SCADA PREVENTATIVE MAINTENANCE: REDUCING THE POTENTIAL OF UNEXPECTED FAILURES

Kyle Feist[1]
Zach Markow[2]
Charles M. Burt[3]

ABSTRACT

Irrigation district infrastructure utilizing Supervisory Control and Data Acquisition (SCADA) systems can perform a critical service to irrigators, but also present the risk of damage to nearby property and humans in certain failure scenarios. It is therefore prudent to minimize the scope, frequency, and duration of SCADA component failure. However, it is typical for irrigation districts to focus on corrective (post-failure) SCADA maintenance activities, instead of investing in preventive maintenance.

Preventive SCADA maintenance requires budget and labor investment. However, it is anticipated that it is possible to balance the effectiveness and expenses of a preventative maintenance program with some strategic forethought. For example, preventative maintenance is a major topic of discussion in other industrial applications with similar economic and safety risks. It follows that preventative maintenance can be a valuable tool, especially for complex systems such as SCADA.

This paper provides a survey of several preventative maintenance philosophies and discusses preventative maintenance strategies for irrigation district applications. A template for a preventative SCADA maintenance program is also provided.

INTRODUCTION

Electrical, electronic, and mechanical items deteriorate over time and use. To keep systems running, worn items must be replaced and components require routine maintenance. While it is well-understood that mechanical systems require periodic attention, maintenance of Supervisory Control and Data Acquisition (SCADA) systems can be less intuitive, but equally important.

Implementing SCADA maintenance can be difficult because many systems lack:

- *Documentation*. SCADA systems are custom assemblies of hardware and software. User manuals with thorough maintenance schedules may not have been provided by the SCADA system integration firm.
- *Awareness.* While most people familiar with mechanical systems know to grease bearings and change oil and filters, there are few obvious maintenance tasks with SCADA systems.

[1] California Polytechnic State University (Cal Poly) Irrigation Training & Research Center (ITRC), 1 Grand Ave, San Luis Obispo, CA, 93407-0730. 805-756-2434. kfeist@calpoly.edu
[2] Cal Poly ITRC, 805-756-2434. zmarkow@calpoly.edu
[3] Cal Poly ITRC, 805-756-2434. cburt@calpoly.edu

- *Budget.* Budgets are generally tight for most irrigation districts and justifying a request to increase the budget for unspecified maintenance is difficult.
- *Experience with failure*. Irrigation district SCADA systems are relatively new and district personnel may not be aware of notable failures that can occur with automated structures.

In the authors' experience, most irrigation districts follow the "fix it when it breaks" philosophy primarily because of the factors listed above, and because it requires less forethought. The down side is that failures tend to negatively impact the level of service provided by the irrigation district. The magnitude of the impact (impact level and duration) depends on the type of failure and availability of both hardware/software and the skilled labor of SCADA technicians.

Not all SCADA component failures result in significant problems; some failures are only frustrating to technicians and operations staff. Examples highlighting the range of SCADA failure impact categories (as defined by the authors) are listed in Table 1.

Table 1. A range of SCADA system failure results, durations and the corresponding impact level category

Scenario	Potential result	Duration range	Impact level category
A key sensor fails on an automated flow control gate without redundant sensors	Operators are forced to visit the site frequently and make manual gate adjustments	A few hours to a few weeks depending on technician readiness	Low
The calibration of a flow measurement device is modified incorrectly at the head of an upstream-controlled canal	Tail end turnouts are shorted water; irrigators complain	A few hours to a few weeks depending on technician readiness	Medium
A key sensor fails on an automated emergency spill gate without redundant sensors	The canal overtops, and property is damaged	A few hours	High

Because each irrigation district has a unique set of circumstances and infrastructure, it is the responsibility of the district to internally assign its own impact levels to various potential failures and failure results. However, for all districts, failures resulting in damage to persons and property is a possibility. It follows that avoiding such high-impact failures altogether is preferred. Avoiding failures in the first place requires:

1. Adequate budget and available skilled labor.
2. A good initial SCADA system design with documentation.
3. A transition from reactive repairs to proactive (preventative) maintenance.

GOOD SCADA SYSTEM DESIGN

There are several aspects to "good" design practices. Appropriate hydraulic control and measurement structures help improve accuracy and provide backup services to SCADA systems. Examples of this include emergency spills, sensor stilling wells and applying adequate safety factors for sizing devices such as trash racks and pumps. Other, more SCADA-specific design choices are equally important, such as using redundant sensors for critical and/or control-related signals, alarm notification systems and selecting components with appropriate environmental ratings.

MOVING BEYOND REACTIONARY REPAIRS

When the failure cause and location are easily identifiable, repairing a component failure is relatively straight-forward. This is because the failure inherently defines the "when" (probably as soon as possible) and "what" (replace the component) of the repair needs. Under preventative maintenance, the "when" (or how often) and "what" must be defined.

It is difficult to perfectly schedule preventative maintenance activities. On one hand, repeating the same maintenance activity too frequently can be considered an unnecessary expense. Conversely, delaying maintenance activities increases the risk of a failure occurring. Under good management, striking the right balance requires consideration of the following key factors:

- Budget – to a large extent, maintenance activities are constrained by budgets
- Criticality – prioritizing major infrastructure over lower impact assets
- Flexibility – timely adaption of policies and procedures based on new evidence

There are several philosophies that can be used to guide preventative maintenance activities:

- Basic Interval – Tasks are triggered by the passing of a specific time duration (e.g., daily, monthly, annual).
- Flexible Interval – Basic task intervals are adjusted based on the frequency of identified problems. When maintenance checks repeatedly fail to identify any problems, the frequency of those maintenance checks are extended to minimize costs until problems are more regularly identified.
- Performance threshold – Tasks are triggered when a certain performance threshold is exceeded; requires continuous or intermittent performance monitoring.

Advantages and disadvantages of these philosophies are discussed in Table 2.

Table 2. Advantages and disadvantages of different preventative maintenance philosophies

Preventative maintenance philosophy	Relative up-front capital costs	Relative ongoing labor input	Comments
Basic interval	$	$$$	Capital costs are low, but there is a higher probability of executing maintenance tasks both too frequently and/or not often enough.
Flexible interval	$$	$$	Asset management software may help increase efficiency at a slightly increased capital cost. The additional labor to analyze maintenance results and determine adjustments to maintenance tasks is likely offset by reducing unnecessary tasks in the field.
Performance	$$$$$	$$	Substantial capital investment is required to install continuous performance monitoring equipment; alternatively, intermittent performance testing can also increase costs.

For readers contemplating the implementation of a preventative maintenance program, a good starting point is the basic interval approach. As the tasks become familiar and good record-keeping practices develop over time, the next logical step is to transition to a flexible interval program and consider a limited deployment of performance-based maintenance for key sub-systems and components.

MAINTENANCE ACTIVITIES

To help readers better distinguish between different maintenance tasks, key terms and categories are defined in Table 3.

Table 3. Categories of maintenance activities for a typical preventative maintenance program

Category	Action	Example
Visual inspections	Looking for visual defects, deficiencies or problems	Looking for cracks in conductor insulation
	Presence checks	Checking for the presence of spare fuses in the correct type and quantity
Functional testing	Simulating control commands or alarm conditions and verifying on/off functionality	Calling a gate to move up and down and verifying functionality
Performance measurements	Comparing actual performance metrics with minimum thresholds	Measuring the current of a gate actuator and comparing the readings with manufacturer specifications
Benchmarking	Recording and tracking performance or environmental characteristics over time	Recording ambient radio noise over time
Administrative	Tracking maintenance activities over time to identify trouble areas, sites or devices	Entering maintenance logs into a database
	Procurement of tools or replacement components	Purchasing consumables (e.g., fuses) or replacement instrumentation such as sensors
Computers and office software	Implementing firmware updates, replacing obsolete equipment	Replacing hardware and updating software that has reached its official end-of-life, or is no longer supported by the manufacturer/vendor

LOGISTICS AND IMPLEMENTATION RECOMMENDATIONS

Good record-keeping practices and traceability are critical aspects to successful preventative maintenance programs. Recommendations regarding logistics and implementation details can include:

- Action item checklists are helpful for technicians. The complete list of tasks is no longer executed based on memory but is written and easily transferrable to new employees.
- A signature or initials from the person doing the work provides traceability and a beneficial transfer of responsibility to perform the work professionally.
- To minimize paperwork and streamline record-keeping, several software options are available to irrigation districts. In most cases, the software would be made available to field technicians on a mobile tablet or similar device. Platform types (but not specific vendors) include:
    - Web forms. Several cloud-based software platforms provide the background architecture necessary for the development and input tracking of custom electronic forms. In some cases, the forms are developed by the software

vendor based on client criteria. In other cases, the district may be able to create its own at any time.

- Complete asset management software can include entire software platforms designed for tracking the maintenance of hard and soft assets.

PREVENTATIVE MAINTENANCE PLAN TEMPLATE

A preventative maintenance plan template is provided in Table 4 as a starting point for discussion and adaption by readers. Table 4 lists several tasks and a preliminary frequency for executing the tasks. If used, it is expected that the template would be modified over time to better represent the specific SCADA system being maintained.

For readers with existing preventative maintenance programs, it is recommended that the template be reviewed and compared to existing program tasks. In many cases, the authors have found many SCADA preventative maintenance programs to be incomplete when compared to the template.

Table 4. Preventative maintenance template for consideration and adaption

Category	Subsystem	Frequency	Task	Justification
Electric power source	Any; utility or photovoltaic systems	3-5 years	Retorque service feeder, branch circuit, grounding, bonding and other critical terminal fasteners	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
			Function test circuit breakers	Circuit breakers, especially some older brands can wear out over time
			Visually check fuses; check for corrosion and test for resistance/impedance	Fuse connections can corrode and be susceptible to oxidation over time
			Test all ground-fault and arc-fault interrupt devices	Verifying safety functions to avoid the risk of damage to persons
	Grounding system	3-5 years	Visually inspect all grounding terminals, conductors and connectors; clean and apply protective coating if necessary	Connections can corrode and be susceptible to oxidation over time
			Benchmark ground resistance/impedance to earth using the fall of potential method or equal	Safety and electronic performance issues can arise when the resistance/impedance to the earth increases
			Benchmark the resistance between key points of the grounding/bonding system	Terminals and connectors can corrode over time, decreasing grounding and bonding performance
	Solar panels	Monthly	Visually inspect for debris and dust on solar panels; clean if necessary	Solar panel shading from dust and debris accumulation will decrease performance
		Annually	Clean solar panels anyway	
			Trim trees to avoid shading if applicable	
		3-5 years	Verify solar panel azimuth and bearing	Wind gusts, seismic activity and vandalism can change the vertical and horizontal pointing of the solar panel;

Category	Subsystem	Frequency	Task	Justification
				poor pointing will decrease performance
			Retorque bracketry and railing fasteners/anchors	Fasteners can loosen over time
	Solar charge controllers	3-5 years	Confirm temperature compensation is functional	Temperature compensation coefficients need to be changed to match battery manufacturer recommendations; batteries with different coefficients can be used over time
			Check charge voltage setpoints	Multi-stage charging setpoints need to be changed to match battery manufacturer recommendations; batteries with different setpoints can be used over time
			Retorque terminals	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
			Benchmark charge profiles	Multi-stage charging is a specific procedure of applying varying voltage and current to a battery as specified by the battery manufacturer
	Conductors (wires)	3-5 years	Visually inspect accessible conductor insulation for cracking and/or melting	As the conductor insulation and jacket material age, the insulation/jackets can crack, creating corrosion and arcing potential
	Enclosures	3-5 years	Visually inspect panels; clean out debris	Dust and debris can be problematic for electronic equipment, decrease the convective cooling capacity and accelerate corrosion
			Visually inspect conduit penetrations; fill openings with conduit putty	Open conduit penetrations allow insect and rodent ingress
	Batteries (not flooded)	Annually	Visually inspect battery terminals for corrosion; clean and coat with battery terminal protective coating	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
		Annually	Replace lead acid batteries over 10 years old	Lead acid batteries should be expected to last 5-8 years under ideal conditions; the probability of more problems increases after 10 years of age
		Annually	Replace lithium batteries over 15 (?) years old	Lithium batteries should be expected to last 10-12 years under ideal conditions; the probability of more problems increases after 15 years of age
		3-5 years	Retorque terminals	
			Discharge test benchmarking	Batteries lose energy storage capacity as they age; discharge testing is a performance test of a true deep cycle battery requiring special equipment to maintain a target discharge current over a number of hours
Electronic controls	Contactors and	3-5 years	Conduct function testing	Electromechanical devices can wear out over time
			Benchmark coil and contact resistance	

Category	Subsystem	Frequency	Task	Justification
	control relays			
	Digital PLC outputs	3-5 years	Conduct function testing	Electromechanical devices can wear out over time
	PLC general	Annually	Clean off any dust	Dust can reduce heat dissipation and cause over-heating
Instrumentation	Analog and serial sensors	Weekly	Compare sensor reading to a reference measurement	Sensors drift over time
		Annually	Check full range calibration	Sensors drift over time
		3-5 years	Recalibrate sensors (including flow meters)	Sensors drift over time
	Digital switches	Annually	Check functionality	Electromechanical devices can wear out over time
		3-5 years	Check contact resistance	Electromechanical devices can wear out over time
	Spliced connection s in the field possibly exposed to weather	Annually	Check connection and apply dielectric grease	Exposed connections can be subject to accelerated corrosion due to environmental conditions
RTU	Vandalism enclosure	Monthly	Check for vandalism or environmental damage on locks and hinges	
	Grounding and bonding system	3-5 years	Benchmark resistance between critical grounding and bonding points	Terminals and connectors can corrode over time, decreasing grounding and bonding performance
	RTU enclosure	Annually	Inspect the enclosure for debris, leaks and dust. Clean as necessary	Dust and debris can be problematic for electronic equipment, decrease the convective cooling capacity and accelerate corrosion
			Visually inspect enclosure door gasket for damage; replace as necessary	Failing gaskets can increase water and dust ingress
	Conductor s (wire)	3-5 years	Check for cracks or other failures in insulation	As the conductor insulation and jacket material age, the insulation/jackets can crack, creating corrosion and arcing potential
	Conduit penetratio ns	3-5 years	Verify or replace conduit putty seal	Open conduit penetrations allow insect and rodent ingress
	Fuses and circuit breakers	Annually	Check for contact corrosion and function	Circuit breakers, especially some older brands can wear out over time; fuse connections can corrode and be susceptible to oxidation over time
		3-5 years	Re-torque critical conductor terminals	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
	PLC	Annually	Check internal battery voltage	The internal PLC battery provides backup memory functions and needs to be replaced intermittently;
		Annually	Verify backup application files are available	Up-to-date backup files are critical when a PLC fails

Category	Subsystem	Frequency	Task	Justification
	Terminal block	3-5 years	Retorque critical terminal block screw connections	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
	Power supplies	3-5 years	Check the output voltage and AC ripple	Power supply output voltages can change over time or be adjusted incorrectly; AC ripple is an imperfect conversion of AC current to DC current and can cause problems
	Operator interface terminal	Annually	Visually inspect and test for functionality	Interface terminals have a limited lifespan, especially touchscreens with backlights
	Alarms	Annually	Function test critical alarms	Alarms are the first indication of a problem and therefore should be functional
		3-5 years	Test all software and hardware-based alarms	
	Misc.	Annually	Check for spare fuse quantity; verify presence of as-built wiring diagram	Small glass fuses are not always available locally with the correct rating; having wiring diagrams in the field, that are accurate, is critical for troubleshooting issues
Gates and valves	Gates	Annually	Clean and lubricate gate stems; check for misalignment and bending	Gate stems should be clean and greased to minimize wear on the lifting nut; bent stem shafts can be problematic to actuators
	Actuators	Annually	Visually inspect actuator for oil leaks	Losing lubricant can be a problem over time
			Fully stroke actuators that are not moved regularly	Actuators should be operated regularly
			Verify full open/close limits and functions	Correct open/close limits on the actuator are critical to achieve expected performance and prevent damage from over travel
		3-5 years	Retorque mounting and enclosure fasteners	Loose hardware can cause damage
			Retorque branch circuit conductors and motor leads	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
			Replace actuator battery as recommended by manufacturer (5 years for some)	Internal batteries lose capacity over time
			Benchmark actuator operating current	Gates and valve can get more difficult to move over time, potentially overloading the actuator motor
Pumps	Variable Frequency Drives	Monthly	Verify cooling system performance; clean all air filters	Cooling systems can be critical for VFD operation; overheating will result in unexpected nuisance tripping that can be frustrating
		Annually	Visually inspect enclosures and clean dust and debris	Dust and debris can be problematic for electronic equipment, decrease the convective cooling capacity and accelerate corrosion
			Verify backup configuration files are available and up to date	Backups need to be verified intermittently; backup files are critical for VFD replacement and troubleshooting; many VFD allow the

Category	Subsystem	Frequency	Task	Justification
				complete configuration to be saved as a readable computer file (spreadsheet) for record keeping
		3-5 years	Retorque branch circuit conductors and motor leads	Heat cycling over time can cause loosening of terminals. Loose terminals can cause arcing
Communications / Networking	Radios and accessories	Annually	Benchmark radio Received Signal Strength Indication (RSSI) and Signal to Noise Ratio (SNR) and data throughput	Monitoring the ambient radio environment and specific radio performance is critical for future troubleshooting
			Verify backup radio configuration files	Having access to the latest radio configuration file is critical if the radio needs to be replaced
		3-5 years	Check antenna alignment	Antenna can shift positioning over time
			Benchmark ambient noise levels using a spectrum analyzer	
	Copper and fiber	3-5 years	Benchmark data throughput and percentages of lost packets across key network links using the "ping" test or equal	Data traffic issues in copper and fiber systems can also occur over time
HMI		Annually	Verify HMI automatic backup frequency and/or dates	Automatic backups need to be verified intermittently; backup files are critical for computer hardware replacements
		3-5 years	Test data and application file backup; test redundant hot-swapping functions	
Security	Network	Weekly	Run software security scans	Frequent security scans for viruses, malware, trojans, etc. are easy to schedule automatically
		Annually	Review, test and implement security operating system patches, firmware updates, etc.	Security and firmware updates are provided intermittently by software and hardware vendors
		3-5 years	Review user access privileges, firewall rules, network segregation, etc.	User access privileges and active accounts should be reviewed regularly and updated as needed
	Firewalls and managed switches	Annually	Verify documentation of system/configuration changes	Up to date documentation and configurations are important
			Verify backup configurations for firewalls, managed switches and images of computers/servers	Backups need to be verified intermittently; backup files are critical for computer hardware replacements
		3-5 years	Update firewall rulesets and managed switch configurations	
	Physical	Weekly	Verify physical access controls (locks, gates, etc.); Verify presence of spare keys	Physical security measures can wear or be lost over time

Category	Subsystem	Frequency	Task	Justification
		Annually	Verify/test and lubricate padlocks	
		Monthly	Review security footage for problems	Review security video footage to identify problems in a timely manner
Computers	General	Annually	Clean out dust and filters	Keeping computers cool and dust free can extend their lifespan
		3-5 years	Test HVAC systems	
			Verify and test all backup application files	Up-to-date backup files are critical when hardware failure and replacements occur
			Verify and provide redundant backups for critical archive data	Maintaining redundant copies of critical data is important; consider storing the two copies in separate, secure locations
	Computers (servers and clients)	Annually	Review, test and implement software updates	Software updates occur over time and should be implemented after testing
		3-5 years	Review, test and implement replacement programs for hardware/software without manufacturer support. Replace end-of-life products	
	Mobile tablets and phones	3-5 years	Replace the device	These items are typically consumables and tend to fail or become obsolete after 5 years

SUMMARY

Implementing a preventative maintenance program is a worthwhile consideration for irrigation districts with sufficient budget and available skilled labor. It is equally worthwhile to periodically evaluate existing preventative maintenance programs, test results and failure events in the field to determine if adjustments to maintenance programs are justified.

All of this requires excellent and organized records. It is anticipated that asset management software tools can assist irrigation district personnel in tracking and updating records. However, the authors are unaware of any irrigation districts using specialized software for preventative maintenance program tracking in the irrigation district SCADA sector currently, despite common use in manufacturing and other industrial sectors.