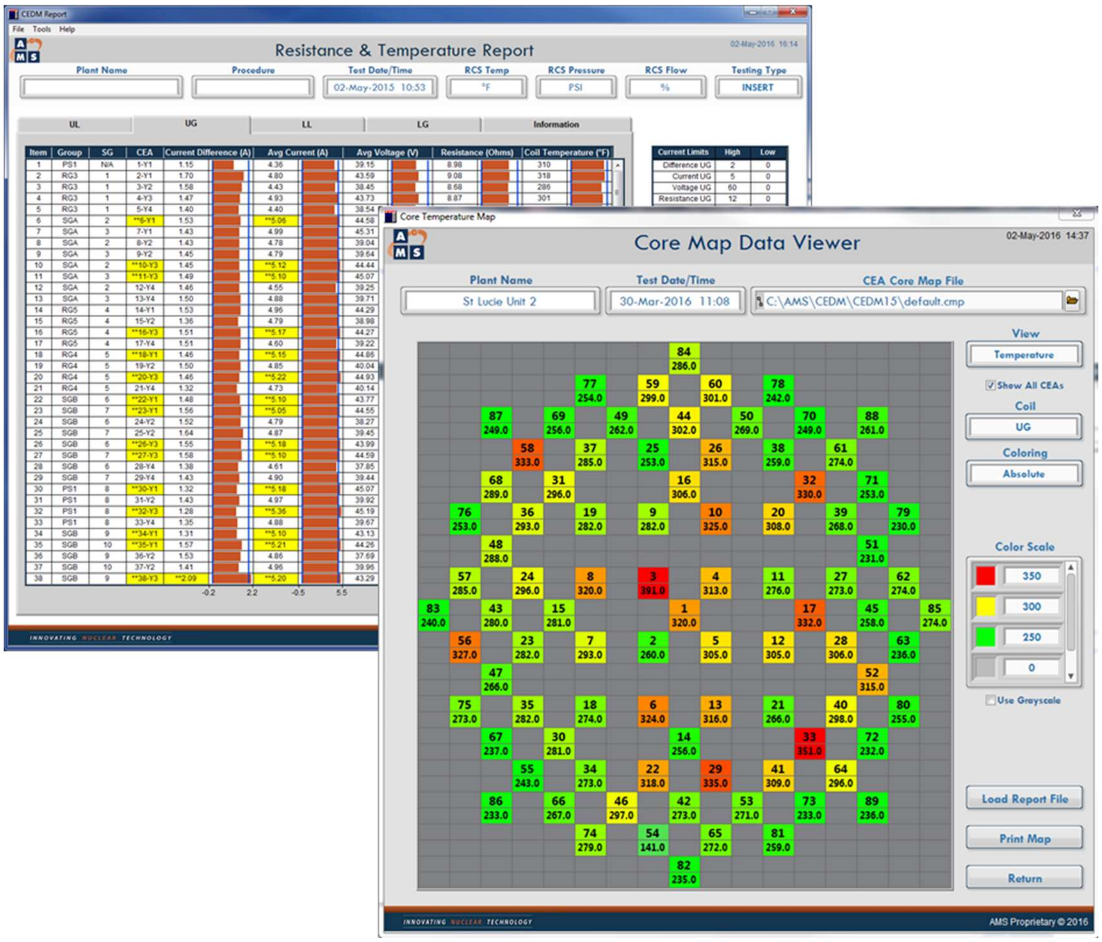

Figure 9. CDA Report Screens

4.2 Stationary Coil Current Peak-to-Peak Amplitude

One method that was identified as a precursor to coil failure is to monitor the peak-to-peak amplitude of the current through the upper gripper coil while the CEA is in stationary mode (i.e., the CEA position is being maintained by the upper gripper and its associated coil). The physical mechanism behind this monitoring technique is a result of the way in which a CEDM coil typically degrades in the presence of elevated temperatures. Over time, the enamel insulating the coil winding will deteriorate. If enough of the enamel has deteriorated, the coil can suffer from turn-to-turn shorts, where the windings of different layers short together. Since the conductor making the coil has a constant resistance per unit length, shorting between turns will reduce the coil resistance. Using Ohm's Law, since the voltage output of the CEDMCS remains constant, a reduction in resistance is accompanied by an increase in current flow through the coil.

This also results in a decrease in inductance, and thus a decrease in the energy of the generated magnetic field. If the magnetic field is reduced enough, CEAs can be inadvertently dropped into the reactor core.

Figure 10 shows actual plant data collected with the CMD. The figure compares a nominal upper gripper hold current trace with a maximum peak-to-peak current of 1.43 Amps with the same coil current data several weeks later. The stationary coil current experienced a dramatic increase, showing a peak-to-peak current of 4.79 Amps. Since the current has increased while the control voltage remained constant, a reduction in the coil's resistance has occurred. This would imply degradation of the coil including turn-to-turn shorts in the coil winding. Because of this investigation, plant personnel were able to switch the CEA from the upper gripper to the lower gripper for the remainder of the fuel cycle. Subsequent outage testing revealed the coil inductance had dropped from a nominal 125 mH to 12.23 mH, prompting a replacement of the coil. Had the plant not discovered this issue, the CEA would have most likely dropped into the core, resulting in an unplanned plant shutdown.

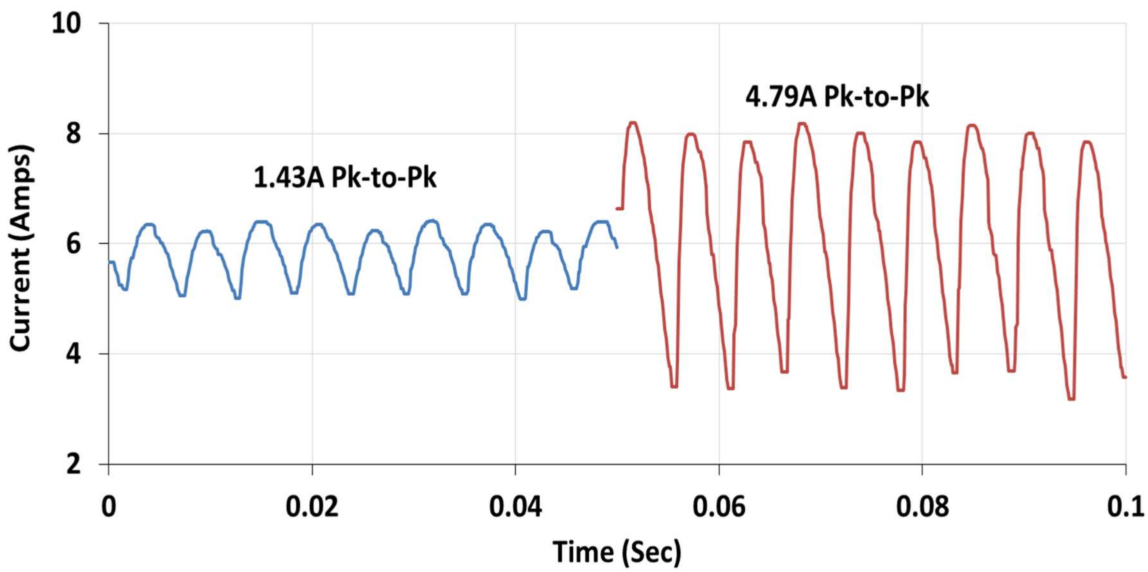

Figure 10. Comparison of Nominal and Elevated Coil Current Peak-to-Peak Amplitude

5 SYSTEM DEPLOYMENT AND USER EXPERIENCE

The following section describes verification and validation testing of the CMD system performed at PVNGS and other operating nuclear reactors, as well as an example of actual system deployment for online condition and health monitoring in operating nuclear units.

5.1 Verification and Validation at PVNGS

In 2014, AMS supported PVNGS engineers during outage activities which included coil voltage calibration and individual CEA movement. Initially, testing proceeded relatively slowly because both PVNGS and AMS procedures were performed sequentially so that AMS results could be verified with results generated from plant personnel. Plant engineers then approved the use of the CDA-1 system alone to perform the calibrations, dramatically increasing the efficiency of the testing, and thus demonstrating the potential of the system.

Later in the same year, AMS returned to PVNGS to validate and test the CMD again in an operating unit. Unlike the previous testing, PVNGS exclusively used the AMS CDA-2 equipment to perform the testing. Figure 11 shows photos taken during this outage testing. Previously for voltage calibration, technicians recorded as-found and as-left values manually from a digital multimeter (DMM), added an oscilloscope if adjustments were needed, then disconnected, and reconnected to the next CEA's test points. This process was not only inefficient, but increased the chance of operator transcription errors. By using the CDA-2 hardware and software, voltage data is streamed in and the individual RMS of each phase is calculated, along with the total DC value. A software data table is used to record as-found and as-left data and any values outside of set limits are highlighted accordingly. By using multiple sets of equipment and teams in parallel, AMS reduced the time required for this critical patch surveillance activity by approximately 50%, according to plant personnel.

Figure 11. AMS and PVNGS Engineers Performing Voltage Calibrations with AMS Equipment

5.2 Testing at Other Nuclear Power Plants

In 2015, AMS travelled to another nuclear power plant at the request of plant engineers to demonstrate the developed system during the plant's refueling outage. This plant's CEDM control system is similar to PVNGS with the addition of the Pull Down (PD) coil. AMS personnel collected 67 data files totaling nearly 1000 CEDM coil traces. Stationary voltage and current data was collected on all 91 CEAs in addition to several files of CEA movement data.

Stationary data was used to perform data analysis which highlighted CEA 82 having excess average current (8.8 A). Further inspection of this CEA revealed that one phase of the Upper Gripper (UG) coil is on continuously when the Lower Gripper (LG) is energized. This can be seen in the left plot shown in Figure 12. The UG should be in a de-energized state, however one phase is clearly still energized. When overlaid with another correctly operating CEA of the same sub-group (Figure 12 right plot), this phase also has an elevated average value, thus contributing to the out-of-tolerance average current indicated in the analysis. As a result, plant personnel replaced the CEA's power switch, after which the current had returned to normal values.

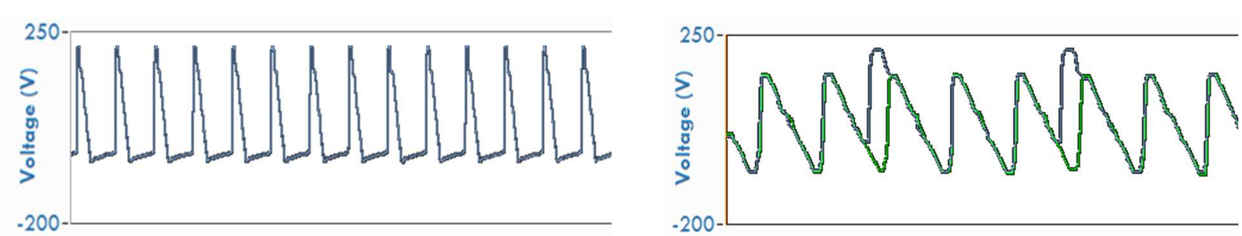

Figure 12. CEA 82 Upper Gripper contains a continuously operating phase (left) and Overlay of CEA 82 Upper Gripper and normal CEA Upper Gripper (right)

5.3 Deployment of the CMD System for Online Monitoring

As discussed in the Section 4.2, stationary current peak-to-peak amplitude was used at PVNGS to identify a CEDM coil problem online before it impacted plant operations. Prior to this event, in early 2016, engineers at PVNGS performed a temporary modification to leave four CDA-2 systems connected to all CEAs of a unit during operation. Using the built-in acquisition scheduler, engineers set up the systems to collect stationary data every hour over the course of the plant's operating cycle. Periodically, technicians would retrieve data from the CMD system computers, which would be analyzed using the CMD software analysis tools. Using this procedure, engineers identified a degrading coil online and prevented a possible reactor trip.

6 CONCLUSION AND NEXT STEPS

The work described herein summarizes a research and development effort aimed at providing personnel at nuclear power plants with a system for monitoring and diagnostics of the CEDMCS. This system offers plant engineers and technicians a tool for streamlining routine maintenance work, troubleshooting existing CEDMCS problems, and diagnosing developing problems before they impact plant operation. The system was tested and validated in two operating nuclear plants, and has proved to be a valuable tool as demonstrated by the user experience of the deployed system discussed here. Currently, engineers at PVNGS and AMS are collaborating on a second-generation system intended for permanent installation and continuous online monitoring of the CEDMCS to ensure efficient and reliable operation for years to come.

7 ACKNOWLEDGEMENTS

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