CHAPTER 61

SMART BUILDING SYSTEMS

SMART building systems are building components that exhibit characteristics analogous to human intelligence. These characteristics include drawing conclusions from data or analyses of data rather than simply generating more data or plots of data, interpreting information or data to reach new conclusions, and making decisions and/or taking action autonomously without being explicitly instructed or programmed to take the specific action. These capabilities are usually associated with software, but they can also be possessed by hardware with embedded software code, or firmware. The line between systems that are “smart” and “not smart” is blurry, and, for purposes of this chapter, does not need to be absolutely defined. The purpose of this chapter is to introduce readers to emerging technologies that possess some of these smart characteristics.

Smart technologies offer opportunities to reduce energy use and cost while improving the performance of HVAC systems to provide better indoor environmental quality (IEQ). This chapter covers smart systems and technologies in the fields of automated fault detection and diagnostics, sensors and actuators, and the emerging modernized electric power grid and its relationship to buildings and facilities.

1. AUTOMATED FAULT DETECTION AND DIAGNOSTICS

Many buildings today use sophisticated building automation systems (BASs) to manage a wide and varied range of building systems. Although the capabilities of BASs have increased over time, many buildings still are not properly commissioned, operated, or maintained, which leads to inefficient operation, excess expenditures on energy, poor indoor conditions at times, and reduced lifetimes for equipment. These operation problems cause an estimated 15 to 30% of unnecessary energy use in commercial buildings (Katipamula and Brambley 2005a, 2005b). Much of this excess consumption could be prevented with widespread adoption of **automated fault detection and diagnostics (AFDD)**. In the long run, automation even offers the potential for automatically correcting problems by reconfiguring controls or changing control algorithms dynamically (Brambley and Katipamula 2005; Fernandez et al. 2009, 2010; Katipamula and Brambley 2007; Katipamula et al. 2003a).

AFDD is an automatic process by which faulty operation, degraded performance, and failed components are detected and understood. The primary objective is early detection of faults and diagnosis of their causes, enabling correction of the faults before additional damage to the system, loss of service, or excessive energy use and cost result. This is accomplished by continuously monitoring the operations of a system, using AFDD processes to detect and diagnose abnormal conditions and the faults associated with them, then evaluating the significance of the detected faults and deciding how to respond. For example, the temperature of the supply air provided by an air-handling unit (AHU) might be observed to be chronically higher than its set point during hot weather. This conclusion might be drawn by a trained analyst visually inspecting a time series plot of the supply air temperature. Alternatively, a computer algorithm could process these data continuously, reach this same conclusion, and report the condition to operators or interact directly with a computer-based maintenance management system (CMMS) to automatically schedule maintenance or repair services.

Automated diagnostics generally goes a step further than simply detecting for out-of-bounds conditions. In this air-handler example, an AFDD system that constantly monitors the temperature and humidity of the outdoor, return, mixed, and supply air, as well as the status of the supply fan, hot-water valve, and chilled-water valve of the air handler, might conclude that the outdoor-air damper is stuck fully open. As a result, during hot weather, too much hot and humid outdoor air is brought into the unit, increasing the mechanical cooling required and often exceeding the capacity of the mechanical cooling system. As a result, the supply air temperature is chronically high. This is an example of how an AFDD system can detect and diagnose this fault.

Over the past two decades, fault detection and diagnostics (FDD) has been an active area of research among the buildings and HVAC&R research communities. Isermann (1984), Katipamula and Brambley (2005a, 2005b), and Rossi and Braun (1997) described an operations and maintenance (O&M) process using AFDD that can be viewed as having four distinct functional processes, as shown in Figure 1. With only a few exceptions, most AFDD systems for building applications existing today lack the evaluation process (Katipamula and Brambley 2005a, 2005b). Automated correction after detection and diagnostics also has been an active area of research in the past decade (Brambley and Katipamula 2005; Fernandez et al. 2009, 2010; Katipamula and Brambley 2007; Katipamula et al. 2003a, 2003b).

As shown in Figure 1, the first functional step of an AFDD process is to monitor the building systems and detect abnormal (faulty)

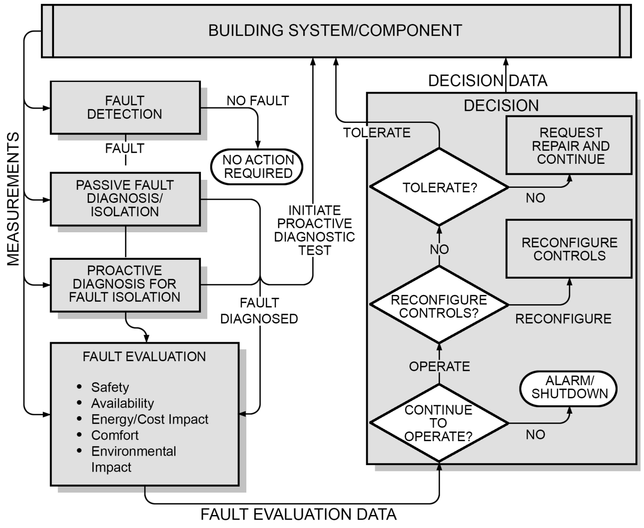


Fig. 1 Generic Process for Using AFDD in Ongoing Operation and Maintenance of Building Systems
Adapted from Katipamula and Brambley (2005a)

The preparation of this chapter is assigned to TC 7.5, Smart Building Systems.

conditions. This step is generally referred to as the **fault detection** phase. If an abnormal condition is detected, then the **fault diagnosis** process identifies the cause. If the fault cannot be diagnosed using passive diagnostic techniques, proactive diagnostics techniques may be required to isolate the fault (Katipamula et al. 2003a). Following diagnosis, **fault evaluation** assesses the impact (energy, cost, and availability) on system performance. Finally, a decision is made on how to react to the fault. In most cases, detection of faults is easier than diagnosing the cause or evaluating the effects of the fault. Detailed descriptions of the four processes are provided in Katipamula and Brambley (2005a, 2005b) and Katipamula et al. (2003a).

Applications of AFDD in Buildings

AFDD has been successfully applied to critical systems such as aerospace applications, nuclear power plants, automobiles, and process controls, in which early identification of malfunctions could prevent loss of life, environmental damage, system failure, and/or damage to equipment. In these applications, AFDD **sensitivity**, the lowest fault severity level required to trigger the correct detection and diagnosis of a fault, is a vital feature; **false-alarm rate** is the rate at which faults are incorrectly indicated when no fault has actually occurred. A high false-alarm rate could result in significant economic loss associated with investigation of nonexistent faults or unnecessary stoppage of equipment operation.

The ability to detect faults in HVAC&R systems has existed for some time, and has been used primarily to protect expensive equipment from catastrophic failure, ensure safety, and provide alarms when a measured variable goes outside its acceptable operating range. In recent years, the motivation for development and use of AFDD has expanded to include expectations of improved energy efficiency and indoor air quality (IAQ), as well as reduced unscheduled equipment downtime (Braun 1999). Developers expect that AFDD will someday be applied ubiquitously, leading to prolonged equipment life for everything from large equipment (e.g., chillers) to small components (e.g., individual actuators).

The need for AFDD capabilities has been established by surveys, site measurements, and commissioning assessments that have documented a wide variety of operational faults in common HVAC&R equipment and systems.

AFDD shows promise in three areas of building engineering: (1) commissioning, (2) operation, and (3) maintenance.

Commissioning of existing buildings involves in part ensuring that systems are installed correctly and that they operate properly. Faults found during commissioning include installation errors (e.g., fans installed backward), incorrectly sized equipment, and improperly implemented controls (e.g., schedules, set points, algorithms). Most commissioning actions that discover these faults, which include visual inspections and functional testing, are performed manually. Data are collected during some tests using automated data loggers, and analysis might be done with computers, but the process of interpreting the data and evaluating results is performed manually. AFDD methods could automate much of the functional testing and interpretation of test results, ensuring completeness of testing, consistency in methods, records of all data and processing, increased cost effectiveness, and the ability to continuously or periodically repeat the tests throughout the life of the facility (Katipamula et al. 2003a; PECI and Battelle 2003). AFDD methods applied during initial building start-up differ from those applied later in a building lifetime. At start-up, no historical data are available, whereas later in the life cycle, data from earlier operation can be used. Selection of methods must consider these differences; however, automated functional testing is likely to involve short-term data collection, whether performed during initial building commissioning or during routine operation later in the building's lifetime, and therefore, the same methods can be used regardless of when the functional tests are performed. Such a short time period is generally required for functional testing to eliminate the possibility that the system being tested changes (e.g., performance degrades) during the test itself. Besides use in functional testing, AFDD methods could be used to verify the proper installation of equipment without requiring visual inspection. Labor intensity could be minimized by only performing visual inspections to confirm installation problems after they have been detected automatically.

During **building operation**, AFDD tools can detect and diagnose performance degradation and faults, many of which go undetected for weeks or months in most commercial buildings. Many building performance problems are automatically compensated by controllers so occupants experience no discomfort, but energy consumption and operating costs often increase. For example, when the capacity of a packaged rooftop air conditioner decreases because of refrigerant loss, the unit runs longer to meet the load, increasing energy use and costs, and occupants experience no discomfort (until design conditions are approached). AFDD tools can detect these, as well as more obvious, faults.

AFDD tools not only detect faults and alert building operation staff to them, but also identify causes of faults so that **maintenance** efforts can be targeted, ultimately lowering maintenance costs and improving operation. By detecting performance degradation rather than just complete failure of physical components, AFDD tools can also help prevent catastrophic failures by alerting building operation and maintenance staff to impending failures before failure occurs. This condition-based maintenance allows convenient scheduling of maintenance, reduced downtime from unexpected faults and failures, and more efficient use of maintenance staff time.

AFDD Methods

AFDD tools use many different methods for detecting faults and subsequently isolating or diagnosing their causes. Figure 2 shows a categorization of these methods (Katipamula and Brambley 2005a), in which fault detection and diagnostic methods are organized into three primary categories based on (1) quantitative models, (2) qualitative models, and (3) process history.

Quantitative model methods use quantitative models of the underlying equipment, relationships between types of equipment, and processes occurring in the equipment and its components. Sets of quantitative mathematical relationships capture the underlying physics of the processes. The quantitative results from applying the models to actual driving conditions represent baseline performance without faults. Differences between measured performance and the baseline performance from the models under identical driving conditions, known as **residuals**, are used to detect the occurrence of faults. Quantitative models can be based on detailed fundamental physical principles and engineering relationships or on simplified models representing the physical processes. Analyses of residuals can also be used to distinguish among possible causes of a fault to provide a fault diagnosis. Quantitative model-based methods are applicable to information-rich systems, where satisfactory models can be built in an affordable way and sufficient sensors are available to provide the data that are required. Methods described by Castro (2002), Dexter and Ngo (2001), Haves and Norford (1997), Li and Braun (2007a, 2007b, 2007c, 2007d, 2009a), Norford et al. (2002), Reddy (2007a), Seem and House (2009), Shaw et al. (2002), and Siegel and Wray (2002) fall into this category.

Qualitative model methods include qualitative physics-based methods and rule-based methods. Qualitative-physics-based methods express the underlying physical relationships (equations) as qualitative expressions (De Kleer and Brown 1984) but have seen limited use in AFDD for HVAC&R. Rule-based methods have been applied widely as the basis for AFDD for HVAC&R, using rules based on the rules of thumb used by expert practitioners in a field (**expert systems**); rules derived from knowledge of the fundamental

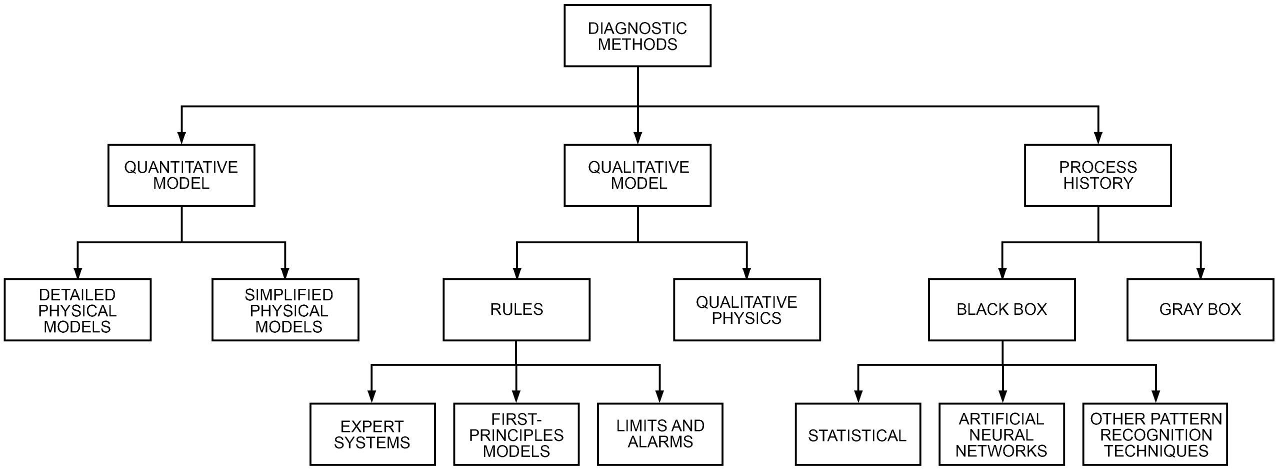


Fig. 2 Classification Scheme for AFDD
Adapted from Katipamula and Brambley (2005a)

physical processes occurring in HVAC&R components, equipment, and systems (i.e., the equations governing the physical processes); and alarms based simply on conditions exceeding prescribed upper and/or lower bounds for acceptable values of variables during operation (e.g., an alarm triggered by duct static pressure exceeding its upper limit). The techniques presented by Dexter and Ngo (2001), Gerasenko (2002), House et al. (2001, 2003), and Lo et al. (2007) are some examples.

Process-history-based methods depend on the availability of a large amount of historical data. These methods include **black-box** (input-output) models derived from the data and **gray-box** models that use first principles or engineering knowledge to specify the mathematical form of terms in the model but for which parameters (e.g., coefficients in the model) are determined from process data. Black-box methods include statistically derived models (e.g., regression), artificial neural networks (ANNs), and pattern-recognition techniques. Approaches based on process history primarily apply to large systems such as whole buildings, where it is difficult to construct an analytical model that captures all important physical behaviors adequately in a cost-effective way, but existing instrumentation yields sufficient data for analysis. Methods used by Bailey (1998), Choi et al. (2004), Li and Braun (2003), Reddy et al. (2003), Riemer et al. (2002), Rossi (2004), and Rossi and Braun (1997) can be classified in this category.

For further details of each of the basic modeling techniques and AFDD methods, any constraints that would limit the application of each technique, and to assess strengths and weaknesses of each technique for application to fault detection and diagnostics, see Katipamula and Brambley (2005a, 2005b).

Benefits of Detecting and Diagnosing Equipment Faults

The benefits of AFDD have been validated in part by studies that documented common HVAC equipment operating faults and their effects (Breuker and Braun 1998a; Breuker et al. 2000; Comstock et al. 2002; House et al. 2001, 2003; Jacobs 2003; Katipamula et al. 1999; Proctor 2004; Rossi 2004; Seem et al. 1999). Faults examined included economizers not operating properly, incorrect refrigerant charges, condenser and filter fouling, faulty sensors, electrical problems, chillers with a variety of faults, air-handling units with too little or too much outdoor-air ventilation, stuck outdoor-air dampers, and other problems.

Studies of the benefits of HVAC fault detection and correction have found positive savings. Rossi's (2004) fault survey of unitary equipment used measurements by service technicians to compute four performance indices from which unit efficiency was estimated and savings potential calculated. Half of the equipment was estimated to have a savings potential of at least $170/year, and 33% had a potential of at least $225/year. Li and Braun (2007e) investigated the following factors that affect the economics of air conditioning: (1) energy efficiency ratio (EER) or coefficient of performance (COP), which quantifies the energy performance of the refrigeration cycle (lower scores equal greater operating costs); (2) cooling capacity Q_{cap}, the degradation of which can affect comfort in the conditioned space, increase compressor run times, and reduce equipment lifetimes; and (3) sensible heat ratio (SHR), which can decrease with many faults, leading to higher total equipment load and greater energy consumption for the same sensible building load. All three factors can be combined in an overall **economic performance degradation index (EPDI)**, which is defined as the net increase in the total operating costs (Li and Braun 2007e) and is given by

$$\mathrm{EPDI} = \frac{1}{1-r_{\Delta\mathrm{SHR}}}\left(\frac{1}{1-r_{\Delta\mathrm{COP}}} \times \frac{\bar{C}_{utility}}{\bar{C}_{utility}+\bar{C}_{equip}} + \frac{1}{1-r_{\Delta cap}} \times \frac{r_{equip}\bar{C}_{equip}}{\bar{C}_{utility}+\bar{C}_{equip}}\right) - 1 \tag{1}$$

where

$r_{\Delta\mathrm{SHR}} = \dfrac{(\mathrm{SHR}_{normal} - \mathrm{SHR})}{\mathrm{SHR}_{normal}} = 1 - r_{\mathrm{SHR}}$ = degradation ratio of SHR

$r_{\Delta\mathrm{COP}} = \dfrac{(\mathrm{COP}_{normal} - \mathrm{COP})}{\mathrm{COP}_{normal}} = 1 - r_{\mathrm{COP}}$ = degradation ratio of COP

$r_{\Delta cap} = \dfrac{(Q_{cap,\,normal} - Q_{cap})}{Q_{cap,\,normal}} = 1 - r_{cap}$ = degradation ratio of capacity

r_{SHR} = SHR/SHR_{normal} = SHR ratio

r_{COP} = COP/COP_{normal} = COP ratio

r_{cap} = $Q_{cap}/Q_{cap,\,normal}$ = capacity ratio

SHR = actual sensible heat ratio

COP = average actual coefficient of performance

Q_{cap} = average actual equipment cooling capacity

$\bar{C}_{equip}$ = average equipment price, $/kWh

$\bar{C}_{utility}$ = $\bar{C}_{elec}\bar{W}_{normal}$ = average normal cost of operation, $/h

$\bar{C}_{elec}$ = average electricity price, $/kWh

$\bar{W}_{normal}$ = power consumption of unit (including both compressors and fans)

The subscript "normal" on a variable indicates that the variable corresponds to the fault-free operating condition.

The total cost penalty ΔOC of not correcting faults, which equals the cost savings from servicing the faults, can be determined from the EPDI from the relation

$$\Delta OC = EPDI \times OC_{normal} = EPDI/(1 + EPDI) \times OC \qquad (2)$$

where OC is the total cost of operation before servicing to correct faults, and OC_{normal} is the total cost of operation expected after correction of the faults (i.e., the cost of fault-free operation).

Using this overall economic performance degradation index, Li and Braun (2007c) estimated the operating cost savings associated with the application of AFDD for rooftop air conditioners in California. Monitoring of 20 field sites, which included small retail, play areas for fast-food restaurants, and modular classrooms in coastal and inland California, for three years found operating cost savings from $5 to $51/kW·yr, the precise savings depending on the specific location and application.

AFDD has the potential to reduce service costs as well as operating costs. Li and Braun (2007b) also developed an economic evaluation procedure to estimate service cost savings, which includes savings from reduced preventive maintenance inspections, fault prevention, lower-cost FDD, better scheduling of multiple service activities, and shifting service to the low season. Based on the 20 monitored field sites, $30/kW·yr (around 70% of the original service costs) can be saved if the AFDD technology in Li and Braun (2007a) could be fully applied. To fully apply the AFDD technology, hardware and software costs were estimated at $250 to $600 for individual units, and $700 to $1500 for a site with four units. Payback periods were less than one year, with savings in operating costs of $5 to $50/kW·yr and an estimated 70% reduction in service costs.

Criteria for Evaluating AFDD Methods

AFDD sensitivity and false-alarm rate are important criteria for evaluating AFDD methods not only for critical systems but also for HVAC&R systems. However, the trade-offs between the savings that could be achieved with early detection of a fault and the cost associated with a false alarm are not easily quantified. The sensitivity of AFDD for HVAC&R applications has been evaluated in terms of loss of efficiency and loss of capacity of the monitored system (Breuker and Braun 1998a, 1998b; Comstock et al. 2001; Reddy 2007b). Many early building automation systems provided an unmanageably large number of alarms, often leading to the alarms either being ignored or turned off. This experience suggests that overly sensitive AFDD methods that provide many false alarms could lead to frustration by users and be disabled by O&M staff. AFFD tools should, therefore, minimize the occurrence of false alarms.

Sensitivity and false-alarm rate are useful for quantifying performance of an AFDD tool; however, AFDD tools and the methods underlying them have numerous other characteristics that affect their performance and the cost of implementation. Dexter and Pakanen (2001) identified the following characteristics that should be considered when selecting an AFDD method or tool: (1) sensors and control signals used, (2) design data used, (3) training data required, and (4) user-selected parameters. Generally, it is desirable to limit each of these.

Types of AFDD Tools

The prevalence of faults in HVAC&R systems, as evidenced by the findings of studies cited previously, and the expectation of performance gains achievable by detecting and diagnosing faults (e.g., improved energy efficiency, occupant comfort, indoor air quality, reduced unscheduled equipment downtime), have spurred the development of a wide range of AFDD algorithms. AFDD tools are created by implementing these algorithms in software. The level of complexity of an AFDD tool rises with the number of components and systems analyzed; however, addressing a broader range of components and systems also generally improves the richness of the types of faults that can be discovered. Some of the types of AFDD tools that have been developed for HVAC&R applications are described here.

Portable Service Tools. Portable service tools are generally applied while a technician is servicing equipment and, therefore, collect data over only short periods of time (e.g., minutes or hours rather than days, weeks, or months), which usually correspond to a steady-state system operating conditions. These products are used by service technicians, commissioning agents, and others to evaluate system performance to guide selection and implementation of corrective measures to address faults. The sensors themselves may be temporarily or permanently installed. If permanently installed, a portable service tool is connected to them during equipment or system servicing. Common measurements include dry-bulb air temperature, air relative humidity, refrigerant temperatures measured on the surfaces of tubes, and refrigerant pressures. These portable tools can perform data acquisition and analysis, providing results on site during servicing. With this class of diagnostic tool, data are collected usually at steady-state operating conditions for a relatively small period of time (e.g., minutes).

An example portable AFDD service tool is one for rooftop packaged air-conditioners. For systems that use direct-expansion vapor compression, diagnostic tools use several performance indicators (e.g., superheat, subcooling, airflow rate) that have corresponding performance expectations based on system characteristics and operating conditions. Patterns of changes in these parameters compared to expected values during proper operation are used to identify occurrence of specific faults. Data and diagnostic messages are then provided to the user to guide the servicing or repair of the system. The diagnostic tool can then be used to validate that the repair has been performed properly and corrected the fault.

Controller-Embedded AFDD. Control-embedded AFDD software code resides in local device- (or application-) specific controllers, where it can be integrated tightly with control logic and have access to data at the sampling interval of the controller. Access to these higher-frequency data may enable the detection of faults, such as unstable control loops, that might be difficult to detect using data collected at longer data-trending intervals. Embedded AFDD tools can reduce network traffic by executing the AFDD code in local controllers and propagating only key parameters or results to higher levels of a BAS architecture for additional analysis, data visualization, and reporting. Embedding AFDD software in controllers can also facilitate integration of the outputs with the alarming capabilities of the building automation system. Computational and memory limits may place practical constraints on the complexity and size of the code embedded in local controllers.

AFDD Software Deployed on Networked Workstations

AFDD software deployed on a BAS-connected workstation uses data collected by the BAS and, in some cases, data from other sensors (e.g., a separate, non-BAS wireless sensor system). The software usually resides on a computer that is part of a BAS or has access to stored data from a BAS. The BAS may serve one or several buildings (e.g., a campus). Generally, workstation-based software uses data collected or recorded at sampling intervals between one and five minutes. Data acquisition and analysis may be near real time or periodic over longer time intervals (e.g., daily) and depend on the specific application. Because the AFDD is implemented on a computer having significant computational resources, analytical methods and historical data can be processed with more complex algorithms than possible with handheld devices and local controllers. A key strength of workstation AFDD software is its ability to detect system-level faults arising from interactions among components. For example, a rogue variable-air-volume (VAV) box controller may cause air-handling unit (AHU) fan power to exceed an expected level during an unoccupied period. In turn, if the VAV box controller has embedded AFDD, the workstation application will be able to report not only the fault at the AHU level, but also the underlying fault at the VAV box. Workstation AFDD software can require extensive effort for configuration before use. In particular, mapping points from the BAS to the AFDD tool can be cumbersome and depends on the number of measurement and control points used by the AFDD tool.

Web-Based AFDD Software. Web-based AFDD software is an extension of controller-embedded and workstation-based capabilities. It may obtain data from the BAS, independent data acquisition systems, and controller-embedded AFDD software, but uses the Internet to remotely acquire and display results. This feature allows gathering data for many buildings and supports enterprise-wide reporting. AFDD processing and analysis may be done locally at the building, with only results reported, or remotely. Updating software remotely is another advantage of web-based AFDD. A significant challenge for web-based AFDD is Internet security, which may require additional hardware and software administration, even if the access is periodic and not continuous.

Current State of AFDD in Buildings

During the 1990s, research and development on AFDD methods for HVAC&R systems grew significantly, yet few commercial AFDD products exist today. AFDD products available commercially are generally very specialized or are not fully automated. Reasons for the lack of widespread availability and use of AFDD systems may include lack of demand by the building O&M community, possibly as a result of insufficient information on the improvements and cost savings possible from them; lack of adequate sensors installed on building systems; the higher cost of reliable sensors; high perceived cost-to-benefit ratio for AFDD; lack of acceptable benchmarks to quantify the potential benefits; the difficulty of accessing real-time data for third-party AFDD software; and few FDD capabilities built directly into building automation systems.

Furthermore, AFDD methods have generally been tested only in laboratories or special test environments (Breuker 1997; Breuker et al. 2000; Castro et al. 2003; Gomez et al. 1996; Li and Braun 2003). Some notable exceptions are reported by Braun et al. (2003), Castro et al. (2003), Dexter and Pakanen (2001), Downey and Proctor (2002), and Katipamula et al. (2003b). Many tools have not been adequately characterized with respect to detection sensitivity and the rate of occurrence of false alarms in real buildings.

Most AFDD methods developed to date work well when a single dominant fault is present in a system, but when multiple faults occur simultaneously or are already present when AFDD is initially applied, many of the methods fail to properly detect or diagnose the causes of the faults. Research in the last decade or so has begun to address detection and diagnosis of multiple simultaneous faults. For example, Braun et al. (2003) extended the previous work by Breuker and Braun (1998b) and Rossi and Braun (1997) to diagnose multiple simultaneous faults. This work has been extended by Li and Braun (2004a, 2004b, 2007a, 2007b, 2007c, 2007d, 2009a, 2009b, 2009c).

As with other software, AFDD tools require installation and, in some cases, input of configuration data before they are ready for use with building systems. Setup can include the installation of sensors dedicated to the AFDD tool or not present in existing monitoring and control systems. Configuration may require specifying the type and possibly even the model of equipment on which the AFDD will operate. It can also include specifying the kind of or basis for control (e.g., air-side economizers may be based on dry-bulb temperature or enthalpy; see the section on Air Handler Sequencing and Economizer Cooling in Chapter 42). Furthermore, fault detection and diagnosis must be followed by evaluation of the fault and decision making regarding whether, when, and how to correct the faults identified.

Future for Automated Fault Detection and Diagnostics

The commercial availability of AFDD tools is increasing, although somewhat slowly, demonstrating some recognition of their value. As market penetration and experience in use increase, the need for improvements will accumulate. Key technical issues still to be completely addressed include the following (Katipamula and Brambley 2005b):

- Eliminating the need to handcraft and configure AFDD systems
- Automatic generation of AFDD systems
- Identifying the best AFDD method for each HVAC&R application
- Developing decision-support tools for using AFDD in operation and maintenance
- Developing prognostic tools to transform HVAC&R maintenance from corrective and preventive to predictive, condition-based maintenance
- Lowering the cost of obtaining data for AFDD and O&M support

Some AFDD tools require users to implement data collection from building automation systems, which is often difficult, costly, and beyond the capabilities of many end users. Other tools require the input of values or selections for many configuration parameters (e.g., the specific method used to control an economizer). Solutions for these problems include (1) developing AFDD tools that include databases sufficient to cover many equipment models, (2) delivering AFDD as part of equipment control packages, and (3) developing methods for automatically generating AFDD tools. The first approach was introduced in a hand tool for air-conditioning service providers more than a decade ago. The second approach of embedding AFDD onboard equipment control has started to be used by some manufacturers of equipment and equipment controls (e.g., chillers). The third approach, involving rapid automatic generation of AFDD, requires research before it emerges in products.

Use of open communication standards for BAS (e.g., BACnet®) is increasing, and use of Internet and intranet technologies is pervasive. These developments make integration of third-party software with AFDD features that use BAS data easier, lowering the cost-to-benefit ratio of deploying AFDD systems. To benefit from these changes, facility managers, owners, operators, and energy service providers need the capabilities and resources to better manage this information and, as a result, their buildings and facilities.

2. SENSING AND ACTUATING SYSTEMS

Sensors

The typical sensors used in smart building systems are not far different from those used in all buildings. Smart building systems rely on sensors to measure quantities such as temperature, humidity, pressure, occupancy, electric power and energy use, fossil fuel energy use, light levels, air speeds, carbon dioxide, and electric harmonics. See Chapter 36, Measurement and Instruments, of the 2013 *ASHRAE Handbook—Fundamentals* for in-depth discussion of measurement techniques for such quantities.

Traditional sensors are connected to control systems via twisted pairs of wires, which conduct voltage or current signals. Sensor calibration (i.e., mapping from electronic signals back to measured physical quantities) can be complicated by nonlinear and/or time-varying functions, which are often implemented in software code by field engineers. The calibration process is time consuming and error prone. In practice, sensors are subject to various defects; therefore, sensor data should not be used without validation. Under certain conditions, multiple physical sensors of different kinds should be used for reliable measure of a physical quantity. Truly smart buildings require pervasive use of smart sensors that possess intelligence and memory to identify, recalibrate, and repair defective sensors.

The intelligence of smart sensors can be described in four categories, discussed in the following paragraphs.

Local Intelligence. In local intelligence, the signal and data-processing capability reside at the local sensor node. For example, some fire detectors are equipped with multiple physical sensors to reduce false alarms and increase reliability, using complicated algorithms. Other sensors may be equipped with flash memory to store historical data. Another type of local intelligence is the ability to compute information based on raw sensor measurements. For instance, a photoresistor can be used to measure luminance, but the mapping from voltage across the resistor in the meter to luminance is not linear. A smart sensor is equipped with circuitry that calculates the desired quantity onboard, either through analog or digital approaches.

Networking Intelligence. Sensors with networking intelligence allow bidirectional communications via scalable, secure, and robust computer networks. Traditional sensors are connected to ports on panels via twisted pairs of wires. While implementing control sequences, engineers must embed the port number and detailed sensor characteristics to calculate the physical quantity of measurement from electronic signals. In practice, there is usually only one quantity that is measured by each sensor, and the direction of information flow is always in one direction from the sensor to control panels. As shown in Figure 3, smart sensors support bidirectional communications, are individually addressable, and form scalable, reliable, and robust networks. Networked sensors can be integrated by either wired or wireless approaches:

- *Wired sensors.* Some sensors are equipped with network ports and can be plugged directly into building control networks. They may support protocols including BACnet (ASHRAE *Standard* 135), LonWorks® (ISO 2012), Modbus® (Modbus 2012), etc.
- *Wireless sensors.* Wireless protocols, such as ZigBee® (ZigBee Alliance 2008), Z-Wave® (Z-Wave® Alliance 2014), and WirelessHART® (IEC *Standard* 62591) are designed for low-energy, low-data-rate sensors. Wi-Fi (IEEE *Standard* 802.11), WiMax (IEEE *Standard* 802.16), Bluetooth® (Bluetooth SIG 2013), and GSM cellular protocols (Eberspächer et al. 2009) are also found in different types of sensors.

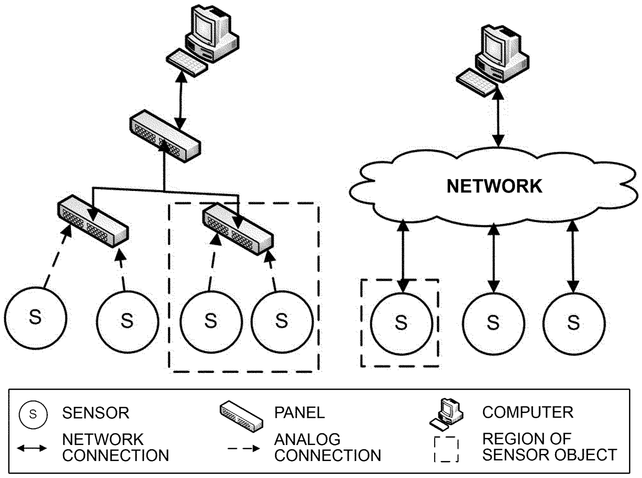


Fig. 3 Traditional Twisted-Pair Wired Sensing Architecture Transmitting Analog Signals (Left) versus Computer Network Architecture Capable of Exchanging Digital Information (Right)

Data Object Intelligence. In this approach, structured data and commands are encapsulated within sensor data objects. Traditional sensors do not have computation capabilities to process high-level commands from control systems. For sensors with data object intelligence, sensor vendors ship sensors with detailed data sheets and sophisticated instructions on diagnostics. It is nontrivial work for field engineers to understand the detailed differences between hundreds of sensors and to implement proper sensor-handling logic in control systems; this type of intelligence automates those tasks. BACnet (ASHRAE *Standard* 135) and IEEE *Standard* 1451 are representative standards that support object models:

- *BACnet*. This protocol supports data objects in traditional system architectures. In addition to reading from sensors, a controller can send commands/messages to sensors. Note that commands are not sent to physical sensors, where information flow is always from sensor to panel. For example, the panel can receive a "who-is" query from other BACnet devices and respond accordingly to describe its attached sensors.
- *IEEE* Standard *1451.* This smart sensor standard has been adopted by the automobile industry for test data acquisition. It features **transducer electronic data sheets (TEDS)**, which make plug-and-play operation feasible. Because sensor data, including calibration parameters, are embedded in TEDS, calibration can be conducted automatically. Numerous IEEE *Standard* 1451 vendors provide smart sensors for HVAC systems. However, the technology has not yet been widely adopted by the building industry, partially because of its high device cost.

Web Automation Intelligence. With this approach, sensor data objects are exposed as web services and integrated with web applications. Today, many sensors are connected to the Internet and expose web services via standard or proprietary application programming interfaces (APIs). These devices are often referred as the "Internet of things," or IoT. For example, a personal weather station can measure and submit air quality data to the cloud, where the data are shared with the world through the Internet. Various vendors collect building performance data from customer sites via the Internet, process the raw data in the cloud, and expose results of business analysis to the web for applications of weather monitoring, lighting control, remote FDD, and IEQ monitoring. Some web data object standards including XML standards, such as Sensor Model Language (SensorML) (OGC® *Standard* 12-000), Transducer Markup Language—TransducerML (retired) (OGC® *Standard* 06-010r6), and numerous OASIS standards for smart grid and security.

The four levels of intelligence for smart sensors are interdependent. Local intelligence is the foundation for the entire architecture. Networking intelligence enables bidirectional data exchange and shields users from the detailed data transportation mechanism. Data object intelligence offers an abstracted and concise sensor data interface for effective software integration and serves as the enabling technology for plug-and-play sensors. As the result, engineers are liberated from tedious work such as manual sensor calibration. The web automation intelligence is the most advanced form of "smart" for sensors. Propelled by increasing applications in cloud computing, smart grid, and mobile devices, smart sensors with web automation intelligence could be widely used to enable smart building systems.

Actuators

The typical actuators used in smart buildings are similar to those used in all buildings. Smart buildings rely on actuators to, among other tasks, modify air flows through damper control and other means, modify chilled-water flow, adjust steam flows, shut off electrical devices, and adjust shading devices. Refer to Chapter 7 of the 2013 *ASHRAE Handbook—Fundamentals* for in-depth discussion of control actuation approaches for building systems.

A smart actuator is one that can correct itself and is possibly self powered. It can also have some sort of display showing the status of the actuator, either on the actuator itself, or on monitoring software having data sent to it directly from the actuator.

Smart actuators are relatively new and are still in the research phase. Not many commercially available smart actuator technologies are currently on the market. Research is ongoing to develop self-correcting HVAC actuators that detect soft faults (e.g., problems in computer software, incorrect set points) and automatically correct to the proper operating condition, as well as to develop ways to automatically correct hard faults (e.g., bent damper linkages) by adjusting actuator response to compensate for the faults (Fernandez et al. 2009; Siemens VAI 2008). Other efforts have pursued developing self-powered actuators that communicate using wireless mechanisms. These devices can control valves and dampers and are powered through harvested thermal or vibrational energy. Because actuators require more energy than sensors, power management is critical in such devices to ensure that they function as desired.

As smart actuators mature, the HVAC field could benefit from this new technology through potential energy savings (e.g., preventing energy waste from faulty actuators and by using self-powered actuators) and through potential maintenance cost savings (e.g., from automated calibration).

Sensor and Actuator Integration

To achieve truly smart buildings, smart sensors and actuators must take advantage of all data obtained throughout the building. Communication between devices is therefore critical. With the large number of sensing and actuating points, conventional sensor wiring may become impractical, especially when attempting to implement these systems on existing buildings. For these reasons, communication (via wireless means and power lines) is a vital technique to integrate smart devices to make a complete building network.

Chapter 40 provides an in-depth discussion of wireless technologies, suitable applications for wireless devices, and selection of wireless systems. For smart sensing and actuating, low-data-rate technologies are most appropriate, though radios based on IEEE *Standard* 802.11 could be used because of their large market. Although reliable communications are of paramount importance when considering wireless communications, low maintenance becomes critical when many devices are present in a building. One of the key maintenance concerns is the need to replace batteries, because many of these devices may not have convenient access to line power. Protocols for low-data-rate applications attempt to minimize energy consumption of these devices by taking steps such as putting the devices to sleep when they are not actively taking measurements, performing actions, or transmitting or receiving commands. IEEE *Standard* 802.15.4 is one such protocol that specifies the physical layers and media access control of radios appropriate for low-data-rate applications. This standard forms the basis of specifications such as ZigBee (ZigBee Alliance 2008), ISA *Standard* 100.11a, WirelessHART (IEC *Standard* 62591), and proprietary protocols, such as MiWi™, which add upper layers to IEEE *Standard* 802.15.4 to increase usability.

Reliability of Wireless Communications in Buildings. Attenuation of signals by building materials and interference from other devices make long-distance signal travel difficult. To overcome these problems, different network topologies can be implemented to make the network more robust. For example, a mesh network can allow each device to transmit and receive, communicating with other devices to relay messages through the network to their intended destinations or to enable direct communication between devices without the need for central control equipment. The intelligence can, therefore, be moved down to specific portions of the building.

Wired Power Line Communications (PLC). Power line communication can also be used to reduce the cost and effort in deploying smart sensors and actuators throughout a building. In this type of communication, signals are sent over the same wires that carry alternating current (ac) electric power in a building. This approach reduces the need to run dedicated control system wiring and is especially useful in existing buildings. Some installation of wiring may still be needed to connect the sensor or actuator to the nearest electrical outlet. Modulated signals are typically sent at frequencies away from the common 50 to 60 Hz frequency of ac electricity. Bandwidth that is appropriate for streaming Internet traffic can be achieved, but noise on the lines and components of the electrical system (e.g., transformers) can make the signal unavailable in certain installations. IEEE *Standard* 1901 provides specifications for providing high-speed broadband networking over power lines using frequencies below 100 MHz. A variety of commercial protocols are available to provide a suite of products that can communicate with each other.

Physical integration of the sensors and actuators is not the final step in developing the components of a smart building; integrating the data streams seamlessly is a challenge, considering the potentially large number of devices. IEEE *Standard* 1451 provides guidance that aims to create plug-and-play devices that automatically report key operating parameters to other devices connected to them. Standards such as these will help to ease the burden in configuring sensing and actuating systems in buildings.

3. SMART GRID BASICS

This section provides the basis for understanding changes occurring in the electric grid infrastructure and how buildings now and in the future interact with the grid. Because this is a rapidly evolving topic area, readers are encouraged to seek additional information on the latest changes and future directions. For additional resources and information, refer to the U.S. Department of Energy's SmartGrid .gov (http://smartgrid.gov) and Energy.gov (http://energy.gov/oe/technology-development/smart-grid/smart-grid-primer-smart-grid-books) web pages.

Brief History of Electric Power Grid

In the early days of commercial electric power, direct current (dc) electricity was transmitted at the same voltage as end users (consumers) required, thus limiting the distance over which electricity could be transmitted. Direct current, however, could not easily be increased in voltage for long-distance transmission without incurring significant line losses. Different classes of loads (e.g., lighting, fixed motors, traction/railway systems) required different voltages, and so used different generators and transmission lines. This specialization of generation and transmission was inefficient for low-voltage, high-current circuits, because generators needed to be near their loads. Thus, the electric grid seemed to be developing into a distributed generation system, with large numbers of small generators located near their loads. However, as electricity use increased, it soon became apparent that using common generating plants and transmission networks for all loads yielded economies of scale that could lower costs and the overall capital investment required. This standardization of the grid also enabled more efficient use of all grid assets.

By allowing multiple generating plants to be interconnected over a wide area on a common network, the cost of electricity was reduced. The most cost-effective and efficient plants could supply electric power reliably to geographically distributed and temporally varying loads. Remote and low-cost sources of energy, such as hydroelectric power or mine-mouth coal, could be exploited to lower energy production cost.

Rapid industrialization in the early 20th century made electric power systems a critical part of the infrastructure in most industrialized nations. Interconnection of local generation plants and small distribution networks was driven by the needs of World War I, with large electric power plants built by governments to provide electricity to munitions factories. Later, these generating plants were used to supply civil loads through long-distance transmission lines. In the United States, an important part of developing the grid occurred with the passage of the Rural Electrification Act of 1936, which provided federal loans for installation of electrical distribution systems to serve rural areas of the United States. The funding was channeled through cooperative electric power companies, most of which still exist today. These member-owned cooperatives purchased power on a wholesale basis and distributed it using their own network of transmission and distribution lines. Because electricity must be produced at the exact rate at which it is consumed, the electric power grid is the largest and one of the most tightly controlled machines in the world today.

Electric Power Grid Operational Characteristics

The modern electric grid is modeled as three interconnected domains (Figure 4). The **generation system** produces electric energy. This domain contains a set of power stations and distributed energy generators (e.g., residential solar photovoltaic systems). The electricity generated is conditioned to reduce losses and is then transmitted over long distances across the **transmission system**. The transmission system typically consists of high-voltage wires that distribute electricity hundreds of miles. When needed to power loads within a region, the electricity is reconditioned (i.e., converted and/or stepped down in voltage) and distributed to customers over the **distribution system**. The distribution system is ordinarily a network of medium-voltage wires that distribute energy across a metropolitan area. The distribution system also includes electrical substations that transform the energy to the low voltages needed by customer loads and transmit it over the wires connected to the customer.

A **transmission grid** is a network of power stations, transmission lines, and substations. Electricity is usually transmitted within a grid as three-phase alternating current (ac). Single-phase ac is used only for distribution to end users, because it is not suitable for large, polyphase induction motors. In the 19th century, two-phase transmission was used but required either four wires or three wires with unequal currents. Higher-order-phase systems require more than three wires, but deliver marginal benefits.

In the United States, the transmission grid is divided into several regional operating units that manage overall electric transmission within their own territories and between regions (see Figure 5).

The capital cost of electric power stations is so high, and electric demand so variable, that it is often less expensive to import some portion of the needed power than to generate it locally. Because nearby loads are often correlated (e.g., hot weather in the Southwestern United States might cause many people to use air conditioners simultaneously), electricity often comes from distant sources. Because of the economics of load balancing, wide-area transmission grids now span across countries and even large portions of continents. The web of interconnections between power producers and consumers ensures that power can flow, even when a few links are inoperative.

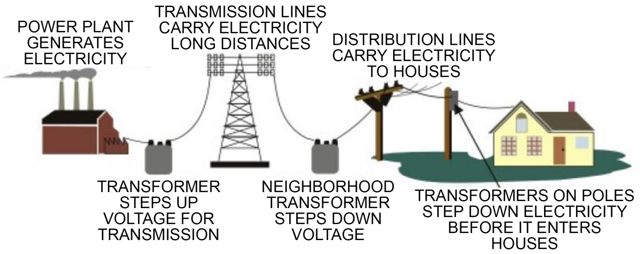


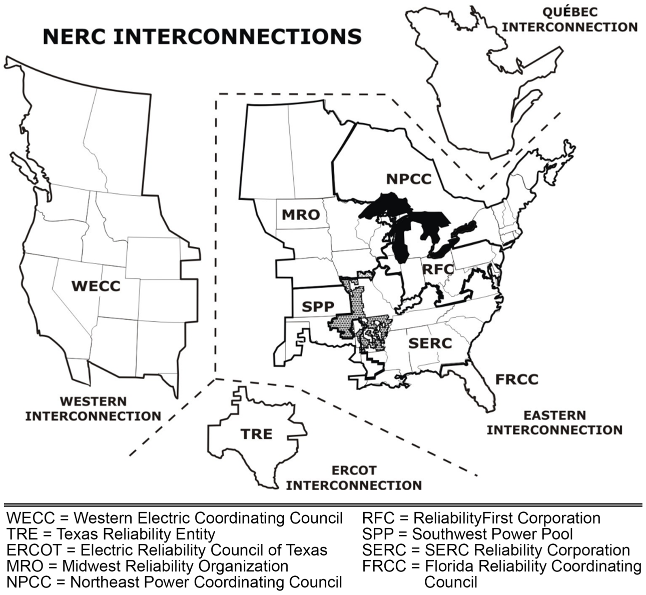
Fig. 4 Electric Power Grid

U.S. Department of Energy (undated)

The unvarying (or slowly varying over many hours) portion of the total electric system demand is known as the **base load** and is generally served by large generation facilities (which are efficient for this purpose because of economies of scale) with low variable costs for fuel and operations. Such facilities might be nuclear, natural-gas, or coal-fired power stations or, in some locations, hydroelectric plants. Variable renewable energy sources, such as solar photovoltaics, wind, and wave power, because of their intermittency, are not considered base-load capable (unless firmed by storage) but can still add power to the grid. The remaining power demand is supplied by intermediate load-following plants and peaking-power plants, which are typically smaller, faster-responding, and higher-cost sources, such as combined-cycle or combustion turbine plants fueled by natural gas.

Subtransmission is part of an electric power transmission system that runs at relatively lower voltages. It is uneconomical to connect all distribution substations to the high main transmission voltage, because the equipment is larger and more expensive. Typically, only larger substations connect with this high voltage. The electric power is stepped down and sent to smaller substations in towns and neighborhoods. Subtransmission circuits are usually arranged in loops so that a single line failure does not cut off service to a large number of customers for more than a short time. Although subtransmission circuits are usually carried on overhead lines, buried cable is also used in urban areas.

The amount of power that can be sent over a transmission line is limited. These limits vary depending on the length of the line and can depend on the ambient temperature. For a short line, heating of conductors because of line losses sets a thermal limit. If too much current is drawn, conductors may sag too close to the ground or other obstructions (e.g., trees), or conductors and equipment may be damaged by overheating. For intermediate-length lines on the order of 100 km, the limit is set by the voltage drop in the line. For longer ac lines, system stability limits the power that can be transferred.



WECC = Western Electric Coordinating Council
TRE = Texas Reliability Entity
ERCOT = Electric Reliability Council of Texas
MRO = Midwest Reliability Organization
NPCC = Northeast Power Coordinating Council
RFC = ReliabilityFirst Corporation
SPP = Southwest Power Pool
SERC = SERC Reliability Corporation
FRCC = Florida Reliability Coordinating Council

Fig. 5 Interconnections in Area of Responsibility of North American Electric Reliability Corporation (NERC)

NERC (2012)

Approximately, the power flowing over an ac line is proportional to the cosine of the phase angle of the voltage and current at the receiving and transmitting ends. This angle depends on system loading and generation, and it is undesirable for the angle to approach 90°. Very approximately, the allowable product of line length and maximum load is proportional to the square of the system voltage. Series capacitors or phase-shifting transformers are used on long lines to improve stability. High-voltage dc lines are restricted only by thermal and voltage drop limits, because the phase angle is not material to their operation.

To ensure safe and predictable operation, the components of the transmission system are controlled with generators, switches, circuit breakers, and even loads. The voltage, power, frequency, load factor, and reliability capabilities of the transmission system are designed to provide reliable, cost-effective performance for customers.

The transmission system provides for base- and peak-load capability, with safety and fault tolerance margins. The peak-load times vary by region largely because of differences in the industry mix. In very hot and very cold climates, home air-conditioning and heating loads can have a significant effect on the overall load at times. These loads are typically highest in the late afternoon in the hottest part of the year, and in mid-mornings and mid-evenings in the coldest part of the year. This variability makes the power requirements differ by season and the time of day. Distribution system designs take the base and peak loads into consideration.

Electricity produced by the generation system has to match the energy consumed by the loads, or the system becomes unstable. The transmission system usually does not have a large storage capability to match the varying energy consumed by loads. Thus, fast-acting balancing generation units (known as spinning reserves) are connected to the transmission system and kept matched to the load to prevent overloading failures of the generation equipment.

Typical Building Load Profile

Figure 6 depicts a typical commercial building load profile in relation to the utility system load profile. The profile reflects the building's individual characteristics, including building use, occupancy and equipment schedules, equipment characteristics, and building control strategies used. In contrast, the utility system load is the aggregate of all the individual loads, including commercial facilities, but also includes residential, industrial, and public facilities. Although individual commercial facility electric loads may have the same general shape as the utility system load, they may not have an identical shape and may peak at different times given the aggregation of the many loads that make up the system load. Understanding the relationship between the load profile of an individual facility and the overall system profile provides the basis for optimizing electricity use and costs to the mutual benefit of the grid and the customer.

Utility Demand Response Strategies

Demand response is the change in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized (DOE 2006).

Flexible load shape attempts to achieve a load shape composed of end-use services with varying degrees of reliability, allowing the utility the flexibility to control/adjust end-use demand in accordance with supply capability. In exchange for accepting a lower level of reliability, a customer receives some financial incentive. A flexible load shape may be achieved using interruptible loads, energy management systems, or individual customer load control devices imposing service constraints.

Peak shaving reduces the amount of energy purchased from a utility company during the peak. Many businesses pay for their electricity consumption on a time-of-use basis. Peak demand charges typically apply to electricity consumed within the peak hours, whereas lesser charges apply to the remainder of the day.

Direct load control involves the utility disabling and enabling consumer end uses. A communication system between the utility and the customer transmits control instructions to a receiver and control actuator on the customer's premises that enables activation/

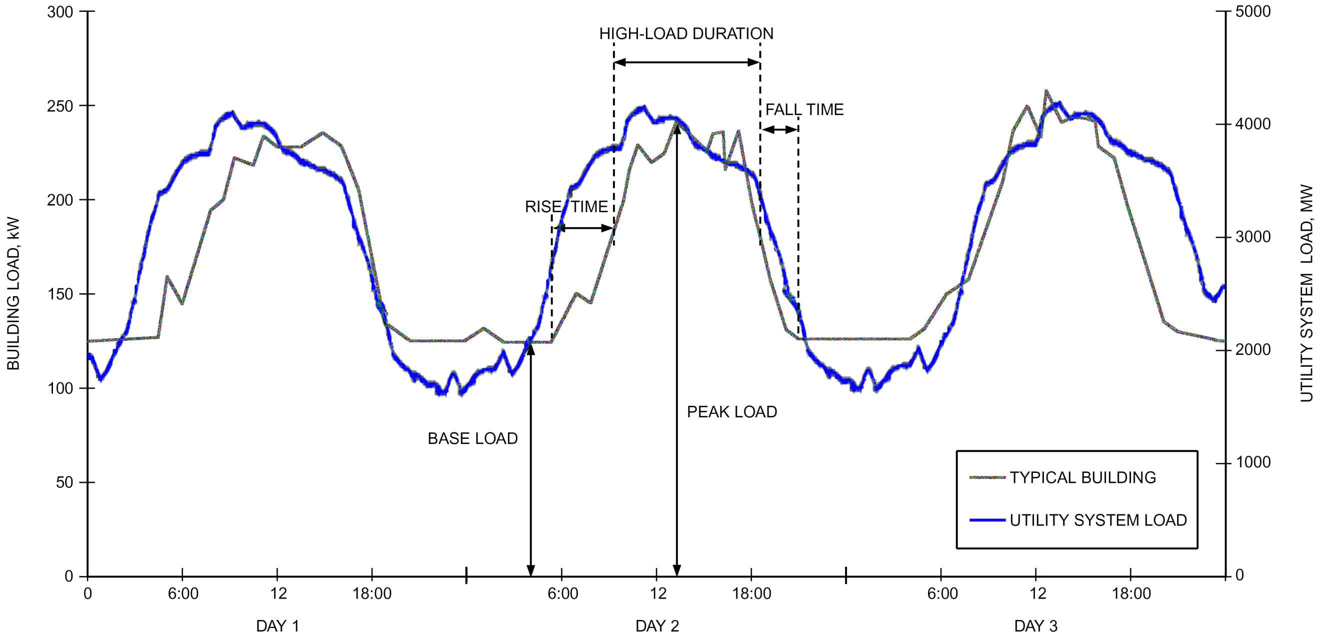


Fig. 6 Example Commercial Building Load Profile in Relation to Utility System Load
Adapted from Price (2010)

deactivation of customer loads. Many utilities use direct load control to reduce peaking requirements, and consider control only during the most probable days of the system peak. Other utilities use direct load control to reduce operating cost and dependence on critical fuels.

Valley filling involves increasing energy consumption in a time period when the electric system is under used. Valley filling may be particularly desirable where the long-run marginal cost of electricity is less than the average price of electricity. Properly priced off-peak load can decrease the average price for the customer and provide cost or capacity benefits to the utility. Valley filling can be accomplished in several ways, including using thermal energy storage (water or space heating or cooling).

Load shifting moves energy consumption to another time period, typically when prices are lower. Common options include storage water heating, storage space heating, cool storage, and time-of-use or other special rates. The shifting usually occurs within a 24 h period. The total energy used by a customer needs not be significantly affected by load shifting.

Strategic conservation is directed at reducing end-use consumption, often through increased efficiency. The change reflects a reduction in sales and a change in the use pattern. Examples include weatherization and appliance efficiency improvement.

Strategic load growth increases end-use consumption by increasing energy sales beyond the valley-filling strategy. The emphasis is often on increasing total sales without regard to the seasonal or daily timing of the load. Strategic load growth may involve area development, electrification, and increased market share of loads that are or can be served by competing fuels.

Utility Rate Options and Strategies

Public regulatory bodies provide incentives to drive customer behaviors using electric tariff design. To increase the reliability and use of existing generation assets or reduce the need for additional generation/transmission assets, there are two methods to reduce customer demand during peak consumption times. Utility customers can be induced to provide demand response either through **dynamic pricing tariffs**, retail electric rates that reflect short-term changes in wholesale electricity costs (e.g., hourly pricing or critical-peak pricing), or through **demand response programs** that offer customers payments in return for reducing consumption when called upon to mitigate high market prices or reserve shortfalls. Table 1 shows common types of demand response programs.

Modern Smart-Grid Strategy

The smart grid represents a modern grid concept that would replace dated infrastructure with currently available and future technologies that enable safe and secure two-way flows of electricity and information between customers and their electricity providers. In the typical grid configuration, energy predominately flows one way, from utilities to consumers, and information flows almost exclusively one-way, from consumers' power meters to grid operators. However, with the smart grid, energy and information would flow easily from the grid to customers, and vice versa, in real time.

The vision for the modern electric grid is one that

- Motivates and includes the consumer
- Accommodates all generation and storage options
- Enables markets
- Provides power quality for 21st-century needs
- Resists attacks
- Self heals
- Optimizes assets and operates efficiently
- Provides less expensive electric power more cleanly

Two-way flows of energy and information would provide customers with valuable information about their electricity prices and consumption patterns. This would enable customers to better manage their electricity use. On the utility side, the grid could be more accurately balanced, brownouts or blackouts could be avoided, and outages could be quickly mitigated. Advantages of the smart grid to the utility and to consumers are compared in Figure 7.

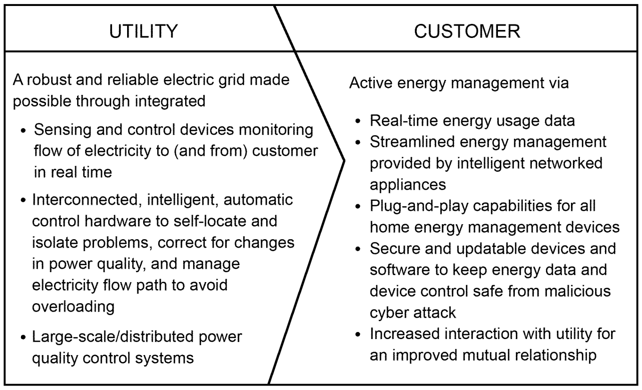
Investments in the smart grid are expected to yield the following four long-lasting effects (Lott et al. 2011):

- Next-generation electric power grid infrastructure that replaces the existing grid
- Substantial improvements in energy efficiency that bring financial and environmental benefits
- Greater use of renewable generation
- Widespread use of distributed generation

Table 1 Common Types of Demand Response (DR) Programs: Price Options and Incentive- or Event-Based Options

Price-Based DR Programs: Higher Prices Used to Induce Demand Reduction	
Time of use (TOU) rates	Rates with fixed price blocks that differ by time of day.
Critical peak pricing (CPP)	Rates include a prespecified, extra-high rate that is triggered by the utility and is in effect for a limited number of hours.
Real-time pricing (RTP)	Rates vary continually (typically hourly) in response to wholesale market prices.
Incentive- or Event-Based Programs: Incentives Provided to Induce Demand Reduction	
Direct load control	Customers receive incentive payments for allowing utility a degree of control over certain equipment.
Demand bidding/ buyback programs	Customers offer bids to curtail load when wholesale market prices are high or identify how much they would be willing to curtail at posted prices.
Emergency demand response programs	Customers receive incentive payments for load reductions when needed to ensure reliability, but curtailments are voluntary.
Capacity market programs	Customers receive incentive payments or rate discounts/bill credits for providing load reductions as substitutes for system capacity.
Interruptible/ curtailable programs	Customers receive a discounted rate or bill credit for agreeing to reduce load upon request. If participants do not curtain when requested, they can be penalized.
Ancillary services market programs	Customers receive payments from a grid for ancillary services provided. Require that customers are able to adjust load quickly.

Sources: FERC (2006), Goldman et al. (2010).



A robust and reliable electric grid made possible through integrated

- Sensing and control devices monitoring flow of electricity to (and from) customer in real time
- Interconnected, intelligent, automatic control hardware to self-locate and isolate problems, correct for changes in power quality, and manage electricity flow path to avoid overloading
- Large-scale/distributed power quality control systems

Active energy management via

- Real-time energy usage data
- Streamlined energy management provided by intelligent networked appliances
- Plug-and-play capabilities for all home energy management devices
- Secure and updatable devices and software to keep energy data and device control safe from malicious cyber attack
- Increased interaction with utility for an improved mutual relationship

Fig. 7 Benefits of Smart Grid as Viewed by Utilities and Customers
Lott et al. (2011)

This smart-grid strategy is intended to enable a new kind of load response, in which loads and generation are on an equal footing with equal visibility of the value of electricity in real time. It includes use of automation and other tools to enable even small customers to manage load in response to the real-time value of energy. It focuses on integrating renewables and higher reliability and resiliency, as well as distributed energy (customer-owned generation and storage) and advancing the regulatory framework to enable customers (and small generators) to manage the distributed energy resources and load in a variable-price environment.

Relevance to Building System Designers

As the modern grid develops, buildings will need grid communications to know the condition of the grid and to determine how to respond to it. Facilities can be operated in ways that support grid reliability while potentially lowering their costs of operation by managing loads and storage to contribute to balancing grid-wide demand and changes to the generation mix. An example is Open Automated Demand Response (OpenADR™), a research and standards development collaboration for power demand management. Typically, OpenADR is used to communicate data and signals that turn off powered devices when electrical demand is high. See OpenADR Alliance (undated) for more information.

Buildings and facilities should be designed for operation in an environment where electricity is valued in real time, varying throughout the day. Building owners, managers, and designers should consider incorporating automation to allow shifting and shedding loads, as well as planning to allow for thermal energy storage and renewable energy generation systems integration. Further, there should be some consideration of microgrid operations, with additional fossil-fuel-based distributed generation (fuel cells, diesel generators, etc.) and electrical storage capability on site.

In the future, not only will electricity costs become more dynamic, energy prices will continue to rise. Controlling energy costs begins with energy efficiency as the cornerstone of an overall energy management plan. Strategies for developing a site-specific plan can be found in EPA (undated).

The success of the smart grid depends on interoperability and communication between energy service providers and facility energy management systems to effectively manage supply and demand. Proposed ASHRAE *Standard* 201P, Facility Smart Grid Information Model (under development), would define an abstract, object-oriented information model to enable appliances and control systems in homes, industrial facilities, and other buildings to manage electrical loads and generation sources in response to communication with a smart electrical grid and to communicate information about those electrical loads to the utility and other electrical service providers. This model defines a comprehensive set of data objects and actions that support a wide range of energy management applications and electrical service provider interactions, including on-site generation, demand response, electrical storage, peak-demand management, direct load control, and other related energy management functions. This standard will become part of the Smart Grid Interoperability Panel (SGIP; http://www.sgip.org) catalog of standards recommended for adoption by utilities and energy service providers.

REFERENCES

ASHRAE. 2012. BACnet®—A data communication protocol for building automation and control networks. ANSI/ASHRAE *Standard* 135-2012.

Bailey, M.B. 1998. *The design and viability of a probabilistic fault detection and diagnosis method for vapor compression cycle equipment*. Ph.D. dissertation. School of Civil Engineering, University of Colorado, Boulder.

Bluetooth SIG. 2013. *Specification of the Bluetooth® system: Core specification 4.1, volume 0: Master table of contents & compliance requirements*. Bluetooth Special Interest Group, Kirkland, WA.

Brambley, M.R., and S. Katipamula. 2004. Beyond commissioning. *Proceedings of 2004 ACEEE Summer Study on Energy Efficiency in Buildings: August 22-27, 2004*, pp. 3-14–3-51. American Council for Energy Efficient Economy, Washington, D.C.

Braun, J.E. 1999. Automated fault detection and diagnostics for the HVAC&R industry. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 5(2):85-86.

Braun, J.E., T. Lawrence, K. Mercer, and H. Li. 2003. *Fault detection and diagnostics for rooftop air conditioners*. P-500-03-096-A1. California Energy Commission, Sacramento.

Breuker, M.S. 1997. *Evaluation of a statistical, rule-based detection and diagnosis method for vapor compression air conditioners*. Master's thesis. School of Mechanical Engineering, Purdue University, West Lafayette, IN.

Breuker, M.S., and J.E. Braun. 1998a. Common faults and their impacts for rooftop air conditioners. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 4(3):303-318.

Breuker, M. S., and J.E. Braun. 1998b. Evaluating the performance of a fault detection and diagnostic system for vapor compression equipment. *International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 4(4):401-425.

Breuker, M., T. Rossi, and J. Braun. 2000. Smart maintenance for rooftop units. *ASHRAE Journal* 42(11):41-47.

Castro, N. 2002. Performance evaluation of a reciprocating chiller using experimental data and model predictions for fault detection and diagnosis. *ASHRAE Transactions* 108(1):889-903.

Castro, N.S., J. Schein, C. Park, M.A. Galler, S.T. Bushby, and J.M. House. 2003. *Results from simulation and laboratory testing of air handling unit and variable air volume box diagnostic tools*. NISTIR 6964, National Institute of Standards and Technology, Gaithersburg, MD.

Choi, K., S. M. Namburu, M. S. Azam, J. Luo, K. R. Pattipati, and A. Patterson-Hine. 2004. Fault diagnosis in HVAC chillers using data-driven techniques. *Proceedings of the IEEE Autotestcon 2004*, pp 407-413.

Comstock, M.C., J.E. Braun, and E.A. Groll. 2001. The sensitivity of chiller performance to common faults. *International Journal of HVAC&R Research* (now *Science and Technology for the Built Environment*) 7(3): 263-279.

Comstock, M.C., J.E. Braun, and E.A. Groll. 2002. A survey of common faults for chillers. *ASHRAE Transactions* 108(1):819-825.

De Kleer, J., and J.S. Brown. 1984. A qualitative physics based on confluences. *Artificial Intelligence* 59(1-2):105-114.

Dexter, A., and J. Pakanen. 2001. Demonstrating automated fault detection and diagnosis methods in real buildings. *Final Report of the International Energy Agency on Energy Conservation in Buildings and Community Systems—Annex 34*. VTT Technical Research Centre of Finland, Espoo.

Dexter, A.L., and D. Ngo. 2001. Fault diagnosis in air-conditioning systems: A multi-step fuzzy model-based approach. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 7(1):83-102.

DOE. 2006. *Benefits of demand response in electricity markets and recommendations for achieving them: A report to the United States Congress pursuant to Section 1252 of the Energy Policy Act of 2005* (February 2006 DOE EPAct Report). U.S. Department of Energy, Washington, D.C.

DOE. Undated. Top 9 things you didn't know about America's power grid. U.S. Department of Energy, Washington, D.C. Available at http://cms.doe.gov/articles/top-9-things-you-didnt-know-about-america-power-grid.

Downey, T., and J. Proctor. 2002. What can 13,000 air conditioners tell us? *Proceedings of the ACEEE 2002 Summer Study on Energy Efficiency in Buildings*, Asilomar, CA, pp. 1.53-1.67. American Council for an Energy Efficient Economy, Washington, D.C.

Eberspächer, J., H-J Vögel, C. Bettstetter, and C. Hartmann. 2009. *GSM: Architecture, protocols and services*. Wiley, West Sussex, UK.

EPA. Undated. *The ENERGY STAR guidelines for energy management*. U.S. Environmental Protection Agency, Washington, D.C. Available from http://www.energystar.gov/buildings/tools-and-resources/energy-star-guidelines-energy-management.

FERC. 2006. *Assessment of demand response and advanced metering staff report*. Docket Number AD06-2-000, Revised 2008. Federal Energy Regulatory Commission, Washington, D.C.

Fernandez, N., M.R. Brambley, and S. Katipamula. 2009. *Self-correcting HVAC controls: Algorithms for sensors and dampers in air-handling units*. PNNL-19104. Pacific Northwest National Laboratory, Richland, WA.

Fernandez, N., M.R. Brambley, S. Katipamula, H. Cho, J.K. Goddard, and L.H. Dinh. 2010. *Self-correcting HVAC controls project final report*. PNNL-19074. Pacific Northwest National Laboratory, Richland, WA.

Gerasenko, S. 2002. *A web-based FDD for HVAC systems*. Master's thesis. University of Cincinnati, Cincinnati, OH.

Goldman, C., M. Reid, R. Levy, and A. Silverstein. 2010. *Coordination of energy efficiency and demand response*. LBNL-3044E. Lawrence Berkeley National Laboratory, Berkeley, CA.

Gomez, E., H. Unbehauen, P. Kortmann, and S. Peters. 1996. Fault detection and diagnosis with the help of fuzzy-logic and with application to a laboratory turbogenerator. *Proceedings of the 13th IFAC World Congress* (Vol. N), pp. 175-180.

Haves, P., and L.K. Norford. 1997. A standard simulation testbed for the evaluation of control algorithms and strategies. ASHRAE Research Project RP-825, *Final Report*.

House, J.M., H. Vaezi-Nejad, and J.M. Whitcomb. 2001. An expert rule set for fault detection in air-handling units. *ASHRAE Transactions* 107(1): 858-871.

House, J.M., K.D. Lee, and L.K. Norford. 2003. Controls and diagnostics for air distribution systems. *ASME Journal of Solar Energy Engineering* 125(3):310-317.

IEEE. 2012. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. IEEE *Standard* 802.11-2012. Institute of Electrical and Electronics Engineers, New York.

IEEE. 2003. Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (LR-WPANs). IEEE *Standard* 802.15.4, Part 15.4. Institute of Electrical and Electronics Engineers, New York.

IEEE. 2012. IEEE standard for air interface for broadband wireless access systems. IEEE *Standard* 802.16™-2012. Institute of Electrical and Electronic Engineers, New York.

IEEE. 2007. Standard for a smart transducer interface for sensors and actuators—Common functions, communication protocols, and transducer electronic data sheet (TEDS) formats. IEEE *Standard* 1451.0™. Institute of Electrical and Electronic Engineers, New York.

IEEE. 2010. Standard for broadband over power line networks: Medium access control and physical layer specifications. IEEE *Standard* 1901-2010. Institute of Electrical and Electronics Engineers, New York.

IEC. 2010. Industrial communication networks—Wireless communication network and communication profiles—WirelessHART™. *Standard* 62591:2010, International Electrotechnical Commission, Geneva, Switzerland.

ISA. 2011. Wireless systems for industrial automation: Process control and related applications. ANSI/ISA *Standard* 100.11a-2011. International Society of Automation, Research Triangle Park, NC.

Isermann, R. 1984. Process fault detection based on modeling and estimation methods—A survey. *Automatica* 20(4):387-404.

ISO/IEC. 2012. Information technology—Control network protocol—Parts 1, 2, 3 and 4. ISO/IEC *Standard* 14908-4:2012. International Standards Organization, Geneva, Switzerland.

Jacobs, P. 2003. *Small HVAC problems and potential savings reports*. Technical Report 500-03-082-A-25, California Energy Commission, Sacramento, CA.

Katipamula, S., and M.R. Brambley. 2005a. Methods for fault detection, diagnostics and prognostics for building systems—A review, part I. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 11(1):3-25.

Katipamula S., and M.R. Brambley. 2005b. Methods for fault detection, diagnostics and prognostics for building systems—A review, part II. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 11(2):169-187.

Katipamula, S., and M. Brambley. 2007. Automated proactive fault isolation: A key to automated commissioning. *ASHRAE Transactions* 113(2): 40-51.

Katipamula S., M.R. Brambley, and L. Luskay. 2003a. Automated proactive techniques for commissioning air-handling units. *Journal of Solar Energy Engineering* 125(3):282-291.

Katipamula, S., M.R. Brambley, N.N. Bauman, and R.G. Pratt. 2003b. Enhancing building operations through automated diagnostics: Field test results. *Proceedings of the Third International Conference for Enhanced Building Operation*, Texas A&M University, College Station, TX.

Katipamula, S., R.G. Pratt, D.P. Chassin, Z.T. Taylor, K. Gowri, and M.R. Brambley. 1999. Automated fault detection and diagnostics for outdoor-air ventilation systems and economizers: Methodology and results from field testing. *ASHRAE Transactions* 105(1):555-567.

Li, H., and J.E. Braun. 2003. An improved method for fault detection and diagnosis applied to packaged air conditioners. *ASHRAE Transactions* 109(2):683-92.

Li, H., and J.E. Braun. 2004a. An economic evaluation of automated fault detection and diagnosis for rooftop air conditioners. *Proceedings of the Tenth International Refrigeration and Air Conditioning Conference at Purdue*, pp. R145.1-R145.10.

Li, H., and J.E. Braun. 2004b. A methodology for diagnosing multiple-simultaneous faults in rooftop air conditioners. *Proceedings of the Tenth International Refrigeration and Air Conditioning Conference at Purdue*, pp. R131.1-R131.10.

Li, H., and J.E. Braun. 2007a. Decoupling features and virtual sensors for diagnosis of faults in vapor compression air conditioners. *International Journal of Refrigeration* 30(3):546-564.

Li, H., and J.E. Braun. 2007b. A methodology for diagnosing multiple-simultaneous faults in vapor compression air conditioners. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 13(2):369-395.

Li, H., and J.E. Braun. 2007c. An economic evaluation of benefits associated with automated fault detection and diagnosis in rooftop air conditioners. *ASHRAE Transactions* 113(2):200-210.

Li, H., and J.E. Braun. 2007d. Decoupling features and virtual sensors for diagnosis of faults in vapor compression air conditioners. *International Journal of Refrigeration* 30(3):546-564.

Li, H., and J.E. Braun. 2007e. An overall performance index for characterizing the economic impact of faults in direct expansion cooling equipment. *International Journal of Refrigeration* 30(2):299-310.

Li, H., and J.E. Braun. 2009a. Decoupling features for diagnosis of faults in vapor compression heat pumps. *International Journal of Refrigeration* 32(2):316-326.

Li, H., and J.E. Braun. 2009b. Development, evaluation, and demonstration of a virtual refrigerant charge sensor. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 15(1):117-136.

Li, H., and J.E. Braun. 2009c. Virtual refrigerant pressure sensors for use in monitoring and fault diagnosis of vapor-compression equipment. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 15(3):597-616.

Lo, C.H., P.T. Chan, Y.K. Wong, A.B. Rad, and K.L. Cheung. 2007. Fuzzy-genetic algorithm for automatic fault detection in HVAC systems. *Applied Soft Computing* 7(2):554-560.

Lott, M.C., T.B. Seaman, C.R. Upshaw, and E.G.K. Haron. 2011. *The smart grid in Texas: A primer*. Power Across Texas, Austin. Available from http://www.poweracrosstexas.org/the-smart-grid-in-texas-primer-now-available/.

Modbus. 2012. *MODBUS application protocol specification v1.1b3*. Modbus Organization, Inc., Hopkinton, MA.

NERC. 2012. *Regional entities*. North American Electric Reliability Corporation, Atlanta, GA. Available at http://www.nerc.com/aboutnerc/keyplayers/pages/regional-entities.aspx.

Norford, L.K., J.A. Wright, R.A. Buswell, D. Luo, C.J. Klaassen, and A. Suby. 2002. Demonstration of fault detection and diagnosis methods for air-handling units (ASHRAE 1020-RP). *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 8(1):41-71.

OGC®. 2007. OpenGIS® transducer markup language (TML) implementation specification. OGC *Standard* 06-010r6 (retired). Open Geospatial Consortium, Wayland, MA.

OGC®. 2014. SensorML: Model and XML encoding standard. OGC *Standard* 12-000. Open Geospatial Consortium, Wayland, MA.

OpenADR Alliance. Undated. *The OpenADR primer*. Available http://www.openadr.org/assets/docs/openadr_primer.pdf.

PECI and Battelle. 2003. *Method for automated and continuous commissioning of building systems*. ARTI-21CR/610-30040-01. Portland Energy Conservation, Inc. and Battelle Northwest Division. Air Conditioning and Refrigeration Technology Institute, Arlington, VA.

Price, P. 2010. *Methods for analyzing electric load shape and its variability.* LBNL-3713E. Lawrence Berkeley National Laboratory, Berkeley, CA.

Proctor, J. 2004. Residential and small commercial air conditioning—Rated efficiency isn't automatic. ASHRAE Public Session, Winter Meeting, Anaheim, CA.

Reddy, T.A. 2007a. Formulation of a generic methodology for assessing FDD methods and its specific adoption to large chillers (RP-1275). *ASHRAE Transactions* 113(2):334-342.

Reddy, T.A. 2007b. Development and evaluation of a simple model-based automated fault detection and diagnosis (FDD) method suitable for process faults of large chillers. *ASHRAE Transactions* 113(2):27-39.

Reddy, T.A., D. Niebur, K.K. Andersen, P.P. Pericolo, and G. Cabrera. 2003. Evaluation of the suitability of different chiller performance models for on-line training applied to automated fault detection and diagnosis. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 9(4):385-414.

Riemer, P.L, J.W. Mitchell, and W.A. Beckman. 2002. The use of time series analysis in fault detection and diagnosis methodologies. *ASHRAE Transactions* 108(2).

Rossi, T.M. 2004. Unitary air conditioning field performance. *Proceedings of the Tenth International Refrigeration and Air Conditioning Conference at Purdue*, pp. R146.1-R146.9.

Rossi, T.M., and J.E. Braun. 1997. A statistical, rule-based fault detection and diagnostic method for vapor compression air conditioners. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 3(1):19-37.

Seem, J.E., and J.M. House. Integrated control and fault detection of air handling units. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 15(1):25-55.

Seem, J.E., J.M. House, and R.H. Monroe. 1999. On-line monitoring and fault detection of control system performance. *ASHRAE Journal* 41(7): 21-26.

Shaw, S.R., Norford, L.K., Luo, D., and S.B. Leeb. 2002. Detection and diagnosis of HVAC faults via electrical load monitoring. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 8(1): 13-40.

Siegel, J.A., and C.P. Wray. 2002. An evaluation of superheat-based refrigerant charge diagnostics for residential cooling systems. *ASHRAE Transactions* 108(2).

Siemens VAI. 2008. *Precision flatness control for SIROLL^{CIS} CM: Highly improved flatness in cold rolling*. Metals Technologies GmbH & Co., Linz, Austria.

ZigBee Alliance. 2008. *ZigBee specification*. Document 053474r17. Zigbee Alliance, San Ramon, CA.

Z-Wave® Alliance. 2014. *About Z-Wave® technology*. Available at http://z-wavealliance.org/about_z-wave_technology/.

BIBLIOGRAPHY

Architectural Energy Corporation (AEC). 2003. Final report: Energy efficient and affordable commercial and re0sidential buildings. report prepared for the california energy commission. *Report* P500-03-096, Architectural Energy Corporation, Boulder, CO.

Avery, G. 2002. Do averaging sensors average? *ASHRAE Journal* 44(12): 42-43.

Bishop, C.M. 1995. *Neural networks for pattern recognition*. Oxford University Press, New York.

Blanchard, B.S., D. Verma, and E.L. Peterson. 1995. *Maintainability: A key to effective serviceability and maintenance management*. John Wiley & Sons, New York.

Bonne, D., and S.B. Jorgensen. 2004. Data-driven modeling of batch processes. *Proceedings of 7th International Symposium on Advanced Control of Chemical Processes*, ADCHEM, F. Allgower and F. Gao, eds., pp. 663-668.

Bose, R., A.A. Helal, V. Sivakumar, and S. Lim. 2007. Virtual sensors for service oriented intelligent environments. *The 3rd IASTED International Conference on Advances in Computer Science and Technology*, ACST 2007, pp. 165-170.

Brambley, M.R., R.G. Pratt, D.P. Chassin, and S. Katipamula. 1998. Automated diagnostics for outdoor air ventilation and economizers. *ASHRAE Journal* 40(10):49-55.

Campbell, J.D. 1995. *Uptime: Strategies for excellence in maintenance management*. Productivity Press, Portland, OR.

Carling, P., and P. Isakson. 1999. Temperature measurement accuracy in an air-handling unit mixing box. *Proceedings of the 3rd International Symposium on HVAC, ISHVAC '99*, Shenzhen, China.

Casali, A., G. Gonzalez, F. Torres, G. Vallebuona, L. Castelli, and P. Gimenez. 1998. Particle size distribution soft-sensor for a grinding circuit. *Powder Technology* 99(1):15-21.

CEC. 2008. *Strategic plan to reduce the energy impact of air conditioners*. CEC-400-2008-010. California Energy Commissioning, Sacramento, CA.

Champagne, M., and M. Dudzic. 2002. Industrial use of multivariate statistical analysis for process monitoring and control. *Proceedings of the 2002 American Control Conference (vol. 1)*, pp. 594-599.

Chen, J., and R.J. Patton. 1999. *Robust model-based fault-diagnosis for dynamic systems*. Kluwer Academic Publishers, Norwell, Massachusetts.

Claridge, D.E., M. Liu, and W.D. Turner. 1999. Whole building diagnostics. *Proceedings of the Workshop on Diagnostics for Commercial Buildings: Research to Practice*, San Francisco, CA, June 16-17, pp. 3.2.1-3.2.17. Available at http://poet.lbl.gov/diagworkshop/proceedings/claridge.htm.

Comstock, M.C., B. Chen, and J.E. Braun. 1999. Literature review for application of fault detection and diagnostic methods to vapor compression cooling equipment. HL 1999-19, *Report* 4036-2. Ray Herrick Laboratories, Purdue University.

Criswell, J.W. 1989. *Planned maintenance for productivity and energy conservation*, 3rd ed. Prentice Hall, Englewood Cliffs, NJ.

Devogelaere, D., M. Rijckaert, O.G. Leon, and G.C. Lemus. 2002. Application of feedforward neural networks for soft sensors in the sugar industry. *Proceedings of the VII Brazilian symposium on neural networks, 2002* (SBRN 2002), pp. 2-6.

DeWolf, S., R.L.E. Cuypers, L.C. Zullo, B.J. Vos, and B.J. Bax. 1996. Model predictive control of a slurry polymerisation reactor. *Computers and Chemical Engineering* 20(Supplement 2):S955-S961.

Doyle, F.J. 1998. Nonlinear inferential control for process applications. *Journal of Process Control* 8(5-6):339-353.

Federspiel, C. 2000. Predicting the frequency and cost of hot and cold complaints in buildings. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 6(4):289-305.

Fernandez, N., M.R. Brambley, and S. Katipamula. 2009. *Self-correcting HVAC controls: Algorithms for sensors and dampers in air-handling units*. PNNL-19104. Pacific Northwest National Laboratory, Richland, WA.

Fortuna, L., S. Graziani, A. Rizzo, and M.G. Xibilia. 2007. *Soft sensors for monitoring and control of industrial processes*. Springer-Verlag, London.

Frank, P.M. 1990. Fault diagnosis in dynamic systems using analytical and knowledge-based redundancy—A survey and some new results. *Automatica* 26:459-474.

Frank, P.M. 1997. New developments using AI in fault diagnosis. *Engineering Applications of Artificial Intelligence* 10(1):3-14.

Friedman, G.2004. Too hot—Too cold: Diagnosing occupant complaints. *ASHRAE Journal* 46(1):S157-S158, S160-S163.

Friedman, H., and M.A. Piette. 2001. Comparison of emerging diagnostic tools for large commercial HVAC systems. *Proceedings of the 9th National Conference on Building Commissioning*, Cherry Hill, NJ.

Fuchs, S.J. 1992. *Complete building equipment maintenance desk book*. Prentice Hall, Englewood Cliffs, NJ.

Gawthrop, P.J. 2005. Virtual actuators with virtual sensors. *Proceedings of the Institution of Mechanical Engineers Part I: Journal of Systems and Control Engineering* 219(5):370-377.

Gertler, J. 1988. Survey of model-based failure detection and isolation in complex plants. *IEEE Control Systems Magazine* 8(6):3-11.

Gonzalez, G.D., 1999. Soft sensors for processing plants. *Proceedings of the second international conference on intelligent processing and manufacturing of materials, IPMM '99*, vol. 1, pp. 59-69.

Haberl J. S., L.K. Norford, and J.V. Spadaro. 1989. Diagnosing building operating problems. *ASHRAE Journal* 31(6):20-30.

Hardy, N., and A.A. Maroof. 1999. ViSIAr—A virtual sensor integration architecture. *Robotica* 17(6):635-647.

Harms, T.M. 2002. *Charge inventory system modeling and validation for unitary air conditioners*. Ph.D. dissertation. School of Mechanical Engineering, Purdue University, West Lafayette, IN.

Healy, W. 2010. Building sensors and energy monitoring systems. Building America Meeting on Diagnostic Measurement and Performance Feedback for Residential Space Conditioning Equipment, National Institute of Standards and Technology, April 26, 2010, Gaithersburg, MD.

Himmelblau, D.M. 1978. *Fault detection and diagnosis in chemical and petrochemical processes*. Elsevier, New York.

IEEE. 1997. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. IEEE *Standard* 802.11-1997. Institute of Electrical and Electronic Engineers, New York.

Isermann, R., and P. Ballé. 1997. Trends in the application of model-based fault detection and diagnosis of technical process. *Control Engineering Practice* 5(5):709-719.

Kadlec, P., B. Gabrys, and S. Strandt. 2009. Data-driven soft sensors in the process industry. *Computers and Chemical Engineering* 33(4):795-814.

Karmar, J., and N. Valerie. 1995. *Energy impacts from commercial air conditioning maintenance—A WDSD evaluation report*. Wisconsin Demand-Side Demonstrations, Madison, WI.

Katipamula S., and N. Lu. 2006. Evaluation of residential HVAC control strategies for demand response programs. *ASHRAE Transactions* 112(1): 535-546.

Kintner-Meyer, M., and M.R. Brambley. 2002. Pros & cons of wireless. *ASHRAE Journal* 44(11):54-61.

Kintner-Meyer, M., M.R. Brambley, T.A. Carlon, and N.N. Bauman. 2002. Wireless sensors: Technology and cost-savings for commercial buildings. *Teaming for Efficiency: Proceedings, 2002 ACEEE Summer Study on Energy Efficiency in Buildings: Aug. 18-23, 2002, Vol. 7; Information and Electronic Technologies; Promises and Pitfalls*. pp. 7.121-7.134. American Council for Energy Efficient Economy, Washington, D.C.

Lee, P.S., and A.L. Dexter. 2005. A fuzzy sensor for measuring the mixed air temperature in air-handling units. *Measurement* 37(1):83-93.

Li, H., and J.E. Braun. 2002. On-line models for use in automated fault detection and diagnosis for HVAC&R equipment. *Proceedings of the 2002 ACEEE Conference on Energy Efficiency in Buildings*, Monterey, CA. American Council for an Energy Efficient Economy, Washington, D.C.

Mangoubi, R.S. 1998. *Robust Estimation and Failure Detection*. Springer-Verlag, New York.

McIntosh, I.B.D., J.W. Mitchell, and W.A. Beckman. 2000. Fault detection and diagnosis in chillers—Part I: Model development and application. *ASHRAE Transactions* 106:268-282.

McKellar, M. G. 1987. *Failure diagnosis for a household refrigerator*. Master's thesis. School of Mechanical Engineering, Purdue University, Purdue, Indiana.

Mobely, R.K. 1989. *An introduction to predictive maintenance*. Van Nostrand Reinhold, New York.

Moubray, J. 1997. *Reliability-centered maintenance*, 2nd ed. Industrial Press, New York.

National Research Council. 1998. *Stewardship of federal facilities: A proactive strategy for managing the nation's public assets*. National Academy Press, Washington, D.C.

NCMS. 1999. *Reliability and maintainability guideline for manufacturing machinery and equipment*, 2nd ed. National Center for Manufacturing Sciences, Ann Arbor, MI.

Patton, R.J., P. Frank, and R. Clark. 1989. *Fault diagnosis in dynamic systems: Theory and application*. Prentice Hall, Upper Saddle River, NJ.

Patton, R.J., C. Fantuzzi, and S. Simani. 2003. *Model-based fault diagnosis in dynamic systems using identification techniques*. Springer-Verlag, New York.

Pau, L.F. 1981. *Failure diagnosis and performance monitoring*. Marcel Dekker, New York.

Petrocelly, K.L. 1988. *Physical plant operations handbook*. Prentice Hall, Englewood Cliffs, NJ.

Portland Energy Conservation Inc. (PECI) and Battelle Northwest Division. 2003. Methods for automated and continuous commissioning of building systems. *Report* ARTI-21CR/610-30040-01. Air Conditioning and Refrigeration Technology Institute, Arlington, VA. Available from http://www.osti.gov/scitech/servlets/purl/810800.

Proctor, J., and T. Downey. 1995. Heat pump and air conditioner performance. Affordable Comfort Conference, March 26-31, Pittsburgh, PA.

Reddy, T.A., and K.K. Andersen. 2002. An evaluation of classical steady-state off-line linear parameter estimation methods applied to chiller performance data. *International Journal of Heating, Ventilating, Air-Conditioning and Refrigerating Research* (now *Science and Technology for the Built Environment*) 8(1):101-124.

Reddy, T.A., D. Niebur, J. Gordon, J. Seem, K.K. Andersen, G. Cabrera, Y. Jia, and P. Pericolo. 2001. Development and comparison of on-line model training techniques for model-based FDD methods applied to vapor compression chillers. ASHRAE Research Project RP-1139, *Final Report*.

Salsbury, T.I., and R.C. Diamond. 2001. Fault detection in HVAC systems using model-based feedforward control. *Energy and Buildings* 33:403-415.

Smith, A.M. 1993. *Reliability-centered maintenance*. McGraw-Hill, New York.

Seem, J.E. 2007. Using intelligent data analysis to detect abnormal energy consumption in buildings. *Energy and Buildings* 39:52-58.

SGIP. 2011. *SGiP standards catalog*. Smart Grid Interoperability Panel, Wakefield, MA. Available at http://www.sgip.org/Catalog-of-Standards.

Shen, B. 2006. *Improvement and validation of unitary air conditioner and heat pump simulation models at off-design conditions*. Ph.D. dissertation. Herrick Laboratories, Purdue University, West Lafayette, IN.

Song,Y., Y. Akashi, and J. Yee. 2008. A development of easy-to-use tool for fault detection and diagnosis in building air-conditioning systems. *Energy and Buildings* 40(2):71-82.

Sreedharan, P., and P. Haves. 2001. Comparison of chiller models for use in model-based fault detection. *International Conference for Enhanced Building Operations (ICEBO)*, Texas A&M University, College Station.

Stallard, L.A. 1989. *Model based expert system for failure detection and identification of household refrigerators*. Master's thesis. School of Mechanical Engineering, Purdue University, West Lafayette, IN.

Stum, K. 2000. Compilation and evaluation of information sources for HVAC&R system operations and maintenance procedures. ASHRAE Research Project RP-1025, *Final Report*.

Tan, H., and A.L. Dexter. 2005. Improving the accuracy of sensors in building automation systems. *Proceedings of the 16th IFAC World Congress*, Prague, Czech Republic. Available at http://www.nt.ntnu.no/users/skoge/prost/proceedings/ifac2005/Fullpapers/01900.pdf.

TIAX. 2005. Energy impact of commercial building controls and performance diagnostics: market characterization, energy impact of building faults and energy savings potential. *Report* D0180. TIAX, Lexington, MA.

TRC Finland. 1996. *International Energy Agency building optimisation and fault diagnosis source book*. J. Hyvärinen and S. Kärki, eds. Technical Research Centre of Finland, Laboratory of Heating and Ventilation, Espoo.

Underwood, C.P. 1997. *HVAC control systems: Modeling, analysis and design*. Spon Press, Abingdon, Oxford, UK.

Venkatasubramanian, V., S. Rengaswamy, K. Yin, and S.N. Kavuri. 2003. A review of process fault detection and diagnosis part I: Quantitative model-based methods. *Computers and Chemical Engineering* 27(3): 293-311.

Venkatasubramanian, V., S. Rengaswamy, K. Yin, and S.N. Kavuri. 2003. A review of process fault detection and diagnosis part II: Qualitative models and search strategies. *Computers and Chemical Engineering* 27(3): 313-326.

Venkatasubramanian, V., S. Rengaswamy, K. Yin, and S.N. Kavuri. 2003. A review of process fault detection and diagnosis part III: Process history based methods. *Computers and Chemical Engineering* 27(3):327-346.

Wang, S., and J. Cui. 2006. A robust fault detection and diagnosis strategy for centrifugal chillers. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 12(3):407-427.

Ward, M., and J. Siegel. 2005. Modeling filter bypass: Impact on filter efficiency. *ASHRAE Transactions* 111(1):1091-1100.

Wichman, A. 2007. *Evaluation of fault detection and diagnosis methods for refrigeration equipment and air-side economizers*. Master's thesis. Ray W. Herrick Laboratories, School of Mechanical Engineering, Purdue University, West Lafayette, IN.

Wichman, A., and J.E. Braun. 2009. A smart mixed-air temperature sensor. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 15(1):101-115.

Willsky, A. S. 1976. A survey of design methods for failure detection in dynamic systems. *Automatica* 29:601-611.

Yang, H., and H. Li. 2010. A generic rating-data-based (GRDB) DX coils modeling method. *HVAC&R Research* (now *Science and Technology for the Built Environment*) 16(3):331-353.

Yu, B., and D.H.C. van Paassen. 2003. Fuzzy neural networks model for building energy diagnosis. *The Eighth International IBSPA Conference*, Eindhoven, Netherlands, August 11-14, pp. 1459-1466. Available at http://www.ibpsa.org\proceedings\CBS2003\BS03_1459_1466.pdf.

Related Commercial Resources