Industry Application
IA08303003E

Effective June 2011

The ABCs of small hydro upgrade and automation

By Ian Peacock (Eaton) and Kevin Mahoney (Casco Systems)

Contents

Description	Page
Keywords	2
Introduction	2
Abstract	2
Determining project scope	3
Equipment selection	4
Mechanical upgrades	5
System protection	5
Machine condition monitoring	5
Automation functions	5
Programmable logic controller concepts	6
SCADA/HMI concepts	7
Mobile monitoring and control	7
Operational enhancements	7
Meeting regulatory requirements	7
Installation and commissioning considerations	7
Conclusion	8
References	8

Powering Business Worldwide

Keywords

Hydroelectric, power plant, automation, Human Machine Interface (HMI), programmable logic controller (PLC), Supervisory Control & Data Acquisition (SCADA), and water level / resource management.

Introduction

The authors have worked together to upgrade and automate numerous low-head hydroelectric facilities. This paper covers the decision-making process, execution, and best practices honed over the course of many projects.

Abstract

Small hydroelectric is increasingly depended on to provide regional power capacity, as municipalities seek more sustainable sources of energy. Yet, hydroelectric or hydro power has some negative perceptions. Other sustainable sources of energy like wind and solar power are early in their equipment and technology life cycles. Hydroelectric facilities are typically older and operate with a mismatched assortment of hardware and controls, which are not optimized to work as a unified system.

Many small hydro owners and operators have similar issues emerging in locales across the country. To update facilities and comply with current regulations, it is important to analyze requirements including:

- Federal Energy Regulatory Committee (FERC) relicensing requirements
- Aging infrastructure
- Automation and asset management needs
- Regulatory compliance
- Occupational Safety and Health Administration (OSHA) safety compliance
- Wildlife impact
- Water flow management

This paper aims to provide a tutorial on upgrading and automating small hydroelectric generating plants. The ideas presented are based on extensive experience with various owners and operators. A road-map for the mechanical and electrical upgrade of a typical facility —with attention to the various water-management and electrical generation and distribution systems—is provided. A key aspect is the detailed discussion of upgrades to the control system, the "brain" of the facility. Ultimately, system upgrades that take a holistic approach to power management can increase production while improving system efficiency, reliability, and safety for decades to come.

Example of a repowered small hydro using front-access medium voltage switchgear before and after

Determining project scope

Many factors need to be considered when upgrading a facility, including regulatory compliance, safety, reliability, capacity, cost, and operational constraints. When considering electrical and control equipment, it is important to define system goals and objectives first. Both new and existing system components in a generation facility need to be evaluated to ensure overall system requirements are being met; assessing existing equipment is a key aspect to upgrading facilities.

Categorizing equipment and evaluating each system is helpful, and ensures that new operation requirements will be met. The following is a checklist of major system components to consider.

Major electrical equipment

- Line switches
- Step-up transformer
- Cable and/or bus duct
- Generator windings
- Metering and relaying
- Plant switchgear
- Generator breakers
- Lighting and surge protection
- Grounding systems
- Station service system
- Battery and DC distribution
- Lighting

Arc-resistant generator switchgear for an eight-unit hydro

Plant control systems

- Machine controls
- Supervisory controls
- Excitation systems
- Governor/gate control systems
- Headwork's/dam controls
- Fire and security systems
- Plant ventilation
- Machine and process instrumentation

It is imperative that each major piece of equipment is evaluated against the operational criteria. It is helpful to look at these categories in an organized and efficient manner. The following study and specification should be completed prior to specifying new equipment.

The power system study

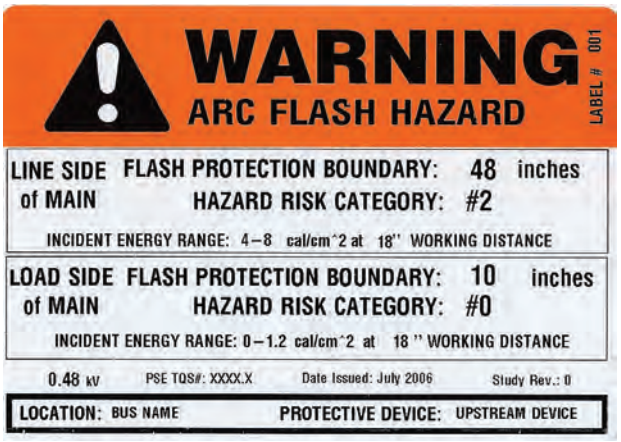
The power system study is a key analysis tool for evaluating electrical equipment. A comprehensive system study should be performed prior to equipment selection or during existing equipment evaluation, and includes:

Short-circuit study allows system engineers to determine if the power system protection equipment is suitable for the application. It is meant to identify the key design parameters needed in the selection of new components, while ascertaining if existing components are safe and meet applicable electrical codes.

Load flow study is performed to determine if all equipment is properly sized for the intended application. Cables, transformers, capacitors, breakers, fuses, and other system components are modeled to make sure that they are all applied within their specific current ratings. This study allows engineers to determine the effects of a generator capacity upgrade on the entire electrical system, making sure that all components are adequate for service.

Protection study is meant to ensure that major electrical system components are protected against system faults. This study should go far beyond a simple relay coordination study, which only looks at overcurrent. The entire protection system needs to be evaluated against today's standards, as practices have evolved. Existing protection may need to be updated. Often owners, interconnected utilities, and/or insurance companies require that protection systems meet current Institute of Electrical and Electronics Engineers (IEEE)® and American National Standards Institute (ANSI) standards.

Arc flash hazard analysis is required, as new additions to the National Electrical Code® (NEC®) require that personnel are to be protected from arc flash hazards associated with electrical systems. This analysis should be performed in the planning stages of a project to guide systems engineers in the selection of the appropriate protection and power equipment.



Control system specification

Control system expectations and requirements need to be established before equipment selection and design criteria decisions are made. Well-defined system expectations will likely avert problems down the road, and may include:

- Manned versus unmanned
- Automatic unit start/stop
- Real-time monitoring
- Remote dispatch and control
- Voltage or power factor control—influenced by changing Independent System Operator (ISO) and Regional Transmission Organization (RTO) requirements
- Governor versus gate actuator
- Water resource management (pond level control, minimum flow, and bypass)
- Alarming and maintenance requirements
- Data collection and reporting requirements
- Redundancy and reliability
- Market and regulatory obligations

Once these questions have been answered and requirements have been defined, it is time to write a functional scope and advance the design process to the next stage—equipment selection. Existing equipment that does not meet any of the above criteria should be replaced or upgraded.

Equipment selection

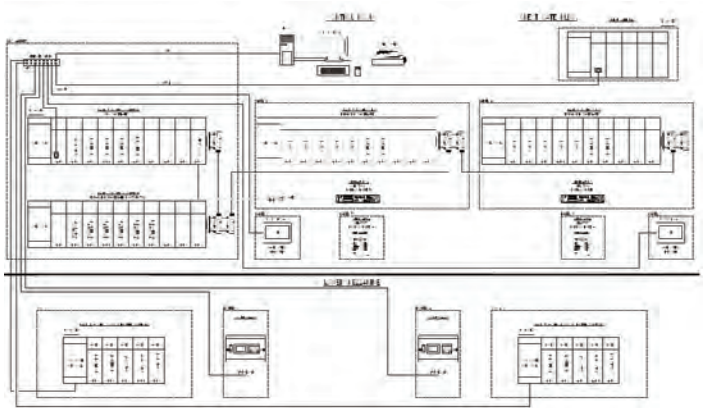
The equipment selection process should take into consideration the specific design requirements of the project in conjunction with the overall preferences based on past experience and local support. To guide in the equipment selection process, several road maps need to be drawn.

One-line diagram for electrical equipment needs to be created, which defines the entire scope of the electrical upgrade including equipment sizes, relaying and logic schemes, metering points, and data requirements. Simple operating one-line diagrams do not provide enough detail to adequately define the project.

Control system network architecture diagram should be created early in the design process before the equipment is specified or purchased. This will guide control and data requirements of the project and determine the communication methods to be used. Modern control and protection systems are packed full of information that can be critical to the control of the system, and aid in tuning, troubleshooting, and commissioning the plant.

Process and instrumentation diagram (P&ID) is a useful tool in defining process-related systems for the facility. Water conveyance diagrams should have all gates and valves clearly identified and labeled such that all stakeholders are calling equipment by the same name. Other P&IDs should include cooling systems, hydraulic systems, temperature monitoring, and other auxiliary systems that require instrumentation. The P&ID serves as a roadmap for all work on subsystems so that all parties (owner, engineer, suppliers, contractors, and so on) work toward the same endpoint.

Once these diagrams are complete, detailed design and equipment selection can begin. All of the effort put into the scoping phase should make equipment selection straightforward.



Small hydro control system network diagram

Mechanical upgrades

Each subsystem in the plant needs to be evaluated to make sure that it can easily be monitored or controlled by the upgraded control system. Performing a complete startup and shutdown of the generating units and noting the functions requiring operator intervention is a good practice. Create a checklist and document special or contingency operating conditions that may deviate from normal startup or shutdown. Any action—including inspection—required to be performed by plant personnel will need to be duplicated by the control system. It is imperative that all systems are in good working order prior to implementing an automated control system. Instrumentation should be added to monitor key operating parameters such as temperatures, pressures, levels, and flow.

System protection

Today's protective relays are designed to protect critical assets against damage due to electrical faults and adverse operating conditions. Recommended practices have evolved over the years to include protection schemes that were not available 20 years ago. Modern digital protection systems are designed to monitor and protect generators and turbines, while collecting vast amounts of usable data. IEEE practices are designed to scale the required protections to the size of the machine or the transformer. Advanced digital relays are capable of communicating with the digital control system—providing operating data and aiding troubleshooting, in the event of a system disturbance or fault. Careful planning for the integration of the protection systems with the control and SCADA systems can reduce recovery and downtime after a system or unit fault by allowing high-speed clearing. Additional benefits include management of arc flash hazards by providing high-speed fault clearing or maintenance mode settings for use during maintenance and switching activities.

Grounding and surge protection are extremely important yet often overlooked when assessing protection of generation assets. When applicable, high-resistance grounding provides grounding of the generator to prevent extreme transient overvoltages, while limiting ground current to levels that do not cause damage. Whenever possible, the best practice is to high-resistance ground the system. Properly sized and applied surge capacitors and lightning arresters should be considered.

For synchronous machines, synchronism check relays should be applied and an auto synchronizer is recommended. The sync-check relay should supervise the generator breaker closing for either manual or automatic synchronizing. Motor starters or contactors should not be used in synchronous machine applications.

Typical small hydro upgrade, protection, and controls

Machine condition monitoring

Depending on the size of the unit(s), it is highly recommended that some form of condition monitoring be implemented as part of the system upgrade. At minimum, machine stator and bearing temperatures should be monitored. Resistance Thermal Detectors (RTDs), if not already installed, can be added to bearings and in some cases to generator windings. Vibration or "run-out" monitors can be added on the turbine shaft; these systems range from simple online measurements to a sophisticated condition monitoring system. Other monitoring systems should be considered and scaled based on the size and the type of equipment to be monitored. The following list includes basic condition monitoring systems for evaluation:

- Stator winding temperature
- Bearing temperature
- Cooling system temperatures
- Bearing vibration or run-out
- Headcover or draft tube vibration
- Rotor gap
- Insulation Integrity—partial discharge for systems over 8 kV
- Transformer temperature
- Transformer online oil analysis

Automation functions

Faced with decreasing revenues and increasing regulatory oversight, hydro operators are driven to introduce more automation solutions to their facilities—so as to better meet licensing requirements, control costs, improve reliability, and increase efficiency. Industrial-grade control and automation systems are designed to monitor equipment status, to facilitate troubleshooting, and to provide remote telemetry and control.

By far the most common solution implemented in the small hydro industry is the use of programmable logic controllers (PLCs) coupled with a graphical human machine interface (HMI). Properly designed and implemented, this powerful combination can provide a full set of features to:

- Automatically start and stop generation units
- Dispatch generation based on water management and/or power pricing requirements
- Run of river, downstream flow, or water storage management
- Equipment condition monitoring
- Regulatory and production reporting
- Alarm annunciation and recording
- Remote telemetry and control

Programmable logic controller concepts

A PLC is typically used as the "brain" of a hydro station control platform. Modern PLCs provide a range of functions, including Boolean "ladder logic" programming, timing and counting, mathematical calculations, and communication options. These flexible systems allow the designer to implement everything including unit start and stop sequences, speed governing, equipment condition monitoring, alarm logic and response, station water level control, water flow management, and other specialized functions.

Regardless of make or model of PLC selected, a disciplined approach to the organization, design, programming, and commissioning of the control system is essential to a successful implementation.

Functional description

The first step is to define in detail what the system will do and how it will do it. Specify all equipment and locations, including gates, buildings, bearings, and generators, so as to prevent confusion later in the project; and to ensure consistency across all documentation including prints, manuals, programs, and user interfaces.

Every aspect of the unit and station operation should be detailed to provide a clear road map. All stakeholders can provide input, and later review to ensure that all operational, maintenance, regulatory, and dispatch requirements are addressed.

For each unit, at a minimum, the following should be defined:

- Steps in the unit start and stop sequences
- Control modes defined and explained
- Alarm monitoring functions and desired responses

For the station, the following should be defined:

- Water level management
- Minimum flow control requirements
- Balance of plant logic

System design

The overall system design should consider the entire life cycle, including installation, commissioning, and maintenance issues. Some critical decisions to consider include:

- Centralized versus distributed processing
- Local versus remote I/O
- Unit and station I/O grouping
- Isolation for maintenance and lockout/tagout
- Construction sequence and schedule
- Communication architecture
- Remote communication interfaces
- System security

Programming

Programming should be performed in a structured and modular fashion. Code should be organized into logical sections or subroutines that parallel the physical plant layout. This will facilitate the design, commissioning, and maintenance of the automation system by presenting the control code in a logical and easy-to-interpret fashion. Structured code also aids in the reuse of code for additional units or for future projects.

For instance, code for each generator should be broken into distinct sections. Each generator may have subroutines for separate functions like start, stop, alarms, governing, temperature monitoring, and other machine control functions.

Common functions that are not specific to any unit should be broken out and grouped at the station level. This may include water level monitoring and control, balance of plant operations, and ancillary systems such as head gates, rubber dams, fish passage, and the like.

Finally, the entire program should be documented with comments explaining how and why the system performs each function. Relevant and sufficient information should be provided to personnel so as to maintain the system over its entire life cycle.

Commissioning

The final step is to perform system commissioning, to verify that all system components are wired correctly, that field devices are working as desired, and that all PLC/HMI programming is correct. Detailed point-to-point wiring checks from the field devices back to the PLC, HMI, and (if appropriate) SCADA should be performed in a controlled and methodical fashion. This "end-to-end" test proves that the individual components are working correctly and that the system as a whole is performing as expected.

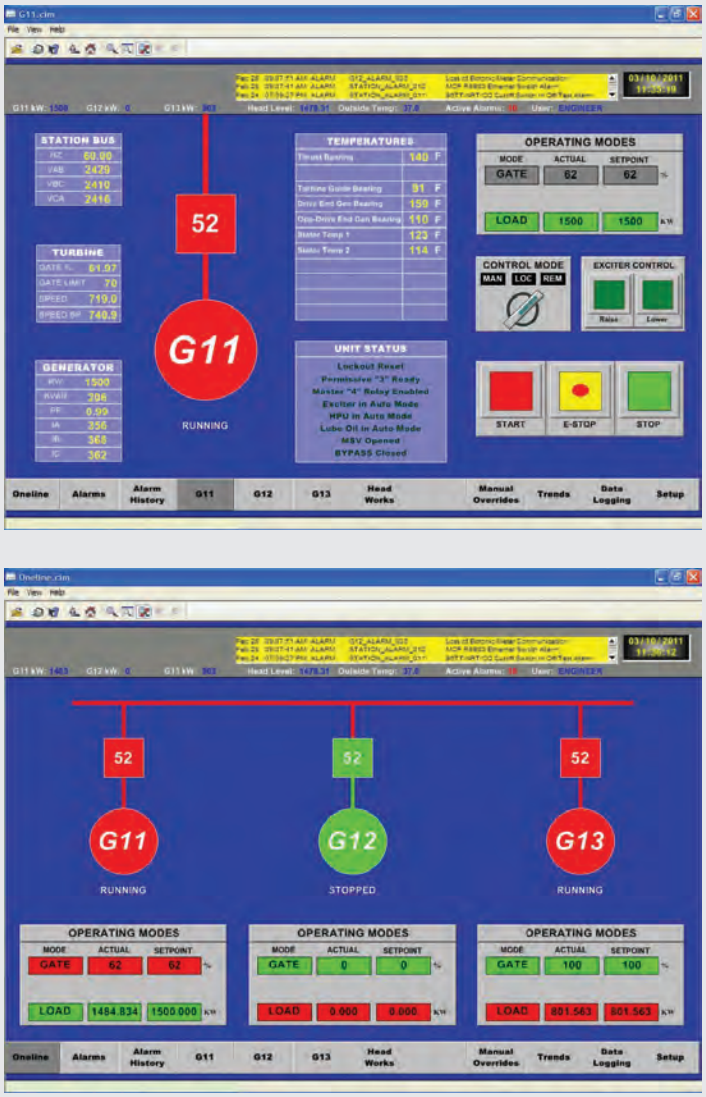
PLC panel for small hydro

SCADA/HMI concepts

Visualization of plant status and condition, logging of events and metering, and annunciation of alarm conditions are generally managed by the station HMI. It serves as the local operator's portal into the process.

Utility and large fleet owners typically use a SCADA system to monitor geographically dispersed assets. In these cases, remote access to the local HMI is generally limited to engineering-level functions for troubleshooting. In select cases, primarily for non-utility generators without a centralized SCADA system, the station HMI is also used for remote access and control.

Often the station HMI is used to log regulatory, alarm, and performance information. This data is commonly stored in an SQL database or an industrial historian. Data may then be pulled from the archive for reporting to meet regulatory obligations, to monitor performance, and to provide insight into plant operations.



Typical HMI screens

Mobile monitoring and control

The 24 hours, 7 days a week nature of the power generation business requires a constant watchful eye on hydro generating facilities. But profitability requirements often don't allow for full-time, onsite staff. The solution is telemetry, which allows remote monitoring and control, particularly at automated, unattended plants. Smart phones have become a mobile telemetry platform, allowing operators to remain informed of plant status and alarm conditions, and even providing access for remote control. This is accomplished using a mixture of technologies including SMS text messaging of alarm conditions generated by the station HMI, automated status and production reporting via e-mail, and even remote access and control through Web-enabled smart phones.

Operational enhancements

Once the basic control system is designed and in place, it is imperative that system integration personnel work closely with operations to determine best practices for operating each system and the overall operation. Water resource management, starting and ramping procedures, alarm trending, and regulatory constraints should all be discussed. Quite frequently, the automated system can be used to optimize the performance of the facility, by implementing best practices as a control strategy.

Meeting regulatory requirements

Hydro station operators are being called upon to meet evolving regulatory requirements that effect storage, water flow, and level control; seasonal adjustments for wildlife management; recreational opportunities; and even aesthetics. The control and automation system is critical to meeting these requirements and to documenting compliance for regulatory bodies and the general public.

For example, the control system can be tasked with automatic up and down ramping to minimize the effect of flow changes on aquatic life and fishermen, with level control to maintain run of river operations, and with managing minimum flow constraints and other operational constraints.

Regulators were calling for the installation of large and expensive valves at a small hydro station in northern Vermont, to provide bypass flow around the station after a utility trip. Due to the location of the plant and the nature of the interconnection, this facility was often knocked offline due to line conditions. As an alternative to bypass valves, the plant implemented a solution that in effect used the turbines as valves to provide the necessary bypass flow after a trip. Basically after an electrical trip, generators were automatically brought to "Speed No Load" and were held there pending further commands. This allowed the plant to quickly restore downstream flow even if the units could not be brought back online. With the line fault condition cleared, the units could quickly be placed back online to start production.

Installation and commissioning considerations

A significant challenge in any upgrade project is scheduling the work to minimize downtime and to yet allow sufficient time for planned work to be executed. Multiple factors impact the schedule, including:

- Weather—spring runoff, winter flows, planned releases, and so on
- Concurrent work at the plant
- Resources—contractors, plant staff, owner's representatives, and the like

It is often difficult to predict exactly when spring runoff will start and finish, with many owners wanting to avoid downtime during the time of peak flows. If possible, build flexibility into the schedule to accommodate seasonal variations. Scheduling too much work during an outage is also a concern, especially at smaller facilities where space and access are limited. One project manager should be responsible for coordinating all activity onsite to ensure that each group (mechanical, electrical, civil) has the time and access required to efficiently perform their scope of work.

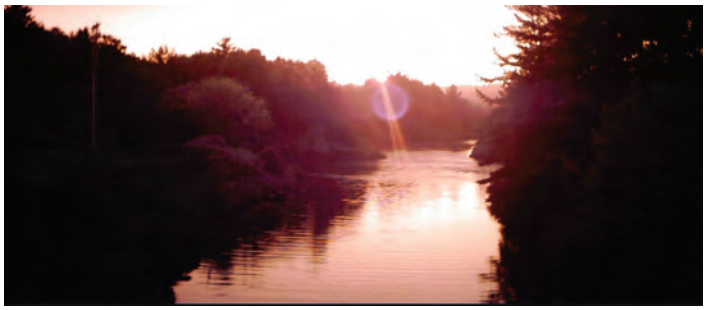
Rigging a new GSU transformer

Conclusion

Our collective demand for power continues to grow, while resources are diminishing. Hydroelectric power generation is a significant resource that can be used to balance the intermittent nature of other renewable energy, and to provide a reliable and predictable power source—all while offering recreational opportunities. By strategically approaching plant upgrades and automation projects, operators can extend the serviceable life of their equipment while improving the efficiency, reliability, and safety of their systems.

References

The information and ideas presented in this paper were developed from the collective experience of the paper's authors. This hard-earned education is based on experience designing, constructing, programming, and commissioning over 100 hydroelectric plants, fish passages, and related water-control structures.



Eaton Corporation
Electrical Sector
1111 Superior Ave.
Cleveland, OH 44114
United States
877-ETN-CARE (877-386-2273)
Eaton.com

© 2011 Eaton Corporation
All Rights Reserved
Printed in USA
Publication No. IA08303003E /Z11205
June 2011

Eaton is a registered trademark of Eaton Corporation.

All other trademarks are property of their respective owners.

Powering Business Worldwide