BUREAU OF RECLAMATION

Predictive Maintenance Program - Research and development of a system to transfer and store secured data in support of a Reclamation-wide Predictive Maintenance Management program for power production assets.

Science and Technology Program
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Predictive Maintenance Program –

Research and development of a system to transfer and store secured data in support of a Reclamation-wide Predictive Maintenance Management program for power production assets.

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Bureau of Reclamation
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Final Report ST-2023-20203-01

Predictive Maintenance Program - Research and development of a system to transfer and store secured data in support of a Reclamation-wide Predictive Maintenance Management program for power production assets.

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Specific references to Reclamation powerplants, powerplant data, field personnel or to specific manufacturers are contained in the appendix section of the report. The appendix section is for internal Reclamation use only and is not included in the public version of the report.

Acronyms and Abbreviations

ATO	Authority to Operate
CARMA	Capital Asset and Resource Management Application
DAQ	Data Acquisition System
DGA	Dissolved Gas Analysis
FBMS	Financial and Business Management System
FIST	Facility Instructions, Standards and Techniques
FTE	Full Time Equivalent
GRID	Generation Resources Information Database
HRI	Hydropower Research Institute
ICS	Industrial Control System
IMT	Information Management and Technology
IRO	Information Resources Office
IoT	Internet of Things
IR	Infrared
IT	Information Technology
MCM	Machine Condition Monitoring
MII	Maintenance Improvements Initiative
NERC	North America Electric Reliability Corporation
O&M	Operation and Maintenance
PD	Partial Discharge
PEB	Power Equipment Bulletin
PRO	Power Resource Office
Reclamation	Bureau of Reclamation
SCADA	Supervisory Control and Data Acquisition
SMEs	Subject Matter Experts
TSC	Technical Service Center
WECC	Western Electricity Coordinating Council

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Executive Summary

To maximize the value of Bureau of Reclamation's (Reclamation's) power production assets, the implementation of a condition-based predictive maintenance program that can be deployed Reclamation wide is necessary to help optimize plant maintenance. To support this implementation this research pursued the following two objectives:

Business Case

To help demonstrate the benefits of pursuing predictive maintenance, a business case for implementing several hydro plant condition monitoring systems at a Reclamation powerplant was evaluated.

Objective

- Monetarize condition monitoring impact at a Reclamation Powerplant.

Parameters:

- Focus on impact to plant labor
- Tabulate maintenance labor costs associated with specific assets
- Include purchasing and installation costs
- Calculate condition monitor Return on Investment (ROI)

Results:

- Condition monitoring reduces labor requirements
    - Payback Period varies from 10 months to over 10 years.
- Significant additional savings anticipated
    - Reduced equipment downtime
    - Increased equipment life expectance

These results can be used, or replicated, by others to assist in developing predictive maintenance implementation plans that obtains a respectable return on investment.

Network Pilot

The second task was to deploy a pilot network infrastructure that supports the transfer and storage of condition monitoring data. This is the foundational infrastructure needed to build a predictive maintenance program.

Objective:

- Deploy a data transfer and storage system via a pilot project at a Reclamation facility and control center.

Results:

- Proposed solution successfully implemented
- Used Reclamation's existing IT infrastructure
- Complies with Reclamation's security requirements

Introduction

This research effort seeks to reduce Operation and Maintenance (O&M) costs, increase plant availability, and preserve Reclamation's infrastructure by identifying and implementing the technologies necessary to provide current, relevant, and accessible data on the present condition of plant equipment. This data can help optimize maintenance via a predictive maintenance program. Given Reclamation's aging facilities, a deregulated market, staff shortages, the increased demand for additional ancillary services due to the integration of wind and solar power, and North American Electric Reliability Corporation (NERC) and Western Electricity Coordinating Council (WECC) requirements, current O&M practices are not optimal. Time-based preventive maintenance, in general, is inefficient, labor intensive, and results in some equipment being under maintained while other equipment over maintained. Condition-based maintenance has been ineffective in the past due to the overwhelming volume of data to be monitored, the inability to transmit this data to a central location for analysis, and the inability to process and analyze the data to produce meaningful maintenance recommendations.

The development of a comprehensive predictive maintenance program within Reclamation provides the tools necessary to help optimize operation and maintenance activities and lower maintenance costs while simultaneously ensuring and enhancing plant sustainability, reliability, and operation. As O&M is one of Reclamation's single largest expenses, corporate-wide savings resulting from optimizing maintenance could be several million dollars a year.[1] In addition to reducing maintenance costs, predictive maintenance also reduces unscheduled outages and can extends equipment life expectancy. These cost savings directly benefit all of Reclamation's power facilities and allow Reclamation to better compete in a deregulated power market Reclamation's power customers and the entire hydropower industry will also benefit.

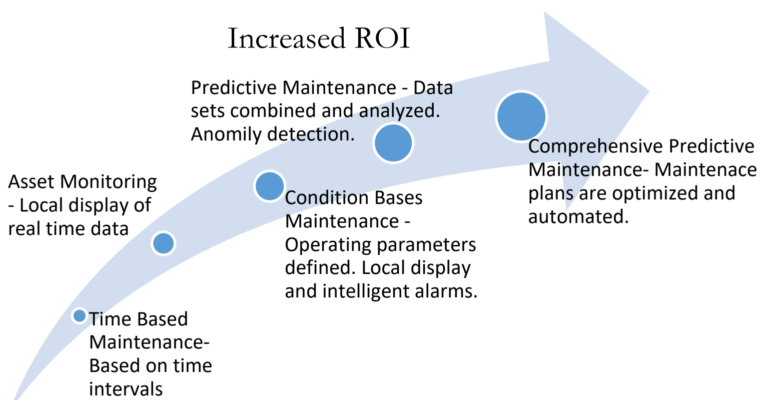

Figure 1- Comprehensive Predictive Maintenance

[1] Reclamation's FY2023 budget justifications (https://www.usbr.gov/budget/) for facility operation, maintenance, and rehabilitation is $674 million. Thus, every 1 percent reduction in O&M costs results in a savings of $6.7 million/year. This value does not include costs funded by power, water, and transferred works and the cost of unscheduled outages that can exceed $150,000/day per unit.

Predictive maintenance uses various data processing methods to analyze data sets collected at powerplants to discover data trends. These data sets consist of control and operation data, periodic monitored data, periodic testing results, and data from condition monitors. Within Reclamation, supervisory control and data acquisition (SCADA) systems provide some of the needed data but its focus is plant control and not maintenance data. Condition monitoring fills this gap. Not only does condition monitoring help reduce labor associated with routine maintenance tasks, it also can be used to help optimize the timing and quantity of maintenance tasks. To enable these maintenance scheduling tasks, condition monitoring data needs to be securely transferred to a location where it is accessible and can be analyzed. Another benefit of a system to transmit secured powerplant data is it can lower cost by reducing field office and Technical Service Center (TSC) travel. Enabling offsite data analysis will provide the opportunity to remotely collect at least some of the data normally collected through site visits. This reduces the number and duration of personnel trips to Reclamation facilities.

The goal of this research project is to support the development of a predictive maintenance management program for power assets with an initial focus on secured data transfer of condition monitor data. Initial tasks to accomplish this goal are to demonstrate the business case of implementing condition monitoring and to design and demonstrate the data transfer and storage system needed to support a predictive maintenance program.

Research Objective and Approach

The condition monitoring business case is developed by examining historic maintenance records and expenditures. Given time and budget constraints these records were limited to one Reclamation plant. In addition, an ongoing Maintenance Improvements Initiative (MII) currently being pursued in Reclamation was leveraged to identify the Facility Instructions, Standards, and Techniques (FIST) tasks that could be impacted by the installation of various condition monitoring systems. These tasks were group by assets and then narrowed down to include monitoring systems that Subject Matter Experts (SMEs) and the plant maintenance manager felt would have the largest impact in reducing maintenance costs. Analysis of this data shows the economic impact of implementation of various condition monitoring systems and identifies monitoring systems that produce a large return on investment. The potential labor cost savings of predictive maintenance by implementing these monitoring systems helps demonstrate the business case for implementing condition monitoring. This is a major steppingstone in realizing a comprehensive predictive maintenance program within Reclamation.

The implementation of a predictive maintenance management program starts with data and the transfer of this data to a location where it can be analyzed. Several data sources already exist within Reclamation including SCADA and Machine Condition Monitoring (MCM) data. However, transferring the data requires the development and deployment of a method to transmit data securely to a central and accessible location for storage. To expedite this process, this research proposed a data network and storage system design, tested it in the laboratory, and then implemented it via a pilot project. The research outcome is that the network and database is currently collecting and storing data.

Design, testing, and deployment of the pilot required input from multiple disciplines from across Reclamation to ensure the proposed system is feasible, works with current and future data collection sources, works with the current and future Reclamation enterprise system, meets Information Technology (IT) security requirements, and is cost effective. In addition to the research team of TSC engineers, this effort also included senior members of Reclamation's Industrial Control System (ICS) team within the Information Resources Office (IRO), Power Resources Office (PRO) personnel, regional engineers, and plant facility managers and crafts.

Previous Work

The in-house development of MCM software was initiated in 2009 with research funding. This system was designed to collect generator and large motor condition monitoring data. The program is based on a server/client platform which allows multiple users to have accounts on the MCM computer (locally and remotely) and to view recorded data simultaneously. MCM systems that have been or are in the process of being installed are monitoring 37 units with an additional 37 generators in the beginning process of design and should be installed in the next couple of years. A cost/benefit analysis of these initial 37 installations have shown a return on investment of 3200%. These saving will only increase as time passes.

Demonstration of a Reclamation historian (database) is underway with funding by PRO. A pilot project has been deployed at two control centers. This project is still in development but is demonstrating a method to collect SCADA data from Reclamation control centers and transfer this data to a central database.

PRO, with assistance from the TSC SMEs and regional reviewers, is pursuing MII. This effort is adding condition monitoring to Reclamation's FIST manuals. The FIST manuals list Reclamation suggested/required time-based maintenance tasks and intervals to perform these tasks. Updated FIST manuals will include condition monitoring techniques and technologies and the impact they have on replacing or extending the interval of these maintenance tasks.

Controlled Data

Specific references to Reclamation powerplants, powerplant data, field personnel, or to specific manufacturers are contained in the appendix section of the report. The appendix section is for internal Reclamation use only and is not included in the public version of the report.

Condition Monitoring Business Case

Industries that have implemented predictive maintenance programs have shown a savings of up to 25%[2] in reduced operation and maintenance expenses. Unscheduled outages also are significantly reduced, and in some cases, equipment life is extended. These resulting impacts will help minimize Reclamation's maintenance costs while simultaneously enhancing power generation sustainability and reliability. However, the cost to implement predictive maintenance is hard to predict and the specific cost saving at Reclamation may not follow the results other industries have seen. Thus, this research effort pursued a business case study as an initial step to identify these cost savings by analyzing several condition monitoring systems that could potentially be installed at Reclamation hydropower facilities and calculating the resultant maintenance labor savings that are anticipated.

Condition monitoring cost saving can be derived from the following:

1) reducing labor cost by automating routine preventive maintenance labor tasks,
2) providing data needed to move from preventive time-based maintenance schedules to condition-based maintenance schedules,
3) making historic data available to help identify failure causes quickly,
4) increasing equipment availability,
5) extending equipment life,
6) immediate notification of monitor alarms to expedite repairs, and
7) providing the information needed to detect data anomalies that indicate maintenance is required.

This study focused only on the first benefit:

1) reducing labor cost by automating routine preventive maintenance labor tasks.

This was felt to present a "base-line" business case to a facility with a definable labor saving that would have a near immediate impact on maintenance costs. It should be noted that it is not anticipated that any facility that implements condition monitoring would reduce the number of employees at their facility. Rather it would free up existing employees time to focus on other deferred maintenance tasks. The payback times presented in this report do not account for the additional cost saving benefits identified above. Thus, actual cost savings are expected to be much higher than presented in this report. For example, if the 25% savings is realized within Reclamation the cost savings per year would be $169M based on Reclamation's FY2023 budget justification.

An initial list of condition monitoring systems was available from ongoing MII work that PRO is pursuing. This initial list was developed by SMEs within the TSC who identified condition monitoring systems that are available and prioritized the targeted maintenance tasks listed in FIST 4-1a and FIST 4-1b that would be impacted if these monitoring systems were installed. The same SMEs prioritized this MII list to identify the monitoring systems they anticipated would have the largest financial impact on maintenance activities listed in the FIST manuals.

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[2]Digitally enabled reliability: Beyond predictive maintenance, McKinsey, 2018. https://www.mckinsey.com/capabilities/operations/our-insights/digitally-enabled-reliability-beyond-predictive-maintenance

To obtain realistic financial results, the research project partnered with a Reclamation hydropower facility, Plant A (see Appendix A for list of Reclamation facilities and partners that participated in this research). The monitoring system list was shared with the Plant A manager to further narrow the list to the ones that would directly impact the plants immediate needs.

This process identified roughly 25 condition monitoring systems to evaluate. For each of these systems the purchase price was determined by either obtaining a budgetary quote from the manufacturer or by list pricing on the internet. Procurement cost of 15% was included for purchases above $10,000. Finally, installation costs were estimated based on input from the manufacturer, plant personnel, or experience related to the installation of similar systems.

To determine the plant maintenance labor costs, the study looked at the plant CARMA[3] and FBMS[4] data to obtain cost associated with the specific maintenance that would be impacted when condition monitoring equipment is utilized. For Plant A, the CARMA data available after 2017 was assumed to be most accurate because at that time personnel had been fully trained in use of the system and were successfully using it to document most maintenance tasks. CARMA data from 2018 – 2021 was used in this study. The specific parameters used to obtain the CARMA reports are included in Appendix B.

CARMA reports for all assets at the plant were downloaded into Microsoft Excel, so that the data could be further analyzed. It was discovered that many maintenance tasks were listed under general locations, rather than more specific assets, so individual tasks were reviewed and assigned to a specific asset as needed. Many maintenance tasks also were shown completed but no actual labor charged. It is thought that this occurs because plant personnel perform multiple jobs throughout the day and sometimes enter their time only under one or two of these tasks. To ensure these tasks without labor charges are not overlooked in the analysis, the estimated task labor was used if the actual labor for these tasks was not available. Thus, some labor charges will be too high if they included extra labor or too low if the estimated labor value is not accurate, but it is felt that when averaged over several years these errors will be minimized. It was also noted that the total CARMA labor cost for years 2018-2021 was less than FBMS total cost for the plant during the same timeframe. After reviewing the FBMS data, this discrepancy is due to the fact the CARMA data does not include plant overhead. This overhead, in part, is related to plant management and engineering costs, plant supplies not billed directly to a CARMA task, and regional and TSC support costs. To account for this overhead cost, an overhead factor was determined by dividing the total FBMS cost by the total CARMA cost. This overhead number was then applied to all maintenance task costs as determined using the CARMA data.

Once the labor costs were identified and totaled, the impact of implementing condition monitoring was then calculated by looking at the various FIST tasks that would be impacted and estimating the resultant labor hours that would be replaced by implementing the identified condition monitoring systems.

[3] CARMA (Capital Asset and Resource Management Application)- Reclamation deployment of Maximo

[4] FBMS (Financial and Business Management System)- Department of Interior enterprise business management software

In summary the business case:

- addresses a pre-selected number of condition monitoring systems based on anticipated financial returns and plant needs,
- focused cost savings to impact on O&M labor costs,
- obtained labor costs from 2018 to 2021 CARMA and FBMS data,
- condition monitoring costs included cost of equipment, procurement (if applicable) and installation costs, and
- significant tangible benefits, such as equipment life extension, are listed but financial impact not analyzed.

The results of this study are shown in the following tables. The tables list the condition monitoring systems that were evaluated, the resultant dollar and labor savings anticipated, and the anticipated payback period.

Table 1- Predictive Maintenance Business Case Summary

FIST Targets Priorities	53
Condition monitoring solutions reviewed	25
High value condition monitoring solutions	10
Solutions on hold	2
Total yearly avoided cost per unit of high value FIST targets	$166,300
Total cost per unit to implement high value solutions	$862,800
Total maintenance impact per unit	0.5 / 1.0 FTE*
Average payback period per unit with full implementation	5.2 years

*Inhouse Full Time Employee (FTE) = 0.5, inhouse plus contract FTE= 1.0.

Table 2- Condition Monitor Study Summary – Estimated Maintenance Impact

Monitor Type	FIST 4-1 Tasks Targeted	Estimated Labor Hours Gained
Battery Monitor	17	208 Hours / Year / Battery
Circuit Breaker Monitor	3	65 Hours / Year / Breaker
Excitation Monitor	4	19 Hours / Year / Unit
Excitation Brush Monitor 1	6	45 Hours / Year / Unit
Excitation Brush Monitor 2	1	22 Hours / Year / Unit
Bearing Vibration Monitor	1	Not identified
Stator Condition Monitor	5	Not significant
Rotor Condition Monitor	3	Not significant
Turbine Condition Monitor 1	1	*Inhouse labor:* 250 Hours / Year / Unit *Contract Labor:* 800 Hours / Year /Unit
Turbine Condition Monitor 2	1	
Protection System Monitor	10	179 Hours / Year / Unit
Transformer DGA Monitor	3	250 Hours / Year / Unit
TOTAL IMPACT / UNIT	**53 Tasks Targeted***	*Inhouse labor:* **785 Hours / Year / Unit**** *Inhouse plus Contractor Labor:* **1,585 Hours / Year / Unit****

* Includes Excitation Brush Monitor 1 tasks.
** Does not include battery monitor as a battery is not unit specific.

Table 3- Condition Monitor Study Summary – Estimated Financial Impact (2020 Pricing)

Monitor Type	Estimated System Cost	Estimated Avoided Maintenance Cost	Estimated Payback Period
Battery Monitor	$52,600 / Battery	$21,850 / Year / Battery	2.4 Years
Circuit Breaker Monitor	$39,450 / Breaker	$6,800 / Year / Breaker	5.8 Years
Excitation Monitor	$6,500 / Unit	$2,015 / Year / Unit	3.2 Years
Excitation Brush Monitor 1	$116,500 / Unit	$4,700 / Year / Unit	24.8 Years
Excitation Brush Monitor 2	$14,840 / Unit	$2,350/ Year / Unit	6.3 Year
Bearing Vibration Monitor	$104,500 / Unit	Not identified	N/A
Stator Condition Monitor	$117,300 / Unit	Not significant	N/A
Rotor Condition Monitor	$37,000 / Unit	Not significant	N/A
Turbine Condition Monitor 1	$275k+$95k/Year/Unit	$15,000 / Year / Unit	12 Years
Turbine Condition Monitor 2	$296k+$10k/Year/Unit	$100,000 / Year / Unit	2.7 Years
Protection System Monitor	$15,500 / Unit	$18,800 / Year / Unit	0.8 Year
Transformer DGA Monitor	$129,575 / Unit	$26,300 / Year / Unit	4.9 Years
TOTAL IMPACT PER UNIT*	**$862,800/Unit**	**$166,300 / Year / Unit**	**5.2 Years**

*Does not include battery monitor. Uses Excitation Brush Monitor 2 and Turbine Condition Monitor 2 in calculation.

In addition to reducing maintenance labor costs, predictive maintenance may also increase the life of the equipment it monitors. As the capital cost for equipment is very large, equipment life extension can result in very significant financial benefits. Thus, the potential for equipment life extension is also noted for each condition monitoring system. For Plant A, estimated equipment replacement costs were available for all the plant equipment being evaluated in this study. These estimated capital costs were adjusted to calendar year 2020 values using Reclamation's price index[5]. An annualized equipment cost was then calculated for the equipment life expectancy as given in Reclamation's replacement manual[6]. Totaling these annualized cost estimates, showed that an annualized equipment replacement budget exceeds the total annual maintenance budget for Plant A. In other words, a percent increase in equipment life has a larger financial impact than the same percent decrease in maintenance costs. Given that the impact that a condition monitoring system will have on equipment life extension is difficult to predict accurately, the economic impact of life extension (dollars saved) was not included in this study. For condition monitoring systems that show promise to increase equipment life expectancy, an estimate has been included on the additional equipment life that could be obtained.

[5] Bureau of Reclamation Construction Cost Trends- 1977 to present, available from Estimating Services Group, 86-68170.

[6] Federal Replacements, Units, Service Lives, Factors, 2017 Revision 1.1, https://www.usbr.gov/power/data/2017_Federal_Hydropower_Replacements_Book_BW_1.1.pdf

Condition Monitoring System Overview

Battery Condition Monitor:

Battery condition monitoring has been around for several decades, but unfortunately offerings from various manufacturers have varied significantly over the years. These systems typically record battery system voltage and current, ambient temperature, cell voltages, cell temperatures, and cell internal resistances. Some systems will also record electrolyte levels and cell interconnect resistances. Raw data, processed data, and output alarms are typically provided.

Payback = 2.4 Years
Estimated Asset Life Impact: Little to no impact
Other Benefits: Rapid detection of critical DC system problems

Circuit Breaker Condition Monitor:

Circuit breaker condition monitoring was limited to SF_6 breakers for this study. It focuses on contact I^2t calculations, open and close timing, motor operations and timing, breaker operation counts, SF_6 density, SF_6 leak monitoring, motor coil current profiles, and motor coil continuity. Raw data, processed data, and output alarms are typically provided.

Payback = 5.8 Years
Estimated Asset Life Impact: Little to no impact
Other Benefits: Reduced outage time of circuit breaker maintenance. Continuous monitoring.

Excitation Condition Monitor:

NERC Modeling, Data, and Analysis standards for excitation systems (Mod 25 and 26)[7] require periodic excitation system testing. This testing confirms correct excitation system response to power system disturbances. Online monitoring of generator terminal and field quantities can be used to confirm proper operation of the excitation system during power system disturbances. Capturing and analysis of this disturbance data along with online performance tests will demonstrate NERC compliance. Reclamation's MCM along with field voltage and current transducers and a custom terminal quantity transducer can capture the required data. The custom generator terminal quantity (voltage, current, watts, vars, and frequency) transducer was specifically designed to allow high fidelity signals to be captured for exciter monitoring.

[7] MOD-025-2: Verification and Data Reporting of Generator Real and Reactive Power Capability and Synchronous Condenser Reactive Power Capability
MOD-026-1: Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions

Payback = 3.2 Years
Estimated Asset Life Impact: Little to no impact
Other Benefits: Real-time monitoring of exciter. Can be expanded to include governor monitoring.

Excitation Brush Condition Monitor:

This is an industrial Internet of Things (IoT) solution where all brush holders are replaced with brush holders with integrated sensors. Each brush holder has a battery power transmitter to wirelessly send data to a central processing unit that displays the status of each brush based on an alphanumeric labeling system. The data is stored and trended to allow facilities to predict when brushes need to be replaced and when abnormal conditions occur. The system captures data on brush length, peak-to-peak vibration, and temperature.

Alternatively, continuous infrared (IR) monitoring of the brushes along with online rotor injection resistance measurement is a lower cost monitoring option. This can be incorporated into Reclamation's MCM system. Brush temperature and rotor resistance trending can be used to predict when to schedule brush maintenance. A standalone IoT monitoring system has an extended payback period while incorporating this function into Reclamation's MCM system significantly reduces this time.

IoT Payback = 24.8 Years, MCM Payback = 6.3 Years
Estimated Asset Life Impact: Little to no impact. May detect repairable issue prior to unit failure.
Other Benefits: Reduce outage time, real-time monitoring of brushes detects issues before damage occurs.

Bearing Vibration Monitor:

Reclamation requires the use of a bearing vibration monitoring system on Reclamation generators unless a variance is in place. These requirements are found in Power Equipment Bulletin (PEB) 42[8]. Reclamation's MCM was initially developed to address PEB 42 by monitoring shaft vibration on Reclamation's large rotating machines. The system is built using off-the-shelf hardware that communicates with custom software developed by Reclamation to record, display and trend data, and annunciate alarms.

Payback = Not calculated
Estimated Asset Life Impact: 10% to 30% life increase
Other Benefits: Allows for operation behavior analysis based on real data enabling operation changes that impact equipment life. E.g., avoid rough zone operation.

[8] PEB 42- *Recommendations for Reclamation Facilities in Response to the Sayano-Shushenskaya Powerplant Accident*, Internal Document, 2010.

Generator Stator Condition Monitor:

The MCM is a flexible platform that enables nearly any kind of signal to be captured, trended, and used to trigger software and/or hardware actions. MCM can monitor stator and core temperatures, unit terminal quantities and stator air gap.

Online partial discharge (PD) monitoring can be used to detect changes in PD measurements indictive of possible insulation failure modes allowing facilities to schedule testing and repairs before a unit is forced offline. PD monitoring may not make sense for all generators. Interpretation of data is not intuitive; therefore, analysis will require specialized knowledge of insulation characteristics and prior test results for comparison.

Some protective relays can measure stator resistance while the unit is on-line by injecting a signal between the stator neutral and ground. This allows for trending of ground resistance and may help predict overall insulation deterioration.

> Payback = Not calculated
> Estimated Asset Life Impact: Little to no impact. May detect repairable issue prior to unit failure.
> Other Benefits: Reduced outage time for temporary equipment setup, reduced risk to personnel performing tests, and reduced risk of equipment damage due to improper assembly/disassembly. May help determine when the stator is reaching end-of-life and reduce risk of an extended force outage.

Generator Rotor Condition Monitor:

The MCM is a flexible platform which enables nearly any kind of signal to be captured, trended, and used to trigger software and/or hardware actions. MCM can monitor airgap proximity probes and flux probes to determine rotor shape and to detect rotor pole shorted turns.

Rotor Ground Resistance Monitor measures field resistance to ground by injecting a signal between the field terminals and ground. This monitor also can be connected to the MCM for long-term trending that can help predict overall insulation condition.

> Payback = Not calculated
> Estimated Asset Life Impact: Little to no impact. May detect repairable issue prior to unit failure.
> Other Benefits: Provides base line data for future mechanical adjustment and measurement comparisons. Long-term trending of components allows detection of slow evolving issues. Real-time detection of step-changes that indicate problems. May help with scheduling offline diagnostic testing. May help determine when the rotor is reaching end-of-life and reduce risk of an extended force outage.

Turbine Condition Monitor:

A standalone cavitation detection solution enables the flexible operation of turbines in a safe and controlled manner. The first part of the solution consists of an initial assessment of the possibility to extend the operating range of given hydropower units and to enhance transition sequences. The second part consists of an analytics platform that captures the high-frequency data and analyzes it with embedded software. System monitors any changes in behavior and uses cavitation models to support operational and maintenance decisions. Accumulative cavitation damage can be used to schedule repairs.

Alternatively, this analysis can be incorporated into Reclamation's MCM system. A standalone monitoring system has an extended payback period while incorporating this function into Reclamation's MCM system significantly reduces this time.

> Standalone Payback = 12 Years, MCM Payback = 2.7 Years
> Estimated Asset Life Impact: Estimate 20% plus depending on pre-existing levels of cavitation and quality of repairs.
> Other Benefits: Increase duration between cavitation repairs.

Protection System Condition Monitor:

Modern microprocessor protection system relays are powerful, multifunctional platforms designed for the most demanding utility and industrial applications. With precise, deterministic processing, integrated cybersecurity features, and rugged, industrial-grade hardware, these devices ensure reliable performance for critical operations, even in the harshest operating environments. Manufacturer specific relay monitoring platforms come with extensive protocol support for communication with multiple relays and an embedded logic engine for custom programming—making it a versatile solution for a variety of condition monitoring applications. Reclamation has developed code designed specifically to address maintenance tasks required to maintain microprocessor relays and instrument transformers leveraging the power of compatible microprocessor-based equipment.

> Payback = 0.8 Years
> Estimated Asset Life Impact: Little to no impact
> Other Benefits: Consistent automated testing reduces chances of human error. Real-time detection of issues that may compromise protection of assets allows for corrective maintenance before damage occurs.

Transformer Condition Monitor:

The gases within transformer oil contains information about the condition of the insulation system in a transformer. Therefore, Dissolved Gas Analysis (DGA) is one of the best kinds of diagnostic tests for transformers that are oil-filled to evaluate the condition of the winding insulation system. The ideal sample period for aging oil-filled transformers is 1 DGA per month. For some facilities, this is not practical. As such, an online DGA condition monitor becomes an invaluable tool for enabling facilities to monitor their transformers.

Payback = 4.9 Years
Estimated Asset Life Impact: Little to no direct impact. May detect repairable issue prior to unit failure.
Other Benefits: Consistent sampling using an automated monitor reduces human-induced error. Reduces employee exposure to hazards working around transformers. Increased frequency of sampling allows facilities to detect step-changes in dissolved gasses quickly. Faster detection of issues combined with an appropriate action plan helps facilities to schedule maintenance when needed and avoid major transformer failures.

Condition Monitoring- Summary of Results

Analysis of various condition monitoring systems and their potential impact on maintenance workload has yielded a list of opportunities that can be prioritized based on potential gains to the facility. Using payback period listed in Table 3 as a guide, condition monitoring systems rank as follows:

- Protection System Monitor- 0.8 Year
- Battery Monitor- 2.4 Years
- Turbine Condition Monitor 2- 2.7 Years
- Excitation Monitor- 3.2 Years
- Transformer DGA Monitor- 4.9 Years
- Circuit Breaker Monitor- 5.8 Years
- Excitation Brush Monitor 2- 6.3 Year
- Turbine Condition Monitor 1- 12.0 Years
- Excitation Brush Monitor 1- 24.8 Years

- Bearing Vibration Monitor- N/A
- Stator Condition Monitor- N/A
- Rotor Condition Monitor- N/A

Since these results are specifically derived from one facility, it is expected that the gains realized at other facilities will vary. This study focused on condition monitoring and the impact on maintenance labor hours. By relieving staff of routine, and often monotonous, equipment monitoring tasks via condition monitors, additional time will be available to focus on the skilled tasks required to maintain a powerplant. Facilities will also gain additional insights into their equipment that will allow them to better optimize how equipment is operated and maintained.

Lessons Learned

Reclamation's maintenance tracking via CARMA is not optimal. Maintenance activity data analysis using CARMA show that maintenance hours need to be accurately categorized, documented, and actual cost assigned to be useful. To evaluate the effectiveness of new condition monitoring equipment, facilities need to carefully track maintenance tasks on equipment with condition monitoring equipment installed.

To help facilitate CARMA data entry, Reclamation would benefit greatly to increase the use of modern technologies that enable employees a way to quickly enter data into a centralized database when performing tasks. These new technologies involve Wi-Fi enabled devices that can be used at the equipment while the maintenance tasks are performed.

The impact of condition monitoring equipment is plant specific and is greatly influenced by the specific issues encountered at each plant. Condition monitoring systems will have the most impact on reducing maintenance costs when implemented on plant equipment that requires significant labor to monitor. At times it may also be more cost effective to repair or replace high maintenance equipment rather than to install a condition monitor. For example, some hydroelectric generator runners may experience significant cavitation damage due to the physical design of the runner or new operating criteria. If the runner was redesigned to minimize cavitation and/or operate without cavitation in these new operating points, then cavitation monitoring would no longer provide the same value.

Next Steps

The facility involved in this study should select three to five systems to install in the next three to five years and begin developing an installation action plan. In addition, the results of this report should be shared with Reclamation facilities to highlight the opportunities available and what condition monitoring systems to consider implementing. The report results can also be used to inform Reclamation leadership on the opportunities available and help provide justification for the necessary budgets to implement condition monitoring. Finally, facilities that install equipment based off the results of this research should closely track the performance of such systems to help validate this study. To pursue this effort, Reclamation needs to better standardize how maintenance tasks are tracked to enhance Reclamation's ability to do this kind of analysis in an automated manner so key performance indicators can be quickly shared with management.

Reclamation Data Network

As stated before, Reclamation's current Preventive Maintenance practices are not optimal. Preventive Maintenance is time-based, and although it is an effective maintenance strategy, it tends to be labor intensive and often results in performing too much or not enough maintenance. Predictive maintenance solves these issues by only scheduling maintenance when specific conditions are met. To monitor the condition of the equipment, data that can be analyzed is required. Every day, millions of data points are collected from rotating machines and stored by various systems within Reclamation. These systems include Reclamation's MCM, relays, SCADA, battery monitoring systems, and transformer monitoring systems, to name a few. As technology increases, the list of data collection devices and systems continues to grow. Much of the data collected by these devices can be used for condition-based and predictive maintenance; however, prior to this research effort, there were no automated methods to transfer the data outside the facility for centralized analysis.

Adding condition monitors that enable online monitoring of equipment has been ineffective in the past due to the overwhelming volume, variety, and velocity of data produced along with this data being largely siloed within the monitor itself. Most of the data acquisition systems at Reclamation facilities are not connected to a network that is accessible outside the facility. As a result, any transfer of data is performed manually by plant personnel by copying the data onto a portable drive and transmitting it using a network-connected computer. Due to the legwork required in this method, it is sometimes referred to as "sneaker net." While this method is acceptable for occasional small dataset analysis, it is not a sustainable way to transfer large amounts of historic monitoring data that is required to build predictive maintenance models and perform large-scale analysis. In addition, disconnected monitoring systems are less likely to receive important software updates and configuration changes to ensure high-quality data is continuously collected. Lack of network connectivity for data acquisition systems results in underutilized, siloed data and outdated software.

Research Objective and Approach

The overall goal of this research is to make condition monitoring data available by developing the necessary network infrastructure to transfer data from powerplant-based condition monitoring systems to a secured historian database. Another project, Generation Resources Information Database (GRID), is an ongoing effort to centrally aggregate power operations datasets. It is funded by PRO and its primary focus is the secured one-way transfer of SCADA data into a historian database. This research project worked closely with the GRID project with both systems utilizing the same database. This database enables the implementation of predictive maintenance by combining data from multiple systems into a single database. Predictive maintenance utilizes software analytic systems that analyze big data sets to discover new insights and track data trends that indicate required maintenance.

In order to develop network infrastructure to transmit condition monitoring data to a central database, this project leveraged two main subtasks. The first task was to work with partners in IRO to design a general network architecture that could be applied to Reclamation's powerplants. The second task, which was contingent on the completion of the first, was to use the designed network architecture to send data from an existing, isolated system to a historian database.

Previous Work

Prior to this work, Reclamation's MCM software was developed with the intent for future network connectivity. The software is currently on its second major version and networking functionality improvements have been made over the past few years to enhance the system's performance on a network. One of the main features of MCM is the ability to deploy a centralized MCM server that collects and stores data from various data acquisition devices. The server can be queried by different computers running the MCM viewer software, which allows MCM data to be viewed and analyzed from several different locations.

In addition to MCM, Reclamation's GRID project is an ongoing effort to centrally aggregate power operations datasets. The primary focus of this project is to improve the collection, storage, and transmission of data from existing SCADA systems. Many SCADA systems have proprietary historians that vary by facility. Due to the security requirements of SCADA systems, this data is typically stored at the powerplant or control center and is not easily accessible for use by regional engineers and asset managers. Success of the GRID project will result in a centralized database that can be used to inform asset management decision making and maintenance strategies. To expand the benefits of GRID, this research project seeks to integrate other condition monitoring data sets into the same, centralized database for analysis. Gathering all this data into one cohesive data set allows Reclamation to implement predictive maintenance strategies.

Reclamation Data Network- Summary of Results

Two main subtasks were conducted as part of the research strategy to ensure the success of this project. The first task was to design a general network architecture that could be used to transmit data from siloed powerplants to a central database. The second task was to implement the designed network at a pilot facility to test its performance under real-world conditions and plan for future improvements. Both tasks were successful, and the overall result is an MCM system that can securely transfer condition monitoring data from the powerplant to a central database.

The functional network architecture that was used in the successful pilot deployment was created in partnership with IRO. One of the underlying successes of this project was the development of strong working relationships between TSC engineers and IRO cybersecurity specialists. Appendix A lists many of the partners in IRO that made this project successful. Over the course of this project, TSC engineers and IRO cybersecurity specialists worked together to create a general network architecture that is both functional and secure. Many iterations of this diagram were created, and several tests were performed in a lab setting to verify that the design would meet the overall goal of securely transmitting condition monitoring data to a central database. Throughout the testing process, several improvements were made to Reclamation's MCM software which will benefit future powerplants that adopt this data transmission architecture.

Although the network architecture was designed to work with Reclamation's MCM systems, careful consideration was given to other data acquisition devices that might be added to the network in the future (e.g., battery monitors, transformer monitors, and brush monitors). As a result, the network was designed to be expandable to accommodate various types of monitoring devices that will be added in the future. The overall, high level network design is shown in Appendix E, Figure E1.

Once the architecture had been thoughtfully designed and thoroughly tested in a lab environment, the second task was to implement the network at a pilot site. A powerplant with an existing Reclamation MCM system, Reclamation Plant B, was chosen, and the necessary modifications were made to securely connect the MCM to Reclamation's network. While the overall vision of the network was the same, many site-specific changes were required to interface with the existing infrastructure at Plant B. These changes were developed and tested in the TSC lab before deployment. Continued testing of the deployment is ongoing in the TSC lab, and specific lab network information has been included in Appendix E.

In pilot deployment of the secured data network at Plant B, all data is initially sent to the regional control center, Control Center A. Control Center A was chosen as the site for the main data repository because it currently holds a SCADA data historian. A new combined database server was configured and installed at Control Center A and was used to store MCM data from Plant B. A data diode was installed to permit one-way data flow from the existing SCADA historian server to the new combined database server. In order to make the combined data readily available for TSC and PRO, a second database server was deployed in Denver. The Denver database server replicates all data stored on the server at Control Center A, which provides redundancy in addition to faster data access. Figure 1 shows an overall diagram of the data flow from powerplant to control center to

Denver. The specific network design, including relevant IP address and hardware information for Plant A, is included in Appendix E.

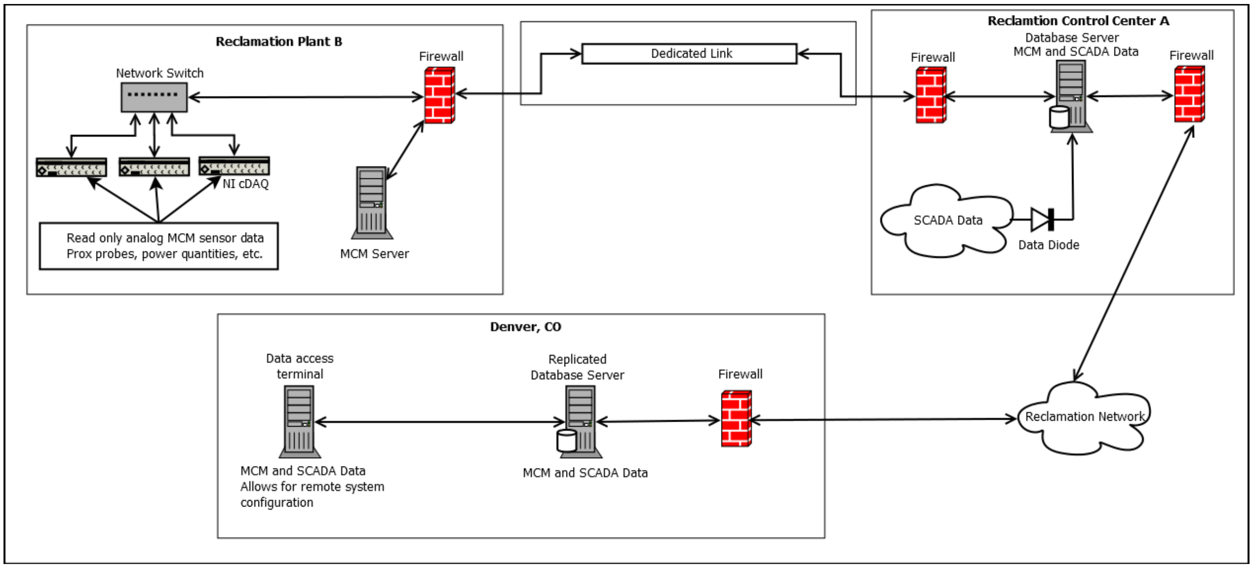

Figure 2 - Diagram showing successful data transmission pilot. MCM data is transmitted from Plant B to Control Center A, where it is merged with SCADA data. The database at Control Center A is replicated in Denver for analysis access.

In addition to condition monitoring data transfer, the pilot network also allows remote management of the MCM server located at Plant B. This remote management allows TSC engineers to update the MCM software, make data acquisition configuration changes, and pull high sample rate data for event diagnostics. Remote management eliminates the need to travel to Plant B to resolve most MCM system issues, which results in reduced system support costs.

In summary, two main tasks were achieved that supported the overall goal of making condition monitoring data more readily available for analysis. First, a detailed yet high level network architecture diagram was created to serve as a reference for future data transmission efforts within Reclamation. The diagram has been thoroughly reviewed to balance both data security and availability. Second, a pilot project was deployed at Plant B using the developed network architecture. The pilot project was successful in transmitting data from Plant B to Control Center A to Denver. In addition, the combined network allows for remote management of the MCM server located at Plant B, which will reduce future support costs.

Lessons Learned

Many of the lessons learned throughout this project were related to technical challenges that arose during lab and pilot system testing. As a result, the documentation for these learning opportunities has been integrated through the numerous revisions made to the diagrams included in Appendix E. As the project progressed, it became apparent that open communication and collaboration between engineering (data acquisition) and IRO was very important to the project's success. Balancing security and functionality require both parties to communicate goals, requirements, and restrictions early and often. Future pilot projects should involve subject matter experts from both groups throughout the project.

Another lesson learned is that network management for future pilot and production sites will require a significant amount of personnel to be successful. Keeping existing and future networks secure requires security audits and frequent software updates for devices. If additional networks are added at powerplants, IT personnel may need to take on additional tasks to ensure those networks remain secured.

Next Steps

The next step for the Reclamation Data Network is to deploy more pilot installations to ensure the process is repeatable and expandable. Several facilities in Reclamation have shown interest, including Plant A. Pilot partners will work with the TSC and IRO to make location-specific changes and ensure the same results are achieved.

Once the process is proven to be repeatable and functional, network deployments can move to the production phase. Converting these networks to production networks may take considerable effort, as each network will need its own Authority to Operate (ATO). The ATO requirement ensures all Reclamation owned and operated Information Management and Technology (IMT) assets and data belong to an authorized security boundary. The ATO management process will either need to be performed by the TSC, regional office, or facility.

Now that some powerplant condition monitoring data is available in a centralized database, testing condition-based maintenance programs can begin. The data from Plant B is already being sent to the Hydropower Research Institute (HRI) as part of an ongoing partnership to make large amounts of hydropower condition monitoring data available for research. Other partnerships with data analysis companies should be explored to fully reap the benefits of historic data availability.

Conclusion

The results of the condition monitoring business case study showed very promising results in that for the maintenance tasks studied the payback time was roughly 5 years with a resultant 0.5 FTE reduction in maintenance labor. This increases to 1.0 FTE if the contract labor for cavitation repair is included. This payback only includes the reduction of labor maintenance costs and when additional predictive maintenance benefits are included the actual cost savings are expected to be much higher. These results can be used, or replicated, by others to assist in developing a predictive maintenance implementation plan that obtains a good return on investment.

In addition, a pilot demonstration of the network infrastructure needed to support the transfer and storage of condition monitoring data was completed. The pilot demonstrated the proposed solution can be successfully implemented using Reclamation existing IT infrastructure while also complying with Reclamation security requirements. This will help expedite the future installation of predictive maintenance software that will analyze this data.

Much more work is required before a complete predictive maintenance program in Reclamation will be realized. Additional research funding will be required to support this effort. Condition monitoring systems need to be installed and evaluated. Additional pilot data network projects need to be completed. Eventually, these pilot networks need to be converted to production networks and an ATO established. Predictive maintenance software needs to be evaluated, demonstrated, and deployed. Enhancements will be needed to ensure this software works with existing Reclamation processes including CARMA. In addition, the human capital infrastructure to support predictive maintenance needs to be established. The resultant support team will consist of both engineers and IT specialists and will include facilities, area offices, regional offices, and Denver office personnel.

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