Machine Condition Monitoring

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14. ABSTRACT Previous research in machine condition monitoring produced and refined 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 expanding functionality and incorporating new condition monitoring tools which add valuable insights for use in condition-based maintenance and allowing offline analysis of collected data and sharing of data with data aggregators for deeper and longer-term analysis. Increased adoption and use of machine condition monitoring inside reclamation and sharing of the technology outside Reclamation was also a goal.						
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Peer Review

Bureau of Reclamation
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Machine Condition Monitoring

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Acronyms and Abbreviations

AI	Artificial Intelligence
BDA	Big Data Aggregator
Core server	MCM2 Core Windows service application which continually collects data in the background
CSV	Comma Separated Values
DAQ	Data Acquisition Hardware. Refers to electronic hardware that converts process signals to digital format for computer storage and analysis
Export Utility	MCM2 Export Utility application
FFT	Fast Fourier Transform
IRO	Reclamation's Information Resource Office
MCM	Machine condition monitoring
MCM2	Version 2 of the Machine Condition Monitoring program (the subject of this report)
MSSQL	Microsoft SQL Server database server software
MW	Megawatt(s)
NERC	North American Electric Reliability Corporation
O&M	Operations and Maintenance
ODVT	Offline Data Visualization Tool application (an application that is part of the MCM2 suite of applications)
OPC-UA	Open Platform Communications United Architecture
PEB	Power Equipment Bulletin
PRO	Power Resources Office
Reclamation	Bureau of Reclamation
SCADA	Supervisory Control and Data Acquisition
SOP	Standing Operating Procedure
TSC	Bureau of Reclamation Technical Service Center
Viewer	MCM2 Viewer application used to view MCM2 data

Measurements

Hz	Hertz, cycles per second
mil	Thousandths of an inch, 1/1000 inch

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Executive Summary

Machine Condition Monitoring (MCM) is the process of monitoring machine parameters and associated systems to identify the condition of a machine by recording 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 unplanned outages. The Hydropower Diagnostics and SCADA Group has developed an MCM system utilizing commercial data acquisition hardware and in-house written code, which was funded under previous research projects starting in 2009. This research has helped to evolve Reclamation's MCM system, making it more robust. More significantly, it has added new tools and means of analysis as afforded by the evolution in machine condition monitoring techniques, technology, and analysis tools.

Over the 4 years of this Research program the following enhancements have been pursued and implemented:

- Easy Export of MCM-format or CSV data with a new MCM2 Export Utility application
- The ability to play back exported data forward or backward at various speeds to review historic events
- Improved evaluation of bearing operating characteristics through addition of the Bearing Analysis plugin
- Air Gap measurements and analysis
- Addition of the Viewer Launch Manager application which allows repeatable positioning of multiple MCM2 Viewer windows across multiple monitors
- Heatmap Plots for several types of analysis
- Cavitation analysis
- Rotor-mounted measurements
- Instantaneous Efficiency monitoring
- Orbital Trend plots
- External Data Manager application to provide easy access to and analysis of non-MCM data
- Offline Data Visualization Tool (ODVT) application to allow easy and deep analysis of MCM2 and external data
- Updates of software tools, libraries, and drivers to the latest technologies

To date there are a total of 43 hydroelectric synchronous machine units where MCM has either been deployed or is currently under development. That includes 28 units where the MCM system is active, 2 units where MCM was used to monitor a specific issue and are now offline, and an additional 13 units where MCM is in the process of being designed or installed. An additional 52 units are being considered for future installation. Research support of the MCM effort over the last 14 years has totaled $1.2 Million. Facilities have covered the MCM equipment and installation costs at their sites. An estimate of their investment into MCM is $3.5M. This equates to a total investment to date of $4.7M.

MCM benefit at facilities has also been tracked over the years. The fiscal impact of these benefits has been estimated at $74.5M. Given this benefit, the return on investment of MCM is estimated to be around 16:1. Additional return on investment will be realized in future years.

MCM installations have been concentrated in a couple Reclamation regions, so future effort to expand MCM use throughout Reclamation will continue.

Introduction

Project Background

Reclamation has developed a Machine Condition Monitoring (MCM) system that utilizes in-house-developed software and commercially available hardware. The in-house development of MCM 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 were not new; they had been in existence for several years by different venders. The new idea of the condition monitoring system developed by Reclamation was twofold:

1. The system was to be specific to hydroelectric synchronous machines, improving system reliability and operating characteristics.
2. The software system would use open-source code that works with a variety of commercial data acquisition hardware. This allows the software, compared to commercial systems, to 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 Powerplant accident in Russia in 2009. High vibration and pressure fluctuations caused the head cover on Unit 2 to fail. The plant quickly flooded within minutes, 75 people were killed, and the ten 640 megawatt (MW) units in the powerplant were damaged. Following this incident, the Power Resources Office (PRO) issued Power Equipment Bulletin (PEB) 42 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 likelihood of an incident like the one in Russia occurring within Reclamation.

Reclamation's MCM system is installed or in the process of being installed to monitor 43 Reclamation generators with an additional 52 units under consideration for future deployment. During the duration of this research, the MCM system has continued to evolve to meet needs of the plants where the systems are installed, and to provide additional Operations and Maintenance (O&M) insights as better techniques and new sensors have made new measurements and analysis possible. While originally designed to monitor guide bearing vibration and operating parameters, additional features have been incorporated including turbine cavitation monitoring and generator air-gap monitoring. These and other features, enhancements, and deployments have increased the system's value as an O&M tool. New data export and data aggregation tools are extending insights and analysis by allowing the data to be exported to external databases.

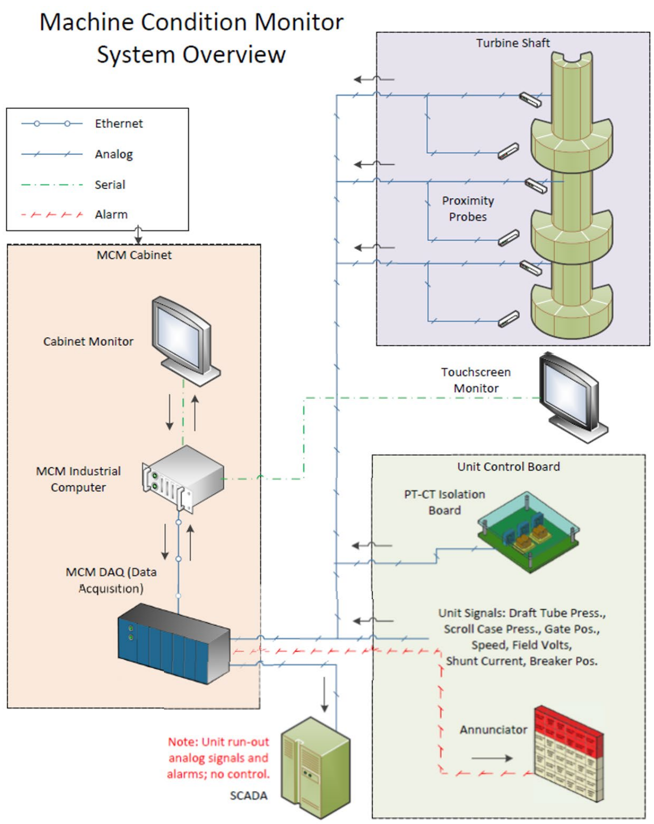

Figure 1 Machine Condition Monitor System Overview

Previous Work

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.

As of 2018 the MCM2 software consisted of a suite of 4 programs. These 4 programs still form the basis of MCM2. The Core program (Windows service) 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. MCM2 utilizes a server/client architecture, allowing the Core program to run in the background, always acquiring data. A Configuration Utility allows the user to configure the Core program and a Viewer application allows the user to customize display screens that can show both present and historic data. MCM2 is primarily written in VB.NET (although C# and Microsoft SQL Server (MSSQL) are employed as well). At the start of this research, MCM2 was targeted at .NET Framework V4.0, and utilized National Instrument Measurement Studio 2013 Enterprise Edition, and MSSQL Express 2012. The four main programs of the MCM2 software suite at the onset of this research included:

- 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.

Additional applications have been added to the MCM2 suite of programs to achieve the goals of this research.

Overall, this latest research project covering the last 4 years focused on improving the reliability of MCM2 and expanding the functionality. These efforts are covered in this report.

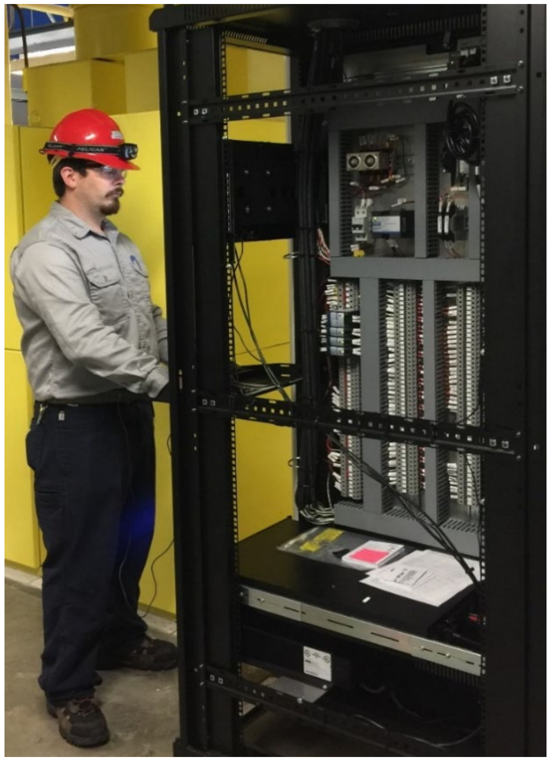

Figure 2 MCM2 installation in rack mount cabinet.

Results

MCM2 Enhancements

Overview of Problems Addressed

MCM2 was useful and functional prior to this work. However, the application had several usability issues. Viewing certain types of data was slow and buggy. Documentation was not available for many of the changes and new features. There were valuable types of analysis that were not yet supported. The ability to export data for offline analysis was lacking. There was a need to reduce the amount of storage required to store data. Development tools, support applications, and drivers required updates from versions that were at end-of-life for support. Adoption and use of MCM2 was not evenly spread across Reclamation. The following tasks were completed to address these issues:

- Trend viewing (especially for historic data) was improved in speed and bugs were fixed to make this feature more reliable and useful.

- Help files and User Manual were updated, documenting current functions and features.
- Analysis tools were greatly expanded. Bearing analysis calculations were added with the new Bearing Analysis plugin and air gap analysis added with the new Air Gap Processor plugin.
- Export of MCM2 data was facilitated and simplified by the new MCM2 Export Utility.
- Offline viewing of exported data was supported and improved.
- Encouraged adoption and use of MCM2 within Reclamation through various presentations and provided means for source code and application installers to be shared with other interested organizations in government and private sectors.
- Support for data acquisition hardware from different hardware manufacturers was added.

Applications Added to the MCM2 Suite of Programs

To broaden the functionality of MCM2, additions were provided in separate applications. These are applications that have been added to the MCM2 suite during this research:

MCM2 Export Utility

This flexible data export application facilitates export of all types of MCM2 data including long-term and short-term data, burst data, and events. This utility can be launched on its own from the start menu, or it can be launched from either the Viewer or the Core Configuration programs. The figure below shows the MCM2 Export Utility user interface which includes:

1. The main menu
2. The export settings panel. This panel is always visible. This is where the type of export is determined and where channels to be exported and date and time range of the export are configured.
3. The Export Profiles panel. This panel can be hidden or shown in the Options menu. Export profiles are preset configurations. Export profiles can be created and saved, and then recalled later. They can also be saved to a file which can then be loaded on another MCM2 system. In this way it is possible for TSC to create a data export configuration which can be sent to a facility to help retrieve data desired for review.
4. The Export Job Queue. This panel can be hidden or shown in the Options menu. When this panel is displayed, you can create multiple export jobs which are added to the queue. Then you can start the queue and let the exports complete unattended. When the queue is hidden, exports are started immediately when the buttons at the bottom of the export settings panel are clicked (and the button text makes this clear - Export MCM2 Viewer Data Export CSV File(s)).

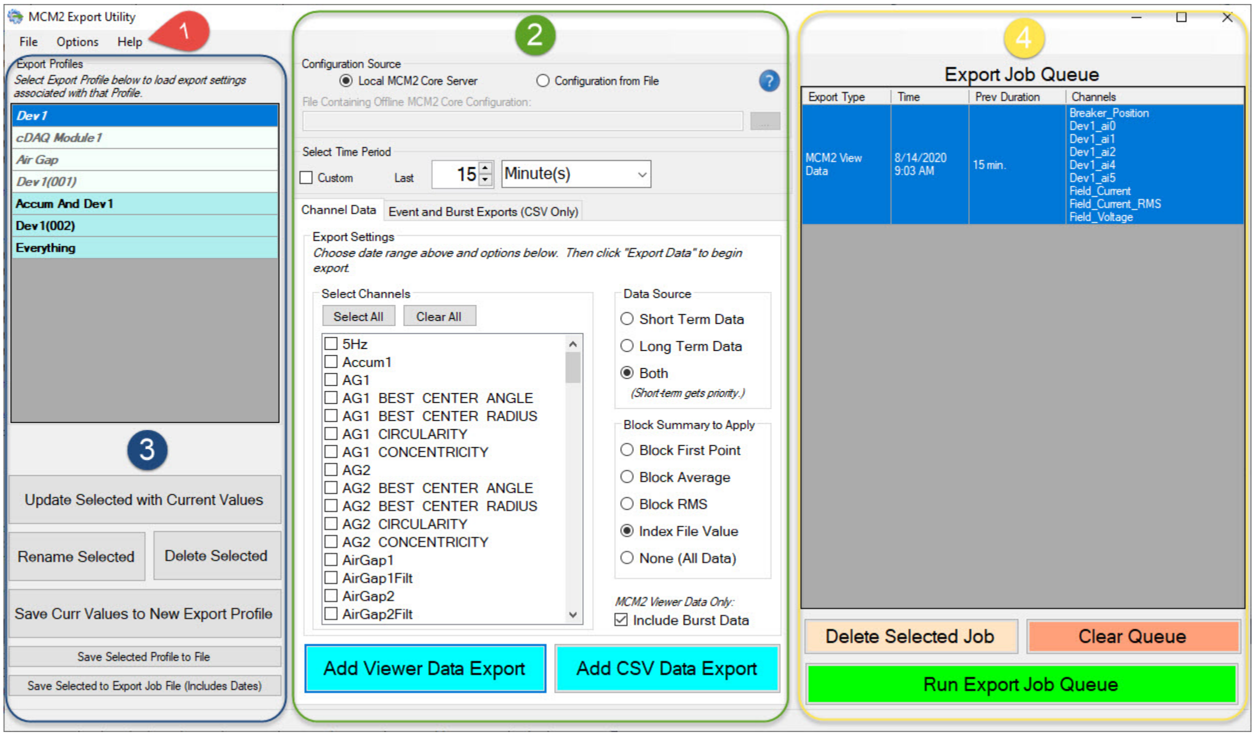

Figure 3 Overview of the MCM2 Export Utility

The MCM2 Export Utility exports to multiple file types. The most powerful format is the MCM2 Viewer Data export format. The resultant export file can be viewed offline using the MCM2 Viewer and the data can be played back forward or backward at various speeds. In addition, if you decide you want CSV data, you can use the MCM2 Export Utility when viewing the MCM2 exported data to generate new CSV exports.

MCM2 Viewer Launch Manager

MCM2 Viewer Launch Manager allows you to configure how MCM2 Viewer instances display on a computer with options of which monitors MCM2 Viewer displays on and at what position on a monitor each instance of the application opens. This allows you to customize an MCM2 system to display different views in different windows across multiple monitors. In addition to configuring which monitor an instance of MCM2 Viewer opens on, you can also configure it to open to full screen or to open on top, bottom right, or left half of the screen.

MCM2 External Data Manager

At times it is desirable to display data that is not available to the MCM2 Core server in MCM2 Viewer. Perhaps such data is brought in from SCADA using a CSV file or a Microsoft Excel file. In addition to MCM2 Viewer, the MCM2 Offline Data Visualization Tool (ODVT) needs a way to bring in external data. Instead of loading these files one at a time each time you need them, the MCM2 External Data Manager catalogs the data and makes it available in MCM2 Viewer (or ODVT) without having to reload it. In addition, the MCM2 External Data Manager allows you to define the timestamp column or columns, and to define the datatype and name of the values in value columns whether or not there is a header in the data file. Most of this is done automatically when you load a data file for the first time, but you can customize settings if the MCM2 External Data

Manager does not load the file the way you want to import it. File information settings are retained in metadata files located in a subfolder of the data file's folder.

MCM2 Offline Data Visualization Tool

The MCM2 Offline Data Visualization Tool (ODVT) is an easy-to-use but powerful data analysis tool.

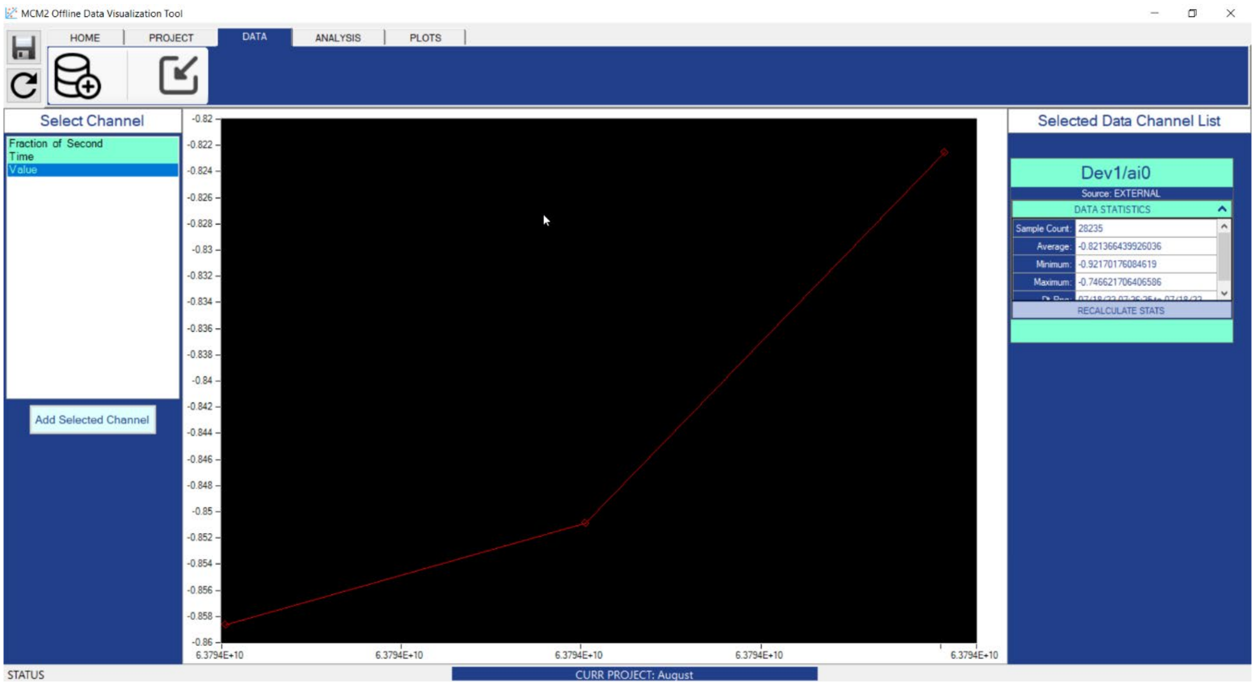

Figure 4 The MCM2 Offline Data Visualization Tool is intended to deliver deep insights about generator health with only a few clicks.

The ODVT can operate as a standalone application, and can be used to analyze CSV, Microsoft Excel, and MCM2 Viewer Export files. When running on an MCM2 computer, the ODVT can also analyze stored MCM2 data. This application is currently being beta tested in the lab and further development is required before it is released.

New and Improved Capabilities

Playback of Historic or Offline Data in MCM2 Viewer

Not only can you step through historic or offline data in the Viewer, but you can play data back either backward or forward at the speed recorded or at various speeds faster or slower than the original speed.

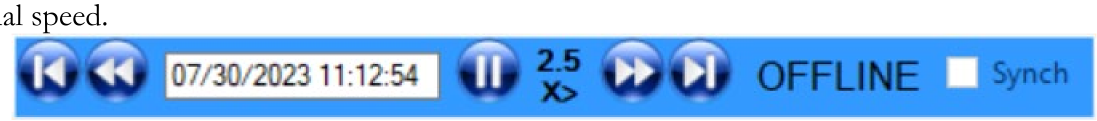

Figure 5 MCM2 Viewer Timebase in historic or offline playback mode - playing forward in time at 2.5x the original recorded speed.

This works while you are connected to an MCM2 Core server or when you are viewing an MCM2 Viewer format export file created by the MCM2 Export Utility. This feature makes it easy to locate events in the data. Then you can pause the data and step forward and back through the data.

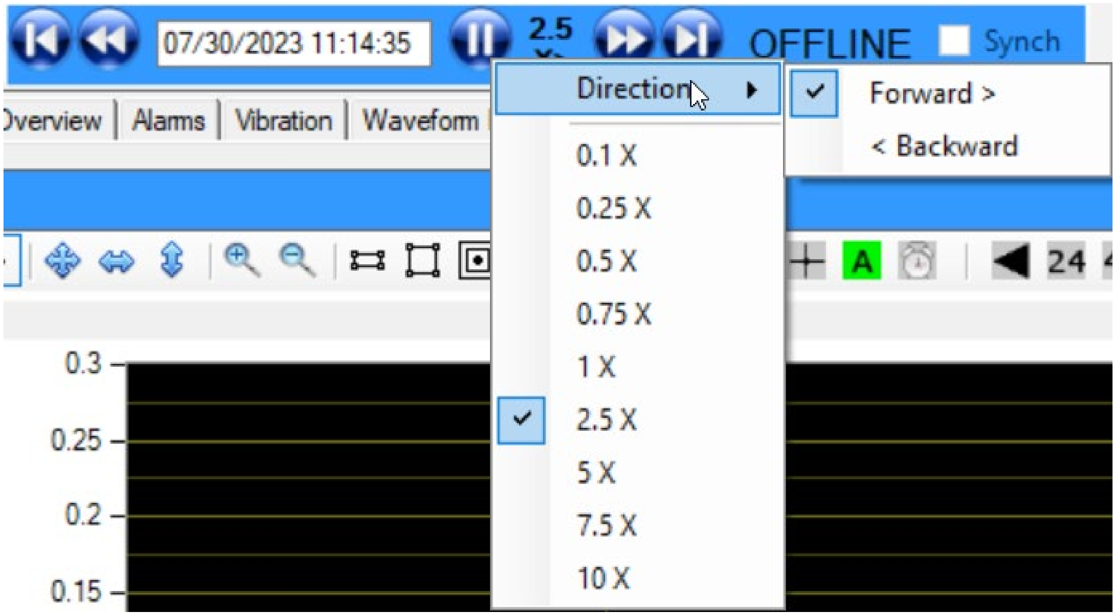

Figure 6 Right-clicking MCM2 Viewer Timebase playback speed or start-stop button in historic playback or offline mode provides means of changing direction and playback speed.

Bearing Analysis

A new plugin was added to MCM2 Core server that enhanced the existing displacement output by adding many new features to fine-tune the analysis:

- Integral low-pass and band-pass filter functions with variable or fixed cutoff frequencies
- Base frequency output
- 1X Output for X and Y channels
- 1X Trend Output (based on X or Y channel, selectable)
- Signal Minus 1X Output
- Center Point Output with selectable source (1X filtered signal or unfiltered signal)

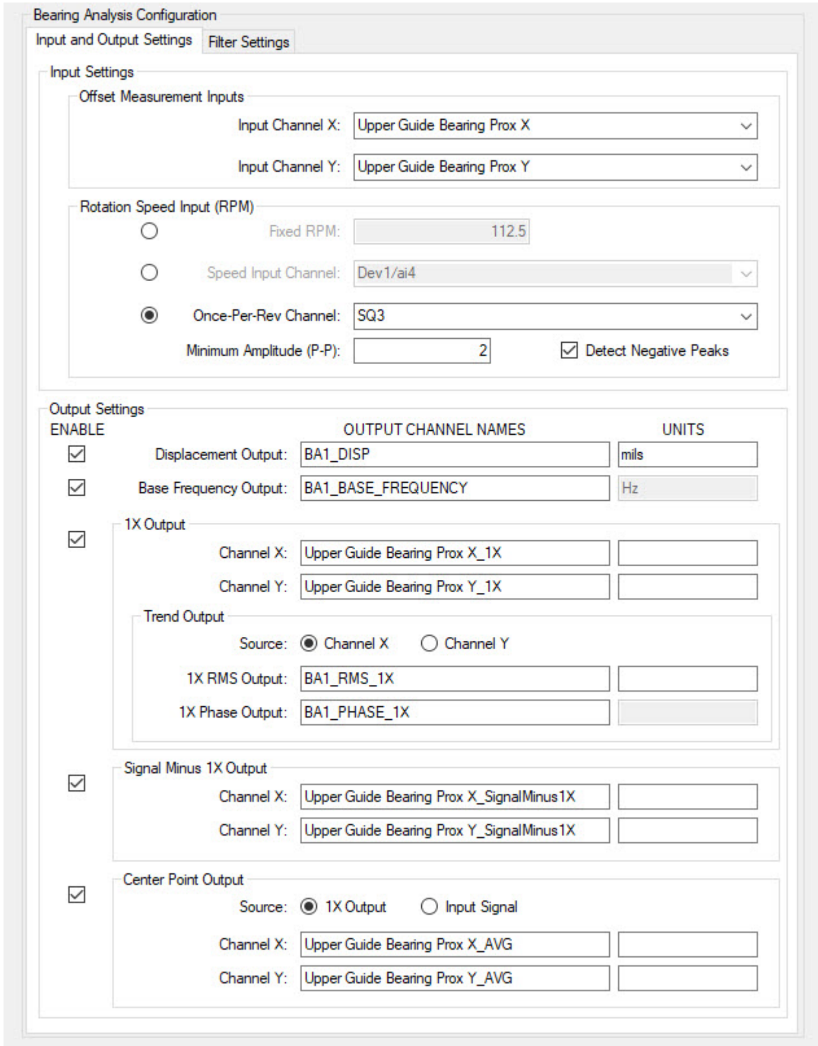

Figure 7 Example Bearing Analysis plugin configuration

Air Gap Measurements and Analysis

An Air Gap Processor plugin was added to MCM2 Core server that takes multiple air gap probe inputs and accommodates probes placed at various points of the stator to measure the distance to the rotor. This plugin facilitates acquisition of data capable of displaying the shape of the rotor. A common configuration is to install probes at the same rotational location at the top and bottom of the rotor, and then a third probe at 90° rotation from one of those probes. For the probes installed in-line at the top and bottom of the rotor, delta air gap is also measured, monitoring for any relative change from top to bottom of the rotor. The Air Gap Processor plugin allows selection of the average or absolute minimum air gap reading per pole over a user-selectable number of rotations. A provision is also made to add a fixed offset to each pole measurement to account for measured variations in the stator shape which often result in the actual gap being less at locations other than the probe locations. The air gap output maintaining per-pole gap measurements is calculated and available to the viewer by default. The following additional outputs for each air gap probe can be enabled:

- Best Center Output with Radius and Angle in degrees or radians (selectable)

- Concentricity Output (percent)
- Circularity Output (percent)
- Minimum Air Gap (scalar output representing the last rotation result pole with least air gap)
- Percent Minimum Air Gap to Average Air Gap Output (percent)

Hydropower airgap reference guides provide acceptable thresholds for several of these calculated outputs. Consequently, threshold alarms have been added in some MCM systems to notify operators when recommended thresholds are exceeded. Concentricity, Circularity, and Minimum Air Gap are the main values in use to annunciate potential issues when thresholds are exceeded. Optional Delta Air Gap measurements between aligned top and bottom air gap probes provide an output that monitors the difference in air gap between top and bottom probes on a per-pole basis. A normalize function is provided to establish a baseline delta for each pole. Alarms can be enabled for minimum and maximum deltas, and if the difference between the average delta and any pole's delta exceeds a threshold.

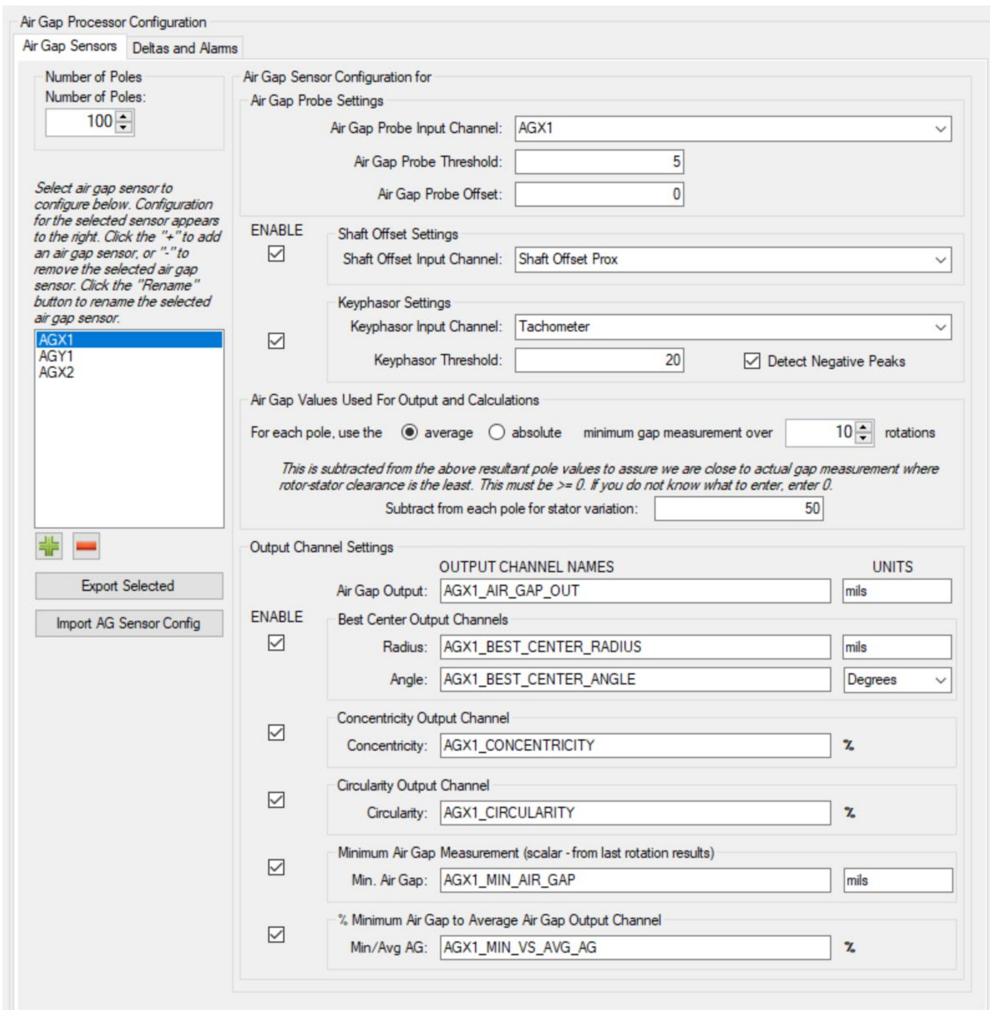

Figure 8 Example MCM2 Core Air Gap Processor plugin configuration.

To complement the Air Gap Processor Core plugin, an Air Gap plugin was added to MCM2 Viewer to display the air gap orbit plots. This plugin includes the ability to invert the shape of the plot so that gap can be relative to the center of the orbit, or relative to the outside of the orbit which is more indicative of the rotor shape. Also, markers can be enabled to indicate which pole has minimum or maximum air gap on each rotation.

A use case of the impact of implementing this feature is featured in the next section below (see *Generator Rotor Shape* in the *Use Cases* section).

Orbital Trend Plot

A Viewer Orbital Trend plugin was added to display X-Y orbit data over longer timespans providing the means to visualize change over time. This plot is useful to display the rotor center. For example, the rotor center can move when excited indicating the change in position of the rotor from its mechanical center to its electrical center.

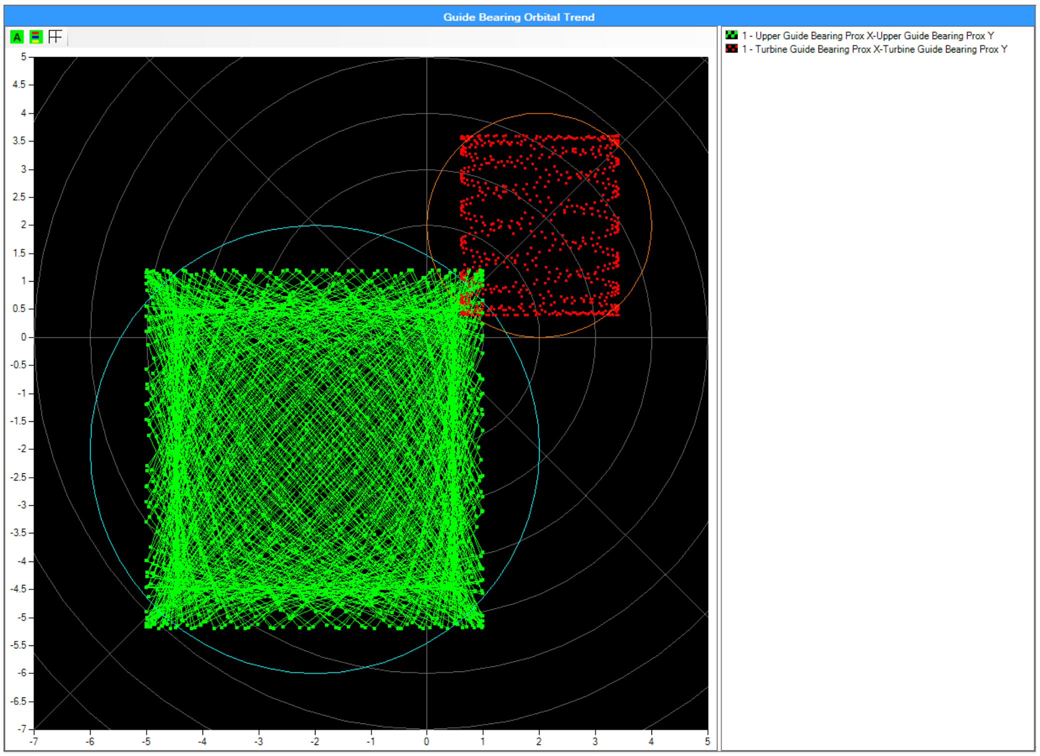

Figure 9 Example MCM2 Viewer Orbit Trend Display using simulated data.

Heatmap Displays

Heatmap displays can be very powerful tools in analyzing trend data. Heatmaps allow 3-dimensional representations of data, using a color scale to represent the Z-dimension value. A heatmap plugin was added to MCM2 Viewer, and 3 types of plots are currently supported:

1. Time-Accumulation Heatmap – The Z axis value is determined by the amount of time that an X signal intersects a Y signal. The longer the X-Y intersection of the input signals spend in a region on the plot, the higher an intensity is displayed in that region of the plot.

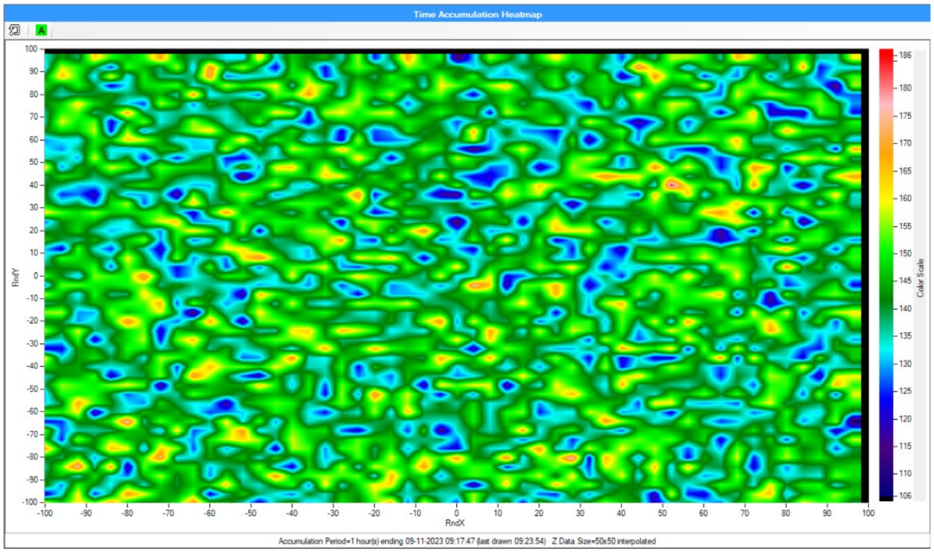

Figure 10 MCM2 Viewer Time Accumulation Heatmap plot with randomly-generated X and Y data.

2. XYZ Heatmap – This plot takes inputs from 3 channels: X, Y, and Z. The resulting plot displays X vs. Y split into a selectable number of regions. For each X/Y region, the Z values are averaged. The resulting Z average is plotted on a color scale indicating its intensity (value) compared to other Z values on the plot.

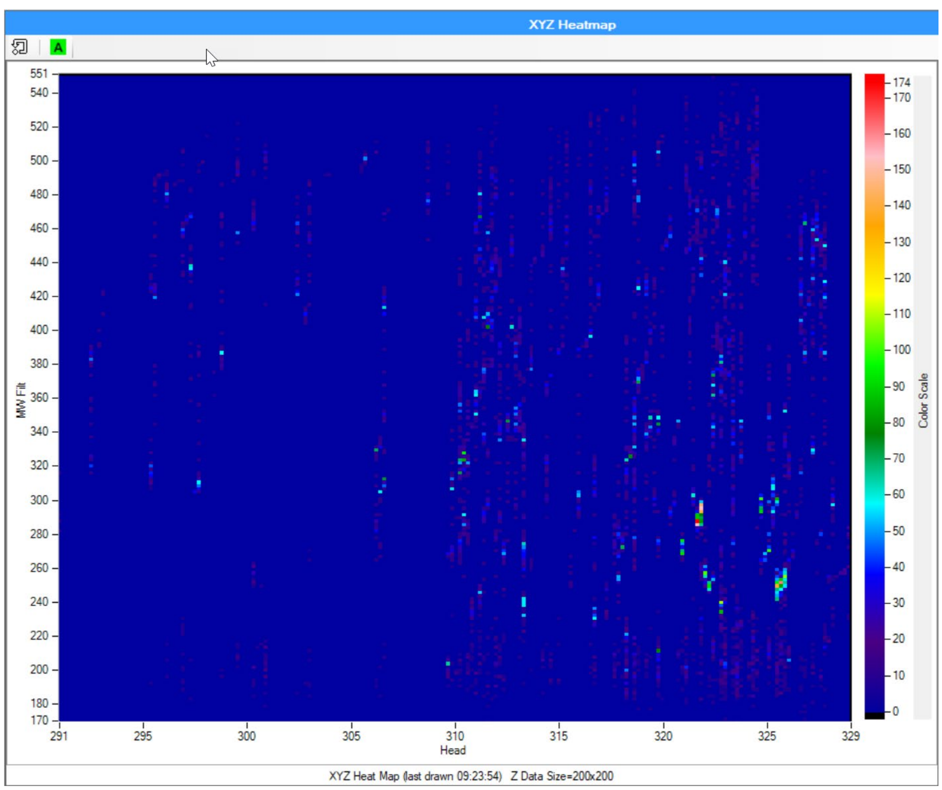

Figure 11 MCM2 Viewer XYZ Heatmap plot displaying data from a CSV file.

3. FFT Spectrum vs Y Heatmap – This plot's X channel is an FFT spectrum plot which takes snapshots of a signal's Fast Fourier Transformation. The FFT spectrum intersections with a

Y input signal in the time domain are tabulated by summing them or averaging them and displaying the results on a color scale representing intensity in X-Y regions on the plot.

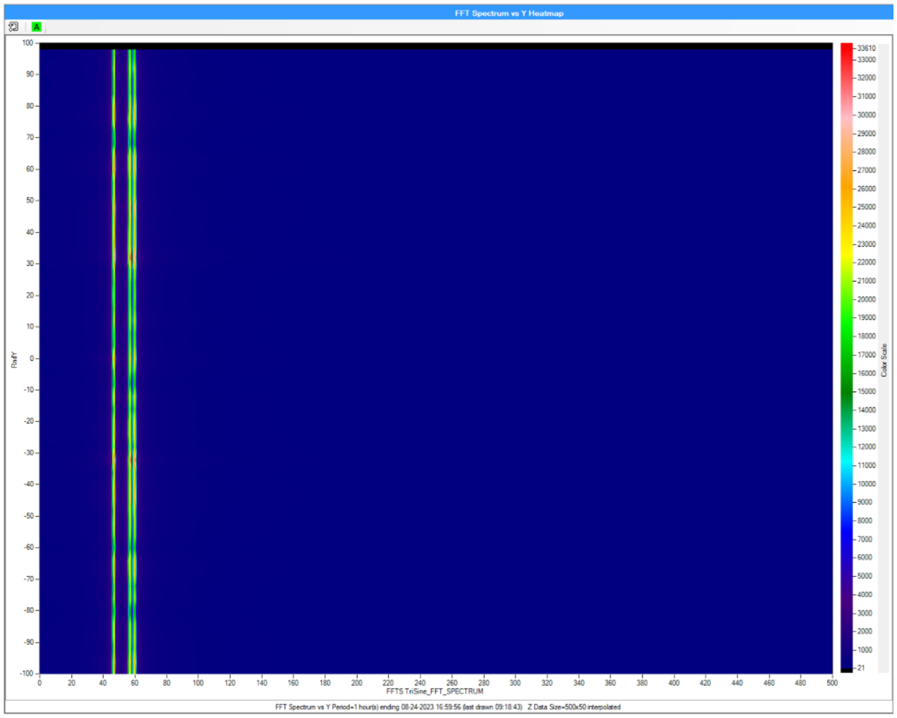

Figure 12 MCM2 Viewer FFT vs. Y Heatmap Plot displaying the Fast Fourier Transform (FFT) of a signal composed of 3 added sine waves vs. a randomized Y value.

Heatmap displays have been used to display maps of unit rough zone. A use case of the impact of this feature appears below in the "*Use Cases*" section.

Cavitation Monitoring

Cavitation monitoring has unique needs not normally included in commercially available data acquisition platforms. Reclamation actively analyzes frequency spectrum data from specialized instrumentation and seasonal performance characteristics using custom data analysis scripts outside of MCM2. The development of such analysis techniques is beyond the scope of this research project and has been funded by a different research project. All scripts, plots, and techniques are byproducts of cavitation research efforts and the MCM research efforts have been integrating them into MCM2. The analysis of this data is greatly influential in how facilities choose to operate their machines. Progress has been made in providing the tools in MCM2 to enable facilities to perform this complex analysis intended to inform production decisions. FFT calculations and visualizations have been developed. The heatmap plots described in the prior section are used to display the FFT results. These tools are in the testing phase. The complexity and computing requirements of these unique features makes their deployment experimental in nature requiring longer testing windows for production level performance. It is expected that this new feature will require additional development iterations as results of its performance is notated with long-term field performance testing. This feature alone greatly influences O&M procedures and decision-making and it is a priority to get this MCM2 feature deployed in the field.

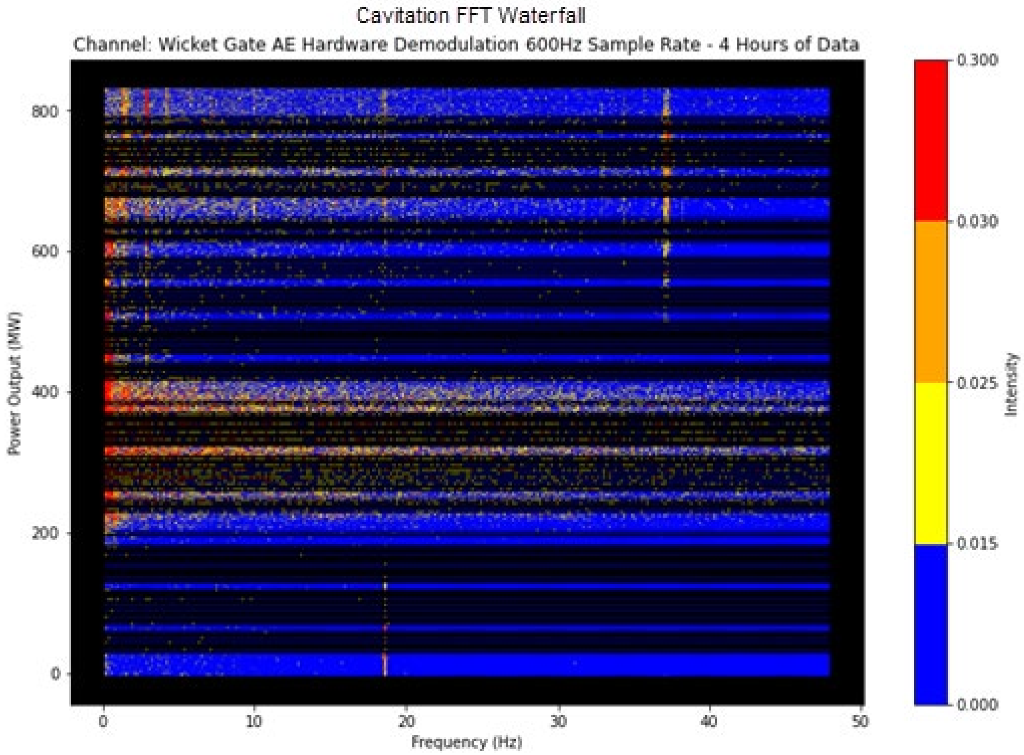

Figure 13 Example of a Cavitation Monitoring plot.

Efficiency Calculation

An Efficiency plugin was added to MCM2 Core to calculate operating efficiency. The plugin takes unit load, flow, and head as inputs and provides an instantaneous efficiency output. Displaying unit efficiency on a heat map, head vs load vs efficiency, is beneficial to for operators to understand the optimal unit loading points at various heads.

Rotor-Mounted Measurements

An MCM2 Core plugin was developed to allow measurement using rotor-mounted battery-powered data acquisition hardware (DAQ) modules from Parker Hannifin Corporation (formerly LORD). The current installation measures strain, but many other types of measurements are possible using this plugin. The plugin was designed to facilitate long battery life of the DAQ devices by letting the devices sleep most of the time but waking them to measure data during events of interest, or on a timed interval.

A use case of the impact of implementing this feature is featured below.

Technology Updates

Technologies used to create and run MCM2 have been updated from end-of-life tools and software to the following versions which were current at the time of updates:

- Updated compiler to Visual Studio 2019 (formerly VS2010) and NI Measurement Studio 2019 extensions for Visual Studio (formerly MS2013).

- Updated the MCM2 suite of applications to run under .NET FrameworkV4.8 (formerly V4.0).
- Updated to MSSQL Server Express 2019 (from 2012).
- Updated to the latest versions of NI DAQ drivers.

Deployment

Reclamation is organized into five regions (Missouri Basin and Arkansas-Rio Grande-Texas Gulf [MB], Lower Colorado Basin [LCB], California-Great Basin Region [CGB], Columbia-Pacific Northwest [CPN], and Upper Colorado Basin [UCB]). The following table summarizes MCM deployments:

Table 1 Reclamation MCM system deployments

Region	Location	Installed	Being Deployed	Deployed but offline
CGB	JF Carr			2
CGB	Stampede	2		
CPN	Grand Coulee	7	3	
CPN	Palisades	4		
MB	Big Thompson		1	
MB	Estes		3	
MB	Flatiron		3	
MB	Green Mountain	2		
MB	Mary's Lake		1	
MB	Mt Elbert	2		
MB	Pole Hill	1		
MB	Yellowtail	4		
UCB	Elephant Butte	3		
UCB	Fontenelle	1		
UCB	Glen Canyon		2	
UCB	Lower Molina	1		
UCB	Upper Molina	1		
	Total	28	13	2
	Grand Total	43		

Deployment of MCM has taken place in 4 of 5 regions. However, most of the deployments have occurred in CPN and MB regions. Future effort to facilitate the adoption of this research products use throughout Reclamation will continue.

Use Cases

The following are three use cases where MCM2 proved valuable.

Rough Zone

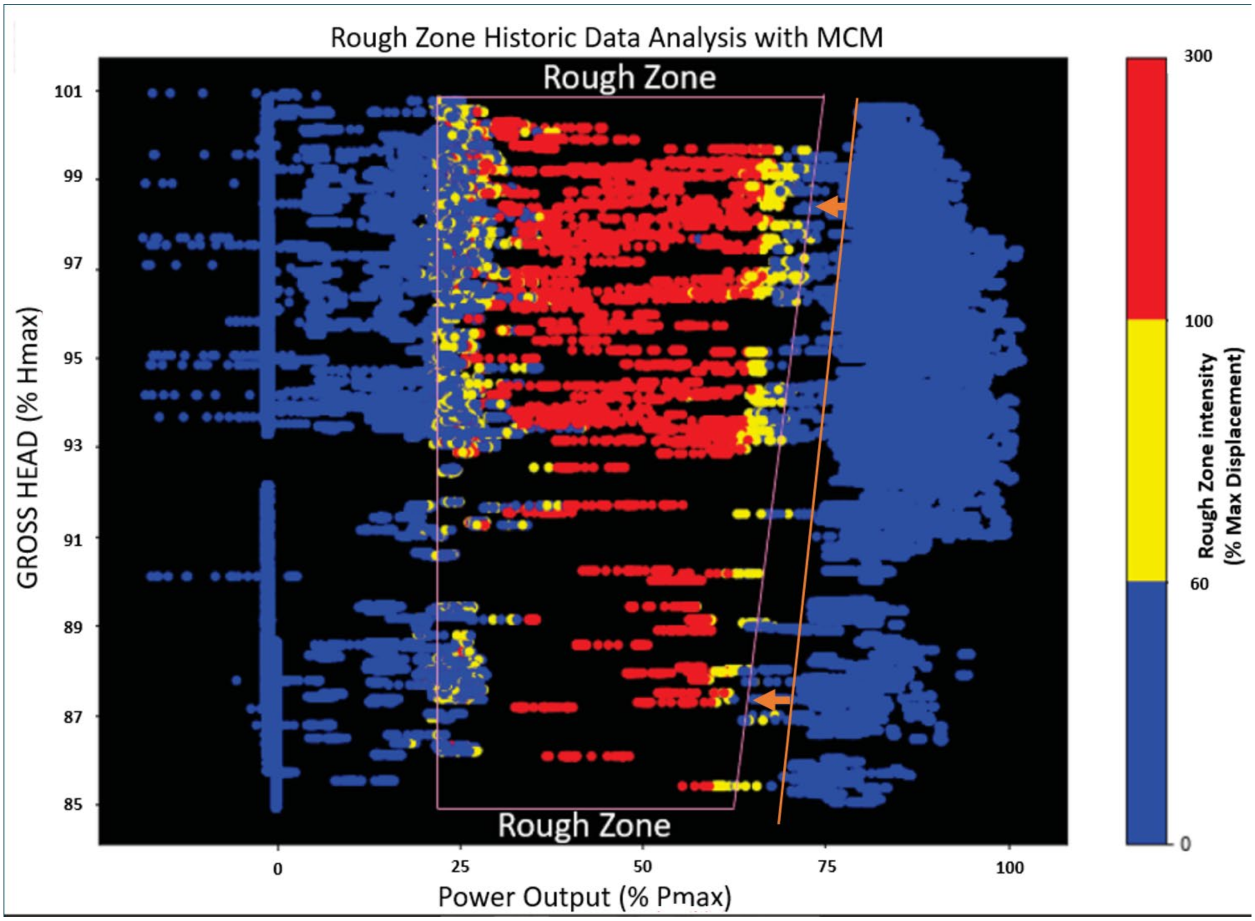

Figure 14 Example rough zone analysis plot.

MCM2's ability to capture and store long-term data has proven to be valuable to Reclamation's powerplants giving engineers the ability to perform analysis of data that would otherwise not be available in traditional SCADA historian systems. In the summer of 2020, a generator's maximum power output was derated due to mechanical issues. This derating placed the maximum power output right inside the upper rough zone as indicated by older standing operating procedures (SOPs) for water elevation levels experienced during the summer season. Operating long-term in the rough zone for hydroelectric generators can cause numerous problems and is not recommended. The facility tasked an engineer to analyze over 12 million data points from both the locally installed MCM and SCADA historian. Custom data analysis scripts outside of MCM2 were developed and funded by the facility within 10 staff days of work that ended up producing a single powerful plot demonstrating a revised upper rough zone. This data allowed the plant to keep the unit online throughout the summer that ultimately produced over $30 million in revenue.

Since this plot was created, engineers and programmers have been adding these types of analysis capabilities in the MCM2 software package with this research. The rough zone mapping feature is still in the testing phase but should be deployed in the near future for performance testing.

Generator Rotor Shape

Hydrogenerator rotors are physically large and can deteriorate over time leading to a change in the rotor shape. This can result in the rotor eccentricity, the deviation of the shape from circularity, to increase. Increased rotor eccentricity can lead to operating issues such as excessive heating of the stator or rotor, increased bearing vibration, rotor or stator fatigue, and if left unchecked can lead to rotor stator contact. Airgap probes can be installed on the stator to measure the shape of the rotor. The rotor shape can be displayed on an X-Y plot and the shape amplified to give maintenance personnel a visual view of the rotor. In addition, rotor concentricity and circularity, defined values that indicate the level of eccentricity, can be calculated and trended. This allows rotor shape metrics to be tracked over time to see if eccentricity is remaining stable or increasing. Threshold limits can be set to alert personnel that additional evaluation, inspection, and perhaps corrective action may be necessary.

Over the last 4 years, air gap measurements and analysis has been used to monitor 3 units with rotor shape issues. A screenshot from one of these units is shown in Figure 7. The orbit plot shows that the top of the rotor is "egg" shaped. In addition, calculated circularity and concentricity are near alarm threshold values. Continuous monitoring of the rotor has allowed these three units to remain online and has avoided a costly annual outage to inspect the rotor. Continuous online monitoring has also lowered the risk of operating these units as it is continuously monitoring for rotor shape changes that would indicate that the unit should be taken offline and inspected.

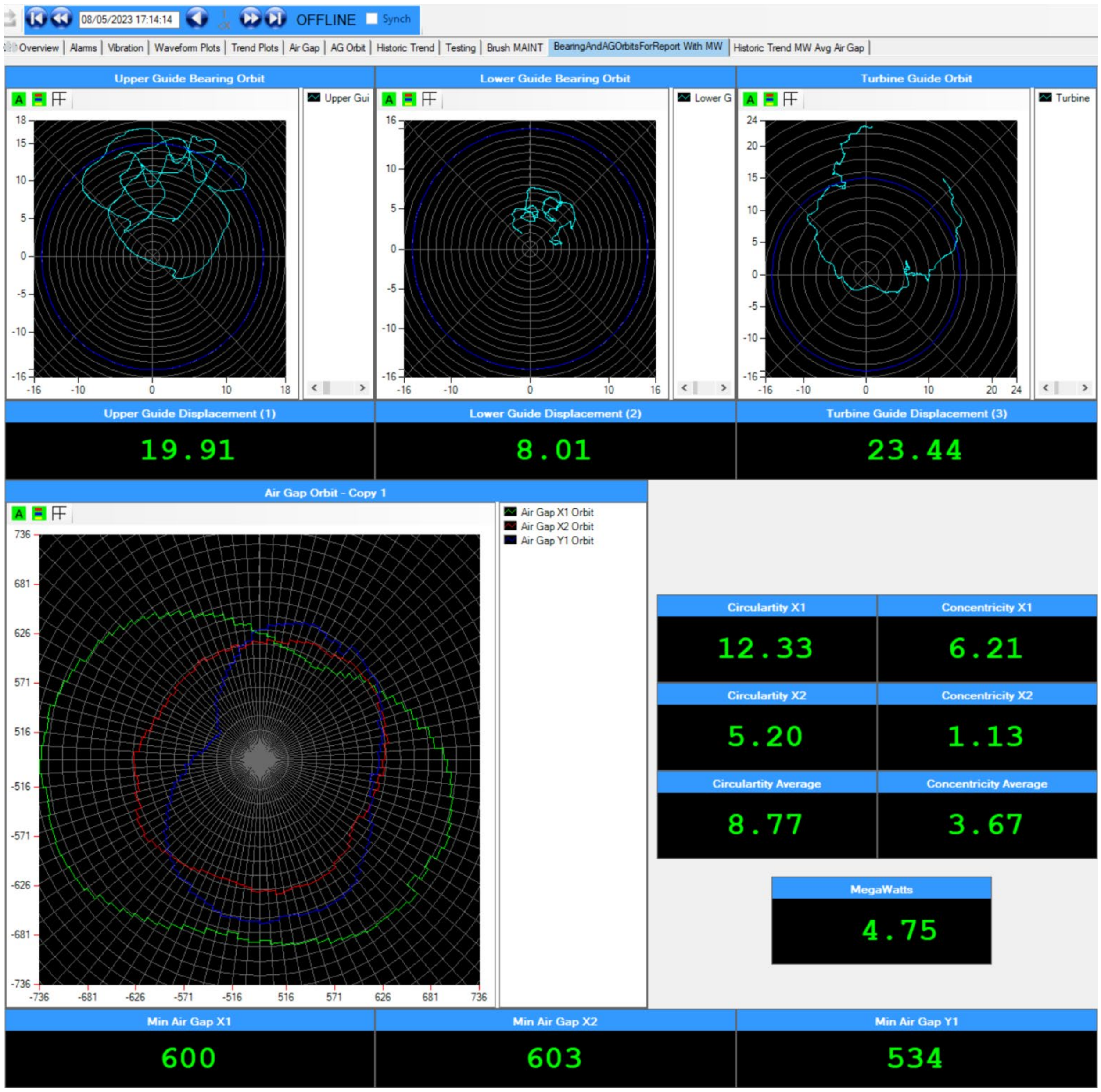

Figure 15 Increased rotor eccentricity impacting vibration and air gap as displayed in MCM2.

Wireless Monitoring

While most generator conditions can be monitored using stationary instrumentation, some specialized issues require monitoring directly on the rotor (rotating part) of the generator. For example, in 2020, a crack was discovered on one of the rotor spider arms of a Reclamation generator. The spider arms are like the spokes of a bicycle and are essential to transfer torque from the generator shaft to the rim (outer edge) of the rotor. A mechanical repair was performed to ensure the forces were transferred around the crack to prevent further crack growth. This crack repair was not intended to be a permanent solution—eventually the rotor will be replaced. The mechanical engineers responsible for the repair advised that the temporary repair be visually inspected monthly. Inspections would require the generator to be taken out of service, which would incur costs both from labor and lost generation revenue. As an alternative to visual inspection, online monitoring was proposed as a solution to keep the generator in service for longer periods of time between visual inspections.

Online monitoring of the rotor crack required specialized equipment that could be mounted on the rotor during operation and transmit data to the MCM system. A wireless data acquisition system was constructed using battery-powered LORD MicroStrain wireless data acquisition nodes. The nodes acquire data from a total of 16 different strain gauges mounted at various locations on the spider arms to detect any changes in the crack repair. A specialized data acquisition plugin was developed for MCM2 to trigger data acquisition from the strain gauges at specific unit operation scenarios. The ability to simultaneously sample generator output quantities, bearing vibration, and rotor-mounted strain gauges led to the success of this monitoring solution.

The rotor-mounted wireless data acquisition system was developed for crack monitoring using strain gauges; however, it has the potential to be applied to numerous other applications in the future. Online wireless monitoring using MCM2 could be applied to monitor rotor rim float, rotor-to-stator air gap, rotor temperature, and other rotor quantities that could be essential to understanding the health of a generator rotor.

Return on Investment

The 2019 MCM Science and Technology Program final research report included a study performed by the economic group in Denver. This report showed a cost of $4.4 million and savings of $25 million. (*Details can be obtained by accessing the report via links in the References section in this document.*) To estimate the current rate of return, the incremental research costs and plant benefits were added to this 2019 baseline data. MCM2 research costs for 2020-2024 is $300k resulting in a total cost of $4.7 million. Additional savings of $49.5 million, as detailed below, have also been realized during this period. This results in a total savings $74.5 million resulting in a return on investment of approximately 16:1.

Savings data

The 2019 MCM Science and Technology Program final research report included savings data totaling $25 million. (*Details can be obtained by accessing the report via links in the References section in this document.*) Between 2020 and 2024 additional savings at two large power plants have been recognized.

1. During the summer of 2020, MCM data was used to recalculate the rough zone on one Reclamation unit. This allowed the unit to remain online throughout the summer. Looking at the actual power produced by this unit for the summer of 2020, it is estimated the unit produced about $30 million in revenue.
2. Online rotor shape monitoring using MCM data has allowed three units to remain online from 2020-2024. This avoids an annual outage and inspection with an estimated savings of $18.5 million.

3. Rotor monitoring has allowed a unit with a cracked rotor to remain online for 1 year. Estimated savings of eliminated monthly outages to inspect unit is $1 million.

These recent numbers are estimates and have not been peer reviewed, but they show the potential of avoided costs using the MCM system. There are other savings that have occurred at other facilities, but the three above were documented. These additional documented savings total $49.5 million. Added to the savings detailed in the 2019 MCM research report, total cumulative savings have reached at least $74.5 million.

Discussion

MCM2 has evolved to a very capable suite of programs providing valuable insights into generator health. The addition of air gap analysis and bearing analysis tools has increased value of MCM2 significantly. Having a history of data to allow trending characteristics is one of the keys to the usefulness of MCM2. Ability to share MCM data with a data aggregator provides an additional avenue to contribute to and obtain additional O&M insights using artificial intelligence (AI) algorithms. These valuable tools raise the urgency for installation of MCM systems on Reclamation generators that do not currently have MCM2 installed.

Next Steps

Continue Deployment and Encourage Additional Adoption

Reclamation's MCM systems have proven to be useful tools in reducing unnecessary O&M activities and reducing unscheduled outages. The installation and use of MCM needs to be encouraged where it has not yet been adopted. Education in use of MCM and integrating the insights it provides in O&M decisions needs to continue. Research-funded facilitated adoption will be used in future years to install MCM systems to monitor an additional 4-6 units. These new installations will focus on Reclamation area offices and regions with limited installations to give facilities direct exposure to the benefits of installing MCM systems at their facility.

Connecting MCM to Reclamation's Internal Intranet

Another step in Reclamation-wide adoption of MCM is the negotiation of security requirements to connect the MCM computer to Reclamation's internal intranet. This will move the burden of routine maintenance and security software updates from occasional visits from TSC's personnel to weekly patches prescribed by Reclamation's Information Resource Office (IRO). In addition, this would provide connectivity useful for export to data aggregators and the possibility for TSC to access data remotely and to tweak configurations or apply patches and feature updates to MCM2 without need to travel onsite.

Leverage Data Aggregation and Big Data Insights

MCM2 currently provides a means of sharing its data with a data aggregator using MCM2 Core's Big Data Aggregator (BDA) plugin. This plugin produces CSV files that can be uploaded on a scheduled basis and saved to central historian. This is being trialed in a pilot test at one Reclamation Powerplant using a PI historian. The PI system is also importing SCADA data. The PI system affords powerplant operators long-term insights drawn from aggregation of multiple powerplant data streams and from many similar hydropower facilities regarding seasonal trends and optimizations and O & M insights. A new plugin is soon to be developed utilizing Open Platform Communications United Architecture (OPC-UA) to transmit real-time data to the PI system when the MCM computer is connected to Reclamation's Intranet. This will allow more immediate feedback to powerplant operators. In the near future AI programs will also be piloted to discover additional benefits using this PI historian data.

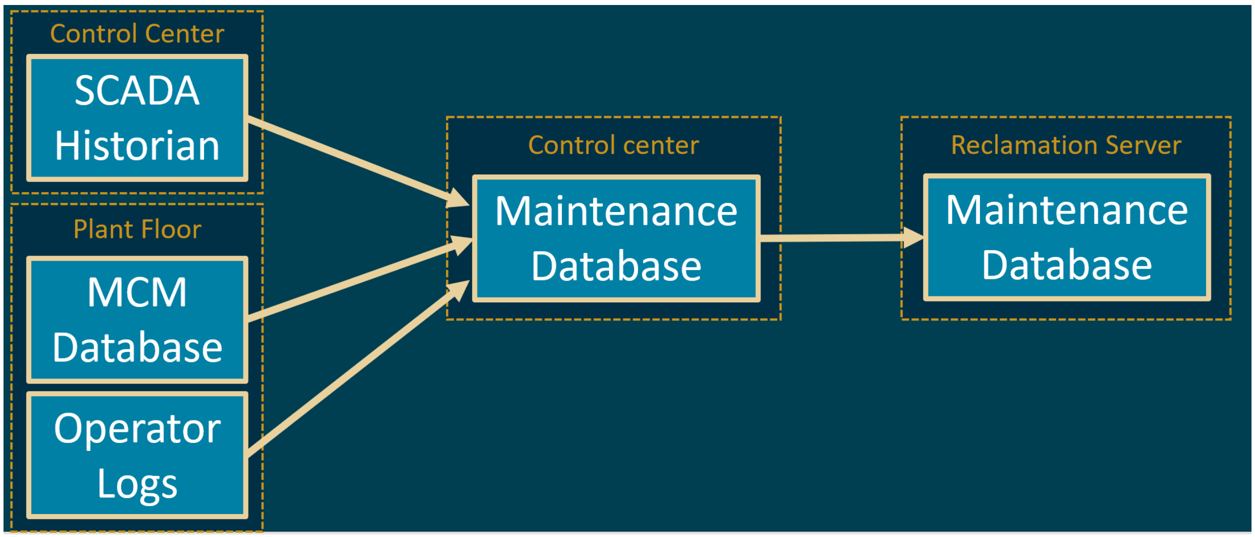

Figure 16 Path of data from MCM2 and SCADA to PI Database.

Deploy Visualizations of Operating Conditions

Heatmaps (and scatterplots) to show rough zone and cavitation, and waterfall analysis plots have been developed and MCM2 is capable of displaying them. However, at times, required process conditions are not available to MCM, or time simply has not been taken to configure the plots. There is desire in the plants to have continuously updating plots showing past operating conditions overlaid with current operating points to see whether operation levels should be increased or decreased to avoid harmful operating conditions. These plots need to be configured and deployed. Where possible, missing process condition signals need to be brought into MCM to enable the display of these useful plots and displays.

Complete and Deploy the Offline Data Visualization Tool (ODVT)

A piece of the MCM2 suite of programs currently in development is the Offline Data Visualization Tool. The ODVT will provide a way for plant personnel to draw conclusions from MCM2-produced data and from other data sources (such as SCADA data exports) that will inform decisions about operation and maintenance. The intent of the ODVT's design is to allow both tabular and graphical imaging analysis projects to be designed, saved, and recalled again for use with new data. It is a standalone application that can be installed on a workstation or laptop separate from the MCM system. It will allow for complex calculations to be run that may take a long time, and if not running on the MCM systems, it will not require resources needed for real-time data acquisition and display of MCM2 data. Also, larger amounts of data and longer-term trend data will be consumed by the ODVT to produce insights that the MCM systems cannot currently produce because of limited resources.

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Glossary

Big Data. Data collected in such volumes that it is beyond the ability of commonly used software tools and computer hardware to store, manage and process within a reasonable amount of time. Such volumes of data can yield new insights into patterns, trends and repeatable results that is not possible with smaller samples of data.

Big Data Aggregation. This is the process of collecting large volumes of data often from multiple similar sources, managing, compiling, simplifying, analyzing and reporting on relevant conclusions. This can be done within an organization but is often done by an external organization that collects similar data from many sources, anonymizes it, and provides tools to easily glean insights from the analysis.

DAQ. This is a common acronym for data acquisition hardware. *See Data Acquisition Hardware.*

Data Acquisition Hardware. Data acquisition hardware can refer to a standalone computer board, but more often refers to hardware that connects to a computer which primarily gathers real-time analog data (in such forms as voltage or temperature) allowing these values to be viewed immediately and/or to be stored for later analysis. Other capabilities of data acquisition hardware include monitoring digital inputs, and sourcing analog and digital outputs.

Machine Condition Monitoring. The process of continually evaluating physical characteristics related to the operation of machinery for the purpose of detecting changes that may indicate a pending operational fault. Specifically for hydro generators and pumps, this primarily includes but is not limited to analysis of vibration characteristics.

O & M. Operations and Maintenance. This refers to planned daily activities monitoring, inspecting, cleaning, lubricating, and maintaining fluid levels to assure proper operation of operating equipment such hydroelectric generators.

Appendix A – Photos and Screenshots of MCM2 Installations

Figure A 1 Reviewing Trigger/Action Mapping

Figure A 2 Typical MCM turbine guide bearing proximity sensors and laser tachometer installation.

Figure A 3 Discussing MCM monitoring features in turbine pit of current MCM2 installation.

Figure A 4 MCM2 System with the Viewer application displaying rotor eccentricity information during operation.

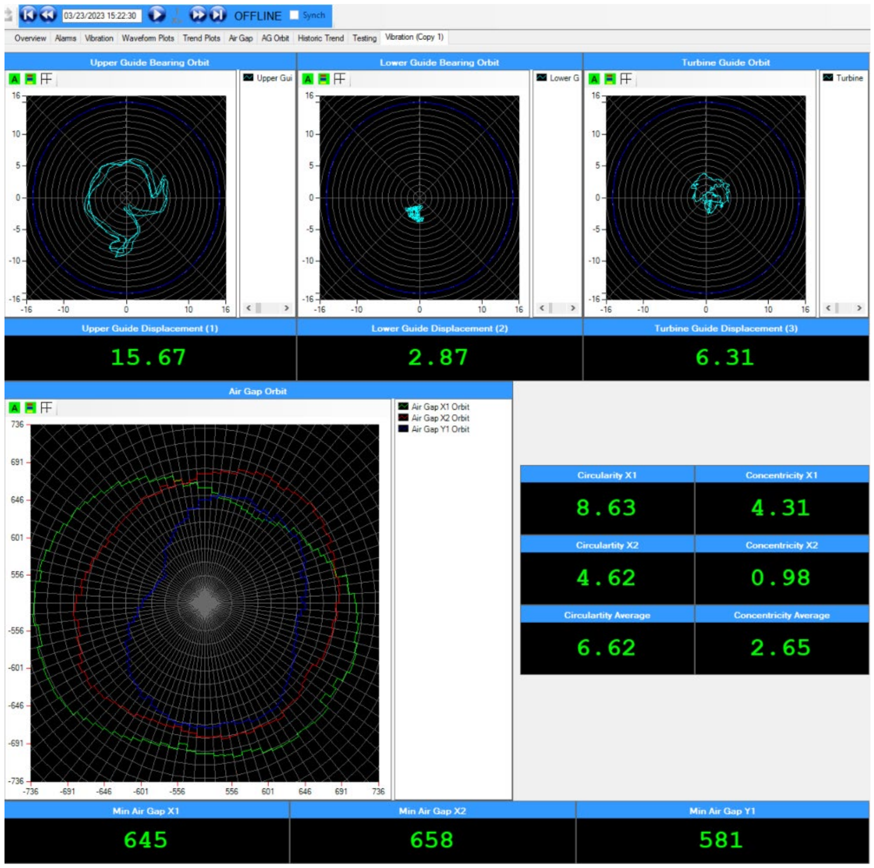

Figure A 5 Example of MCM2 Viewer display used to monitor air gap data

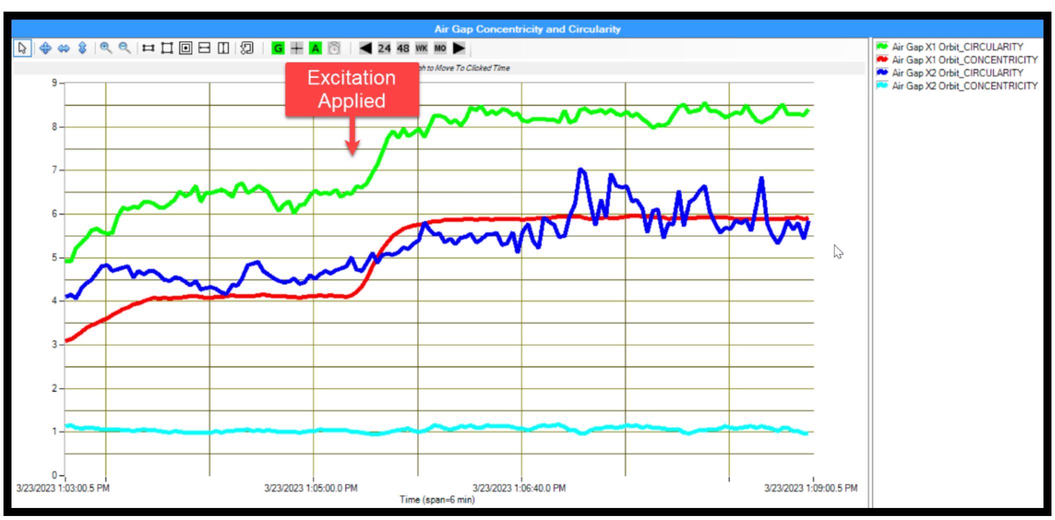

Figure A 6 Example of air gap analysis plot based on new MCM2 Core Air Gap Processor plugin calculations