RECLAMATION

*Managing Water in the West*

# Machine Condition Monitoring

**Research and Development Office**
**Science and Technology Program**
**(Final Report) ST-2019-1719-01**

**U.S. Department of the Interior**
**Bureau of Reclamation**
**Research and Development Office** **9-30-2019**

# Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

| REPORT DOCUMENTATION PAGE | | *Form Approved*<br>*OMB No. 0704-0188* |
|---|---|---|
| **T1. REPORT DATE:**<br>OCTOBER, 2019 | **T2. REPORT TYPE:**<br>RESEARCH | **T3. DATES COVERED**<br>FY17-19 |
| **T4. TITLE AND SUBTITLE**<br>Machine Condition Monitoring | | **5a. CONTRACT NUMBER**<br>XXXR4524KS-RR4888FARD1804801 |
| | | **5b. GRANT NUMBER** |
| | | **5c. PROGRAM ELEMENT NUMBER**<br>1541 (S&T) |
| **6. AUTHOR(S)**<br>**James DeHaan, 303-445-2305,** jdehaan@usbr.gov | | **5d. PROJECT NUMBER**<br>ST-2019-1719-01 |
| | | **5e. TASK NUMBER** |
| | | **5f. WORK UNIT NUMBER**<br>86-68450 |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**<br>**James DeHaan**<br><br>**Hydropower Diagnostics and SCADA Group**<br><br>U.S. Department of the Interior, Bureau of Reclamation,<br>PO Box 25007, Denver CO 80225-0007 | | **8. PERFORMING ORGANIZATION REPORT NUMBER** |
| **9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**<br>Research and Development Office<br>U.S. Department of the Interior, Bureau of Reclamation,<br>PO Box 25007, Denver CO 80225-0007 | | **10. SPONSOR/MONITOR'S ACRONYM(S)**<br>**R&D:** Research and Development Office<br>**BOR/USBR:** Bureau of Reclamation<br>DOI: Department of the Interior |
| | | **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**<br>ST-2019-1719-01 |
| **12. DISTRIBUTION / AVAILABILITY STATEMENT**<br>**Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/** | | |
| **13. SUPPLEMENTARY NOTES** | | |
| **14. ABSTRACT** **Previous research in** machine **condition monitoring produced a system which quantifies generator operation characteristics. This system has helped Reclamation facilities better predict maintenance requirements; avoiding several million dollars of unnecessary, unscheduled outage costs. This research effort focused on making the system more reliable**, **easier to use**, and incorporating new condition monitoring tools. | | |
| **15. SUBJECT TERMS** **Condition Monitoring, Vibration, Predictive Maintenance** | | |

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| | | | **U** | 39 | James DeHaan |
| **a. REPORT**<br>U | **b. ABSTRACT**<br>U | **c. THIS PAGE**<br>U | | | **19b. TELEPHONE NUMBER**<br>303-445-2305 |

S Standard Form 298 (Rev. 8/98)
P Prescribed by ANSI Std. 239-18

RECLAMATION
*Managing Water in the West*

**BUREAU OF RECLAMATION**

**Research and Development Office**
**Science and Technology Program**

**Hydropower Diagnostics and SCADA Group, TSC, 86-68450**

**(Final Report) ST-2019-1719-01**

# Machine Condition Monitoring


JAMES DEHAAN Digitally signed by JAMES DEHAAN
Date: 2019.09.30 13:20:03 -06'00'

Prepared by: James DeHaan, P.E.
Electrical Engineer, Hydropower Diagnostics and SCADA Group, TSC, 86-68450

Patrick D. Council Digitally signed by PATRICK COUNCIL
Date: 2019.09.30 13:30:07 -06'00'

Peer Review: Patrick Council
Electrical Engineer, Hydropower Diagnostics and SCADA Group, TSC, 86-68450

NATHAN MYERS Digitally signed by NATHAN MYERS
Date: 2019.09.30 13:54:14 -06'00'

Group Manager: Nathan Myers, P.E.
Electrical Engineer, Hydropower Diagnostics and SCADA Group, TSC, 86-68450

RECLAMATION
*Managing Water in the West*

# Executive Summary

Machine Condition Monitoring is the process of monitoring rotating synchronous machine parameters and associated systems to identify the condition of a machine by identifying changes that are indicative of an issue. Trends in the data provide information about the machine and can help predict when to schedule maintenance or other intervention activities to prevent machine damage and consequential outages. For example, in hydroelectric generators and pumps excessive hydro-turbine machine shaft runout, also called vibration, is an indicator for multiple conditions which can damage the machine. Consequently, monitoring shaft runout is a standard condition monitoring practice.

Multiple manual or digital monitoring techniques are utilized in condition monitoring. These techniques include periodic monitoring such as visual inspections and/or manual data readings, off-line periodic testing, online machine monitoring utilizing embedded sensors to continuously monitor machine parameters, and machine protection systems. The Bureau of Reclamation (Reclamation) Facility Instructions, Standards, and Techniques (FIST) manuals outline Reclamation's periodic maintenance program and provides a good basic program for periodic monitoring and testing of hydroelectric generators and pumps. Reclamation's program for machine protection is also very mature and provides good protection of the hydroelectric machine assets in Reclamation. However, online machine condition monitoring within Reclamation is limited. While supervisory control and data acquisition (SCADA) systems provide some of this function their focus is plant control and not condition monitoring.

Multiple commercial online condition monitoring platforms exist, but Reclamation facilities have experienced unsatisfactory results with these systems due to hardware and software restraints as well as long-term engineering support issues. In addition, these systems did not meet Reclamation's needs within a reasonable budget. In 2010 the Science and Technology (S&T) office funded a research project for the Hydropower Diagnostics and SCADA Group to create Reclamations own condition monitoring platform by developing custom software and using commercially available sensors and hardware. This software system, termed MCM (for Machine Condition Monitoring), proved to be immediately useful and cost-effective. It also highlighted some needs to improve the initial system's reliability and ease-of-use. Again, with research funding a major re-write of the software, termed MCM2, was completed in 2015.

This latest version of the software has a data acquisition and storage process that runs as a self-monitoring service in the background while a data visualization program runs separately as a client application. This configuration has demonstrated improved reliability with the added benefit that multiple data viewer applications can run simultaneously on local and remote workstations. A user manual developed alongside the new software has created a generic condition monitoring manual for use by the end user.

The latest MCM research project that spanned fiscal years 2017- 2019 focused on expanding the functionality of MCM2. Multiple enhancements were pursued to improve the data acquisition,

processing, data storage, and graphical data visualization displays. The focus of these enhancements was to better analyze, trend, and display the condition of one or more hydroelectric synchronous machines. This enables Reclamation plant personnel to make better decisions in scheduling maintenance and help determine when specific intervention maintenance activities are required. MCM2 has also proven to be very useful in capturing data during unplanned events. This aids facilities to in providing invaluable information to quickly analyze the event and determine what activities are required to return the generator to service, thus minimizing the unscheduled outage. Several examples of cost savings as the results of MCM2 are included in this report and a high-level cost benefit analysis is included. This analysis shows a return on research dollars of nearly 30:1 that the MCM2 system has already provided during the short time since it was initially deployed. The advancements accomplished in this latest research program provide a foundation for expanding this system as a Reclamation-wide asset in the coming years.

# Contents

# Figures

# Past Work

The in-house development of Machine Condition Monitoring software was initiated in 2009. The decision to pursue an in-house system was made after a thorough investigation of commercially available systems revealed that none met Reclamation's needs within a reasonable budget. Condition monitoring systems are not new; they have been in existence for several years by different venders. The new idea of the condition monitoring system developed by Reclamation is twofold:

- The system is specific to hydroelectric synchronous machines, improving system reliability and operating characteristics.
- The software system uses open source code that works with a variety of commercial data acquisition hardware. The software, compared to commercial systems, can be easily modified to meet the specific needs of each facility.

The importance of vibration monitoring, which is a subset of condition monitoring, was underscored following the incident at the Sayano-Sheshenskya Power Plant accident in Russia in 2009. High vibration and pressure fluctuations cause the head cover on Unit 2 to fail. The plant quickly flooded within minutes, 75 people were killed and the 10 - 640 MW units in the powerplant were damaged. Following this incident, the Power Resources Office (PRO) issued a Power Equipment Bulletin (PEB) to provide recommendations to Reclamation facilities that would mitigate the likelihood of a similar incident.

The document requires Reclamation facilities to install vibration monitoring on all hydroelectric synchronous machines. As vibration monitoring is one of the main objectives of the condition monitoring system being developed under this research project it helped to underscore the urgency and criticality of this research effort. The vibration monitoring portion of this system meets PEB 42 requirements by taking proximity probe measurements, performing vibration calculations, and providing alarmed outputs to inform plant personnel with the data necessary to minimize the chances that an incident like the one in Russia does not occur within Reclamation.

Research funded the initial software system, labeled Machine Condition Monitoring (MCM), that was completed in 2011 and installed for beta testing at several Reclamation facilities. Enhancements and improvements were identified based on these installations and a significant update to software, labeled MCM2, was completed in 2015. This latest research project covering the last 3 years focused on expanding the functionality of MCM2. These enhancements are covered in this report.

# MCM2 Software Development

The MCM2 software consists of a suite of programs. The core program acquires data from several different types of hardware sources, performs calculations on acquired data, analyzes data, and stores it. During the analysis process, the data is compared to a user-defined set of conditions. If any of these conditions are met, an event is recorded and custom actions (data storage and digital or analog outputs) are triggered. The program utilizes a server/client configuration allowing the core program to run in the background. A configuration utility allows the user to configure the core program and a data visualization utility allows the user to customize display screens that can show both present and historic data. The software is written in VB.NET 4.0, utilizes National Instrument Measurement Studio 2012 Enterprise Edition, and Microsoft SQL Server Express 2012. The software suite is split into four main programs:

- MCM2 Core –
  This software is a server application running as a Windows service. It acquires, synchronizes, performs calculations on, analyzes, compresses, and stores the data. Based on storage rules, data can be stored at higher resolution for a shorter term, typically of a week or less, and at a lower resolution for long-term trend viewing. Data can conditionally be stored long-term with high resolution based on trigger events. Using a "plugin" framework, certain functions can be expanded with user-provided plugins. For example, the software needs to acquire data from many pieces of hardware. Instead of incorporating an interface into the core for every existing piece of hardware, plugins allow the user to provide modules to interface between the core and their specific hardware. Plugins are also used for the various math and triggered functions. These include Once per Revolution, RMS Function, Single Input Math Function, Maximum Displacement, Multiple Input Math Function, Filter, Extreme Finder, Analog Current Output, Analog Voltage Output, Air Gap Processor, Accumulator, Weekly Trigger, Time Trigger, Threshold Trigger, Manual Trigger, Change Trigger, and Hard Drive Full Trigger. Output plugins are used for Data Reduction, Message Boxes, Digital Output, and Data Logger Function.

- Configuration Utility –
  This utility is a client application that allows the user to easily configure all aspects of the MCM Core server including the Windows Service Configuration, Data Storage Location and Storage Rules, Application Users and Roles, and Backup Settings. In addition, this application allows addition, deletion, and configuration of all plugins as listed above. Finally, it provides the ability to generate documentation of your configuration, to import and export configurations, to export data and to otherwise delete or clear configuration or data.

- MCM2 Viewer –
  This software is a client application that allows viewing and analysis of the acquired data. The viewer can display both historic and real-time data simultaneously. The viewer has over a dozen display plugins that the user can configured in multiple tabs to display data. These plugins include the following: Air Gap Plot, Bar Meter, Digital Outputs, Digital Readout, Event List, FFT (Fast-Fourier Transform) Plot, Gauge, Indicator, Meter, Note List, Orbital Plot, Slim Bar Meter, Thermometer, Trend Plot, and Waveform Plot. The viewer also allows activation of manual triggers and clearing of latched inputs. It can run in "Appliance Mode" which turns a PC into more of an appliance, making it very difficult for the normal user to access windows or to exit or minimize the viewer application.

- MCM2 Monitor –
  This software is an application that runs in the background and displays an icon in the Windows system tray. This application has several functions including giving a visual indication of whether the MCM Core Windows service is stopped or running, alerting the user when MCM Core windows service stops or starts, displaying other messages generated by MCM Core or MCM Viewer, and giving quick access to the MCM Core Configuration Utility.

External documentation is available that describes the major pieces and data flow of the software. These documents consist of a 138-page Operation and Maintenance Manual that includes a user's manual and a programming manual. In addition, an 8-hour hands-on training seminar has been developed to train powerplant personnel and allow them to get the full benefits of the MCM2 system.

# MCM2 Deployment

The initial version (MCM) was initially installed at about a dozen Reclamation facilities using facility funding. One system at Judge Francis Carr (J.F. Carr) Powerplant, California included additional hardware to monitor turbine cavitation to inform operators of cavitation levels. Another system at Grand Coulee Third Powerplant, Washington included generator airgap sensors to monitor the rotor shape. In the last three years most of these original systems were updated to the latest MCM2 version and about a dozen more installations were completed. Presently the MCM system is being installed to monitor 18 additional units. Several more sites including an additional 37 generators at Grand Coulee and Hungry Horse are now in the process of design and procurement of parts with the goal of completing installation in the next couple of years. Once all currently expected installations are complete, the total number of Reclamation units being monitored by the MCM2 system will be 74. Reclamation field offices where systems have been installed are now providing useful, direct feedback on desired improvement of the system.

MCM systems have been delivered to following Reclamation Powerplants:

- PN- 10 Units- Grand Coulee G6, G19-G24, Palisades G1-G4,
- MP- 4 Units- JF Carr G1-G2, Stampede G1-G2
- LC- No systems presently installed.
- UC – 6 Units- Fontenelle G1, Upper Molina G1, Lower Molina G1, Elephant Butte G1-G3
- GP – 17 Units- Mt. Elbert G1-G2, Flatiron G1-G3, Estes G1-G3, Mary's Lake G1, Pole Hill G1, Big Thompson G1, Green Mountain G1-G2, Yellowtail G1-G4

MCM installation are currently in the design stage for the following Reclamation Powerplants:

- PN- 37 Units- Grand Coulee Left Power House G1-G9,Right Power House G10-18, Station Service Units G1-G3, Keys Pump/Generate Powerplant P1-P6 and PG7-PG12, and Hungry Horse Powerplant (G1-G4)

A few pilot installations for the United States Army Corps of Engineers have also been completed at the following Powerplants:

- Truman (G1)
- Dworshak (G1-G2)

# Vibration Monitoring

The use of vibration monitoring systems for hydro units is a common and standard practice in the hydro industry. There is a wide industry consensus in the value of vibration monitoring and protecting the unit from harmful operational modes. In the past Reclamation did not have vibration monitoring systems in many of its plants. In plants that did have proximity probe vibration monitoring equipment installed, it was not being used for continuous monitoring due to nuisance alarms. Historically at many Reclamation plants, high vibration levels are judged by feel or sound, not instrumentation.

Proximity probe shaft vibration monitoring systems are the type of vibration instrumentation best suited for hydroelectric synchronous machines. Proximity probes measure the displacement of the shaft relative to a stationary component, such as the bearing housing. A basic proximity probe shaft vibration monitoring system consists of two proximity probes, 90 degrees apart, mounted at each guide bearing elevation, connected to a monitor that alarms when the peak-to-peak vibration levels reach a predetermined level.

Most hydroelectric generators have a rough zone where vibration increases significantly. Often extended operation in the rough zone is not advised as this places the guide bearings and associated infrastructure under significant stress. Excess fatigue on the hydraulic assembly of a hydroelectric synchronous machine due to excess vibration reduces the service life of bolts, seals, and large assembly pins that prevent water from entering the plant. This extra fatigue can make maintenance schedules insufficient for preventing unscheduled outages and components may fail sooner than expected creating hidden vulnerabilities in the integrity of the full hydraulic assembly between scheduled outages. The loss of integrity of critical components may result in serious damage to hydroelectric facilities ranging from machine damage to full facility flooding. Vibration monitoring systems utilizing frequency analysis of proximity probe signals along with monitoring draft tube pressure fluctuations can detect a rough zone condition. Auto detection of rough zone operation has been incorporated in MCM2 vibration monitoring algorithms that can be used to:

- Keep unit out of rough zones (especially with changing reservoir head which cause the rough zone to vary)
- Determine if air injection is effective to minimize rough zones (especially with changing reservoir head)

MCM2 also incorporates intelligent alarms. This is very beneficial in vibration monitoring as alarm thresholds can be raised when the unit is operating in the rough zone. Intelligent alarms significantly reduce the number of false vibration alarms that are typical if only peak-to-peak vibration level alarms are utilized.

Graphical and 3-dimensional displays of bearing orbit plots are also very beneficial in analyzing unit vibration along with frequency analysis and displays. Significant improvements in MCM2 vibration analysis and displays were completed by this research project. Benefits and the diagnostic capabilities of MCM2 vibration monitoring capabilities include detection of the following items:

- Unbalance of generator unit
- Misalignment of the shaft
- Loose bearings
- Turbine runner/blade problems
- Wicket gate problems (shear pin failures)
- Bearing wear, fatigue, and over loading

MCM2 can also assist in the ability to identify:

- Rotor rim iron elasticity and shrink fit changes
- Seal and discharge ring distortion
- Rotor Rubs
- Foundation problems

# MCM2 Improvements

Since the use and variety of applications increase the system hardware, the software must be updated to meet new demands. This 3-year research project funded updates and improvements to MCM2. Many of these updates were based on field operation experience and feedback from the end users. This software is being developed and improved in-house, therefore it can be customized and enhanced to meet Reclamation needs. The updates are summarized as follows:

Vibration Monitoring:

- Bearing runout displays were significantly improved to allow for better diagnostics. This included adding multiple plots per orbit plot, adding a defined maximum circle to orbit plots, adding manual X and Y axis scaling to orbit plots, and adding a Three-Dimensional orbit plot graph.
- Better vibration analysis is now possible with the addition of 1X filter, NX filters, and plot average calculations.

Windows 10 operating System:

- The MCM2 software suite was optimized to run on Windows 10 to meet Reclamation IT requirements for all Windows based systems.

Data Storage:

- New larger hard drives are now supported to allow for multiple months of short-term data storage to allow for more in-depth diagnostics.
- Data storage rules were added to short term data to reduce the size of high-resolution data files.
- A new data entry input table was developed to expedite setting up data rules for short term, trend and long-term data.
- Storage to database was improved to eliminate storage errors.
- Automated long-term data backup to external/secondary drive was added.

Offline Date Viewing:

- Added additional methods to export short term, trend, and long term MCM2 data to USB removable storage devices.
- Added ability to view exported data from USB removable storage devices on offsite computer with MCM2 viewer software installed.

Data Acquisition:

- Added digital filters to data acquisition configuration table.
- Improved operation with Nation Instrument Data Acquisition hardware.
- Added support for Measurement Computing Data Acquisition (MCDAQ) hardware.
- Added burst mode that allows for high speed (1 MHz) snapshot data acquisition.
- Added support to allow data acquisition sample rates to be configured separately for each piece of hardware connected to the MCM. (NI Cards, MCDAQ, etc)
- Added support for distributed data acquisition that allows multiple data acquisition systems in remote locations to be recorded by the centrally located computer system. This will help reduce installation costs and improve signal quality.

Data Displays:

- Reduced trend plot display time and added customizable display times.
- Added new airgap orbit plots for rotor shape.

Data Hardware:

- Developed and implemented new fully digital Potential Transformer (PT) and Current Transformer (CT) Power Quantity Transducer Boards (PTCT Boards). These boards measure three-phase synchronous machine PT and CT signals then calculate Terminal Voltage, Bus Current, Power Output, Reactive Power Output, and Frequency as well as

direct access to raw transduced three-phase voltage and current waveforms. Digital boards reduce signal noise, improve accuracy, and eliminate the need for recalibration.
- Developed and implemented new modular signal input boards for use with National Instruments Data Acquisition equipment that incorporate signal noise filtering.
- Developed custom signal processing electronics for accelerometers and Acoustic Emissions (AE) probe that allow MCM2 system to measure turbine cavitation.
- Developed custom signal processing cards for accelerometers probes that allow MCM2 system to measure stator vibration.

The condition monitoring features of the MCM2 system has greatly expanded in the last three years. It is currently used to measure the following machine conditions:

- Unit bearing vibration with orbit plots.
- Rough zone detection.
- Turbine cavitation detection.
- Stator core vibration.
- Shear pin monitoring.
- Stator core, winding and guide bearing RTD monitoring.
- Stator parallel circuit circulating currents.
- Turbine flow and generator efficiency.
- Generator/Pump loading – Power (Watts), Reactive Power (VARs), Terminal Voltage and Bus Current.
- Generator/Pump frequency and rotation speed.
- Exciter performance.
- Generator Governor performance.
- Generator/Pump airgap monitoring.
- Rotor shape plots.

# Benefits

The benefits of machine condition monitoring are multifaceted. One of the main benefits is the MCM2 system is cost.  MCM2 is significantly more cost effective than current commercial systems. Savings of $150k per installation can be expected compared to similar commercial systems. To date, 37 systems have been delivered (some are still in the process in installation) which equates to a savings of $6.75 million (M) to Reclamation. An additional 37 units to be monitored by MCM2 are in the planning stage. Once these systems are installed the upfront savings will be approximately $14M. The near-term goal of monitoring over half of Reclamation units, about 150 generators, will ultimately result in approximately $28M in savings to Reclamation. Such savings to Reclamation directly contributes to Reclamation’s mission.

MCM2 also has proven to be very useful in capturing data during unplanned events. This provides invaluable data that allowed facilities to quickly analyze the event and determine what activities are required to return the generator to service, thus minimizing the duration of the unscheduled outage. A number of these cases have been documented as described in the next section. For these examples the savings to Reclamation is calculated at an additional approximate $16.5M in reduced costs and lost revenue from water and power production.

Another longer-term benefit will be realized as MCM2 becomes an integral part of the condition monitoring process used in determining the condition of the hydroelectric machine and associated equipment. MCM2 is just beginning to enhance Reclamation’s current condition monitoring process that currently includes periodic monitoring such as visual inspections or manual data readings, portable non-destructive periodic testing, and machine protection system data. MCM2 condition monitoring system at Reclamation's hydro plants will provide valuable information to facility managers that enables informed decisions on what equipment needs maintenance and when to perform these activities. Such decisions optimize maintenance by reducing unneeded maintenance and revealing equipment that needs maintenance sooner than expected, ultimately reducing unscheduled outages of equipment.

Since O&M is Reclamation's single largest expense, agency-wide savings resulting from reducing unnecessary operation and maintenance activities and reducing unscheduled outages could easily save several million dollars a year.[1] These cost savings directly benefit all of Reclamation's power facilities and allow Reclamation to better compete in a deregulated environment. Water districts, Reclamation's water and power customers, and the entire hydro power industry will also benefit.

The following is a list of some additional cost saving benefits that are starting to be realized by the implementation of MCM2 at Reclamation facilities:

- The increasing age of plant equipment necessitates closer monitoring to prevent extensive damage to the equipment which in most cases is nearing the end of its original design life.
- Operation and maintenance costs can be reduced by early detection of problems.
- Risk to personnel safety and extensive equipment damage can be reduced.
- Major breakdowns can be reduced.
- Outage frequencies can be minimized.
- Life and efficiency of the equipment can be improved.

[1] Reclamation's FY2020 budget justification (https://www.usbr.gov/budget/) for facility operation, maintenance, and rehabilitation is $527.2 million. Thus, every 0.1 percent reduction in O&M costs results in a savings of $527,200/year. This value does not include the cost of unscheduled outages that can exceed $150,000/day.

# Return on Investment

The machine condition monitoring research program was established in 2010. To date research has provided $660k to the development effort and the Power Resources Office as provided $80k for a total contribution of $740k. Roughly half of this cost went to the development of the software program and new hardware and the remaining money was used to develop the MCM architecture, lab testing of the software system, help fund design of the initial pilot projects, improve MCM application techniques, improve MCM support techniques, and help promote the use of the system within Reclamation.

As of the end of fiscal year 2019, 37 units within Reclamation are being monitored by the MCM2 systems or are currently being installed. During the last three years the rate of MCM installation has accelerated. Of these 37 units, 27 were added in the last 3 years.

The cost to procure, build, deliver and provide installation drawings for Reclamation's MCM system is significantly less than equivalent commercially available systems. The installation cost of Reclamation's 37 MCM system is roughly $3.7 Million (M). The cost saving realized compared to an equivalent monitoring system is estimated to be $6.75 M.

In addition, the MCM system is helping lower Reclamation Operation and Maintenance (O&M) costs. These will be ongoing cost savings that will continue for decades to come. These cost savings have started to accumulate over the last several years. An incomplete list of some major cost savings over the last several years indicate Reclamation MCM system has help defer at least $16.5M in O&M costs.

In summary:

Development costs = $740k (Mainly Research and some PRO funds)
Installation costs = $3.7M (Facility funds)
Savings = $24.5M (See next section for details)

## Savings data

The following is used to determine the cost saving of installing Reclamation's MCM system compared to installing a compatible commercial system:

- Reclamation MCM cost per system (average) $100k-$175k
    - MCM System delivery cost (includes drawings, sensors, MCM cabinet) $50k
    - MCM plant installation costs per unit $50k
    - Each additional generator, +$25k, max three extra $25k - $75k
- Commercial system cost per unit (average) $250k
    - Equivalent commercial monitor system (minimum) $175k
    - Commercial system procurement costs $25k
    - Commercial system plant installation costs per unit $50k
- Saving per installation (e.g. 1-generator installation, $250k-$100k) $150k
- Saving per installation (e.g. 4-generator installation $1M-$175k) $825k

- Total Realized Savings (12 x $150k + 4 x $375k + 3 x $600 + 2 x $825k) $6,750k

The following are examples and saving estimates where the MCM system data was used to defer unplanned maintenance activities or help avoid additional equipment damage.

- Grand Coulee Third Power House (TPH):
  - Coulee G21 Turbine Guide bearing – 2016
    - MCM defer removal from service for 6 weeks (42 days) = $5,900k
  - Coulee G19 – Saturated GSU – 2019
    - MCM identified source of abnormal startup current and reduced unnecessary inspection and tests by 3 days = $421K
  - Coulee G24 external fault – 2019
    - MCM captured generator fault current and help reduce diagnostic time by 3 days = $421k
  - Coulee G19-21 – 2018-2019
    - MCM monitoring rotor shape, eliminating need for periodic measurements. Reduced downtime by 5 days per year per unit. (30 days) = $4,214k
  - Coulee TPH cost assumptions:
    - $30/MWh (low end for average electrical rates)
    - 8760 hours per year
    - Typical unit loading – 650 MW
    - 30% capacity factor (C.F.)
    - (650) x (8,760 h) x ($30/MWh) x (30% C.F.) = $51.2M/year or $140,400/day
- JF Carr Powerplant:
  - MCM used to identify when turbine is cavitating. Dispatch and Operators are using this data to avoid damage and extended life of $2 - $5M turbines. Assume life can be doubled. Life time savings of up to $5M per turbine.
- Yellowtail Powerplant:
  - MCM is used to monitor increased stator vibration on 4 units following a $30M rewind contract = Peace of mind.
  - MCM help identify source of overspeed switch mis-operation during external fault = Avoided future unscheduled outages.
- Mt. Elbert Pump/Generator Plant:
  - MCM defer removal from service to check guide bearing, eliminating a 5-day unscheduled outage. Assume replacement power is $100k/day = $500k.
- Elephant Butte Powerplant:
  - MCM helped identify source of unit trip = Avoided future unscheduled outages.

# Recommendations

As the use and variety of applications increase the system hardware and software must be updated and enhanced to meet the resulting new demands. Continued development, enhancements, and deployments are proposed in the coming years, which will increase the MCM2 system's value as a condition monitoring tool. Some specific challenges that will need to be address with additional research include the following.

- Improved access to MCM2 data will significantly increase the value of this system. Currently access to this data is limited to local personnel only. Sharing of this data via the intranet has been restricted due to IT security concerns. To provide better access to data the following needs to be pursues.
    - Enhance MCM2 ability to download data to a portable storage media that can be shared with others. Enhance MCM2 ability to view this offline data.
    - Work with Reclamation IT professionals to develop a secure method to transmit data via Reclamation's internal intranet.
    - Work with Reclamation IT professionals to develop a secured method to transmit data to commercial databases for further evaluation.
    - Work with Reclamation IT professionals to develop method to remotely service the MCM2 computer-based system.
- Continue with the development of hardware and software tools to allow for online excitation and governor performance monitoring with the goal to significantly reduce the time required for TSC personnel to perform NERC required tests on the exciter and governor systems.
- Develop new tools to record, monitor and display generator operating zones where damage due to operating in rough zone and/or during cavitation is occurring. Output this data in a manner that will be easily incorporated into generator automated operation system (SCADA).
- Pursue efforts to make this software program available to other public and private hydro utilities as opportunities become available. This will maximize the benefit of this research product via technology transfer and reduce costs by broadening the support community.

In addition, the benefit of any condition monitoring system is only available if the data is used. Utilization of this data requires knowledgeable facility personnel. This requires ongoing training. An initial training module is available on how to use the system, but enhanced training on condition monitoring is necessary.

Ultimately, the development of a predictive maintenance program within Reclamation would provide the most benefit to Reclamation. The predictive maintenance approach benefit over Reclamation's current preventive maintenance program would be that only maintenance tasks that are warranted based on measured conditions are performed. A predictive maintenance program uses various data processing methods such as Artificial Intelligence (AI) or machine learning of very large data sets to discover data trends. Often referred to as "Big Data" these data set consist of condition-based data collected across Reclamation including periodic monitored data, periodic testing results, condition monitoring systems database data, and protection system information. The incorporation of MCM2 data sets into a predictive monitoring data base would help optimize Reclamation's operation and maintenance practices.

# References


DeHaan, James. *Plant Condition Monitoring*. Research and Development Office Science and Technology Program Final Report ST-2016-2879-01. September, 2016. https://www.usbr.gov/research/projects/researcher.cfm?id=13.

DeHaan, Jim. *Machine Condition/Vibration Monitoring*. EPRI Fleet-Wide and Generator On-line Monitoring Interest Group Meeting. October, 2012. https://www.usbr.gov/research/projects/download_product.cfm?id=1224

DeHaan, Jim. Clair, Kyle. Travers, Ben. *Machine Condition/Vibration Monitoring*. Power O&M Workshop, August 2011. https://www.usbr.gov/research/projects/download_product.cfm?id=1226

*Recommendations for Reclamation Facilities in Response to the Sayano-Shushenskaya Powerplant Accident*. Power Equipment Bulletin N0. 42. July 2010. http://intra.usbr.gov/~hydrores/POMBullet/peb42.htm

# Appendix A – Photos of MCM2 Installations

**Figure A1 – MCM2 installation in rack mount cabinet.**
**Cabinet located behind control panels.**


**Figure A2 - MCM2 touch screen display located next to control panel**


**Figure A3 - MCM2 installation with side panel removed.**

**Figure A4 - MCM2 installation in rack.**


**Figure A5 - MCM2 electrical panel.**
**Date Acquisition equipment located along top.**

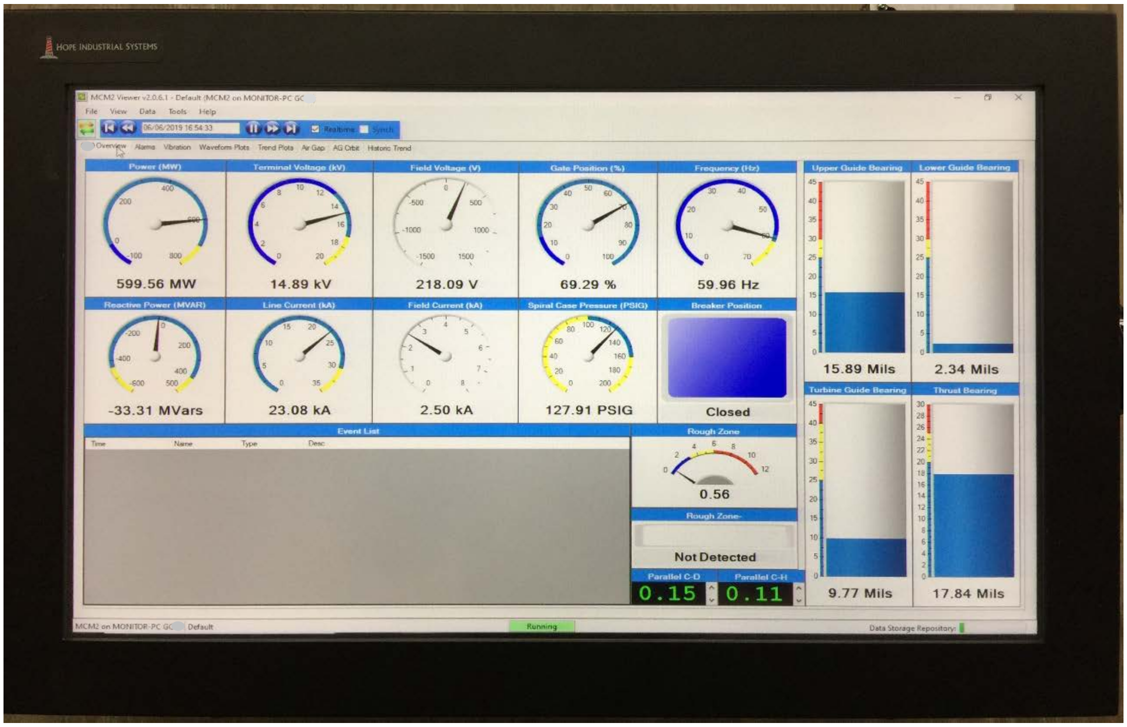


**Figure A6 - Typical panel meter display.**

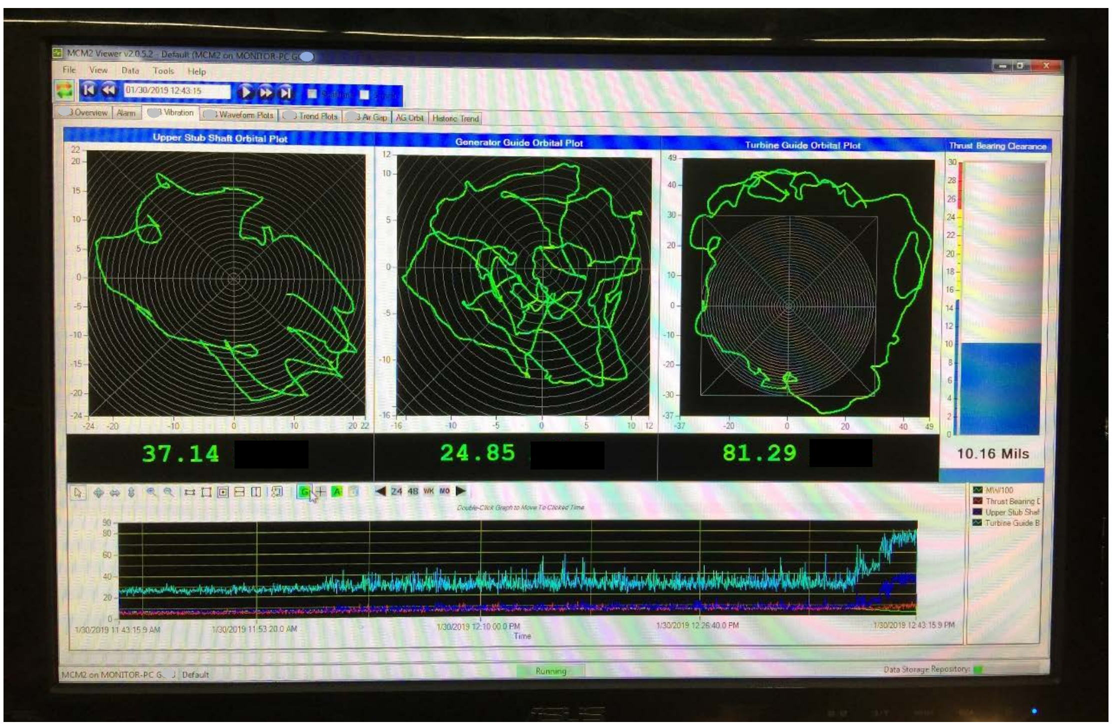


**Figure A7 - Bearing orbit display.**

**Orbit shape indicates unit is operating in a rough zone.**

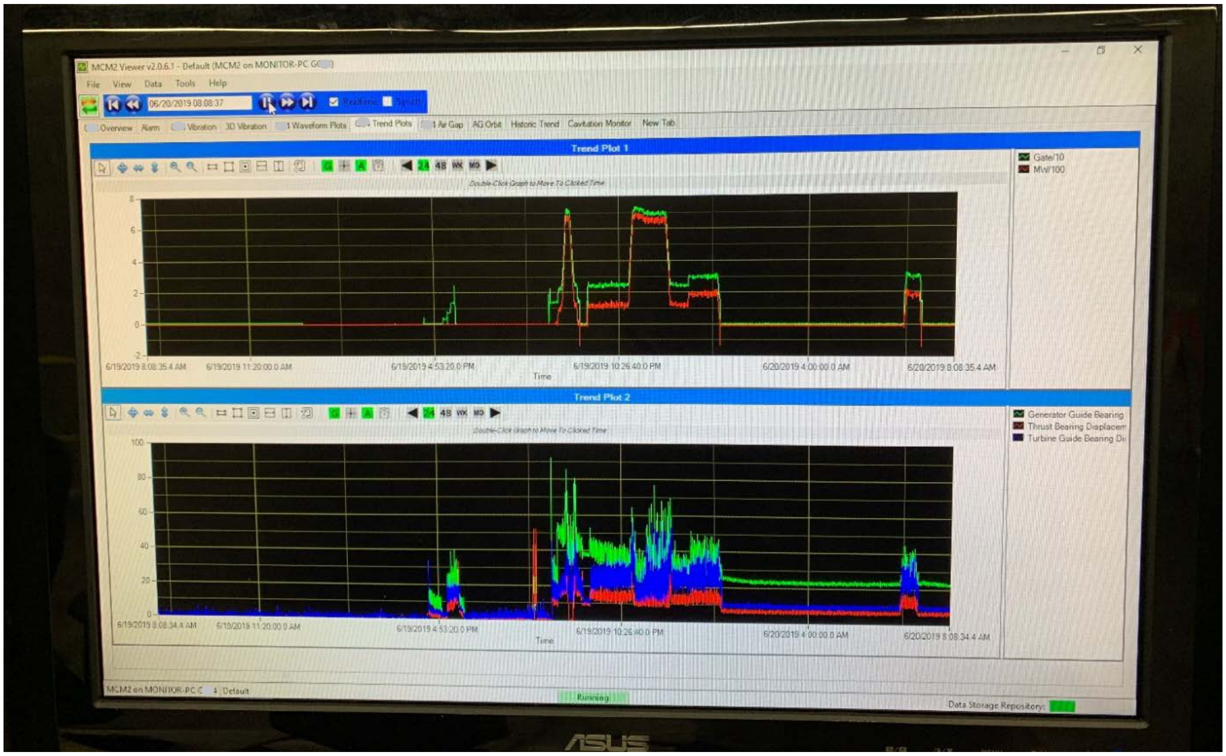

**Figure A8 - Typical trend display.**

**5 minutes to 1 month of trend data can be displayed.**

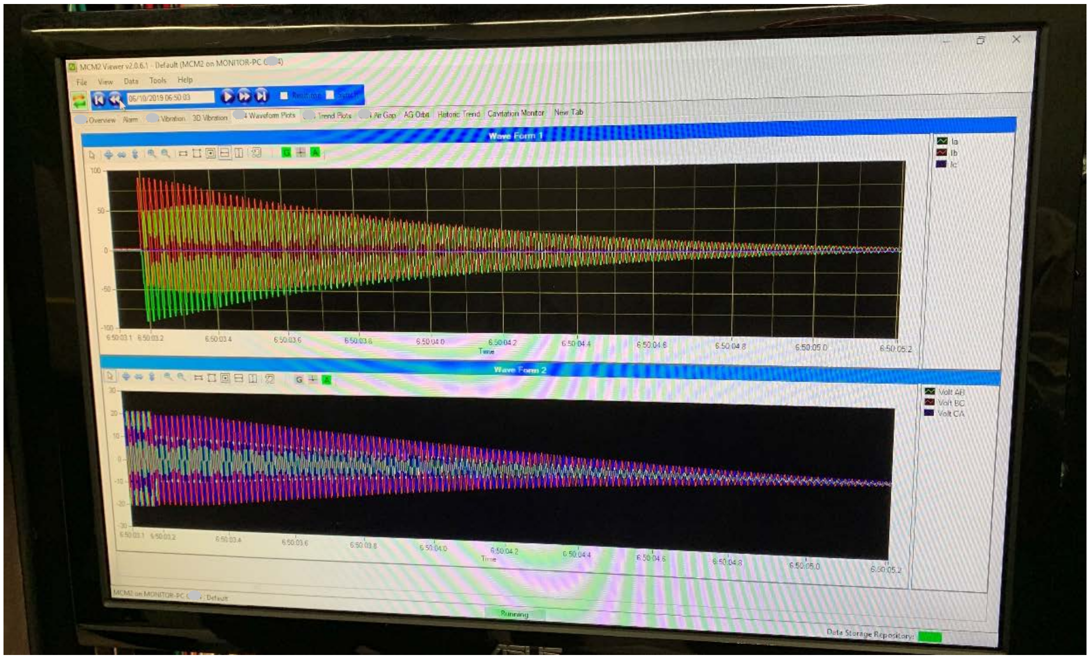

**Figure A9 - Typical waveform display.**

**This display is of generator fault currents and voltages following a line-to-ground fault on high side of transformer.**


**Figure A10 - Panel display with inclusion of rough zone intensity meter.**

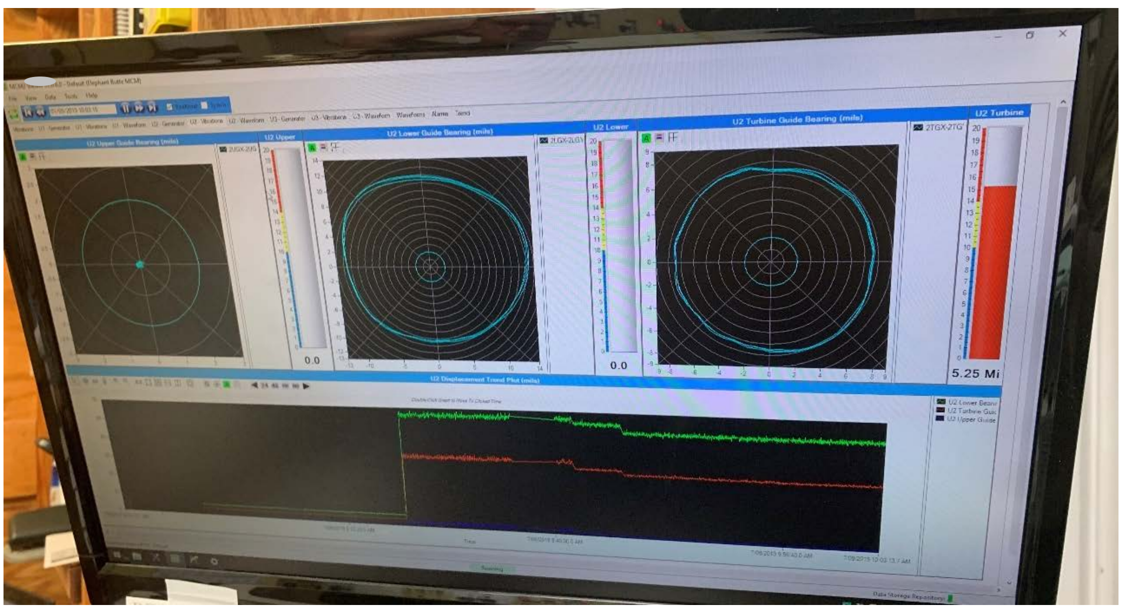


**Figure A11 – Upper guide, lower guide and turbine guide bearing plots. Orbit and trend data following generator start up.**

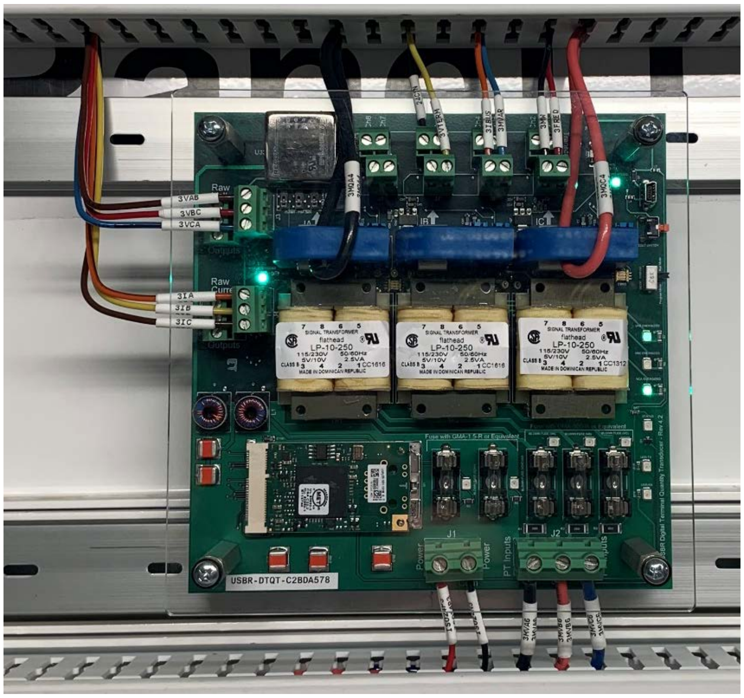

**Figure A12 - PT/CT digital transducer board.**

**In-house built board with high frequency response rate.**


**Figure A13 - Exciter current and voltage transducers**

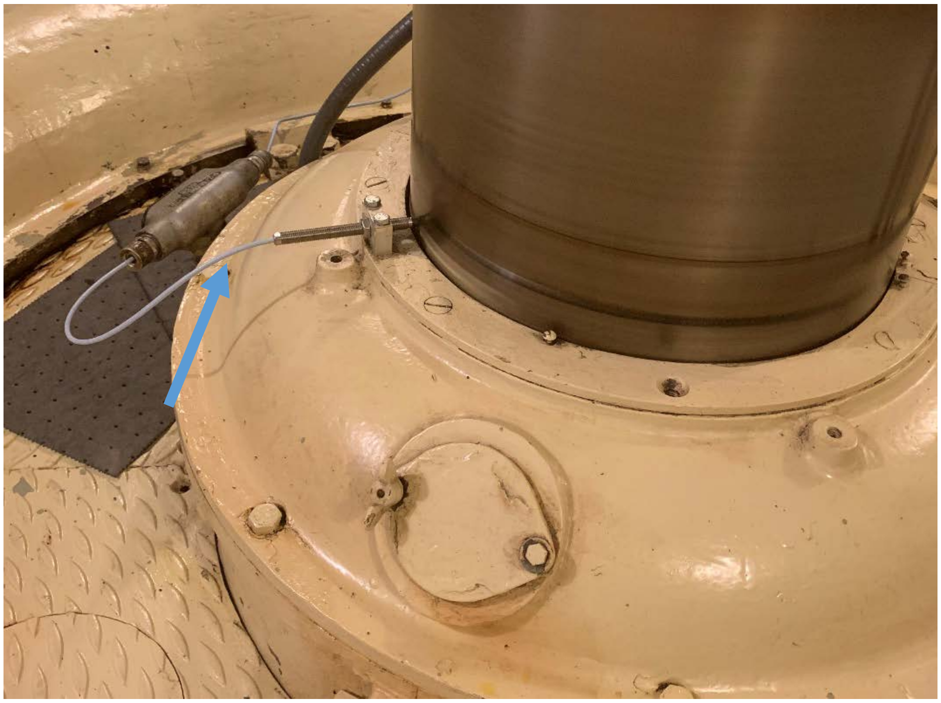

**Figure A14 - Typical proximity probe installation.**

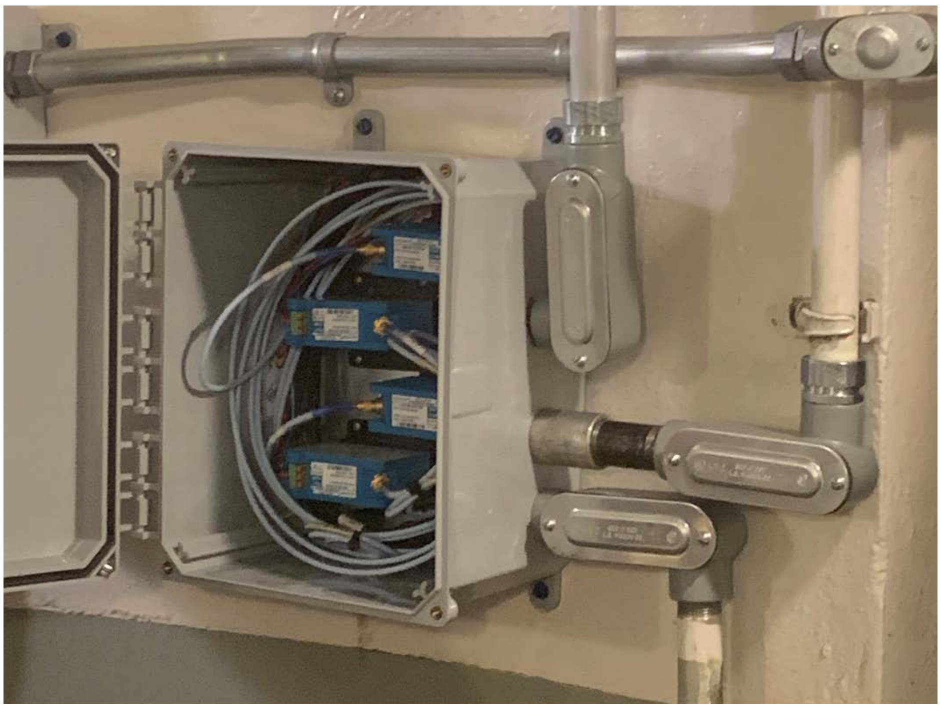

**Figure A15- Typical proximity transducer installation.**

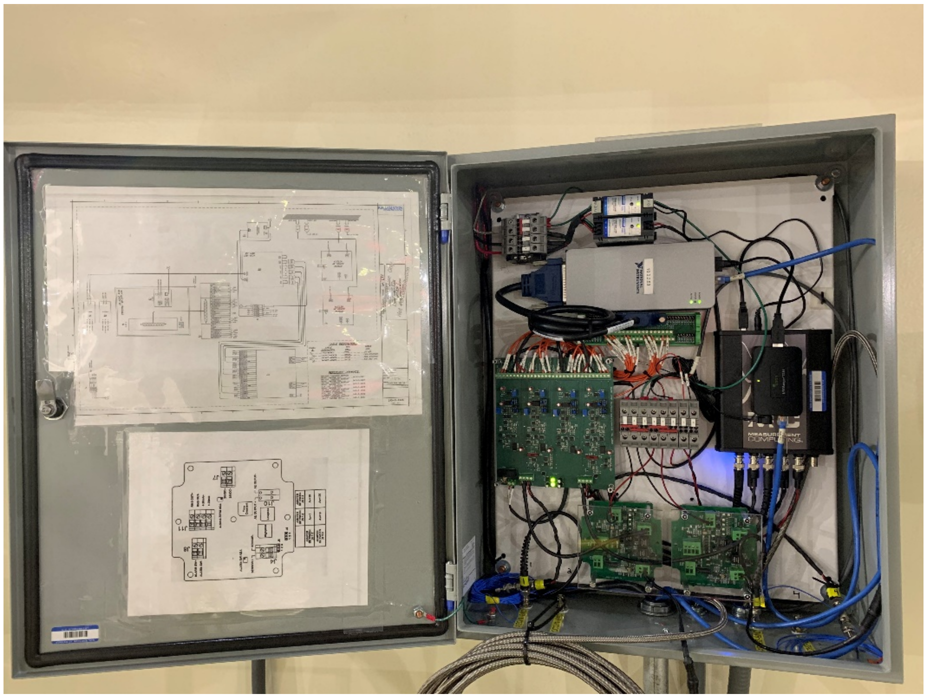

**Figure A16 - Cavitation monitoring cabinet.**

**Measures accelerometers and AE probes located on turbine wicket gates and head cover.**

**Figure A17 - Cavitation monitor install on draft tube.**

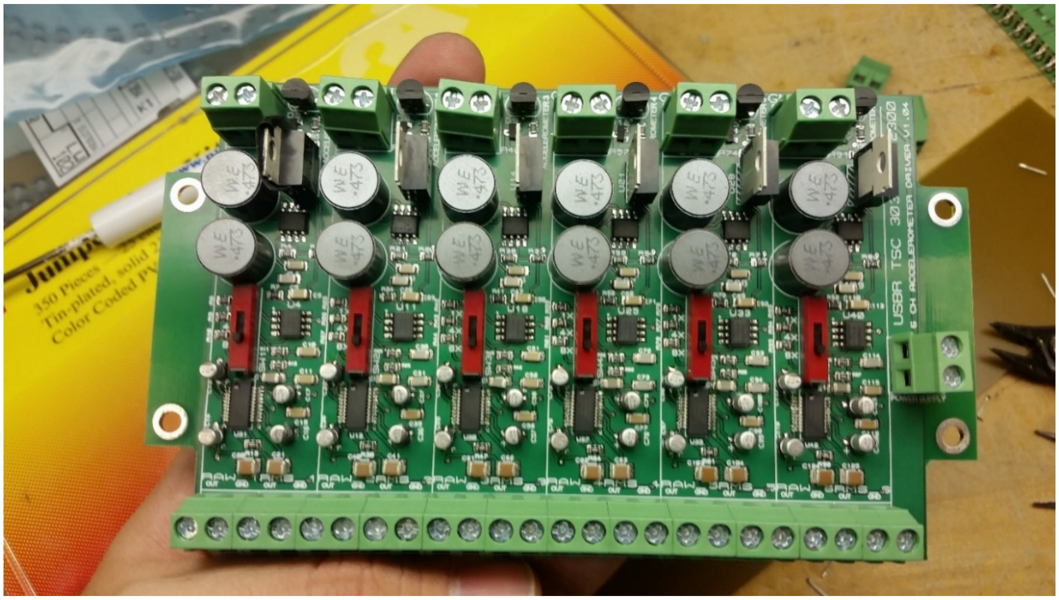

**Figure A18 – In-house built 6-channel accelerometer transducers.**

**Accelerometers used for measuring stator frame vibration.**

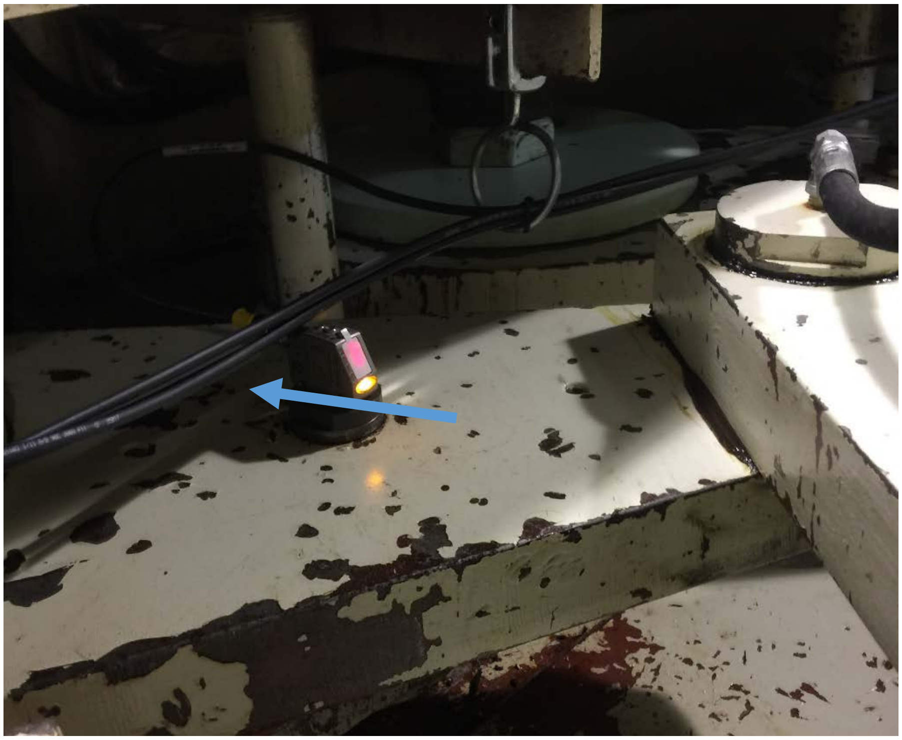

**Figure A19 - Shear pin monitor.**

**Uses laser light to detect small change in shear pin length.**