

Successfully Designing Integrated Substations

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INTRODUCTION

Before substation integration, substations were constructed of many single-purpose devices and systems. For example, electromechanical protective relays each served a single protection purpose and remote terminal units (RTUs) had complete wiring to collect the same discrete and analog inputs connected to protective relays, meters, and other devices in the station. This type of design was complex, expensive, and less reliable than integrated systems.

Today, many protection, monitoring, and control functions are integrated into multifunction protective relays. The benefit for system complexity, expense, and reliability is that there is only one measurement and interface point required for each input in the station. In addition, internal logic in protective relays can be used for interlocking and permissives, which also greatly reduces the complexity of circuit breaker control wiring. Integrating substation devices into a single, coordinated system for control, metering, and monitoring can produce similar savings in complexity and cost while the overall system reliability and effectiveness are increased.

In a substation environment, an integrated substation is one where smart devices or Intelligent Electronic Devices (IEDs) are connected to provide pathways to move data for the following functions:

- Local centralized monitoring and control via a human-machine interface (HMI) through a computer or similar display and input equipment.
- Remote monitoring and control, typically with an Energy Management System (EMS) or Supervisory Control and Data Acquisition (SCADA) system.
- Collection of historical data reports, including event oscillography.
- Distribution of commonly required data, including time synchronization.

This concept of station integration has advanced rapidly as IEDs—including protective relays, metering, and monitoring devices—have taken advantage of increasing digital processing power and communications capabilities. However, the design practices prevalent in the electrical power industry have not advanced to produce more efficient design, installation, and operation of these systems. The integration issues the power industry faces today have existed in the industrial process control industry for 30 years; therefore, design practices in that industry can point the way to opportunities for improvement in the power industry.

The power industry has adopted IEDs and advanced communications technologies more slowly than industrial process control and automation, for a variety of reasons. While the development has been slow, it is also important to realize that the power industry has a very different set of goals than those for most industrial process control and automation projects. Nonetheless, lessons learned in the industrial process control and automation field can be of great benefit to the substation integration field. One example is a set of system design and documentation techniques developed over years of experience. Industrial process control system design varies

depending on the industry and application, but includes several basic concepts and tools that can be very powerful when applied to substation integrated system design.

This paper describes a representative design method used for many process control industries, including an example from the wastewater treatment industry. These techniques are easily adapted to increase the efficiency, accuracy, and flexibility of the design of power industry installations. After describing the process, this paper describes how it might be applied to substation design.



Figure 1 Wastewater Treatment Facility

INDUSTRIAL PROCESS CONTROL SYSTEM DESIGN

One of the interesting and often fun parts of working as an electrical engineer designing electrical, instrumentation, and control systems is that you must understand all disciplines that are involved in the design. For example, you must learn about the process being controlled, and the mechanical equipment controlling and driving the process. You are also responsible, in the wastewater example, for providing the energy, control, and automation to turn tanks, pumps, valves, and instruments into a living and breathing plant accomplishing its goals.

Similarly, many industrial control engineers have migrated to the substation integration field and are interested in the challenge of understanding power system control, protection, and monitoring techniques. These engineers are interested in expanding the field by developing new methods and techniques for implementing these solutions and making systems more robust and less expensive to construct.

System Design

The design of a process and system (Figure 2) in the wastewater industry begins with civil engineers determining the requirements for a treatment system. Permits to operate wastewater treatment facilities are granted based on the quality measurement of the effluent. This means that the ultimate goals for the output drive the process sophistication, expense, and complexity.

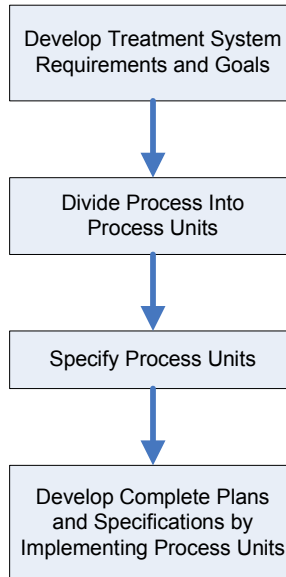


Figure 2 Process Unit Design Flow Chart

Based on the treatment requirements, engineers choose the specific process techniques to employ and begin designing the system to have the necessary capacity for the application at hand. At that stage, we can start the most important step of this process: division of the overall process into a series of Process Units.

The concept of a Process Unit is quite simple. Divide the overall process into smaller processes that can each be specified individually. Also, because most plants include multiple instances of each Process Unit, the designs can be constructed on a type basis and then duplicated rapidly to populate the complete design.

Process Unit Design

The key to Process Unit design is that it divides the system into manageable pieces that can be specified independently. Each Process Unit contains many components, devices, valves, etc. Some of these devices are manually operated, some are automated, but all equipment with a common process purpose is gathered together and related.

In order to manage the plant design, system designers must first choose a standard numbering system for equipment and begin an equipment list. In early design phases, the equipment list had a low level of detail and was often refined, but the list allowed modifications to be tracked and managed. This list also provided the initial division of the system into Process Units.

Several numbering and naming schemes are used in industrial process design, and each allows all of the devices to be numbered, managed, sorted, and manipulated using standard design methods. One system uses a three-letter designator and a three-digit identifier for each device. The three-letter designators identify the device as a flow meter, pump, flow element, or other type of device, and the three digits make it unique within the plant. Numbering systems of this type again make it easy to duplicate standard Process Units to include all plant equipment.

A single device or component may relate to more than one Process Unit. To avoid confusion, Process Units may also be nested within other larger Process Units that describe the interaction between Process Units.

The most important concept of Process Units is that they are specified completely, including the HMI interface, automation, manual equipment, and instrumentation. For example, the specification might require that the flow be displayed on the HMI and that a valve have both manual and automatic modes with a description of those modes.

The benefit of Process Unit design is that it requires the engineers to coordinate between disciplines to design complete systems. Each Process Unit is small enough to make the design process easier to manage and maintain. Process Unit design also makes interaction between systems clear and well specified. Each Process Unit is typically described with a series of both narrative and graphical design descriptions.

Narrative Design Descriptions

In my experience, each Process Unit was called a control loop. The process control engineer worked closely with the mechanical engineer, civil engineers, process design engineers, and others to define the process operation. The control loop descriptions included several sections and were usually similar to the following:

- Process Description: The purpose and general process intent
- Operation: The manual and automatic operation of the equipment to achieve the process intent
- HMI Interface: Specific requirements for screen elements, displays, and operator input points
- Equipment list: List of all process equipment and instrumentation elements related to the control loop

Graphical Designs

In addition to developing the design descriptions, process control engineers lay out the Process and Instrumentation Diagrams (P&IDs). The P&IDs graphically depict the process, instrumentation, and automation. Figure 3 [1] shows an example P&ID.

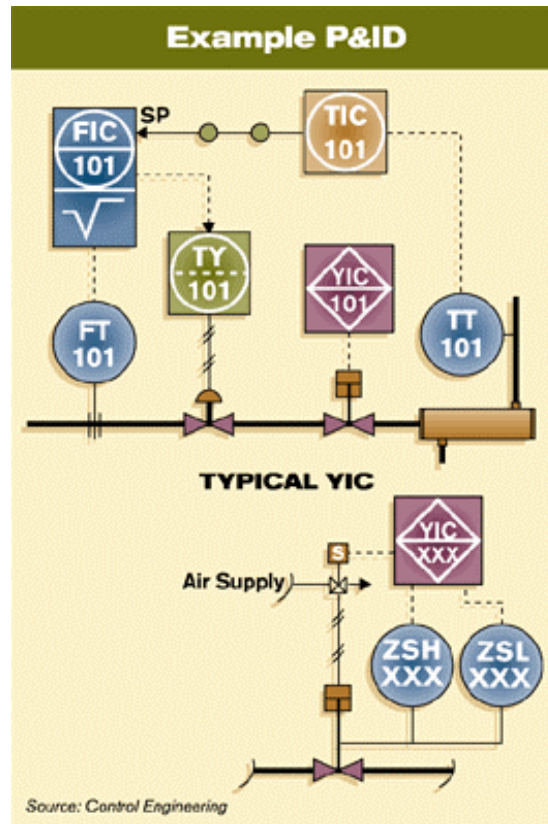


Figure 3 Example P&ID

The example P&ID shows piping, valves, and process equipment, as well as measurement and instrumentation elements and control devices. This system provides quick recognition of systems, interactions, and divisions between distinct Process Units.

If the process automation is complex, some engineers create additional documentation of the logic in the form of Boolean logic diagrams. These diagrams depict how elements that are inputs to the programmable logic controller (PLC) or distributed control system (DCS) interact and produce outputs that control equipment operation.

After the development of the P&IDs is sufficient, the engineers begin to work on increasing levels of detail and develop drawings for building construction and the physical installation of the equipment.

Example Process Unit Specification

The following figures and example text are a simple Process Unit specification for a typical Waste Activated Sludge (WAS) pump system. Figure 3 shows the P&ID for the WAS pump Process Unit. The text below is the Process Description and specifies the equipment and operation of the Process Unit. In the final system design, the WAS pump Process Unit is integrated into a larger Process Unit that controls automated WAS pump operation of multiple WAS pumps.

Because this generic process unit has not been integrated into a design, the numbering system uses the proper designations, but the numbering reflects device numbers only within the process

design. For example, if this Process Unit becomes Control Loop 15080, the numbering of the hand switches would become HS-15081, HS-15082, HS-15083.

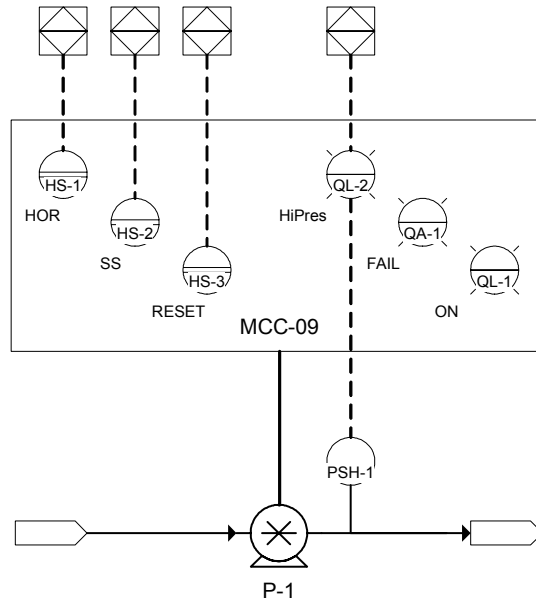


Figure 4 P&ID for WAS Pump Process Unit

Process Unit—WAS Pump

Function: Monitor pump in REMOTE, provide high-pressure alarm, pump failure, and field selection of pump operating mode between local and PLC control.

Instrumentation

Instrument Number	Type	Comments
HS-1	Hand/Off/Remote	Located on MCC
HS-2	Start/Stop	Located on MCC
HS-3	Reset	High pressure alarm reset
QL-1	On	Power on
QA-1	Fail	Alarm
QL-2	High Pressure	
PSH-1	High	Pressure Switch

PLC Functions: Monitor pump running status and selector switches. Provide pump automatic operation specified in WAS Pump System Process Unit.

Operation:

1. When selected to REMOTE, the pump is operated by the PLC using selection of pump sequencing mode.
2. The high pressure switch, PSH-1, is hard-wired to the motor control center to provide automatic high pressure shut down and lockout of the pump in both Hand and Remote operation.
3. Upon high pressure sensed by PSH-1, the pump will shut down and indicate Fail, QA-1, and high pressure, QL-2, until reset by the pushbutton, HS-3.

Automating Design and Configuration

As with electric power, the process control industry now relies on IEDs, PLCs, HMIs, and other equipment that each require independent configuration. Two examples are PLCs and HMIs. Each one includes documentation of input and output points that lead to the control devices and equipment. One way to create this information is to enter it on a point-by-point basis into each system. This, however, leads to duplication of work in each system.

An alternative way to automate the work is a database system (for example, Microsoft Access) that manages a list of input and output points within the entire project. This means that an input to the PLC is documented as flow from a particular device and can be traced to an HMI point. The engineer can then run reports against this database that match the import requirements of the PLC programming software or HMI and allow this information to pass automatically between systems.

Additionally, by tracking each point and its location on P&IDs or logic diagrams, the engineer can generate additional reports to cross check between drawings and other documents, verifying that each point has been addressed in all elements of the design.

During construction, the engineer can generate reports for control panel design, factory testing, and field commissioning of the control system. This streamlines the process of producing and installing the control system. The engineer can also provide specialized reports for the long-term ownership and maintenance of the system. For example, a report that allows a technician to follow an input point as an information element from the field instrument to the PLC and to the HMI is an excellent troubleshooting tool.

INTEGRATED SUBSTATION DESIGN

It is not difficult to apply the tools of industrial process design to the design of electric power systems. This can include substations, power generation plants, and large industrial electrical installations. These techniques yield a great increase in efficiency and the opportunity to create utility wide standards that increase the efficiency and reliability of both system expansion and operation while decreasing engineering and maintenance costs.

System Design

The system design phase of designing power stations is not as complex as large industrial projects, but it is still important. The system design is the place to list site-specific requirements and constraints that must be considered when applying the standard process units.

Process Unit Design

The engineers can undertake the Process Unit design as part of each substation or create standard process units for utilities. In order to get the full benefit of this design approach, engineers should standardize Process Units and maintain those standards on a utility wide basis. Organizing and creating standards with a Process Unit approach has significant advantages over trying to create a single substation design standard.

No single standard substation design covers all of the types of design necessary for a full set of utility standards. Therefore, no single substation design standard covers all requirements of the utility. Also, creating standards for every possible design type is often such a large project that it is overwhelming and would require an unreasonable drain on engineering resources. By

designing the standard Process Units applicable to the substations that are required as they are designed, the utility can gain the efficiency and design control of design standards without the need to dedicate full-time engineers to a massive design standard project.

An example of a utility Process Unit would be a distribution transformer. This could be additionally classified by the voltages and size of the transformer. Then, the specification of the Process Unit would describe the protective devices, instruments, automation, SCADA interface, HMI interface, and other features. This Process Unit design requires early coordination by the HMI, SCADA, protection, and operations departments, but yields large gains in design efficiency by preventing last second design changes due to poor coordination between the requirements of the different departments involved.

Observation suggests that the cost of design changes or corrections increases by as much as 10 times as they are caught in later phases of a design. This means that an error that gets to the field construction may cost thousands of times the cost of fixing the error early in the design phase. For example, a change order during construction to add wiring or purchase different equipment becomes very expensive compared to the cost of changing the narratives and data point lists in the design phase.

The degree of detail in the standard design can vary significantly, depending on the intent and the design process of the utility. The test for whether the Process Unit design has sufficient detail for the future is whether or not it could be successfully repeated on a future project performed by different engineers. Depending on how closely the engineers at a utility work together, more or less detail may be required, but if someone with the average degree of understanding within the utility cannot apply the standard design, it is useless.

The effort of creating Process Unit designs will increase design cost somewhat, but leads to significant savings on the project at hand because it increases the design quality and savings on future projects by eliminating redesign of the same Process Units. The cost of ownership of a utility designed using standard Process Units is also significantly lower because of similarity between installations. Overall, Process Unit design is a cost-saving opportunity in terms of engineering input, design quality, and maintenance.

Narrative Design Description

In my experience, narrative design description is often overlooked in power system design. I have worked with several utilities that feel that they have a design standard, but no narrative text that describes how the system should work. A single line diagram without some description of design intent and operation is incomplete. Therefore, SCADA and operations staff must be consulted early in the design process as the initial single line diagrams are completed, but this again represents a savings because of a reduction in errors and an effort to make all design requirements visible as early as possible in the process.

Graphical Designs

Within the electric power substation designs that I have seen, two primary graphical descriptions of the system are important. First, the single line defines the overall substation elements, equipment numbering, and relationships of the devices to the power system. Figure 5 is an example partial single line diagram.

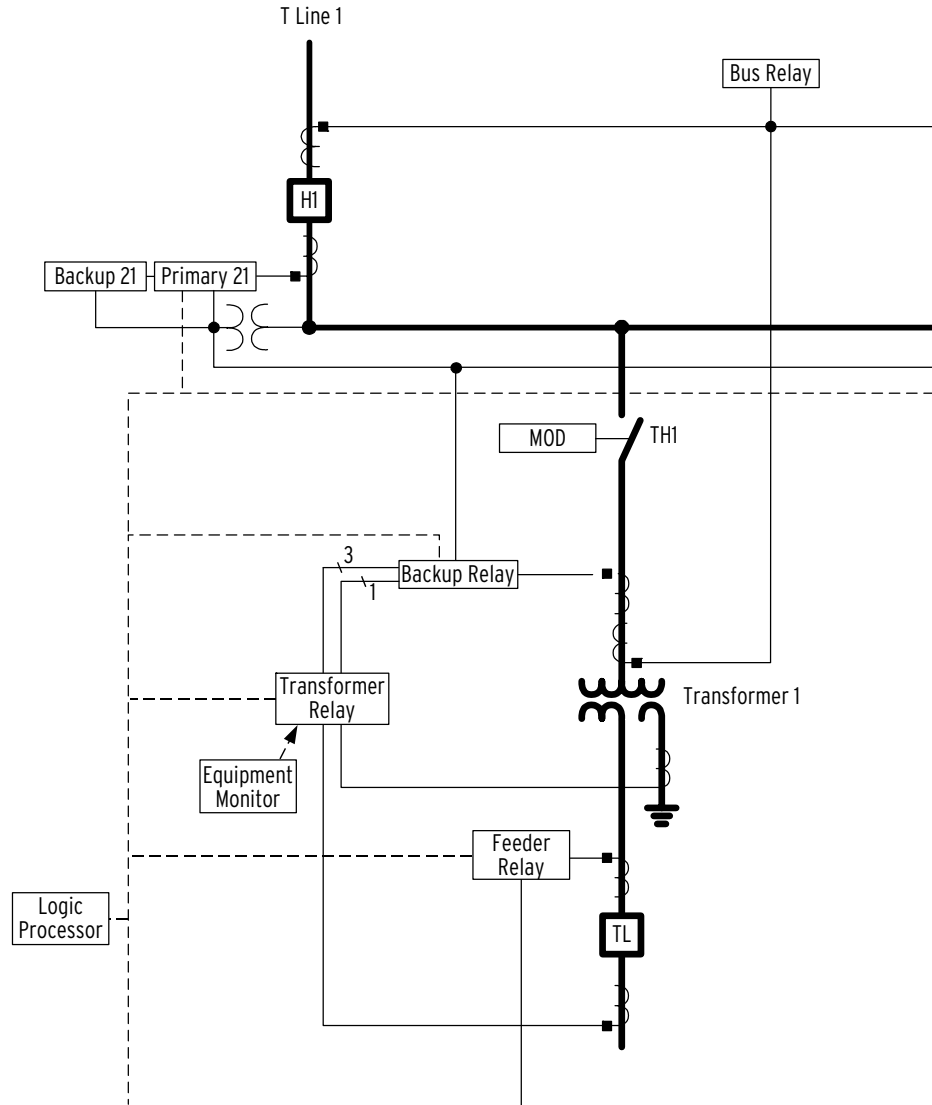


Figure 5 Example Single Line Diagram

The example in Figure 5 shows a single line diagram that depicts equipment, but not all protection elements within the equipment, as in some traditional single line diagrams. Traditional single line diagrams that show all protection elements were based on single function electromechanical protective devices. This additional step may be beneficial, depending on the complexity of the system. However, the detailed single line diagrams could also be constructed for the standard Process Units and may or may not be re-created for the individual system implementations.

Another important graphical representation is a communications block diagram that depicts how devices will be interconnected. Figure 6 is an example communications block diagram. The important elements of the communications block diagram are the individual links, networks, and supporting equipment required to understand the paths for data exchange between devices. The example in Figure 6 depicts communications for protection interlocking and operation, as well as SCADA, time synchronization, and HMI functions.

It is important that all design phases specifically include information required by all of the disciplines involved. Involving everyone as early as possible drives design from a complete system perspective and integrates design. Thus, opportunities to reduce design cost or complexity can be recognized as early as possible and be included in the utility standard Process Unit designs.

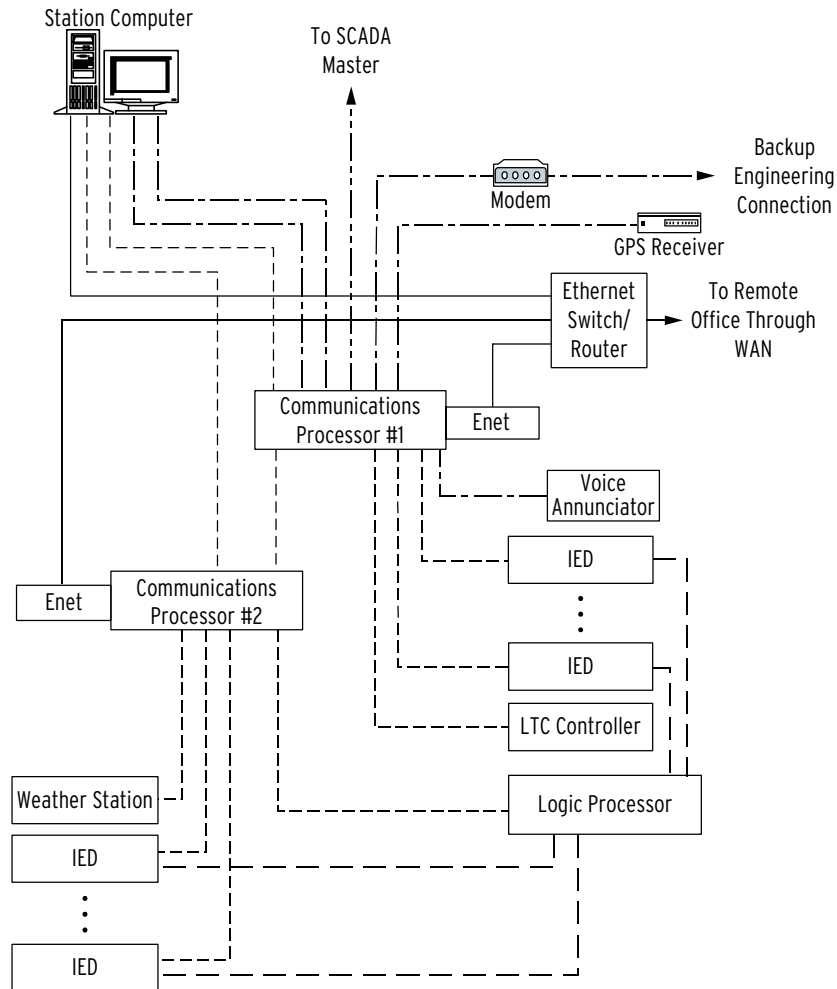


Figure 6 Example Communications Block Diagram

Automating Design and Configuration

A number of tools available or being developed in the industry can automate design and configuration. During the initial design, engineers can create a standard design, called an application design, and then use it for both protection and integration designs.

Protection

A protection application design would be a standard design for how to apply a multifunction protective relay. While some may attempt this by reusing old settings, an application design concept is much more powerful because it reduces deployment effort required for a device in a particular installation, requiring modification of only the site-specific details and settings while

hiding unnecessary detail. With a protection application design, you can create a custom settings interface that allows you to customize settings with the following features:

1. Hide and lock unused features and settings. This feature allows the engineers and technicians to ignore unused features and have confidence that unused features will not negatively impact the features that are being used.
2. Rename settings and add comments. This feature allows documentation of settings using the individual utility's internal standards, rather than adopting the standards of the manufacturer. Also, incorporating design documentation in the form of comments makes entry of required settings easier.
3. Calculate settings from user entries. This feature redirects the deployment effort from determining requirements of the manufacturer to entering universal parameters that describe the installation, and allowing an automated process to convert those parameters into the required settings.

Protection setting application designs are most powerful when they are created as part of the standard Process Unit design standards. This provides the opportunity to address protection, monitoring, and communications settings of the protective devices.

Integration

The application design process applied to the integration of IEDs is somewhat different than for protective device settings. As an integration design tool, a device application design defines the data collection mechanisms, control points, and data collected by devices connected to an IED. It also defines which consumers of the data ultimately need access to specific data elements. For example, it would contain whether or not A-phase current would be required by the HMI or SCADA systems.

If Process Unit designs contain integration device application designs, the integration process becomes very simple. A computer can automatically use rules to combine the required instances of the device application designs and create an overall system design. The system design can then automatically produce files following the standard import format for SCADA or HMI database configuration or files that configure intermediate devices like communications processors to collect, scale, and move the data internally.

A computer can also use the system design to produce the types of documentation required for testing and maintenance of the system. This greatly enhances troubleshooting efforts and decreases overall system ownership costs.

CONCLUSIONS

1. Industrial design processes offer opportunities to improve power system design processes. The industrial process control field has been under pressure to increase efficiency in design and construction and reduce costs, resulting in optimized design techniques that can be a model for improvements in power system design.
2. Involve all responsible parties early in the design process. Involving people early controls costs through reduction in late-phase design changes and provides a forum to realize design improvements based on common concerns or requirements.

3. Standardize process units, not complete designs. By focusing on process units, utilities can reduce large standard design projects to elements of the standard design created on an as-needed basis. This scales the standard design effort to the ongoing design needs of the utility.
4. Automate design processes wherever possible. Automated design processes reduce errors and help provide documentation that is useful for testing, design checking, and ownership of the completed system.

REFERENCES

- [1] D. Harrold, "How to read P&IDs," *Control Engineering*, August 2000.

BIOGRAPHY

Darold Woodward has a B.S. in Electrical Engineering from Washington State University. He is a member of the Instrument Society of America (ISA). He joined Schweitzer Engineering Laboratories in 1998 in the position of System Integration Engineer. Before joining SEL, he participated in design and commissioning projects for electrical, automation, and instrumentation systems in water, wastewater, and hydroelectric facilities. He is a registered professional engineer in the state of Washington.