ADVANCED DIGITAL ROD POSITION INDICATION SYSTEM FOR EXISTING AND NEXT GENERATION NUCLEAR REACTORS

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Abstract

The designs of many existing pressurized water reactors (PWRs) incorporate a digital rod position indication (DRPI) system to monitor the positions of the control and shutdown rods within the reactor. Recently, aging and obsolescence issues have led to an increase in problems with the DRPI systems including analog card failures and coil cable connection problems. These problems, along with plans for plant life extension, have prompted the industry to actively seek new options to monitor the health and accuracy of these DRPI systems in order to ensure reliable plant operation.

1. Introduction

Existing nuclear power plants are approaching the end of qualified life for several components of the existing DRPI systems during the next decade and are actively seeking replacement options at this time. There has been a significant push in recent years for plants to replace aging analog systems with digital systems made from commercial-off-the-shelf (COTS) parts. Using these commercial parts can provide plants with more options for replacement in the future.

In addition to obsolescence concerns, the lack of diagnostic capabilities in the existing DRPI design is a significant problem. The current DRPI systems do not include any diagnostic information on their health other than the current rod position indication. As such, DRPI failures can occur without warning, which can lead to increased costs for the plant, especially if replacement parts cannot be requisitioned in a timely manner. A means to monitor the DRPI system is needed which can warn plant engineers of developing problems so that resources can be put in place before a failure occurs.

Recent advances in commercial data acquisition hardware design have made possible the creation of data acquisition systems that are cheaper, faster, more accurate, and provide more capabilities than the technology that is currently in service in most nuclear power plants. In an effort to take advantage of these technological advances, the Southern Nuclear Company that operates the Farley and Vogtle nuclear power plants, enlisted Analysis and Measurement Services Corporation (AMS) to develop a DRPI system based on the National Instruments Compact RIO technology. A prototype DRPI system was constructed and tested at the Farley nuclear power plant during a recent refueling outage.

2. Background of rod control system

A PWR is equipped with control and shutdown rods which are inserted into and withdrawn from the reactor core to control the power level in the reactor. The control rod drive mechanism (CRDM), which is a magnetically coupled positioning system, is provided to raise or lower the control and shutdown rods under manual or automatic control. The CRDM is designed so that, in the event of a reactor trip, all withdrawn control and shutdown rods will fall into the reactor core to shut down the nuclear reaction. [1]

The DRPI system is designed to continuously sense and display the positions of each of the control and shutdown rods. This is accomplished through the use of coil stacks which are mounted on the rod control housing above the reactor as shown in Figure 1. The coils are excited with an AC voltage and magnetically sense the presence of the control rod drive shaft in the center of the coil. [2]

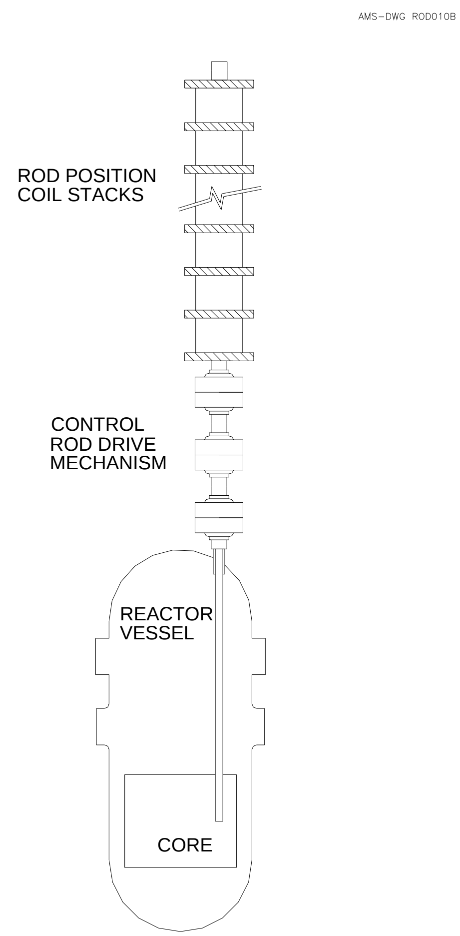

Figure 1 Location of rod position indication coil stacks.

The DRPI system consists of two redundant components (Data Cabinets A and B) which are located inside containment to monitor the coil currents and convert them into a digital position signal. The digital position information is then transmitted to the rod position display in the control room. Figure 2 shows an example of the DRPI system. The coils are excited with an AC voltage. When the control rod shaft enters the coil, it changes the coil impedance to the AC voltage thus changing the AC current through the coil. The analog electronics in the existing DRPI system detect the change in current and create a digital bit for each coil in the coil stack. These digital bits are transmitted to the control room to provide the rod position.

The prototype system measures the coil voltages/currents and provides the same digital position information as well as enhanced step position, coil impedance assessment, and rod drop data availability. The prototype can be used as a replacement or added as an advanced rod diagnostic system to supplement the existing DRPI system.

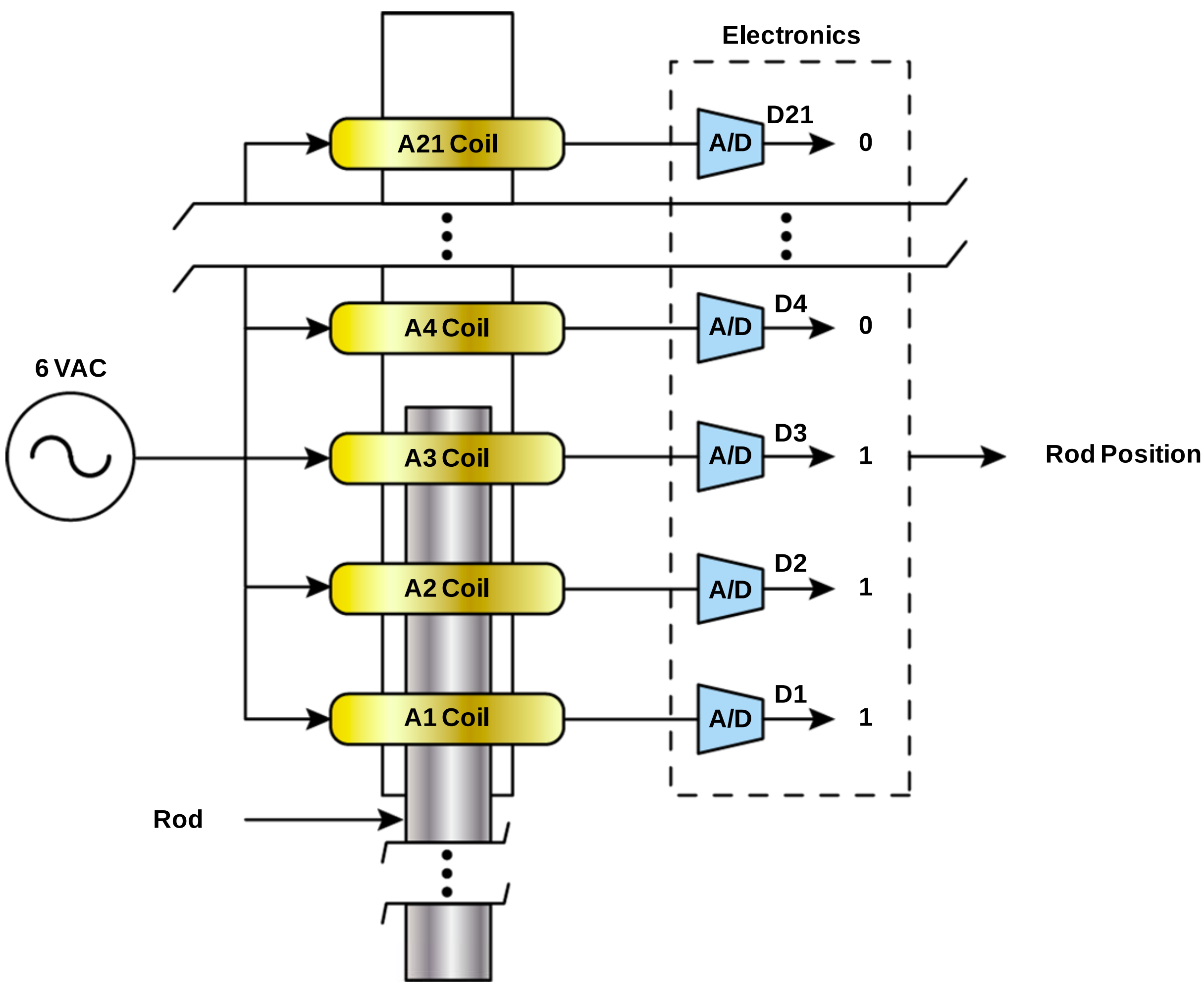

Figure 2 Example of existing DRPI system.

Another use of the DRPI system is to perform the rod drop time test by monitoring the voltage across all the coils in the stack while the rod is dropped. The motion of the rod drive shaft through the coil stack induces a voltage in the coils which is proportional to the drive shaft velocity through the coil stack. Rod drop time testing is typically performed after each refueling outage.

3. Description of the prototype system

The prototype system consists of a single chassis including a Compact RIO controller, field programmable gate array (FPGA) backplane, and input / output (I/O) modules to monitor 21 coils on a single rod. This equipment is produced by National Instruments [3]. The architecture can easily be scaled to accommodate any number of rods. The position monitoring component of the system is implemented completely on an FPGA for true hardware reliability. Additionally, the real-time controller of each chassis can be connected via Ethernet to a single control computer to share position data remotely via a local area network (LAN). A photo of this equipment configured for 32 rods is shown in Figure 3. Each Compact RIO chassis will collect data on the coil signals from 8 rods.

The Nuclear Regulatory Commission (NRC) has been extremely cautious allowing the nuclear industry to implement FPGAs and COTS digital systems due to their high complexity resulting in difficult safety assessments. However, now that many of the new nuclear plants being constructed have digital systems, these safety concerns and methods of assessments for digital systems will be established laying the ground work for COTS digital systems [4].

Figure 3 Photo of AMS prototype advanced rod diagnostic system.

During the Farley Unit 1 CRDM timing and rod drop time testing in November 2007, the prototype system was connected to the DRPI A Data Cabinet and to a network link to the power cabinets outside containment, as shown in Figure 4.

4. Description of the in-plant prototype testing

The prototype system testing was performed in conjunction with the CRDM timing tests and rod drop time tests that were performed on one control rod in Control Bank D (CBD). The test sequence for CBD is shown in Figure 5. First the bank was withdrawn from 0 to 48 steps, stopping every 12 steps to verify DRPI indication. A step is the minimum distance a rod may be moved in or out of the core and is equivalent to 5/8". Next the bank was withdrawn 12 steps from step 48 to step 60 and then inserted 12 steps from step 60 back to step 48 while the CRDM timing data was acquired. Then the bank was withdrawn from step 48 to step 226 stopping every 12 steps to verify DRPI indication. After the DRPI indication was verified, the bank was fully inserted from step 226 to step 0 and withdrawn from step 0 to step 226 twice. The bank was then dropped by opening the reactor trip breaker to obtain the rod drop times. These tests were conducted during Mode 3 as the plant proceeded toward power operation at the end of a refueling outage.

During the Control Bank D testing, the DRPI position was monitored from the control computer. The control computer communicates with the prototype system connected to the DRPI A coils for Control Rod K06. It retrieves the rod position as well as a snapshot of the data. The prototype system also allows the complete data to be saved in the compact RIO if desired. This data was then retrieved after the testing and analyzed.

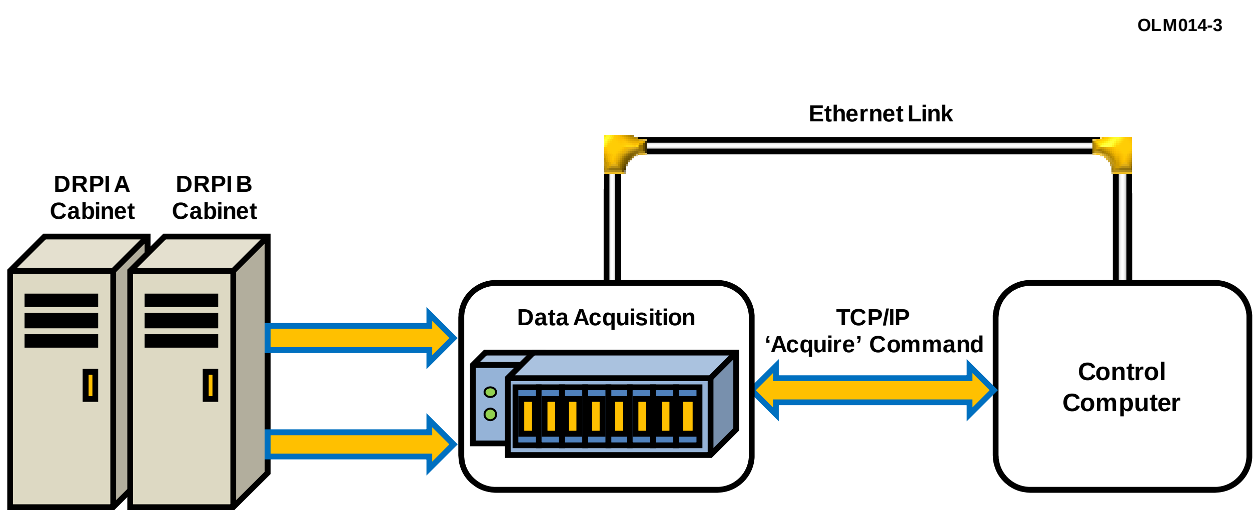

Figure 4 Test equipment setup for prototype system test.

An example showing the root-mean-square (RMS) voltages during rod withdraw through 226 steps is shown in Figure 6. The top graph shows how the RMS voltage decreases for each coil as the rod is stepped through that coil. The middle graph shows the difference in the RMS voltage between each successive coil. The largest coil difference voltage determines the rod position. The bottom graph shows the rod coil position as it moves through each coil. The prototype system correctly provided the rod position (as compared with the step count) thus verifying both the hardware and the software algorithms.

5. Prototype system benefits

Another data file was collected as the rod was withdrawn 12 steps from step 48 to step 60 and then inserted 12 steps from step 60 back to step 48. An example of the 12-step withdraw data is

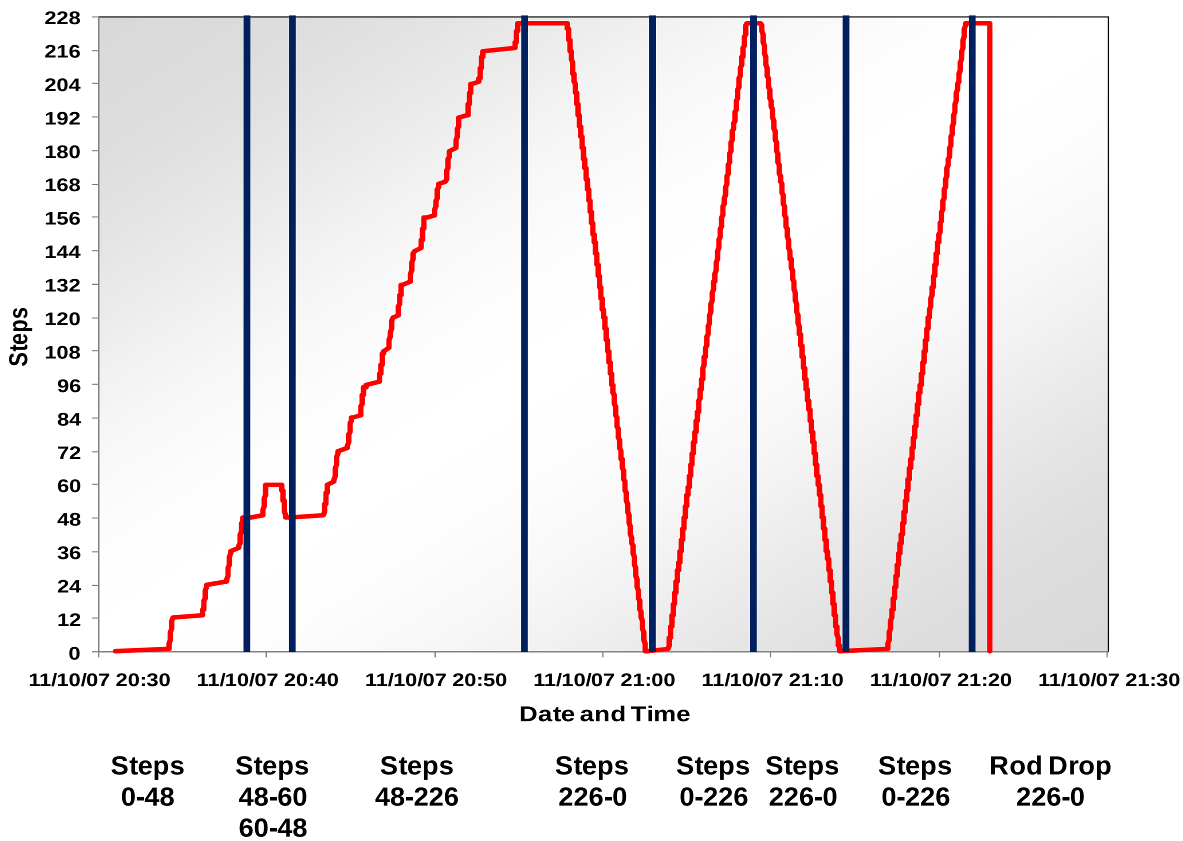

Figure 5 Control Bank D test sequence.

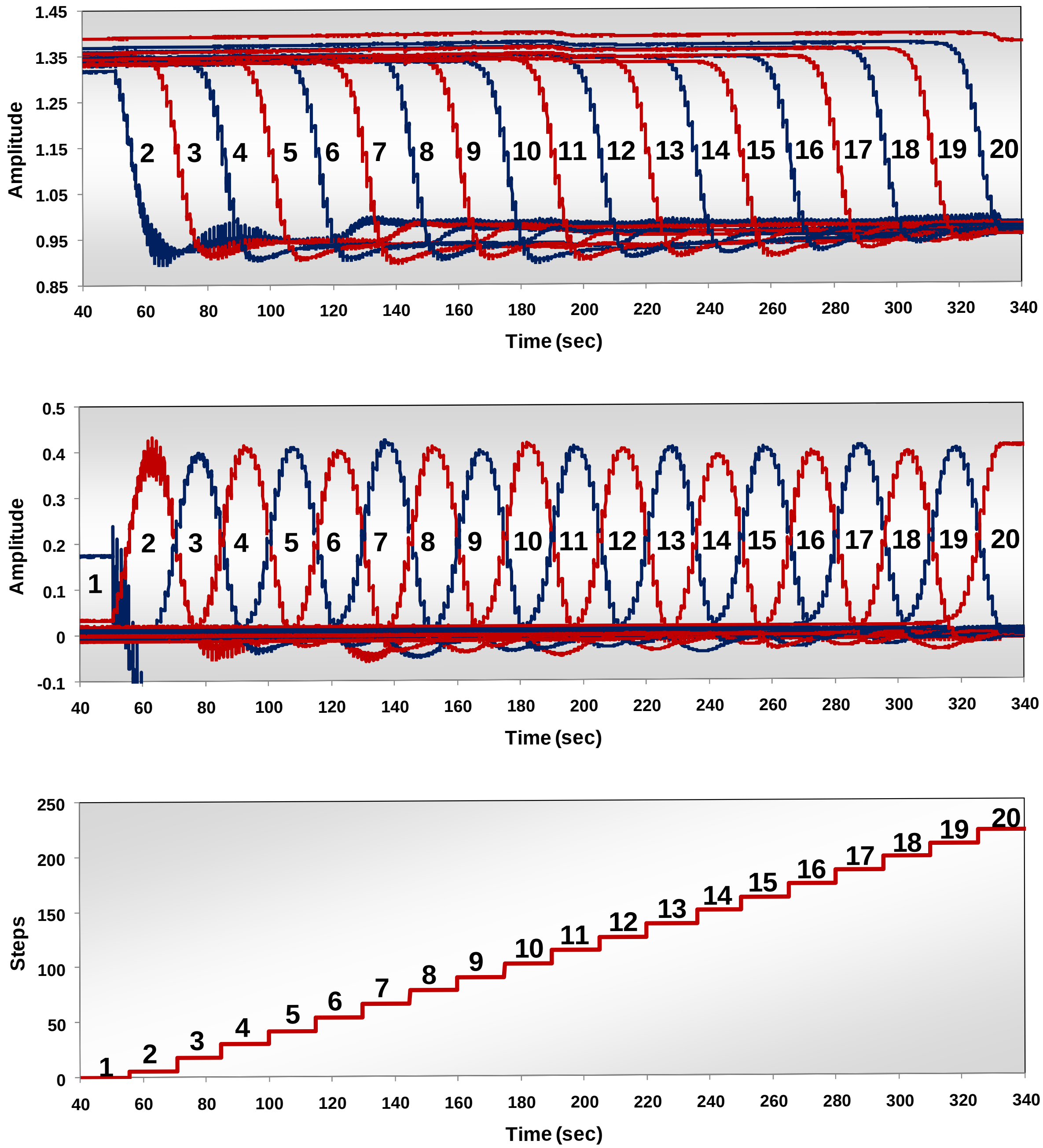

Figure 6 Position measurement during rod withdraw 226 steps.

shown in Figure 7. The top graph in the figure shows the DC data from DRPI coil 6. As the rod is stepped closer to this coil, the current induced in the coil from the rod movement increases. After the rod passes through the coil, the induced current in the coil from the rod movement again decreases. The bottom graph shows the RMS voltage through DRPI Coil 6 (purple) and DRPI Coil 7 (red) as the rod is stepped through DRPI Coil 6. Similar to the DC Data, the AC RMS voltage change increases until the rod passes through the coil. From this data, it is clear that the prototype system can provide rod position indication for every rod step.

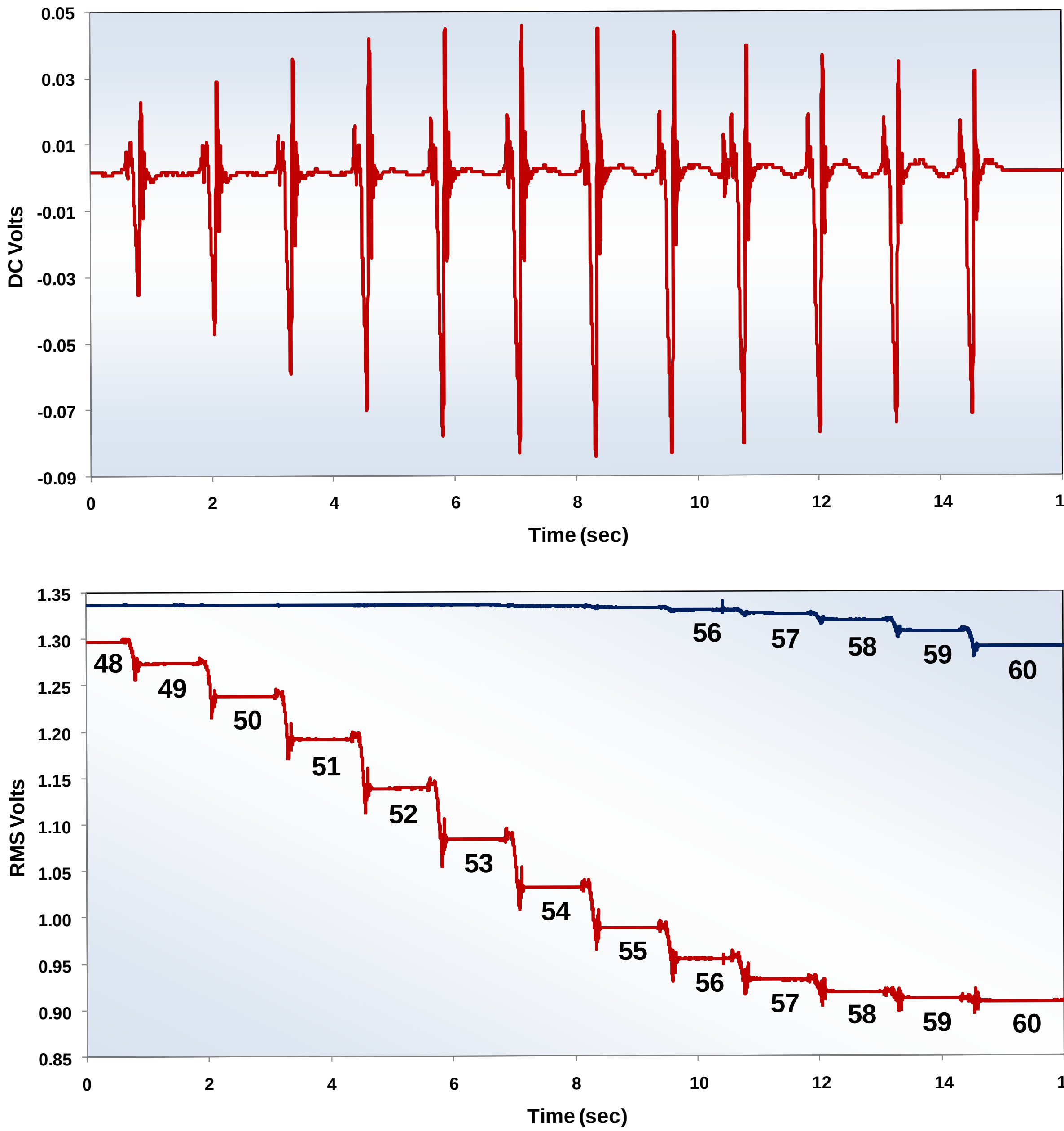

Figure 7 DRPI data during rod withdraw 48-60 steps.

Figure 8 shows a close-up of the data as the rod transitions from step 52 to step 53. In this figure the rod movement from the DC data and the AC RMS data can be easily seen. Evaluation of this data can allow the prototype system to monitor and confirm rod movement which would provide significant diagnostic value when troubleshooting rod movement and position systems.

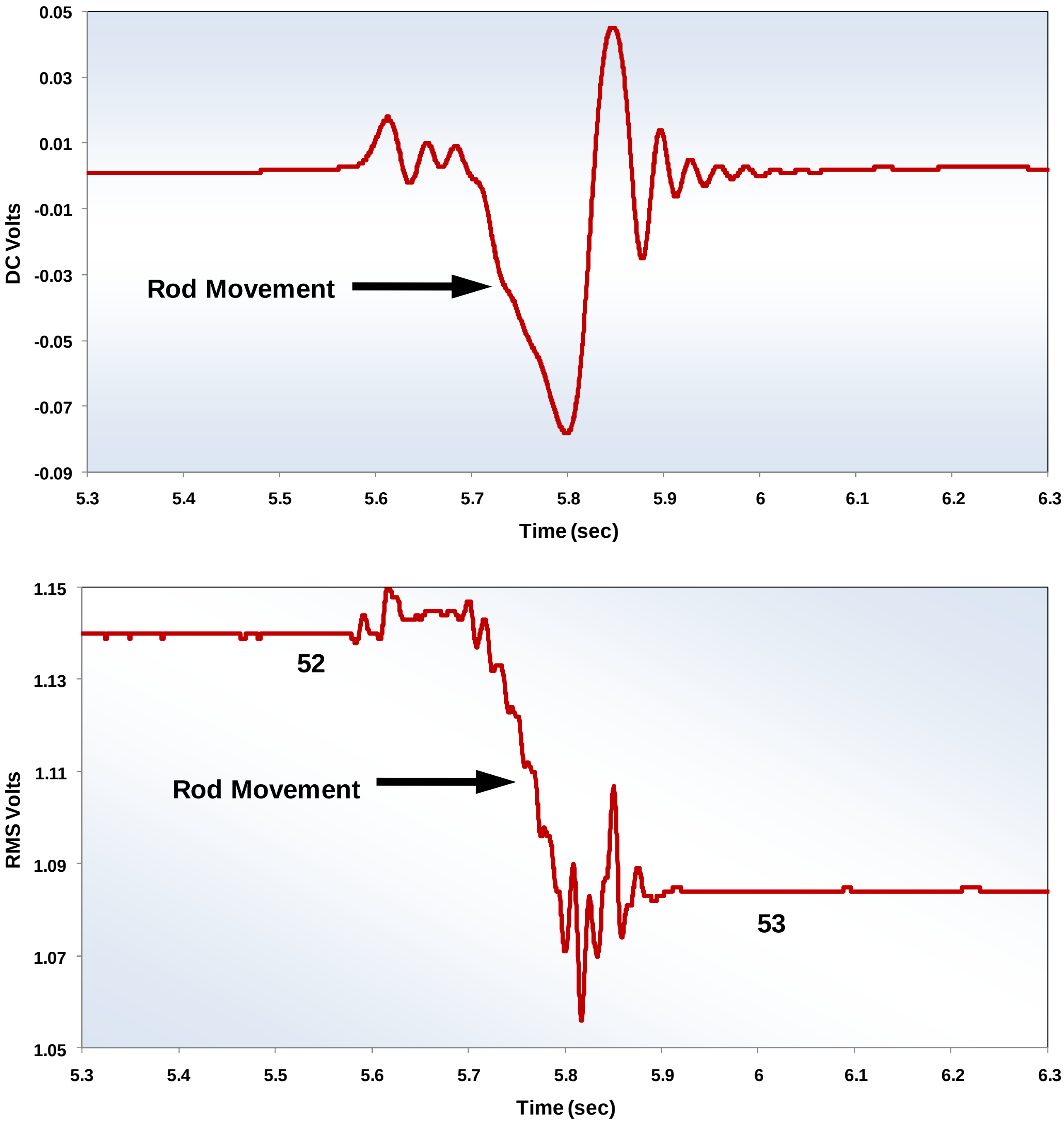

Figure 8 DRPI data during rod withdraw step 52 to step 53.

For comparison with rod drop data, Figure 9 shows an example of the rod drop data obtained for each of the 21 DRPI coils and overlaid with the typical rod drop trace obtained by summing the 21 DRPI coil signals. This data indicates it is possible to automatically obtain the rod drop data during any rod drop from the DRPI coil signals. For proper timing, the system will also need to acquire a trigger signal from the reactor trip breaker.

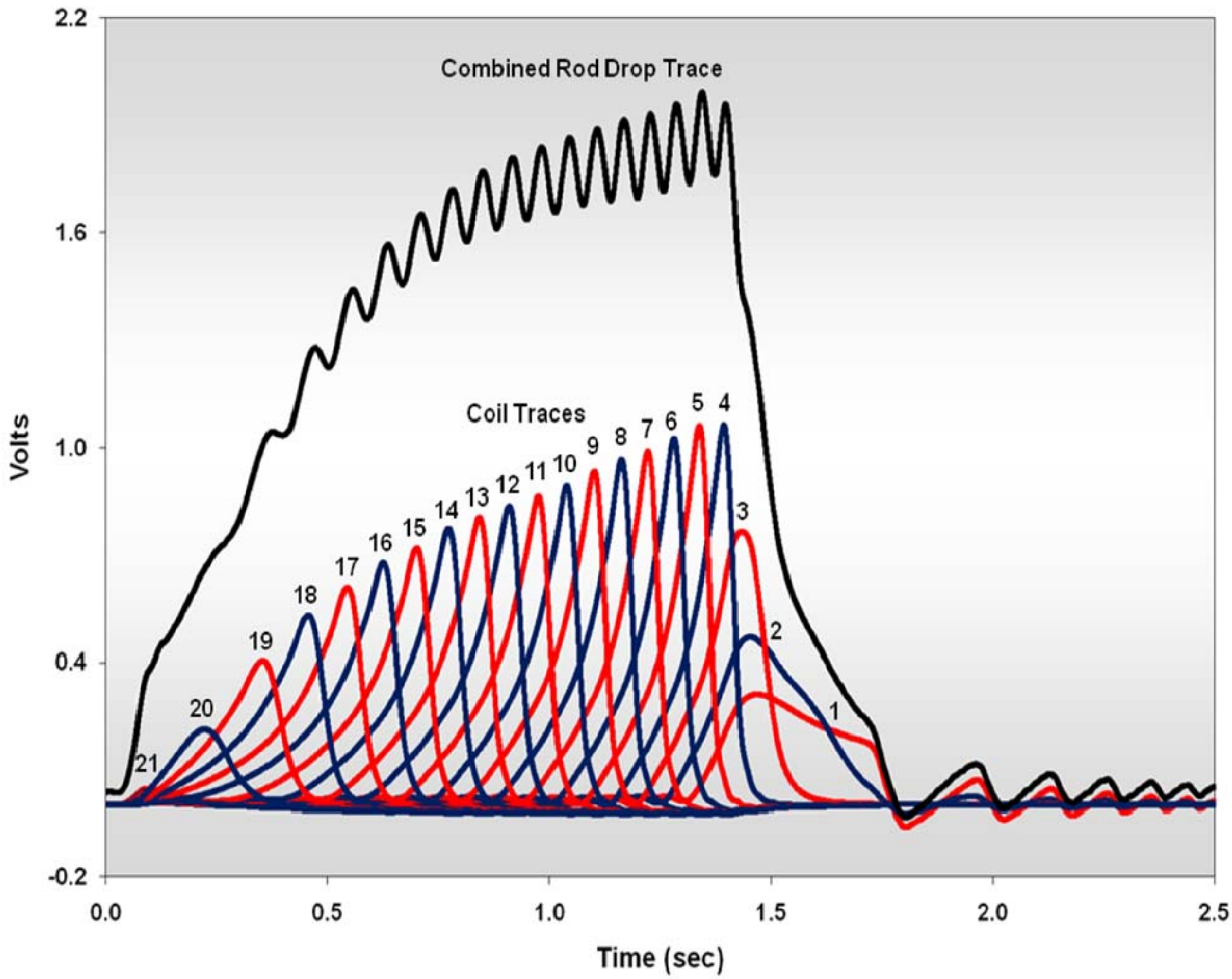

Figure 9 DRPI data during rod drop from step 226 to step 0.

By analyzing the sine wave data from each coil, the coil impedance can also be calculated for 60Hz AC. From the coil impedance, the coil resistance and inductance can be calculated for 60Hz AC as shown in Table 1. The coil impedance changes as the rod moves through each coil. Therefore, if the data is to be trended, is best to verify the coils when the rods are on bottom. The bottom coil has a different impedance compared with the other 20 coils when the rod is on bottom because it remains in the bottom coil. However, once a baseline is established for a specific rod position, the coil resistance and inductance can be monitored throughout the cycle to verify the coil health.

Table 1 Farley Unit 1 Rod K06 DRPI A coil impedances at 60Hz AC.

DRPI A Coil	Resistance (Ohms)	Inductance (mH)
1	13.36	36.08
2	8.15	42.67
3	7.40	42.09
4	7.61	42.26
5	7.44	42.46
6	7.51	42.22
7	7.68	42.20
8	7.57	41.83
9	7.54	42.20
10	7.74	42.16
11	7.77	41.74
12	7.71	41.64
13	7.75	41.44
14	7.70	41.39
15	7.95	41.39
16	7.82	41.07
17	8.02	40.56
18	7.85	40.09
19	8.04	39.67
20	8.02	39.13
21	7.96	38.25

6. Conclusion

The purpose of the prototype testing was to establish the feasibility of using a COTS system to replace or supplement the existing DRPI system. Not only did this succeed, but the capabilities of the prototype system allowed for several additional diagnostic functions that have been identified and incorporated in the design of the system. The application of a COTS digital system to replace the analog electronics of the DRPI system is just one example. There are many systems in a nuclear power plant that can benefit from COTS technology to not only maintain the plant, but to provide additional features that assist in plant life management [5].

7. References

[1] H.M. Hashemian, "Maintenance of Process Instrumentation in Nuclear Power Plants." Springer-Verlag, Berlin, Germany, 2006.

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[5] P. Salaün, F. Daumas, T. Nguyen, and C. Esmenjaud , "Why FPGA/ASIC Is Considered As A Key Technology For The Future Of I&C In The Power Industry At Edf," 18th Annual Joint ISA POWID/EPRI Controls and Instrumentation Conference and the 51st ISA POWID Symposia, Scottsdale, Arizona, June 2008.