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What is Sustainable Design?

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SUMMARY

Sustainable design of protection, automation, and control (PAC) systems comprises a combination of engineering design strategies and features, along with organizational management systems and team-member activities, which result in standardization of PAC installations along with performance data gathering and routine evolution of the PAC asset fleet in stages.

Sustainable design is becoming critical to PAC system management. The convergence of functions into microprocessor-based relays, while providing great benefits, also introduces challenges around complexity along with the application and hardware lifespan of the devices. Coupled with the rapidly changing nature of the power system due to inverter-based resources and renewable energy, PAC systems are likely to undergo rapid change.

Sustainable design starts with a defined philosophy for every zone of protection. This formal philosophy then drives standard functional designs, including application and physical designs; processes for managing the design lifecycles; standard documentation packages; sustainable maintenance practices; and a process for training and knowledge transfer.

Sustainable design can be done with traditional PAC systems. However, IEC 61850 adoption is directly supportive of sustainable PAC design. In addition, sustainable PAC design also directly supports the adoption of condition-based maintenance programs.

KEYWORDS

Sustainable design, protective relaying, condition-based maintenance, IEC 61850.

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WHY IS SUSTAINABLE DESIGN IMPORTANT?

A sustainable design approach is becoming critical to survival as PAC systems and equipment move towards communications-based architectures and IT-like modularity of functions with rapid obsolescence of underlying technology platforms. A utility that carries on with legacy design and installation approaches tends to adapt new products individually at each substation until the diversity of equipment types, schemes, wiring and installation techniques, firmware versions, and performance evidence are difficult to track and manage. Maintaining protection systems becomes a business of triage of the most challenging failures and misoperations with a great deal of customized manual work.

This article presents a checklist of methods, tools, and management strategies that can sustain the PAC fleet and its design in these times of rapid change and obsolescence. The authors have seen how many utilities have adapted and are already positioned to check off many items in the list. Adapting legacy practices to sustainable ones requires acceptance and enthusiastic vision by multiple stakeholder departments of the utility, along with investment of financial and human resources by the utility business management.

Advancing beyond the legacy of electromechanical protection systems

In the electromechanical relay era, many utilities created standard schemes and panel designs that were replicated throughout the system in steel panels that served for 50 years or more, often built offsite production-line style in a vendor shop. These relays, described by one vendor as ‘Silent Sentinels’, had little to communicate and became very familiar to maintenance technicians who visited them routinely to correct misoperation causes or to carry out periodic performance testing. The functionality of each unit was limited and was fixed in the vendor’s electrical and mechanical design with only the essential behavior settings. System logic was defined by wiring. Engineering and maintenance management systems were largely manual and based on drawings and paper records.

Meeting the sustainability demands of today’s PAC business

The introduction of microprocessor-based multifunctional relays with programmable logic, followed by system integration of relays based on data communications, brought a combination of new functional arrangements and rapid product obsolescence that upset the stability and usability of many old systems and procedures. Utilities have been learning to manage fleets of relays with thousands of configuration settings, vendor-specific interaction of functions, and constantly changing firmware versions. Relay manufacturers supply products that change substantially every few years, driven by their own component vendor change cycles as well as competitive marketplace demands.

This is combined with a rapid increase in regulatory requirements that impact PAC design, setting, and maintenance; cybersecurity requirements for communications integration; as well as operating restrictions for the power system that make outages harder to schedule.

Helpfully, the evolution of P&C design and operating demands has taken place in a business world that also brings new tools for management in times of rapid change. By applying these tools and methods and recapturing the underlying core principles of stabilizing designs in a rapid process of stepped evolution, utility engineering, operation, maintenance, and asset management teams can achieve the reality of being in full control of the domains for which they are responsible, as well as the business and work life benefits that result.

Role of IEC 61850 integration

There are many industry drivers for IEC 61850 communications services, based on data exchanges of functional models on flexible Ethernet architectures and on function-level rather than point-level engineering and integration methods. IEC 61850 adoption is directly supportive of a sustainable PAC design and management regimen – it was designed as it is for this reason and is recommended in this paper. However, it is not in itself the whole solution to sustainability; it is feasible to create a sustainable PAC designs and processes with or without the use of IEC 61850 services. Non-users face more work with manual mapping of data points or wiring connections; but may choose that path as the organization evolves capabilities and skillsets needed for IEC 61850 and IT-like Ethernet based systems.

THE ELEMENTS OF SUSTAINABLE PAC DESIGN

We summarize here the elements of a sustainable program for PAC design and management. Each is explained in a subsequent section.

1. Philosophy – living, updated principles that form the foundation for each utility’s total approach to PAC design and management – and not limited to just protective relaying approaches.
2. Standard functional designs that are managed and kept stable for entire revision cycles.
 - a. Includes panel, installation, and maintenance design with sustainable panel and user facility focus.
3. Process for managing and updating the design standard in cycles of several years.
 - a. Workflow management systems or processes that confirm routine updating for each of the above elements.
4. Standard documentation packages
 - a. Layers include specific of IEC 61850 design configuration and architecture if used, and other architectural documentation in any case.
5. Sustainable maintenance packages.
6. Training programs and knowledge base.

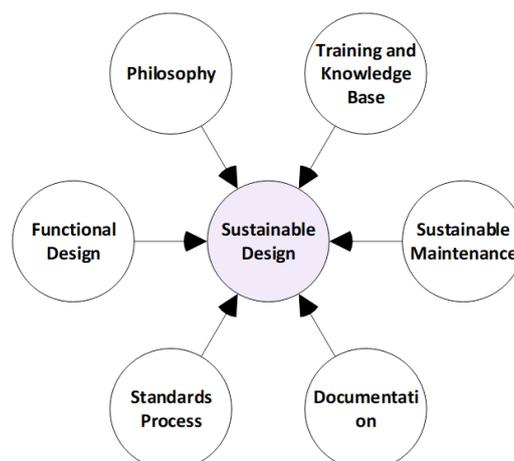


Figure 1: The elements of sustainable design

PHILOSOPHY - THE FOUNDATION FOR SUSTAINABLE STANDARD DESIGN

The goal of philosophy documentation is to set down any durable principles impacting PAC design and application which transcend a particular project need and will remain applicable for the foreseeable future. The philosophy is updated as practices evolve over time. The philosophy is then available to guide development of design standards and of project documents descended from those standards. They also educate team members and serve as a platform of agreed and shared technical and practical specifics.

All of the details in a sustainable standard design should descend from and be aligned with a set of principles and requirements embodied in this broad concept of philosophy. A team of engineers developing a new standard design or updating existing standards can use the philosophy to achieve a consistent evolution of approach at the most effective point the design process that will make the transition easier for project engineers, construction personnel, field maintenance personnel, and system operators. They will save time spent in unnecessary revisiting of basic approaches or evaluating products that don't fit these well-established approaches. Many utilities have documented their protection philosophies and typically record experience-based design requirements for:

- Protection applications and settings as a function of type of protection zone, configuration, voltage level, criticality.
- Use of special protection functions as provided by product manufacturers or with custom logic.
- Redundancy and isolation requirements.
- Teleprotection applications and selections.

Additional topics for which philosophy documents can help a team of engineers with varying levels of experience create consistent standard designs include:

- Panel configurations by protection zone or function so panels are easy to update in the future.
- Wiring and fiber configurations and terminations, also for easy replacement and updating.
- Grounding and field wiring design.
- Regulatory compliance strategy for each relevant standard.
- Maintenance strategy with panel and installation facilities to enable it.
- Local and remote presentation of situational and event information.
- Naming and identification standards for substations, lines, equipment, panels, wiring and fibers, and primary equipment.
- Approach to the development and maintenance of design standards as explained below – separate from the resulting design standards themselves.
- Approach to project handling and workflow management, including maintenance of the philosophy documentation itself.

The creation and periodic maintenance of philosophy documents is a significant effort, but engineers and managers who embrace and document specific philosophy topics become subject matter experts who can then effectively develop and maintain specific design standards. Decisions captured in the philosophy and design standards are made at the most effective point in the design process, from which all downstream project work benefits from consistency. Project engineering is faster, more predictable, less prone to errors, and easier to build and commission when based on philosophy and standards that have been vetted by all stakeholders. New PAC engineering team members are better positioned to learn from the

philosophy and standards documentation and to succeed with specific projects assigned to them.

Evolutionary drivers like new regulatory requirements, misoperation experiences, adoption of special situational grid operating practices, penetration of DER, or changes in skills and tools of field personnel are best accommodated by updating the specific affected topics of philosophy and design standards, even if they are first encountered in specific installation projects. Future projects can benefit from the evolution of core protection knowledge.

STANDARD DESIGNS THAT ARE REPLICATED ACROSS THE SYSTEM

The selected philosophy drives a functional design that is the basic specification for protection and control for each zone type in the substation. The transmission line terminal shown in the block diagram of Figure 2 is one such design, describing the functionality for a specific zone; the required number and type of current, voltage, control, and status inputs; and the required number and type of equipment control and equipment status outputs. The design includes the intent of any control logic, teleprotection requirements, SCADA reporting and control details, device and equipment naming and naming conventions, and operator interfaces. This functional design is fixed as a standard and will only be changed through a formal revision process.

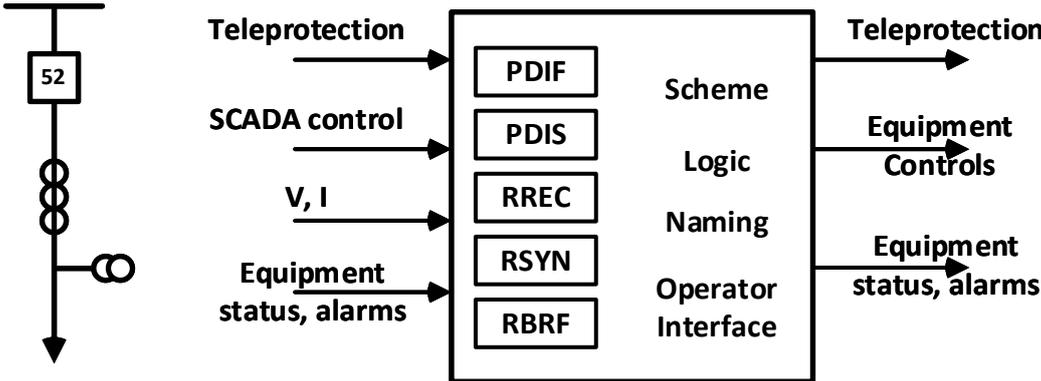


Figure 2: Functional block diagram

The actual design standard for the zone maps functional requirements into actual products and installation details as in Figure 3. The specific products, internal logic, device configuration templates, panel design, and physical wiring are part of the standard design. The result of this is a standard design package that includes the design, design documentation, and calculation sheets needed to apply the protection philosophy to the devices, with the goal of minimizing the need for hand-crafting solutions for specific projects. A good functional design standard does provide some coded options to account for practical details such as differing types of teleprotection schemes, long- versus short-line, or bus configurations.

A benefit to this approach is the ability to update the standard design due to changes in the availability or desirability of component devices, or to replace field wiring with IEC 61850 communications. As important for sustainability, design modules can accommodate the reduced application lifespan and reduced operating lifespan of microprocessor-based devices. A specific version of a device may have an application lifespan of 6 months to 5 years due to firmware enhancements and hardware changes, and an operating lifespan of 15 years.

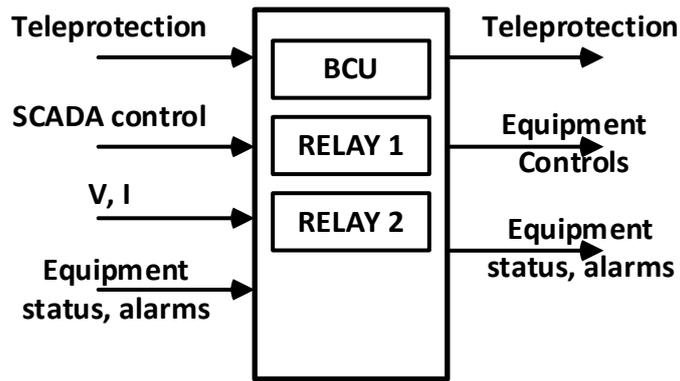


Figure 3: Functional design mapped into products

The modularity of the functional design of Figure 2 and Figure 3 carries over to the physical design as well, resulting in standard panel designs with standard wiring layouts, as in Figure 4. The value of this modular physical design becomes apparent when working on replacement projects. With a well thought out design, it is possible to perform live replacement of redundant systems using safe replacement procedures without requiring an outage. The standard functional design includes standard naming conventions for primary equipment and secondary devices, which are used for standard labeling and identification on the actual panels.



Figure 4: Standard panel design¹



Figure 5: Standard panels for a sustainable project²

It is obvious that this standard design provides great flexibility in installation, especially in refurbishment projects in existing substations. Projects can be performed one panel at a time, or a whole building replaced at once. And the standard design can accommodate different component devices to match existing pilot schemes such as line differential to limit the work required at the remote end of transmission lines.

THE STANDARDS PROCESS

¹ Picture courtesy of Pacific Gas and Electric

² Picture courtesy of Pacific Gas and Electric

The goal in creating design standards is to develop all the materials that can help a protection engineer deliver a design package for a project with these features:

- Highest consistency among installations – construction, maintenance, and operating personnel understand from experience how to deal with it.
- Lowest risk of human errors by the design engineer, project construction and commissioning personnel, and test technicians.
- Fastest execution and lowest cost for successive projects.
- Accurate and easy access to well-organized database of design documents and data.

The most sustainable standards packages include components with coded options to support normally encountered project variations like bus configurations or long- versus short-line protection schemes. They also include calculation or configuration software tools that a project engineer can use to apply the protection philosophy to the devices used in the standard design consistently and quickly. Good tools also show the calculation process, for monitoring by the engineer; and create familiar and clear documentation. Complete standards minimize the need for hand crafting of project-specific solutions.

Elements of a design standard process

1. Fixed standard design with periodic revision cycle – The standard design is kept in place with only essential modifications for a fixed period, typically 3 to 5 years. This results in a generation of field project installations that are consistent and familiar to maintenance and operating personnel. These projects have the lowest possible development and construction times, fewest errors, smoothest supply-chain process, and lowest cost for the functionality. The only changes are those to correct design issues or errors found after launch, to accommodate supply drivers like discontinuation of a specified relay, or regulatory and operating change imperatives.
2. Separate parallel next-generation standard development track - As the current design is deployed over years, a parallel effort evolves and completes the next-generation design standard. This track includes evaluation and testing of new products, technologies, and schemes including laboratory testing as in the next element. When all stakeholders have endorsed and been trained on the new standard, it is ready for a specific changeover date or project when the existing standard expires.
3. Standard development and maintenance laboratory – Panel assemblies capable of implementing commonly used standard functions and zone types in a typical substation standard are permanently set up in a laboratory with space and test equipment for experimentation and validation. A power-system real-time simulation tool supporting hardware-in-the-loop (HIL) tests is a common and best practice. The obvious use for this laboratory is to validate firmware versions and try new products. The sustainable use for this laboratory is to develop scheme logic and settings with event testing scripts; and vet operating and testing procedures by collaborating with field personnel to improve the design while the standard is still under development. A lab configuration for a standard in current use should be kept for replay of evaluation of events and misoperations to understand responses. Laboratories are best assembled in open, accessible, inviting spaces where protection engineering teams can demonstrate new standards and technologies to managers whose funding support

enables the work, and visiting experts who will spread the positive reputation of the utility.

4. Configuration management systems – design documents, including setting or configuration files of relays and IEDs that must be quickly and accurately accessed for maintenance, are to be kept in a managed system with versions of every item, status versus stages of development, and tracking of delays or of items overdue for attention. With Ethernet networking devices and multifunctional relays each having thousands of settings and effectively infinite configuration options, one error can disable the installation – rigid control and reliable access of exactly the intended configuration file or data is critical to power system reliability.
5. Workflow management systems – All the activities in PAC development for a project, from inception to in-service status, are managed with team process tools that help team members who could lose track of overdue deliverables. Tracking is visible on a dashboard; even if the workload becomes excessive, the team and management can see the situation and decide where to focus efforts, while managing unavoidable delays. All work items are tracked by unique version and project identification.

Notably, development of the next-generation standards, and maintenance of philosophy documentation, are workflows that should be managed in this way so that the status is always known.

The following section describes some of the specific design standard documents that serve as the model for each specific project.

DOCUMENTATION OF STANDARD DESIGNS

Sustainable repeatable design carries through to the documentation. Every standard design has a documentation package with identical content. This documentation is a complete description of the standard, including protection calculations, device configurations, and physical design and layout. The package includes:

- Description of the standard. What the functions are, the inputs and outputs, devices, naming conventions, logic, and interfaces to other zones. This includes the model number and firmware version of the IEDs used in the design.
- Drawings including panel layouts, AC and DC schematics, and logic diagrams.
- Maintenance documentation, including descriptions and drawings showing maintenance and indication facilities, along with test plans for the devices.
- Communications design, including network architecture and network data flow diagrams. Also covered is polling / reporting data for SCADA and PMU clients. General cyber security provisions are included as well.
- Relay and device documentation. This includes protection setting calculations sheets, compliance elements to be checked when performing calculation, and templated configuration files for all devices.

This standard documentation package is the basis for project engineering, maintenance activities, and training through consistent documentation delivered in consistent formats for all standard designs.

SUSTAINABLE MAINTENANCE DESIGN

Documented and highly standardized sustainable designs, with monitoring and testability built in and proven during the standards development process, create a familiar and convenient interface, along with standard scripts, for routine testing or for diagnosis and correction of malfunctions in PAC installations. This leads to options for sustainable maintenance practices.

There are multiple maintenance strategies from which to choose, including legacy periodic or time-based maintenance (TBM) testing, whose efficiency can be greatly improved with tuning according to performance-based maintenance (PBM) principles, for example the Annex A PBM program described in the North American NERC reliability standard PRC-005-6. An asset database for all the components in standard PAC designs can categorize specified components according to standard versions, manufacturers, and device types. Failure data can be used to adjust testing intervals up for reliable components and down for troublesome ones. Ultimately, statistical failure data for a population of devices is the key information the utility needs to see the onset of end-of-life and plan for capital replacement, made easier by the standard processes recommended above.

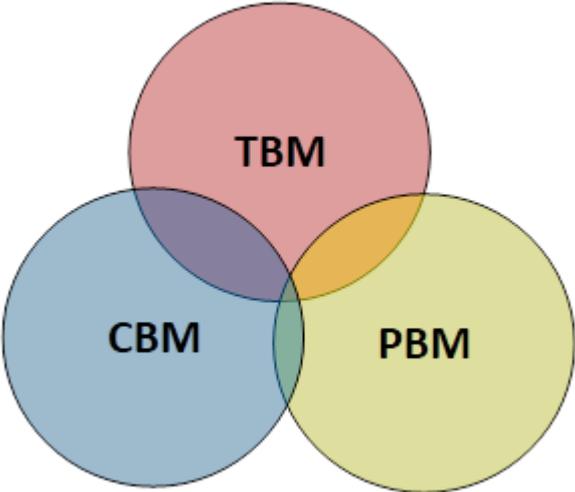


Figure 6: Maintenance program types

Condition-based maintenance (CBM) program

CBM refers to a program in which PAC system elements are able to monitor their own integrity and performance, alarming for failures, and requiring no periodic testing. Electromechanical devices and other unmonitored components or wiring gaps are to be avoided. A full CBM program has no unmonitored gaps in the system and requires no periodic testing. Opportunities for utility TBM operating expense savings are massive.

IEC 61850 designs are particularly well suited to full CBM programs – they are assembled from self-monitoring relays and IEDs exchanging critical data by heartbeat messaging exchanges over Ethernet optical fibers. A PAC scheme designed for full CBM can detect and alarm for any protection-impacting device failure or misconfiguration out to the periphery of the PAC system, even reaching out to instrument transformers or apparatus process signals.

Documented and highly standardized sustainable designs are key to a successful full-CBM program. An important design activity for monitoring or testability of any PAC scheme is to

validate that the testing approach is effective without any gaps in coverage and that testing is nondisruptive. In the case of full CBM, a design document set maps the monitoring features and communications path exchanges and shows how every element is monitored – there can be no protection failure that is not caught and alarmed by a monitoring function of a processor in an IED or by the failure of repetitive or heartbeat messaging sequences. For rapid field repair, the design or its documentation includes diagnostic help by which the pattern of failure alarms and indications is mapped to specific hardware failures that would cause that pattern of alarms. GOOSE publisher and subscriber failure mapping is a familiar example of this troubleshooting help.

A NERC PRC-005-6 CBM protection system maintenance program (PSMP) requires documentation of condition monitoring compliance of a design. Developing CBM documentation for a unique PAC system design is a huge undertaking for a project engineer – only experts with full design details can easily approach the task. With standard designs and documentation, one such effort produces the CBM designs and PSMP documentation for a whole generation of installations – it is this standardization and documentation that makes full CBM practical. Standard zone protection panels with standardized interface wiring and connections that can safely be opened during live service, along with trustworthy standard settings files to configure the replacement panel, make it easy to correct PAC failures with no outage or a short outage.

With full CBM and no routine in-service testing, the asset statistics collected from failures and corrective actions for the range of device types in the standard PAC generation become the basis for determining which components are reaching end of service life and what actions are best to sustain performance. With today's communicating microprocessor relays, easy replacement of whole zone panels with a new standard design may be the most cost-effective solution when the old unit has served for 10 to 15 years.

TRAINING AND KNOWLEDGE BASE

Sustainable design simplifies training in multiple ways. Training cycles are simpler and more efficient, as training changes from on-the-job experience and general application principles to teaching all stakeholders, such as engineering, field technicians, and operating personnel the specifics of applying their roles based on the standard designs. The standard documentation packages include information, such as philosophy, functional scheme documentation and standard test plans, to form the basis of this training. The standard development laboratory is an important tool in this training.

Another simplification is in institutional knowledge, as the overall protection and control knowledge base is contained in the standards and described in documentation. The standard, and the accompanying documentation, captures why a functional design is used, details around using the design, how to operate, and how to test. Personnel responsible for these standards become subject matter experts. Field knowledge and experience is captured during standards development, especially in the parallel development of the next standard.

ROLE OF IEC 61850

Adopting IEC 61850 is a logical enhancement to this sustainable design. IEC 61850 turns every analog interface into digital data, which can be shared throughout the substation. From a functional design perspective, the inputs and outputs for the transmission line terminal

simply become the GOOSE and SV messaging of Figure 6. This standardization of the functional interfaces to be fiber optic cabling has the obvious advantage of reducing the amount of field wiring that must be designed, installed, and managed. But the gains from IEC 61850 accrue in every step of the standards process.

Some benefits of IEC 61850 in sustainable design include:

- Functional design maps directly into the system specification model of IEC 61850, a virtual description of the data models and data sharing needed for this design.
- Standard designs work off this system specification model by adding the IEC 61850 capabilities descriptions of specific devices, and specifying all the data models, data sets, and messaging to share data with other modules.
- Standard designs are easily lab tested for performance and are simply duplicated for every project.
- Project engineering uses standard tools to finalize these standard configurations by simply updating naming and addressing, eliminating manual point mapping.
- IEC 61850 is self-documented in XML files that become part of a standard documentation package.
- Live device testing using safe procedures is supported through virtual isolation and simulation of data.
- IEC 61850 designs support full CBM programs as they are assembled from self-monitoring IEDs exchanging critical data by heartbeat messaging. Messaging failure is alarmed to assist in troubleshooting issues.

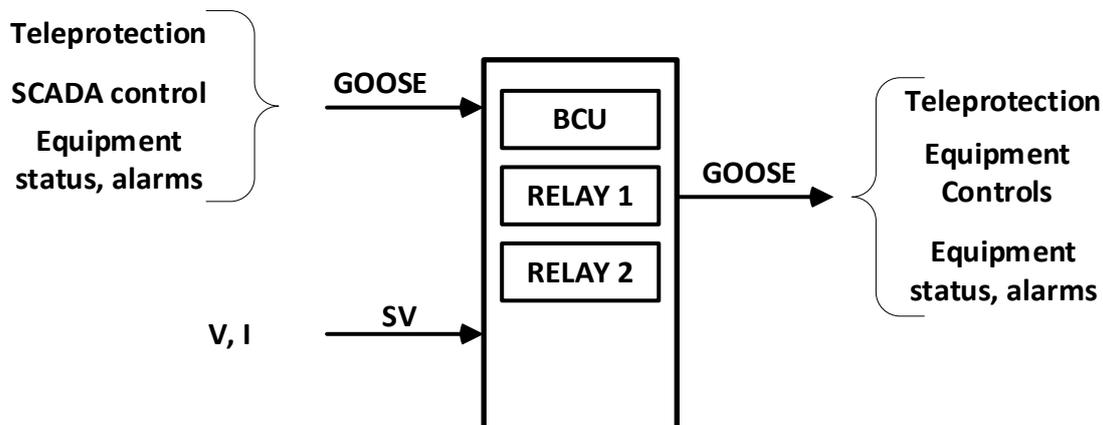


Figure 7: Functional design with IEC 61850

IEC 61850 also simplifies work once the project is installed. IEC 61850 is self-documenting: all configuration, from system specification to end device configuration, is stored in XML files. These files will form a key part of the standard documentation package. Maintenance is simplified through standard test methods, testing tools, and test plans that make use of virtual isolation and simulation of data. IEC 61850 also support condition-based maintenance through functionality such as heartbeat communications for signals and alarms. Training is enhanced as the data models and techniques for communications are common across all zones, projects, and devices.

IEC 61850 also offers additional capabilities that future designs may take advantage of. One of these is functional flexibility, or the ability to distribute and assign functions to the optimal device to perform this function. Breaker failure protection, for example, could be assigned to a protective relay, a bay control unit, or a merging unit. Another is the idea of virtualization

and cloud backup in lieu of legacy configuration information formats, storing the XML files for a project as a living and testable as-built document.

BENEFITS

Benefits of sustainable design are numerous. To highlight some of these:

- Consistency of installations. Field installations are well-vetted by all stakeholders and are integrated with compliance, maintenance, and operations organizations and work.
- Supports live no-outage replacements as well as evolution of installations with minimized outages.
- Consistency of design. Engineering work is more efficient and productive by shifting from custom project engineering to philosophy and descended standard designs. Standards and underlying philosophy ensure uniformity of documentation and understanding of each installation.
- Faster project execution. Vastly reduces project engineering time. Supports construction and testing components of installation off site to reduce commissioning time and effort.
- Effective, focused training. All designs are described in philosophy and documentation.
- Easier event analysis. Installations are consistent and well documented; event response is easily duplicated in a the standards development lab.
- More efficient supply chain. Reuse of standard design elements in each project results in larger purchases of a limited array of components and devices. Maintenance spares inventory is greatly reduced and spare unit or assembly availability to handle failures is assured.

CONCLUSION

The direction of the utility PAC equipment base is inescapable: more change is coming, and coming more rapidly. Inverter-based resource impact the operations of the power system, including PAC functions. More layers of regulatory compliance are likely. Operating organizations face more stress on T&D systems and more limitations on equipment outages. With the rapid application obsolescence and shorter lifespan of microprocessor-based devices, the way to navigate these changes is the sustainable design of PAC systems.

Sustainable design means developing an overall PAC philosophy, with standard design documentation, standard physical designs, and a workflow process to manage the development cycle of designs over years. The end goal of sustainable design is simplification and efficiency. Designs are continually repeated to speed engineering and project work, to simplify testing and training, and to reduce errors. This simplification is key to reliability performance in the changing environment of the modern utility.