

Building as a Power Plant Proposed Control Architecture

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Abstract

Carnegie Mellon University (CMU), led by the Center for Building Performance and Diagnostics (CBPD) - a National Science Foundation Industry/University Cooperative Research Center - in close cooperation with the Advanced Building Consortium (ABSIC), is preparing the design of the Building as Power Plant (BAAP) on the CMU campus. The project anticipates to meet all of the building's energy needs for heating, cooling, power, ventilating and lighting on-site by the use of a decentralized combined heating and power plant. This will include a 250 kW Solid Oxide Fuel Cell (SOFC), steam turbine and absorption chiller/boiler technologies. In addition, advanced photovoltaic, solar, hot water and geo-thermal systems are to be integrated. This energy management integration goes far beyond the typical building control strategy requirements. A control architecture is proposed which will provide the necessary integration and provide intelligent monitoring and fault detection as well.

Keywords: building intelligent control architecture, fault detection, control system monitoring

Introduction

Nearly 40% of the energy in the USA is being consumed to heat, light, ventilate and cool buildings¹. The construction and operation of commercial buildings, which house approximately 50% of the American workforce, is estimated to require 25% of the nation's energy budget¹. Carnegie Mellon University (CMU), led by the Center for Building Performance and Diagnostics (CBPD) - a National Science Foundation Industry/University Cooperative Research Center - in close cooperation with the Advanced Building Consortium (ABSIC), is preparing the design of the Building as Power Plant (BAPP) on the CMU campus. BAPP is designed as a 6-story building comprising 64,175 sq.ft. [5,962 m²] which houses classrooms, studios, laboratories and administrative offices for the College of Fine Arts. The project anticipates meeting all of the building's energy needs for heating, cooling, power, ventilating and lighting on-site by the use of a decentralized combined heating and power plant. Improvements in operations within the operation of commercial office space would have an immense impact on the national energy budget. As a part of the BAPP project a control architecture that has the following objectives is envisioned⁵:

- Safe and smooth process operation
- Tight setpoint regulation in the face of disturbances
- Avoidance of unsafe process conditions
- Minimal operator attention
- Rapid response to set point changes or state transitions
- Minimize environmental damage
- Optimize energy consumption
- Fault detection for maintenance planning

The conceptual scheme for a building-integrated energy system is shown in Figure 1.

Conceptual scheme for the BAPP energy system

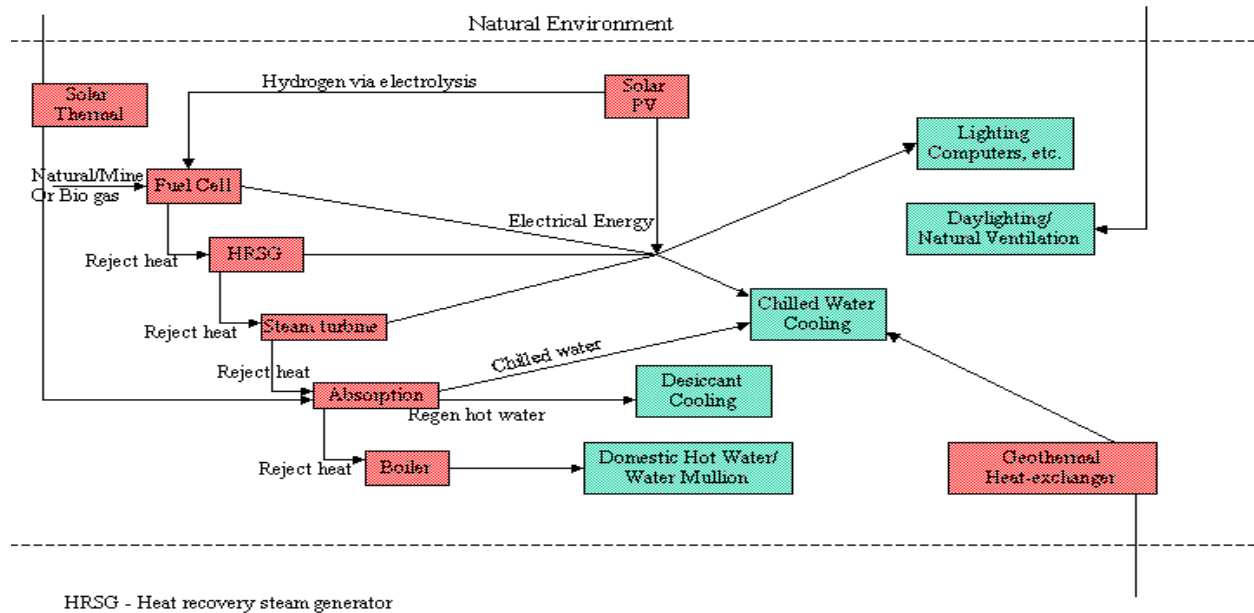


Figure 1 CMU Building As a Power Plant (BAPP) energy scheme

By inspection the four BAPP electrical energy sources (PV, fuel cell, HRSG, Steam turbine) must be coordinated with respect to the amount of electrical energy as well as thermal energy they produce. The paper is organized as follows: architecture design, building simulation, intelligent monitoring, control loop tuning, and predictive maintenance. The above chart summarizes the major elements of the architecture.

Control Architecture Design

A control architecture for a complex system should have the following objectives repeated from above:

- Safe and smooth process operation
- Tight setpoint regulation in the face of disturbances
- Avoidance of unsafe process conditions
- Minimal operator attention
- Rapid response to set point changes or state transitions
- Minimize environmental damage
- Optimize energy consumption
- Fault detection for maintenance planning

In order to achieve these objectives the control architecture must incorporate building simulation, intelligent monitoring, control loop tuning, and predictive maintenance. Figure 2 summarizes these areas. The control architecture must satisfy fundamental conservation of energy. It is more than simply combining control loops from individual units. A typical design procedure is: 1) establish control objectives, 2) determine manipulated and control variables at all levels, 3) establish energy management system (fundamental conservation of energy), 4) set performance measures in conjunction with safety and operational constraints, 5) determine on-line energy balances and performance criteria, 6) individual control at zone and unit levels, 7) establish sufficient flexibility to permit economic optimization and operational improvements. The subsystems to be controlled include heating, ventilating, and air conditioning (HVAC), power production, lighting, heat exchangers, air handlers, security, elevators, fire

detection, access control, irrigation control, and window blinds. The high energy consuming subsystems – HVAC, power production heat exchangers, and air handlers will have a unique BAPP flavor. These subsystems will require coordination and will become part of a multivariable control system.

Summary of the Control Architecture

- Simulation of Building for testbed for:
 - Control strategy
 - Operations testing
 - Fault detection (FD)
 - Intelligent monitoring and diagnostics
 - Verify sensor type and location
- Design of control architecture
 - Low level robust control loops
 - Supervisory Control
 - Real-time optimization
- Intelligent monitoring
 - Low-level sensor FD
 - Process FD to enable debottlenecking & energy shaving
 - High level energy consumption as health indicator
 - Drill down capability for diagnostics
 - Objective is to have high-level indicators that point to lower level faults requiring fewer operators
- Predictive Maintenance
 - Detect incipient faults before damage occurs to permit planned maintenance rather than break-down maintenance only
 - Analytical redundancy model-based procedures for drift & bias faults due to sensor or process faults
 - Statistical analysis for excessive noise or ‘dead’ sensor faults
 - Noninvasive vibroacoustic monitoring for rotating equipment
 - Sensor location for process & vibration monitoring

BAPP

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Figure 2 Important features of the BAPP Control Architecture

Building Simulation

A building simulation should be developed with sufficient fidelity to enable necessary software testing. The simulation will emulate the energy/mass balances that will exist in the BAPP as envisioned, so as to predict the building response due to various stimuli. The simulation will consist of a combination of 1st principles and empirical formulas based on ASHRAE guidelines and industrial convention. It should represent seasonal, daily, occupational, and weather-related disturbances to validate software algorithm robustness at all control levels. The simulation may evolve into several versions depending on how extensive hardware-in-the-loop testing becomes necessary. After initial algorithm design it may be used for operational studies to help optimize performance, reduce energy consumption, operator training, root-cause diagnostic studies, and enhance reliability. It should also be designed to aid in operator training and testing of state transition procedures such as start-up, shutdown, heating-to-cooling, cooling-to-heating, and emergency procedures.

Intelligent Monitoring

Intelligent control monitoring systems must not only provide data to a central bus; it must provide a tool for process improvement, debottlenecking, economic analysis, and root cause diagnostics. Intelligent monitoring is the main mechanism to allow automatic operation and reduce operator workload. Its components include sensor/process fault detection, energy shaving, drill down capability, and health indicators. Energy shaving will require accurate measurements; hence, on-line sensor fault detection is a component of monitoring. At the highest level energy management may be represented by changes in exergy⁵, which is based on entropy, internal energy, and volume

changes throughout the system. Exergy is defined as ‘the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes⁵.’ Exergy and other energy indicator parameters will be computed and recorded throughout the system to track energy consumption. This will permit economic calculations, debottlenecking and system tuning. From a control standpoint, minimum exergy destruction or loss is a major optimization objective. Another useful approach to energy optimization is pinch technology¹⁰, which is based on composite temperature vs. enthalpy analysis. By using such analysis the operator may keep track of energy flows and highlight losses. If there is an anomaly the operator may further investigate. Pinch technology has been developed as a method of identifying energy savings by the use of composite temperature-enthalpy curves and these ideas will be incorporated into the monitoring strategy.

Control Loop Tuning

The BAPP concept of adaptive individual control alternatives allows for continuous reconfiguration of thermal zones and controllers that even allows individual rezoning and control². Several competing alternatives for temperature control include²: 1) separate thermal conditioning and ventilation systems, 2) mixing control of cool supply air with warmer room air, and 3) additional water or air-based heating or cooling components. Separating ventilation and thermal regulation requires that another constituent [CO₂ or volatile organic carbons (VOC)] be regulated. The ventilation air not only will be regulated, but the temperature control loop will be separately applied to the thermal system. Humidity control strategies have not been fully addressed². The online reconfiguration requirement places additional stress on the capability of the typical proportional-integral-derivative (PID) digital control loops. As the number of necessary feedback control loops increase there is added stress on the control system in the area of tuning. Figure 3 shows a typical control block diagram for a low level zone.

Control Loops for low level zone control

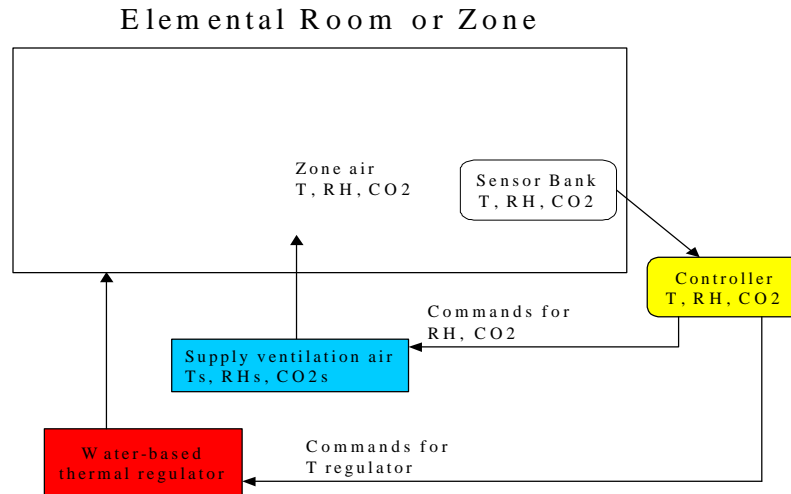


Figure 3 Control strategy for a low-level zone

Control options for PID algorithms include autotuning and adaptive. Many strategies for PID loop autotuning³ have been developed over the past three decades. When autotuning is performed, an extra loop is introduced. This loop consists of a process identification scheme and a design procedure that computes the PID parameters. An additional perturbation signal may be added to ensure proper excitation of the process. Tuning is based on either closed loop or open loop transient response analysis. Most methods use either step or impulse responses. The PID gains are

An approach has been shown toward developing intelligent building control architectures. There are significant challenges in low-level, unit level, and supervisory control, monitoring and fault detection. As the building simulation and control architecture is developed these areas will be addressed. Further studies will be necessary to improve control systems and monitoring at all levels.

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