AUTOMATED POWER MANAGEMENT SYSTEMS FOR POWER CONSUMERS WITH ON-SITE GENERATION

Scott Manson and Saurabh Shah
Schweitzer Engineering Laboratories, Inc.
Pullman, WA USA

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ABSTRACT

Colocated generation capabilities are finding great popularity among industrial, commercial, retail, and governmental power consumers. As the number of individual unit generators increases, so does the need for more powerful methods to monitor, control, and optimize the operation of the generation and load throughout their facilities.

In the last decade, powerful microprocessor-controlled protection, automation, and communications devices have become available, which greatly simplify the task of automation and management of power systems. In addition to greatly enhanced features, these modern devices have made complete power management systems more reliable and economical than ever before.

This paper identifies several best practices in the design of fully integrated power management systems using modern devices. A power management system recently commissioned at the Motor Oil Hellas (MOH) refinery in Greece will be used as an implementation example of these best practices.

INTRODUCTION

Protective relays are an absolute necessity in all power systems. These relays are, therefore, a logical base of electronic devices upon which a complete power management system can be built. Modern protective relaying devices offer all the I/O, programmability, data collection, metering, and power system diagnostics that previously required the integration of Remote Terminal Units (RTUs), PLCs (Programmable Logic Controllers), DFRs (Digital Fault Recorders), transducers, meters, and multiple single-function protective relays. By reducing device counts, these modern, multifunction protective devices have significantly reduced the price and greatly increased the reliability of automatically protecting and controlling modern power systems.

Modern power management systems are a complete integration of an installed base of protective relays, remote I/O modules, wide area control systems, communications, monitoring, and engineering toolsets. Figure 1 shows all the major components of these systems.
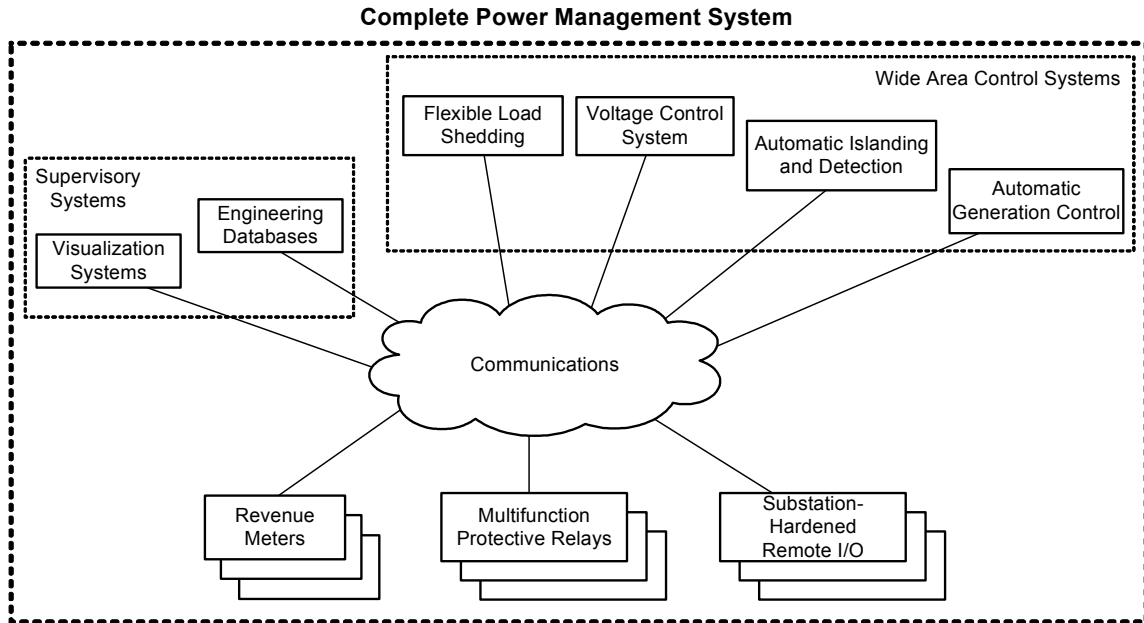
Complete Power Management System

Figure 1   Architecture of Modern Power Management Systems

Microprocessor-based multifunction protective relays, substation-hardened remote I/O modules, and revenue meters are used to gather data throughout a power system. The power management system algorithms acquire this information, make decisions, and send commands back to these relays, meters, and I/O modules. Closed loop, wide area control systems run on independent substation-hardened computation engines. Large capacity servers are used for the SCADA and engineering databases.

This paper will enable you to design and specify the most reliable, economical, and full-featured power management system available today. To accomplish this, the first section identifies all the major pieces required in a full-featured power management system. This is followed by explanations of how to design reliable systems and economical solutions.

SPECIFYING A FULL-FEATURED POWER MANAGEMENT SYSTEM

The major pieces of a power management system include (in order of decreasing importance):

1. Protection systems

2. Wide area control systems

3. Diagnostic and engineering tools

4. Visualization and data archiving systems

Protection systems protect the tremendously expensive assets such as transformers, buses, lines, generators, motors, heaters, capacitors, and switchgear. These systems can prevent or minimize catastrophic damage to equipment, thereby minimizing process downtime.

Wide area control systems for utilities are not new. Some utilities in North America have historically termed wide area control systems as Remedial Action Schemes (RAS) or wide area protection schemes in utilities. Systems that do not fall into the traditional Supervisory Control and Data Acquisition (SCADA) or protection categories are often lumped into the category of

RAS schemes. Some examples of RAS systems include dc intertie control, system breaking, voltage/MVAR control, load shedding, and generation-shedding schemes [1].

Some wide area control systems are commonly used as blackout mitigation techniques. Some can also be used for optimizing economic dispatch. In some cases, they can do both. For example, a generic Automatic Generation Control (AGC) scheme can operate to buy or sell exact amounts of power on an intertie. Additionally, an advanced AGC scheme can control the system to maintain the intertie value at zero during periods of time when system separation is likely (e.g., extreme weather conditions). Another example of wide area control schemes is a load and generation shedding scheme that quickly stabilizes system frequency during periods of sudden loss of generation and/or load [2].

Engineering databases are generally used by operations staff as diagnostic tools to determine the root cause of a power system event. For example, detailed oscillography stored as event reports can be retrieved from modern, multifunction motor protective relays in a few seconds. At the MOH refinery, this enables operators to determine if a motor can be restarted safely after a protective trip. Some of the most common diagnostic and engineering tools include automatic event report (oscillograph) retrieval, detailed Sequential Events Recorder (SER) reports with one millisecond timestamped accuracy, and settings management for all protective, metering, and monitoring equipment in the substations.

Visualization and data repository systems are monitored continuously by operations staff, and, therefore, are often given an undue amount of fiscal attention. However, without all of the aforementioned pieces, the visualization and data archiving quickly becomes meaningless. Highly evolved visualization and data archiving systems are commonly integrated into asset management tools. An example of this is the continuous monitoring of the accumulated through-fault current in transformers at MOH. Through-fault current is calculated inside multifunction relays to quickly indicate the deterioration of their transformers.

DESIGNING RELIABLE SYSTEMS

Large physical assets in power systems are designed to last decades. Likewise, protection and automated control systems for power systems are required to last over 30 years. Additionally, because power systems operate continuously, all power system protection and control systems must have the greatest system uptime or availability possible.

This contrasts greatly with industrial manufacturing automation systems. Automated control systems for industrial manufacturing systems generally have expected lifetimes of less than ten years. Additionally, availability in industrial manufacturing systems is not emphasized nearly as much as it is for utility systems. This creates a difficulty for the power system automation/integration engineer that must supply full-featured capabilities (with features similar to industrial manufacturing systems) yet provide systems with extraordinary availability. This is one of the major reasons why it is generally inadvisable to use industrial automation hardware for power industry applications [3].

System reliability is the probability that a system will perform as required at any time. By designing systems with high availability, system reliability is automatically improved. However, reliability requires that a system respond properly under every possible set of operating conditions. Whereas availability numbers can be demonstrated with quality hardware, firmware, and system architectures, reliability also requires high quality hardware, firmware, and algorithms.

The following subsections focus on several best practices that can be used to construct highly reliable power management systems.

Design Availability Metrics

It is critically important that a consistent procedure is used to evaluate the reliability of a proposed power management system design. There are several industry-accepted methods used to evaluate the availability of proposed control and monitoring systems. The most well used and accepted of these methods is a simple method called fault tree analysis [4]. Fault tree analysis uses manufacturer-provided equipment reliability numbers to calculate system availability numbers.

An explanation of device unavailability and fault tree construction is included in [5]. Reference [4] is a handbook covering these subjects. The metrics required to apply this method are:

- MTTR is the mean time to detect and repair a failure. This is a function of spare parts, skilled labor statistics (or manufacturer-supplied statistics), the ability of the failed device to self-diagnose a failure and send an alarm, and the ability of the monitoring system to properly alert operations staff.

- MTTF is the mean time to fail. This is a measurement index provided by your equipment manufacturer. This metric is an indication of the longevity of the equipment. Equipment with large MTTF numbers will last longer and require less maintenance.

- MTBF is the mean time between failures, defined as the sum of MTTR and MTTF.

Utilize Multifunction Protective Relays

The consolidation of multiple functions into a single microprocessor-based protective relaying device reduces wiring, costs, and complexity. Most importantly, fault tree analysis quickly proves that multifunction relays significantly improve the availability, and therefore, reliability of a complete power management system.

As more functionality is added to protective relays, fewer devices are necessary to accomplish automation and protection-related tasks in power plants and substations. A single, modern protective relay will replace all of the following devices:

1. Single-function protective relays: 50, 51, 67, 27, 59, etc.
2. Battery monitor
3. Digital fault recorder (oscillograph)
4. Sequential Events Recorder (SER)
5. Remote Terminal Unit (RTU)
6. Programmable Logic Controller (PLC)
7. Bay Controller Unit (BCU)
8. Power quality meter
9. Non-revenue class meter
10. Remote I/O modules
11. CT and PT transducers
12. Breaker failure devices

13. Breaker wear monitoring
14. Control switches, pushbuttons, lights, etc.

At MOH, older protection and metering panels were removed, and a single multifunction relay was placed on panel swing doors. In addition to replacing the devices listed above, these multifunction relays provided new functionality such as automatic bus transfer, synchronism check, and remote monitoring and control. This greatly simplified some of the older panels that had over forty years worth of panel equipment additions, modifications, and wiring changes.

Wide Area Control Functions Must Be Completely Independent

Fault tree analysis shows that single points of failure greatly reduce system availability. Therefore, the reliability of a power management system is greatly increased by placing all wide area control functions on independent pieces of hardware.

This design yields a very modular, expandable, and easily commissionable system. Integrating a new wide area control algorithm can take place while all other systems are running. Modifications to an existing control system will not affect other systems.

A very common mistake made by some integrators is to make all control functions dependent on a single database. This is often done because the addition of new tags or functions to the database system can be done once and will automatically be available to all wide area control functions. However, these advantages are equally available using the modern capability of IEC 61131 programming environments. Sharing new tag changes or improved functional routines is done by automatically exporting from one controller and importing to another.

For example, at MOH, the wide area control schemes all run on separate substation-hardened devices. Each of these algorithms run completely autonomous of the others. Therefore, the loss or modification of one system will not affect the others.

Continuously Operate During All System Topologies

A power system topology changes as breakers open and close, as loads start and stop, and as real and reactive power sources turn on and off. Keeping all wide area control algorithms operating in a smooth and continuous fashion during all possible topologies or contingencies greatly enhances a power management system's reliability.

This flexibility can also greatly increase the complexity of a control system. For example, a system breaks into two pieces then two wide area control algorithms will be required rather than one.
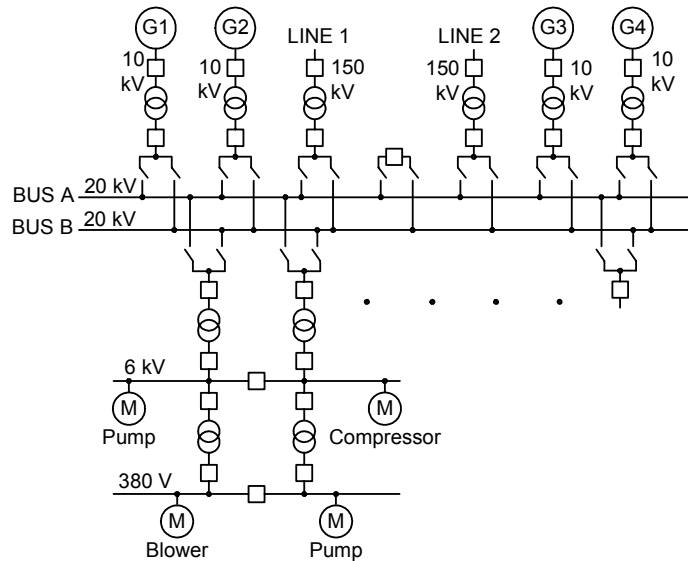
Figure 2   Multiple Generator, Tie Line Example

For example, in the picture above, if we have an algorithm that is controlling the MW and MVAR flow across the Line 1 and 2 transformers, the algorithm must adapt itself to control capacitors and generators to every possible switching combination (there are thousands in this picture alone). In this example, consider what happens if the 20 kV bus tie breaker opens up with three generators on Bus A, a capacitor bank, and only one generator on Bus B. It is possible that load shedding may have to occur on Bus B and generation shedding on Bus A. The system has just been given a tremendous disturbance to deal with and this is exactly the time an algorithm needs to continue functioning and bring the interties back to their set points smoothly. MW, MVAR, voltage, and frequency control algorithms inside the wide area controls at MOH do exactly this.

With all the possible permutations a power system can take on, it is very valuable to test all wide area control systems prior to installation. Prior to commissioning the system at MOH, real-time simulation of the control system was done in the model power systems testing laboratory. The hardware in this laboratory allowed testing the control systems with realistic voltages, currents, and load levels during the simulation of system break-ups.

Fault-Tolerant Designs

Using fault-tolerant design principles in wide area control systems will greatly enhance system reliability. Using some simple techniques, it is possible to build control algorithms to be very robust.

One example is called self-healing data selection. This technique works by switching the data used by the algorithms from one source to another when communications are lost to the first source. For example, if you need to measure power flow through a transformer, the measurements coming from either the low- or high-side protective relay can be used.

An example of self-healing is the high-speed load-shedding system at MOH that selects an alternative load to shed when the algorithm cannot verify the status of the first-choice load.

Adapt to Poor Data Quality

Unnecessarily reacting to incorrect data may create a misoperation. Therefore, for a design to be reliable, it is imperative that all systems properly detect and manage poor quality data.

The actual data value from a measurement is often only half the information needed by a control system. Some form of data quality and timestamp is also required. Poor data quality requires the algorithm to either select another source or shut down the algorithm. Old timestamps indicate unacceptable communications latency and may also require reselection of a data source or shutting down.

Some examples of poor data quality indication include:

- Data are out of range, unrealistic, or intermittent
- Communications latencies
- Communication to a field device has failed
- Self-diagnostic hardware watchdog alarm
- System is not responding to commands
- Miscellaneous equipment alarms
- Unable to maintain set points (e.g., bus voltage, system frequency, or intertie set point)

Maximize Operational Dependability

Operational dependability indicates the likelihood of a system acting when it is not required (false operation). Low dependability occurs in systems because of user errors or device failures. Sometimes the consequences of a single false operation can outweigh the benefit of a multitude of proper operations. Some of the common methods used to maximize operational dependability include:

- Performing thorough precommissioning testing
- Using protection quality devices
- Blocking misoperations caused by communications problems with appropriate protocols
- Using devoted purpose communications networks
- Using point-to-point serial devoted serial communications
- Monitoring communication latency and data quality
- Encrypting of all status and control message data
- Sending redundant control messages
- Using hardware with self-diagnostics and hardware contact outputs indicating failures

Maximize Cybersecurity

Cybersecurity refers to methods used to deflect malicious intruders from causing damage to the computers or network of a system. A malicious attack may cause system downtime and even

misoperations. Therefore, it is imperative that a power management system be designed to maximize system cybersecurity.

One simple way to accomplish effective cybersecurity is to only use equipment with full United States Department of Energy (US DOE)-compliant passwords. US DOE-compliant passwords require different passwords for each level of access control. First level passwords stop hackers from identifying the equipment, and second level passwords are an additional hurdle to change system settings or issuing misoperations.

It is also imperative that all SCADA and visualization systems monitor and record every access and/or change to each device in the system. It is suggested that online engineering access to all substation devices be blocked by operations unless specifically requested.

The substation equipment used at MOH contained all of the aforementioned features.

Robust Communications Architectures

Time-proven, substation-hardened communications processing devices provide robust communications architectures. Using fiber in all serial and Ethernet communications also greatly increases noise immunity. Both of these techniques enhance system reliability.

Managed Ethernet switches with rugged fiber connections between all equipment were used at MOH. All switches were put on the substation battery just like the protective relays and wide area control hardware. Additionally, all serial communications traveling further than eight feet were installed using fiber-optic media.

The visualization system at MOH utilizes a fully redundant, server-based data acquisition and monitoring system. Object Linking and Embedding (OLE) for Process Control (OPC) transports roughly 45,000 tags between a local communications driver and the visualization system. Approximately 70,000 tags are kept synchronized between the local communications driver and the substations via TCP/IP-based Ethernet communications. All communications are report-by-exception with a periodic integrity poll for security. All status and commands are processed to/from the wide area control algorithms and the substations via encrypted, data packed, peer-to-peer IP-based Ethernet communications.

DESIGN AN ECONOMICAL SOLUTION

Designing an economical system is no longer at odds with designing a reliable, full-featured system. Reliability can be increased with decreased costs by leveraging an installed base of multifunction protective relays.

Design and installation costs can be avoided by using only multifunction equipment with long warranties. Multifunction protective relays require less wiring, testing, and documentation. During the design process, carefully analyze the long-term cost impact of low-reliability equipment. Warranty periods are a critical measurement of supplier quality. Ten-year equipment warranties are available from some manufacturers.

Substation-hardened equipment with large MTTF numbers will reduce maintenance and repair budgets. Use only equipment with MTTF numbers based on real observations. Never accept MTTF values from manufacturers that are based on "estimated" or "expected" failure rates. Only use devices with self-diagnosing alarm contacts, and make certain that all alarm contacts are reported to your visualization and monitoring system.

Thorough upfront precommissioning testing saves money by ensuring successful installations of equipment and algorithms. The MOH system was fully mocked-up and tested against a real-time digital simulator in a model power systems testing laboratory. Because of proper upfront testing, there was not a single misoperation during the commissioning of the 70,000-tag MOH system.

Designing an open solution creates a lower cost solution long term. By using IEC 61131 programming, engineers can investigate the logic behind the power management system. IEC 61131-3 software tools are also self-documenting and, therefore, reduce drafting time.

Managed Ethernet switches are understood by IT professionals across the world. Virtual Private Network (VPN) equipment provides low-cost remote access to the customer's industrial network.

Using your favorite human-machine interfaces (HMIs) is possible given that all wide area controls and engineering access are done through separate hardware. Avoid costly, troublesome, quickly outdated proprietary databases. Finding programmers becomes difficult. Invariably, these database developers get more expensive as time proceeds.

Voting schemes were historically required for the unreliable hardware (PLC rack/slot/chassis) designs of a previous era. Modern substation-hardened equipment improves system availability compared with historical PLC rack/slot/chassis type designs [3]. Additionally, multifunction devices also increase system availability.

The dramatically increased wiring and hardware requirements of a voting scheme can actually reduce your system availability numbers. For example, to create a full two-out-of-three voting scheme, you will need three processing engines (whereas a single scheme will only require one) and six times more output contacts (and subsequent wiring) than a nonvoting scheme. This can create much more than three times the equipment and labor. The massively increased wiring requirements and quantity of hardware can actually reduce system availability numbers. Additional connections and increased complexity invariably jeopardize the long-term maintainability of such equipment. An alternative to voting schemes is to use secure, reliable, protection-grade equipment and fault-tolerant algorithms.

SUMMARY

Power management systems can now be built with significantly higher reliability and lower cost than ever before. Reliable systems require high quality hardware, firmware, and algorithms. Use fault tree analysis and manufacturer numbers to analyze the effect of hardware (and firmware) choices on your total system reliability. Multifunction protective relays significantly improve the availability of a complete power management system. Placing each wide area control algorithm on independent hardware also increases system availability.

Reliable algorithms should be designed into the wide area controls of a modern power management system. The algorithms can be designed to operate under every possible system-switching scenario. Fault-tolerant algorithms can be built that will self-heal and select new data sources. There are many ways of detecting poor quality data. Operational dependability and cybersecurity must be maintained throughout the design. Robust communications architectures and protocols must always be used.

Designing a full-featured and reliable power management system is now more economical than ever before. Two ways to accomplish this are using the proper designs and avoiding unnecessary voting schemes.

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BIOGRAPHIES

Scott Manson is a supervising engineer for the Systems and Services Division of Schweitzer Engineering Laboratories, Inc. He received a Masters in Electrical Engineering from University of Wisconsin—Madison and his Bachelors in Electrical Engineering from Washington State University. Scott has extensive experience in designing and implementing automated control systems for industrial manufacturers and electrical utility customers.

Saurabh Shah is the Business Manager in the Systems and Services Division at the Schweitzer Engineering Laboratories, Inc. Charlotte, office. He has also served as a testing manager, international account manger, and international sales and marketing engineer during his nine and one-half years at Schweitzer Engineering Laboratories, Inc. His international experience includes executing and managing large contracts and panel projects.