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COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Building End Use Energy Efficiency

**CONTROL OF ON-OFF EQUIPMENT IN
BUILDINGS**

FEASIBILITY ANALYSIS

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Gray Davis, Governor

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which \$2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to \$75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:

<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049 or email

eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at

<http://www.energy.ca.gov/research/index.html>.

Executive Summary

Introduction

Equipment used to control process variables such as temperature in buildings often operate by cycling on and off (or between stages if more than one “on” state) rather than as continuously modulating. Examples of such equipment include small to mid-sized packaged air-conditioning systems, furnaces, chillers operating at low loads, cooling tower fans, and some types of electrical heaters. On-off control units normally start and stop equipment when the process variable (e.g., space temperature) crosses a level. There are a number of disadvantages to using level-crossing logic. One disadvantage is that it is difficult to control the variation in the process variable with level-crossing logic, even if it is implemented digitally, because of the phase lag of the process. Another disadvantage is that level-crossing logic is not well suited for staged operation in which there exists more than one “on” state. A third disadvantage of level-crossing logic is that it makes the coordination of multiple units difficult.

This project developed and tested the feasibility of a new control strategy for the operation of "on-off" and staged equipment in buildings using computer simulation methods. Specifically, it developed the control logic so that it could be used to coordinate the operation of multiple units, and compared the performance of the new strategy with level-crossing logic. This technology was proposed as a means of reducing the energy consumption of HVAC equipment by reducing the frequency of start-stop operations. If the hourly start-stop cycling is reduced by two-thirds, the coefficient of performance of vapor compression equipment is raised an estimated 10%. The corresponding improvement for non-electric heating equipment efficiency is estimated at 6%.

This project applied pulse-width modulation (PWM) logic and a finite state machine to start and stop individual units. This control software was combined with a model of the heat transfer dynamics of a building and a transient model of HVAC equipment to study the performance of the new strategy and compare it to alternative strategies.

The metrics used to assess performance were energy consumption, peak demand, thermal comfort, and maintenance cost. The variability of the space temperature was used as a proxy for thermal comfort. Start-stop operations were used as a proxy for maintenance cost.

Objectives

The goal of this project was to determine the feasibility of reducing the energy consumption of HVAC equipment by reducing the frequency of start-stop operations. This was to be achieved by use of a newly developed control logic to coordinate the operation of multiple HVAC sub-systems. The following project objectives were established:

1. Develop new control software for operating energy-intensive, on-off, or staged equipment in buildings by adapting existing concepts for designing pulse-width modulation logic and finite state machines to this application.
2. Perform a computer simulation analysis of the performance of the control software to determine whether or not the new control strategy has energy, thermal comfort, or maintenance benefits relative to existing methods of operating this equipment.
3. Assess the change in energy efficiency as a result of the change in start-stop operations of vapor compression equipment with a target of 13% improvement, and non-electric heating equipment with a target of 6% improvement.
4. Maintain occupant thermal comfort levels.

Outcomes

1. The control software development yielded code that could be used to operate a wide variety of staged HVAC equipment in buildings.
2. The computer simulations determined that the proposed control logic had no beneficial impact on overall energy consumption, thermal comfort or maintenance costs.
3. The new control logic increased the frequency of start and stop operations by 27%.
4. The new control logic increased the size of the deviation from the space temperature set point by 11%
5. An unanticipated outcome was the discovery that the new control logic combined with an optimized coordinator could load-level the power consumption of HVAC equipment, reducing excursions by 20% relative to level-crossing logic.

Conclusions

1. Commercialization would involve control software development. The existing code would have to be adapted to a particular platform, but no hardware would be required as long as there was an existing control communication system in place so that a coordinator running on a networked computer could supervise a number of HVAC control units.
2. Using the proposed metric for equipment efficiency, the 27% increase in frequency of start-stop operations corresponds to an estimated seven percent (7%) decrease in coefficient of performance of vapor compression equipment and a greater than one percent (1%) decrease in non-electric heating equipment efficiency.
3. Equipment manufacturers are sensitive to the increased warranty risks due to increased on-off cycling.
4. Equipment installers may be reluctant to utilize this control logic because weaker temperature and humidity control may result in decreased comfort levels.
5. For commercial businesses with high power consumption the cost of power consumed during peak generation periods is high. Using the software control logic developed by this project to level the demand load during peak periods may save on energy costs associated with exceeding a billing rate threshold but any savings may be offset by increased energy consumption, higher maintenance and lower thermal comfort.

Benefits to California

This project proposed the benefit of increased HVAC equipment efficiency derived from reduced on-off cycling. It discovered that PWM control strategy did not achieve this desired result. While the feature of load leveling by PWM control is an interesting development of this study, it is unclear to what extent California might benefit from this secondary result.

Recommendations

Additional work is needed to investigate whether or not it is possible to provide energy benefits from the new strategy and to reduce the maintenance penalty. It is possible that by operating the PWM signals asynchronously and at different frequencies the maintenance penalty could be reduced. Asynchronous operation may also yield additional energy benefits. Asynchronous operation would increase the complexity of the design of the control logic, though not necessarily the complexity of its implementation.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: <http://www.energy.ca.gov/research/innovations> and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop- ment	5 Product Develop- ment	6 Demon- stration	7 Market Transfor- mation	8 Commer- cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator’s assessment was based on the following supporting details:

Marketing/Connection to the Market

There has been no activity in this area other than investigating opportunities for continued funding. To date, efforts to secure additional funding have been unsuccessful.

Engineering/technical

The idea generation was fairly mature when the proposal was first written. Additional ideas extending the original technical concepts include considering asynchronous coordination, where units do not cycle on and off at a fixed period. This approach may solve some of the drawbacks of the approach that was tested including increased temperature variance and increased number of starts and stops.

Technical analysis included reviewing the open literature for related innovations and testing the concept with computer simulation methods. This analysis and research resulted in graphs and software that could serve as the starting point for technology development

Legal/Contractual

There has been no activity in this area.

Environmental, Safety, Risk Assessments/ Quality Plans

This project recognized the need to study the impact of the innovation on temperature control performance (variation from set point), and on start-stop frequency. Technical analysis and research included these metrics because they will be important to facility managers and equipment manufacturers. Initial drafts of the following Quality Plans are needed prior to initiation of Stage 4 development activity; Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization

There has been no activity in this area.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

Based on our interpretation of the information provided in Appendix A, there is no clear public benefit derived from this project's research results.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

**ENERGY INNOVATIONS SMALL GRANT
(EISG) PROGRAM**

EISG FINAL REPORT

CONTROL OF ON-OFF EQUIPMENT IN BUILDINGS

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

TABLE OF CONTENTS

Abstract	1
Executive Summary	2
1 Introduction	4
2 Project Approach	5
2.1 Control Logic and Optimization.....	5
2.1.1 Pulse-Width Modulation Logic	5
2.1.2 State Charts	8
2.1.3 Demand Minimization by Coordination	8
2.1.4 Other Control System Components	9
2.2 Computer Simulations	9
2.2.1 HVAC System and Building Model	9
2.2.2 Numerical Integration Details	12
2.2.3 Benchmarks and Performance Metrics	12
2.2.4 Simulation Conditions	13
3 Project Outcomes	15
3.1 Control Software.....	15
3.1.1 Pulse-Width Modulation Logic	15
3.1.2 State Charts	18
3.2 Computer Simulations	20
4 Conclusions and Recommendations	22
4.1 Conclusions	22
4.2 Commercialization Potential.....	23
4.3 Recommendations.....	23
4.4 Benefits to California	23
5 Development Stage Assessment	23
5.1 Marketing.....	24
5.2 Engineering/Technical	24
5.3 Legal/Contractual	24
5.4 Risk Assessment/Quality Plans	24
5.5 Strategic	24
5.6 Production Readiness.....	24
5.7 Public Benefits/Costs	24
6 References	25

Abstract

This project researched new control logic for starting and stopping energy-intensive equipment in buildings such as staged air-conditioning units. The concept is to use pulse-width modulation (PWM) instead of level-crossing logic. A finite state machine is used to handle the case where a single unit has multiple stages of operation. An optimized coordinator determines the phase of the PWM signals of each unit so that peak demand for power is minimized over each PWM period. Control logic for the PWM function was developed so that the phase could be manipulated by the coordinator. Computer simulations were used to assess the performance of the new strategy and to compare it to level-crossing logic. The following five metrics were used to assess the performance: 1) magnitude of the control error, 2) start/stop frequency, 3) average power consumption, 4) standard deviation of the power consumption, 5) peak power consumption. The computer simulations showed that the new strategy could reduce peak power consumption by 20% relative to level-crossing logic. The computer simulations also showed that the new strategy increased the magnitude of the space temperature control error by 11% and increased the number of start/stop operations by 27% relative to level-crossing logic.

Key Words:

Coordination, control, equipment, demand, energy, optimization, scheduling

Executive Summary

Equipment used to control process variables in buildings such as temperature is often designed to be operated by cycling on and off (or between stages if more than one “on” state) rather than as continuously modulating. Examples of such equipment include small to mid-sized packaged air-conditioning systems, furnaces, chillers operating at low loads, cooling tower fans, and some types of electrical heaters. On-off control units normally start and stop equipment when the process variable (e.g., space temperature) crosses a level. There are a number of disadvantages to using level-crossing logic. One disadvantage is that it is difficult to control the variation in the process variable with level-crossing logic, even if it is implemented digitally, because of the phase lag of the process. Another disadvantage of is that level-crossing logic is also not well-suited for staged operation in which there exists more than one “on” state. A third disadvantage of level-crossing logic is that it makes the coordination of multiple units difficult.

The overall goal of this project was to develop and test the feasibility of a new control strategy for the operation of on-off and staged equipment in buildings using computer simulation methods. Specific goals were to develop the control logic so that it could be used to coordinate the operation of multiple units, and to compare the performance of the new strategy with level-crossing logic.

The approach was to use pulse-width modulation (PWM) logic and a finite state machine to start and stop individual units. This control software was combined with a model of the heat transfer dynamics of a building and a transient model of HVAC equipment to study the performance of the new strategy and compare it to alternative strategies.

The metrics used to assess performance were energy consumption, peak demand, thermal comfort, and maintenance cost. The variability of the space temperature was used as a proxy for thermal comfort. Start-stop operations are used as a proxy for maintenance cost.

This project had two basic objectives. The first was to develop new control software for operating energy-intensive, on-off or staged equipment in buildings. Existing concepts for designing pulse-width modulation logic and finite state machines were adapted to this application.

The second objective was to perform a computer simulation analysis of the performance of the control software. The question to be answered was whether or not the new control strategy has energy, thermal comfort or maintenance benefits relative to existing methods of operating this equipment.

The control software development yielded code that could be used to operate a wide variety of staged HVAC equipment in buildings. The resulting PWM logic enabled the use of coordination logic that could be used to reduce peak demand.

The computer simulations showed that the new control logic combined with a optimized coordinator could reduce peak demand for power by 20% relative to level-crossing logic. This result was achieved by reducing the variability of the power consumption. However, the new control logic also increased the size of the deviation from the space temperature setpoint by 11% and increased the frequency of start and stop operations by 27%.

The new control strategy has the potential to reduce energy costs for end users. Commercialization would involve primarily control software development. The existing code would have to be adapted to a particular platform, but no hardware would be required as long as there was an existing control communication system in place so that a coordinator running on a networked computer could supervise a number of HVAC control units.

Equipment manufacturers may be resistant to commercializing the new strategy because of the increase in start-stop operations. Equipment manufacturers are sensitive to warranty risks. Control system vendors may be less sensitive to warranty risks in some cases.

Additional work is needed to investigate whether or not it is possible to maintain the energy benefits of the new strategy while reducing the maintenance penalty. It is possible that by operating the PWM signals asynchronously and at different frequencies the maintenance penalty could be reduced. Asynchronous operation may also yield additional energy benefits. Asynchronous operation would increase the complexity of the design of the control logic, though not necessarily the complexity of implementing it.

If the new control strategy were widely deployed in California, end users would benefit by paying less for electrical power. The reduction would be derived primarily from the reduction in the peak demand for power. The amount of cost reduction would depend on specific details of the end user's utility contract. The greatest cost savings would be derived during part-load months when coordination of the loads can have the greatest impact on the peak demand.

1 INTRODUCTION

Equipment used to control process variables in buildings such as temperature is often designed to be operated by cycling on and off (or between stages if more than one “on” state) rather than as continuously modulating. Examples of such equipment include small to mid-sized packaged air-conditioning systems, furnaces, chillers operating at low loads, cooling tower fans, and some types of electrical heaters. In U.S. commercial buildings, approximately 2.2 quadrillion Btu of primary electrical consumption (30% of the total) can be attributed to on-off and staged electrical devices (EIA, 1998). Consumption for California is roughly one-eighth of the U.S. consumption. An equally large quantity of energy is consumed by on-off equipment in residential buildings. On-off equipment is so prevalent in buildings that even modest improvements in efficiency can have a tremendous cumulative effect on reducing energy consumption.

On-off control units normally start and stop equipment when the process variable (e.g., space temperature) crosses a level. The advantage of using level-crossings to trigger operation is that the control logic is extremely simple. However, there are a number of disadvantages. One disadvantage is that it is difficult to control the variation in the process variable with level-crossing logic, even if it is implemented digitally, because of the phase lag of the process. Even if the differential between the levels that trigger the on and off events is very small, the variation in the process variable may be large because of the lag or delay between the action of the controller and its effect on the process. This lag differs from one installation to another, which further complicates the problem.

Another problem is that level-crossing logic is also not well-suited for staged operation in which there exists more than one “on” state. One approach to operating staged units with level-crossing logic is to choose a different set of on-off levels for each stage. This is essentially proportional-only control action. Proportional-only control action leads to offset; the process variable increases or decreases with the load. For air-conditioning systems, this is undesirable for comfort and humidity control. It also is difficult to select the appropriate difference between the levels for each stage because of the inherently oscillatory nature of on-off systems even when they are tuned properly. If the sets of on-off levels for each stage are too close, then the unit will short-cycle, which wastes energy. Discriminating between short-cycling and normal cycling takes time and expertise. The fact that each installation is different complicates the problem even further.

An alternative method to using different on-off levels for each stage is operate the stages based on the output of a proportional-integral-derivative (PID) controller. If the integral gain is not zero, then this eliminates the problem of offset. However, it is more difficult to tune this kind of control system because there are now at least two parameters that must be chosen instead of just one.

The objective of this project is to develop and test the feasibility of a new control strategy for the operation of on-off and staged equipment in buildings using computer simulation methods. The performance metrics used to determine whether or not the objective has been met are energy consumption, peak demand, thermal comfort, and maintenance cost. Energy consumption and peak demand are derived from the equipment model. Thermal comfort is assessed by comparing the variability of the space temperature. Start-stop operations are used as a proxy for maintenance cost.

2 PROJECT APPROACH

The project involved the development of computer-based models of control system components (state machine logic and pulse-width modulation logic), HVAC equipment, and building heat transfer, and the use of these models to study how an alternative method of starting and stopping equipment affects energy usage. This section describes the development of the models and their use in computer simulations.

2.1 Control Logic and Optimization

2.1.1 Pulse-Width Modulation Logic

Pulse-width modulation (PWM) is a technique for continuously modulating a process that has binary input states. It is commonly used for motion control problems involving DC motors and is sometimes used for controlling flow with solenoid valves. The input is switched rapidly between two states, and the fraction of the time that input is in the “on” state determines the fraction of input effort applied to the process.

For most PWM applications, the frequency of the PWM signal is high compared to the control bandwidth, so the PWM residual in the process output is very small. When using PWM signal with electro-mechanical devices such as compressors or fans, the PWM signal cannot be high because these devices cannot be cycled on and off frequently. Since the PWM frequency must be low, the PWM residual will be significant. Since the PWM frequency must be low, there is an opportunity to use the phase of the PWM signal to control the demand for power.

We developed capacity control logic that uses pulse-width modulation (PWM) and level-crossing logic. The PWM logic was designed so that the phase could be manipulated by a controller. The code was implemented in Matlab as an m-file. The syntax for Matlab m-files is similar to C.

Figures 2-4 show examples of PWM signals that can be produced. The PWM signals in these figures have a PWM period of 30 minutes. The first figure shows a PWM signal with a phase of zero and a duty cycle of 25%. The second figure shows a PWM signal with a phase of 10 minutes and a duty cycle of 50%. The third figure shows a PWM signal with a phase of 20 minutes and a duty cycle of 50%. The third figure shows that when the phase gets sufficiently high, the signal “wraps around” so that the “end” of the pulse is at the beginning of the period and the beginning of the pulse is at the end of the period.

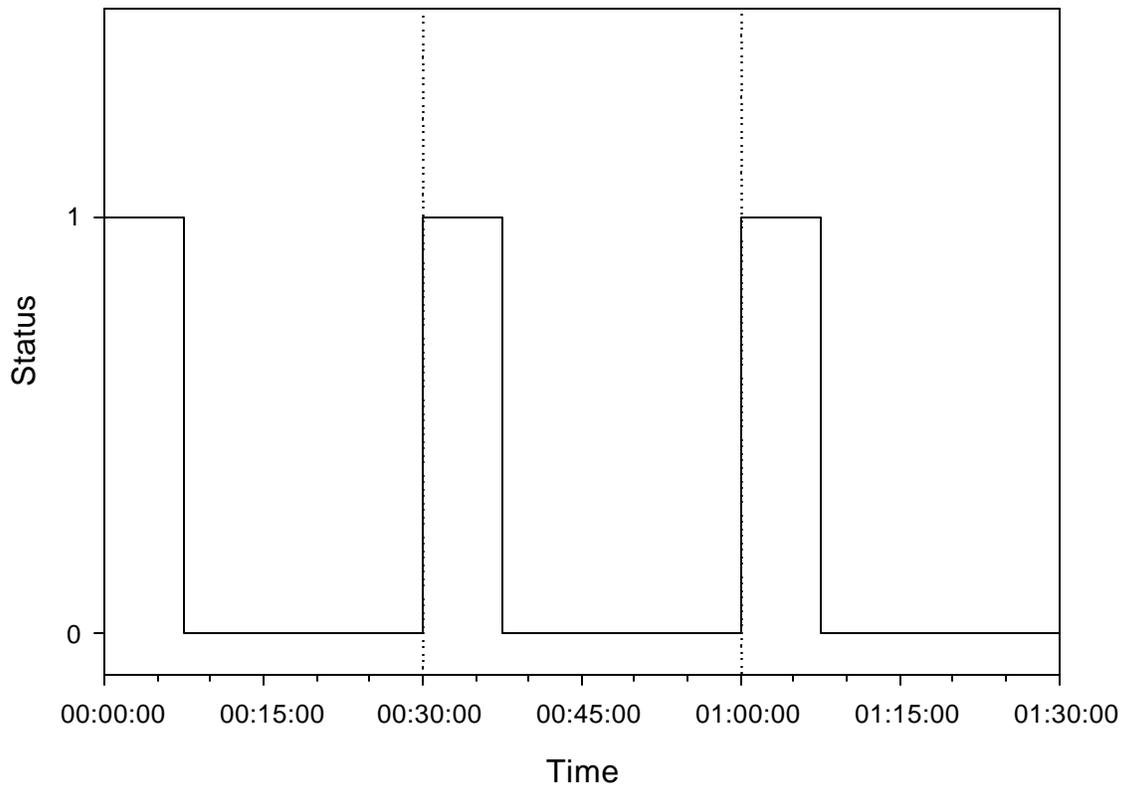


Figure 2-1: PWM signal with 30 minute period, 25% duty cycle and zero phase.

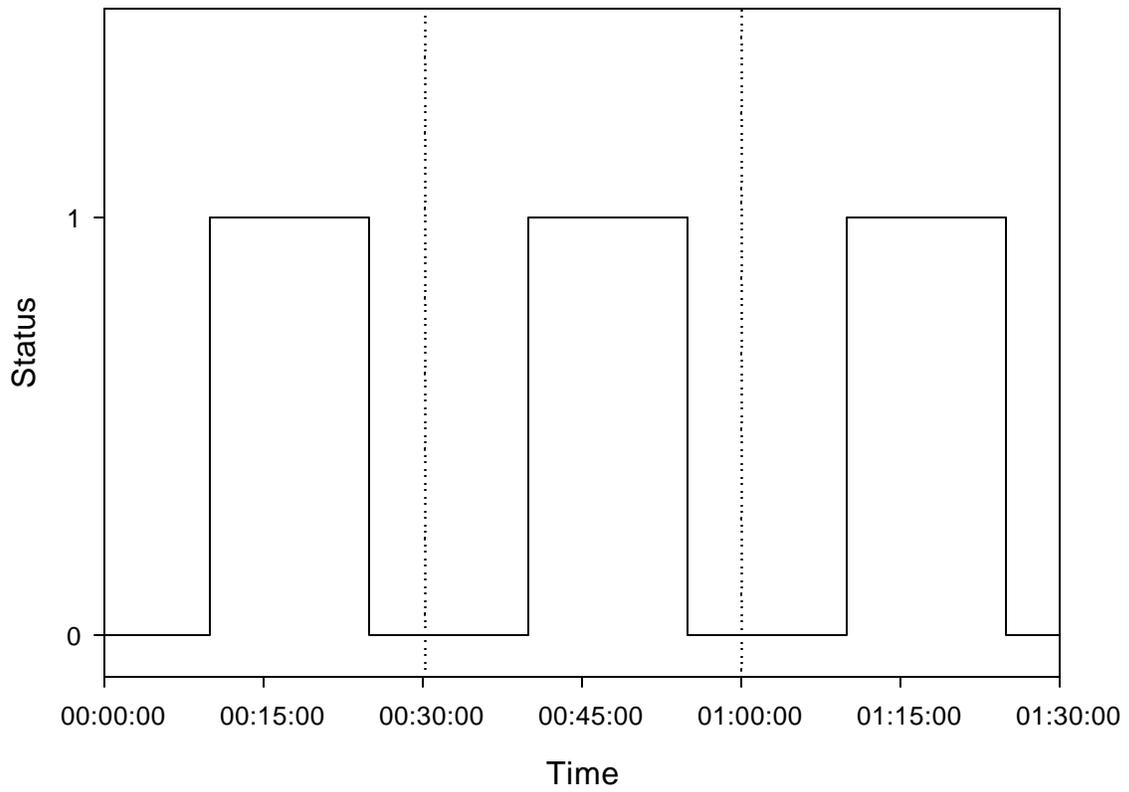


Figure 2-2: PWM signal with a period of 30 minutes, a duty cycle of 50%, and a phase of 10 minutes.

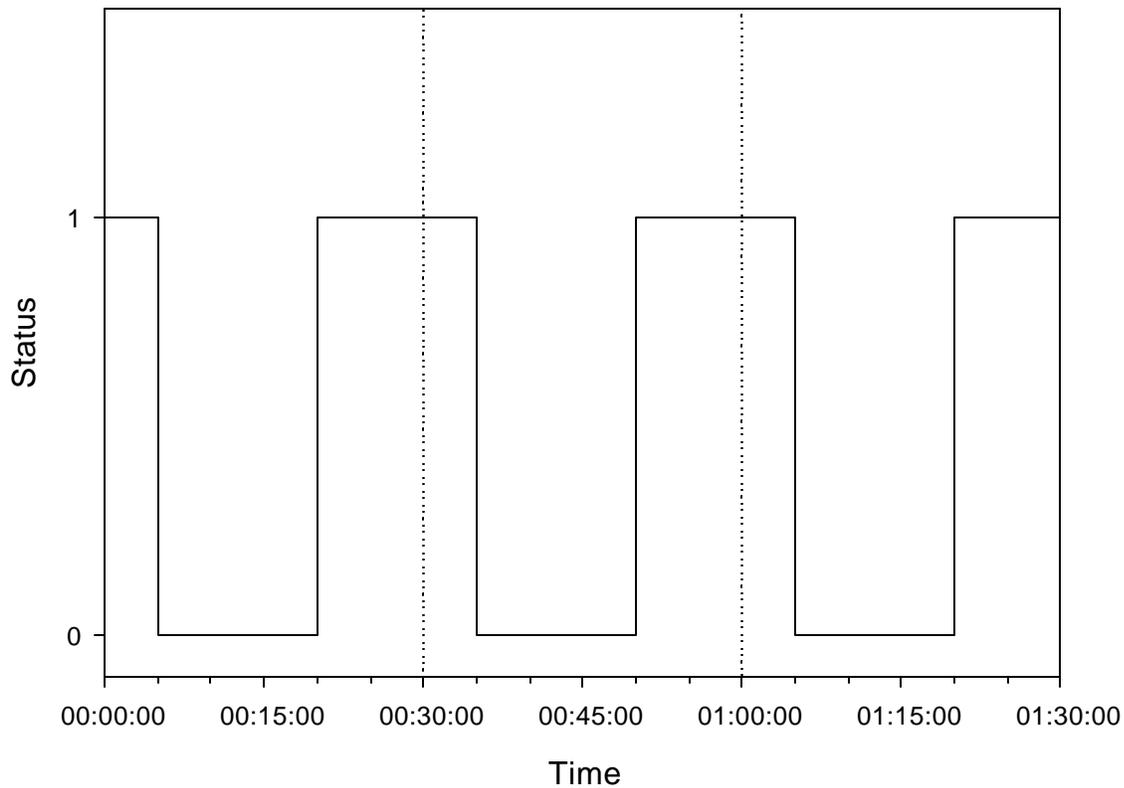


Figure 2-3: PWM signal with a period of 30 minutes, a duty cycle of 50%, and a phase of 20 minutes.

2.1.2 State Charts

We developed state charts and associated software so that we could simulate the operation of staged HVAC systems. This method of designing control logic for HVAC systems has been proposed by Seem et.al. (1999) for the operation air-handling controls. We chose to model the behavior of systems with two stages of mechanical cooling, an economizer, and four stages of heating based on personal interviews with representatives from HVAC control companies.

2.1.3 Demand Minimization by Coordination

A primary advantage of using PWM signals to start and stop equipment is that the phase of the PWM signal can be manipulated to improve the cumulative energy consumption characteristic of a number of systems. We developed a strategy for determining the optimal phase values every PWM period for a set of systems using PWM logic for starting and stopping equipment. That strategy is described below.

The optimal phase for reducing peak power was calculated using a grid search. The resolution of the grid corresponds to the time resolution of the computer simulation. The combination of phase values that minimizes peak demand for power is not unique, so we selected the phase values that minimize peak demand for power and that minimize the phase change from the previous PWM period.

2.1.4 Other Control System Components

In addition to the state machine logic and the pulse-width modulation logic, the system included a proportional plus integral (PI) controller and a moving average filter. The PI controller was tuned by first selecting the controller gains using the Ziegler-Nichols step response method and then fine-tuning the gains by hand.

A moving-average filter was added to the feedback loop to eliminate the residual from the PWM signal. When using PWM signals to control electro-mechanical devices such as compressors or fans the cycling frequency must be low or the equipment may be damaged. This means that there is always a significant residual in the controlled variable due to the operation of the PWM function. A moving average filter with a filter length equal to the PWM period will exactly cancel the residual. Canceling the PWM residual will ensure that the PI controller does not respond to the PWM residual. It also makes it easier to tune the PI controller.

2.2 Computer Simulations

2.2.1 HVAC System and Building Model

In order to test the control logic, we developed a mathematical model of the heat transfer dynamics of a section of a building and reduced the mathematical equations to Matlab code.

The HVAC system model consists of equations for the heat and mass transport through an air distribution system and equations describing the behavior of heating and cooling equipment. Figure 2-4 shows a schematic diagram of the HVAC system. The system consists of a five ducts for outdoor air, supply air, return air, exhaust air, and recirculation. The system has a supply fan and a return fan. Heating and cooling is provided in the supply duct.

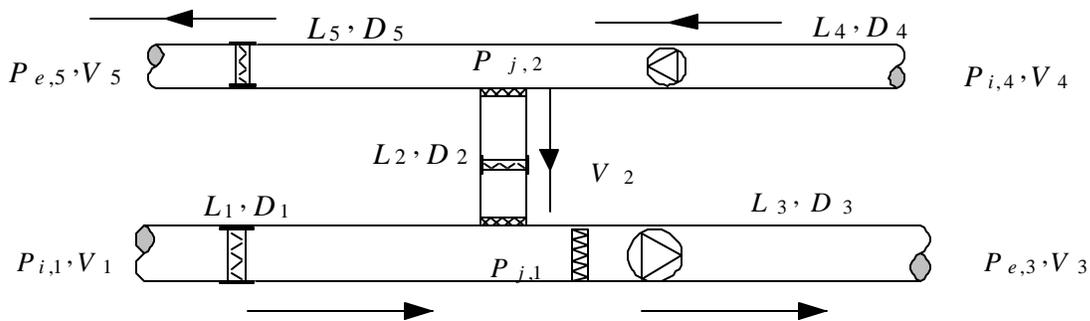


Figure 2-4: Schematic diagram of HVAC system

The transient behavior of the system includes the energy transport throughout the distribution system and the momentum transport (acceleration and deceleration of air and fan wheels). The momentum transport is important because the settling time of the air velocities after starting or stopping the fans is comparable to the minimum on-time and minimum off-time for compressors (1-5 minutes).

The momentum equations are as follows:

$$M\dot{V} = -F\langle V|V\rangle - K\langle V|V\rangle + A_f P_f + A_e P_e + A_j P_j \quad (1)$$

In Equation 1, M is a diagonal mass matrix, V is a vector of velocities in each branch, F is a matrix containing the friction factors in each branch of the air distribution system, K is a matrix containing the minor loss coefficients, A_f is a matrix of cross-sectional areas at each fan location, P_f is the static pressure across each fan, A_e is the cross-sectional duct areas at the points where the system connects of external points such as the outdoors or indoor spaces, P_e are the external pressures (outdoors or indoors), A_j is a matrix describing the areas at the junctions of the air distribution system, and P_j is a vector of pressures at each junction. The quantity $\langle V|V\rangle$ is a vector whose elements are the product of the velocity times its magnitude.

At each junction there is a mass continuity constraint that can be expressed as follows:

$$-A_j^T V = 0 \quad (2)$$

The pressure at each junction can be computed explicitly by differentiating the constraint equation and substituting the state equation. The result is as follows:

$$P_j = (A_j^T M^{-1} A_j)^{-1} A_j^T M^{-1} [(F + K)\langle V|V\rangle - A_f P_f - A_e P_e] \quad (3)$$

For the system shown in Figure 2-4, the system coefficients are as follows. The mass matrix, M , is a diagonal matrix where $M_{i,i} = \rho A_i L_i$. The duct friction matrix, F , is a diagonal matrix where

$F_{i,i} = \rho D_i L_i f_i / 8$. $\langle V|V\rangle$ is a vector where the i th element is $V_i |V_i|$. The minor loss matrix is a

diagonal matrix where $K_{i,i} = A_i \rho K_i / 2$. The joint pressure vector is $P_j = [P_{j,1} \quad P_{j,2}]^T$. The external

pressure vector is $P_e = [P_{o,1} \quad P_{o,3} \quad P_{i,4} \quad P_{o,5}]^T$. The fan pressure vector is $P_f = [P_{f,3} \quad P_{f,4}]^T$. The

joint area matrix, the external pressure area matrix, and the fan area matrix are as follows:

$$A_j = \begin{bmatrix} -A_1 & 0 \\ -A_2 & A_2 \\ A_3 & 0 \\ 0 & -A_4 \\ 0 & A_5 \end{bmatrix} \quad A_e = \begin{bmatrix} A_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & A_3 & 0 & 0 \\ 0 & 0 & A_4 & 0 \\ 0 & 0 & 0 & A_5 \end{bmatrix} \quad A_f = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ A_3 & 0 \\ 0 & A_4 \\ 0 & 0 \end{bmatrix}$$

Equations 1-3 describe the momentum equations for the air in the HVAC ducts. The fan wheels also have a significant amount of momentum that affects the dynamic behavior. For each fan, the momentum equation is as follows:

$$J\dot{\mathbf{w}} = \mathbf{t}_m - \mathbf{t}_a \quad (4)$$

where J is the moment of inertia of the fan wheel, \mathbf{w} is the speed of the fan wheel, \mathbf{t}_m is the torque exerted by the motor on the fan wheel, and \mathbf{t}_a is the torque exerted by the air on the fan wheel. We modeled an AC motor with the following torque-speed relationship:

$$\mathbf{t}_m = \begin{cases} \mathbf{t}_{\max}, & \mathbf{w} \leq \mathbf{w}_L \\ \frac{\mathbf{t}_{\max}}{\mathbf{w}_L - \mathbf{w}_r} + \mathbf{t}_{\max} \frac{\mathbf{w}_r}{\mathbf{w}_r - \mathbf{w}_L}, & \mathbf{w} \geq \mathbf{w}_L \end{cases} \quad (5)$$

The torque-speed characteristic is constant when the speed is below \mathbf{w}_L . Above \mathbf{w}_L the torque is proportional to the speed, decreasing with increasing speed. The torque-speed characteristics of real AC motors are more complex than predicted by this model, but this model captures the most relevant features for this application.

The momentum transport equations use standard, steady-state fan models to relate fan speed and air velocity to the static pressure across the fan wheel and the efficiency of the fan. We use a model that has been used for in other simulation environments such as HVACSIM+ (Park et al., 1986). The non-dimensional pressure coefficient is a polynomial function of the non-dimensional speed, and the efficiency is also a polynomial function of non-dimensional speed. Outside of the normal operating range, we use extrapolation functions proposed by Haves and Norford (1998). The non-dimensional pressure is a quadratic function of the non-dimensional speed, and the efficiency is constant.

We model the dynamic behavior of the heating and cooling components by assuming the coefficient of performance has a first-order transient response characteristic. We used time constants of 1.5 minutes for both heating and cooling. These values were derived from the experiments reported by Mulroy (1986).

Energy transport in ducts was modeled by assuming perfect mixing in each branch of the distribution system. The energy transport equations have velocity variables that have only a positive sign that is dependent on the sign of the velocities in the branches. This technique makes it easy to model the energy transport even if the flow in one or more branches reverses direction.

The building model includes heat accumulation by walls, indoor air, and furniture, and the dynamic behavior of the space temperature sensor. Time-dependent internal loads and external temperatures were used to simulate real disturbances. The building section was modeled as a single room with one exterior wall.

The wall was modeled as a three-layer slab. The heat accumulation for a layer is as follows:

$$\mathbf{r}_l V_l C_l \dot{T}_l = h_l A_l (-T_l + T_{a1} + T_{a2}) \quad (6)$$

where ρ_l is the density of the layer, V_l is the volume of the layer, C_l is the specific heat of the layer, T_l is the temperature of the layer, h_l is the heat transfer coefficient, A_l is the surface area of the layer, and T_a is the temperatures with which the layer exchanges heat. The values of T_a may come from adjacent layers or the indoor or outdoor temperatures. The heat transfer coefficients may differ from one layer to another and from one surface to another.

Furniture and other indoor furnishings accumulate a significant amount of heat. The model we used assumes that all of the heat transfer with the furniture is my convection with the indoor air. The equation for the heat accumulation of the furniture is as follows:

$$\rho_f V_f C_f \dot{T}_f = h_f A_f (-T_f + T_a) \quad (7)$$

where T_a is the indoor air temperature.

The heat accumulation of the air in the space is as follows:

$$\rho_a V_a C_{p,a} \dot{T}_a = f C_{p,a} (T_s - T_a) - h_f A_f (-T_f + T_a) - h_w A_w (-T_w + T_a) \quad (8)$$

Only sensible heat transfer was modeled. The first term on the right-hand side of Equation 8 is advection due to air supplied by and exhausted to the HVAC system. The second term is heat transfer between the furniture and the air. The third term is heat transfer between the inner wall layer and the air.

The reading from the space temperature sensor normally lags the actual temperature by several minutes. We modeled this lag using as a first-order, linear, time-invariant transfer function with a time constant of 7.5 minutes.

2.2.2 Numerical Integration Details

We used Matlab to simulate the dynamic behavior of the system. Matlab has several built-in numerical integration methods. We used `ode45()`, which is a fourth-order Runge-Kutta algorithm with adaptive step size control. Runge-Kutta is an explicit numerical integration method, so it is slow when used with stiff systems. Our model contains a combination of relatively fast dynamics associated with momentum transport and equipment behavior, and relatively slow dynamics associated with building heat transfer. The result was that the simulations ran slowly, about 10 times as fast as real time.

The `ode45()` function has a feature that enables the solver to integrate from event-to-event. We used this feature to force the solver to integrate up to each starting or stopping event. We also used it to produce periodic outputs of important variables.

The control logic code and system model code was designed as modules representing distinct components of the system. This modularity makes it easy to test and modify component models. Each component was an m-file. For the HVAC system and building dynamics components, the m-file returned the differential values of the state variables associated with that component. A separate file was used to assemble the entire state equation and pass it to the ODE solver.

2.2.3 Benchmarks and Performance Metrics

As a performance benchmark, we used PWM signals with constant-delayed phase. The constant-delayed phase signals are delayed by a uniform fraction of the PWM period. For example, if there were three systems operating with a period of 30 minutes, then the first system of a constant-delayed set would have a phase of zero minutes, the second system would have a phase of 10 minutes, and the third system would be operated with a phase of 20 minutes. This strategy is extremely simple, and minimizes peak demand under some, but not all, conditions.

Simple thermostats use level-crossing logic for starting and stopping equipment, so we included level-crossing logic as a benchmark. To avoid rapid cycling caused by noise or high-frequency disturbances, the level-crossing logic contained a differential. We defined the setpoint as the average of the upper and lower level, and the differential as the magnitude of the difference between the setpoint and one of the levels.

We used five metrics to compare the performance of the three start-stop methods. The first is the mean absolute deviation of the space temperature from setpoint. This metric is a standard control performance metric, and is a proxy for thermal comfort, since large temperature swings from a desired temperature should be associated with discomfort. We used the number of start and stop events per hour as a proxy for maintenance cost. If the controls force the units to start and stop more frequently they will fail sooner. We used average power, the standard deviation of the power, and the peak demand for power as energy performance metrics.

2.2.4 Simulation Conditions

We simulated one week of wintertime operation of three HVAC systems conditioning three independent spaces. Each space had 1500 square feet of floor area. Typical meteorological year (TMY) data from Sacramento California were used to simulate outdoor conditions. Figure 2-5 shows the outdoor temperatures used for the simulation. Internal loads were simulated using the profiles shown in Figure 2-6. Each system operated at a different setpoint. The values we used were 21.9 °C, 22.4 °C, and 23.1 °C for systems 1-3, respectively. For the simulations using PWM logic, the PWM period was 30 minutes. The level-crossing logic had a differential of 1 °C.

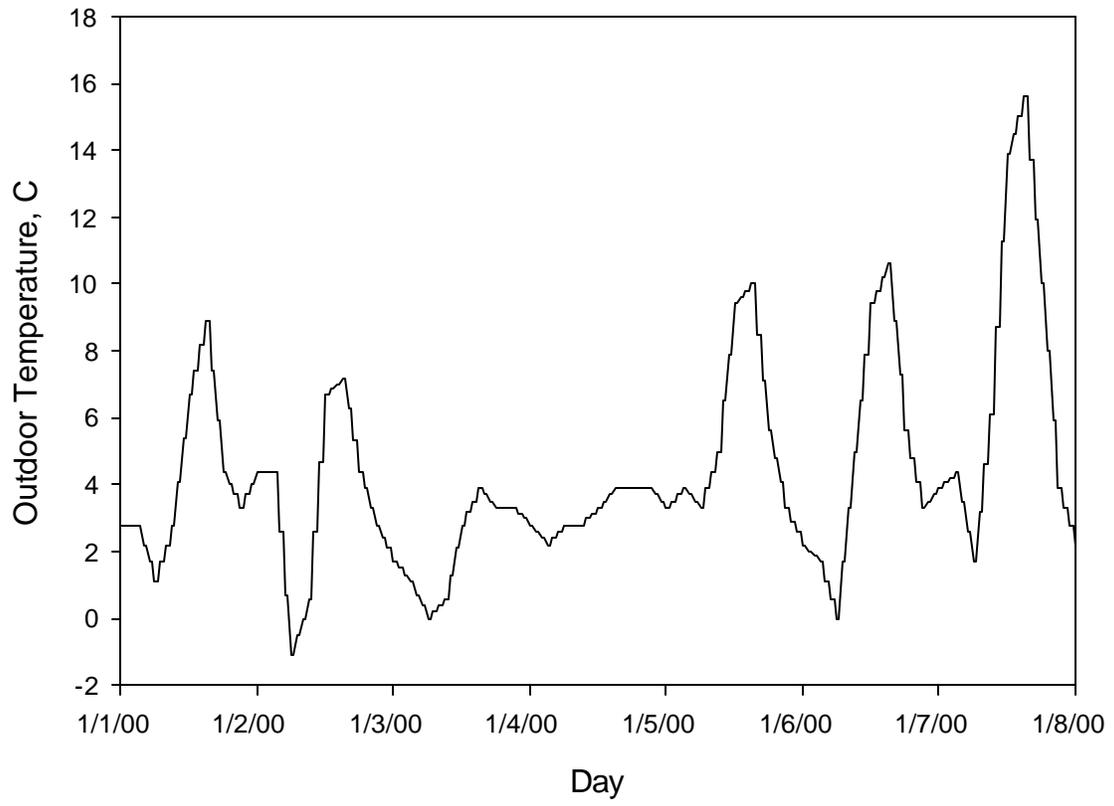


Figure 2-5: Weather data.

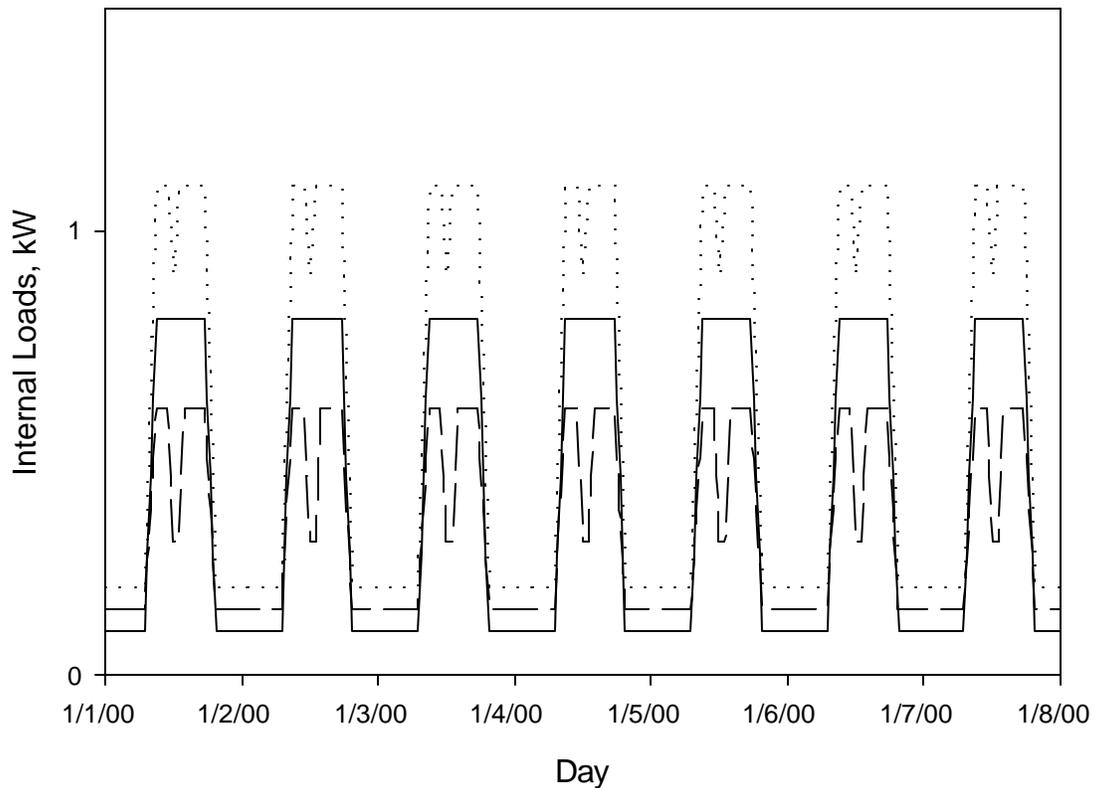


Figure 2-6: Internal loads.

3 PROJECT OUTCOMES

3.1 Control Software

3.1.1 Pulse-Width Modulation Logic

Figures 3-1, 3-2 and 3-3 show examples of PWM signals that can be produced. The PWM signals in these figures have a PWM period of 30 minutes. The first figure shows a PWM signal with a phase of zero and a duty cycle of 25%. The second figure shows a PWM signal with a phase of 10 minutes and a duty cycle of 50%. The third figure shows a PWM signal with a phase of 20 minutes and a duty cycle of 50%. The third figure shows that when the phase gets sufficiently high, the signal “wraps around” so that the “end” of the pulse is at the beginning of the period and the beginning of the pulse is at the end of the period.

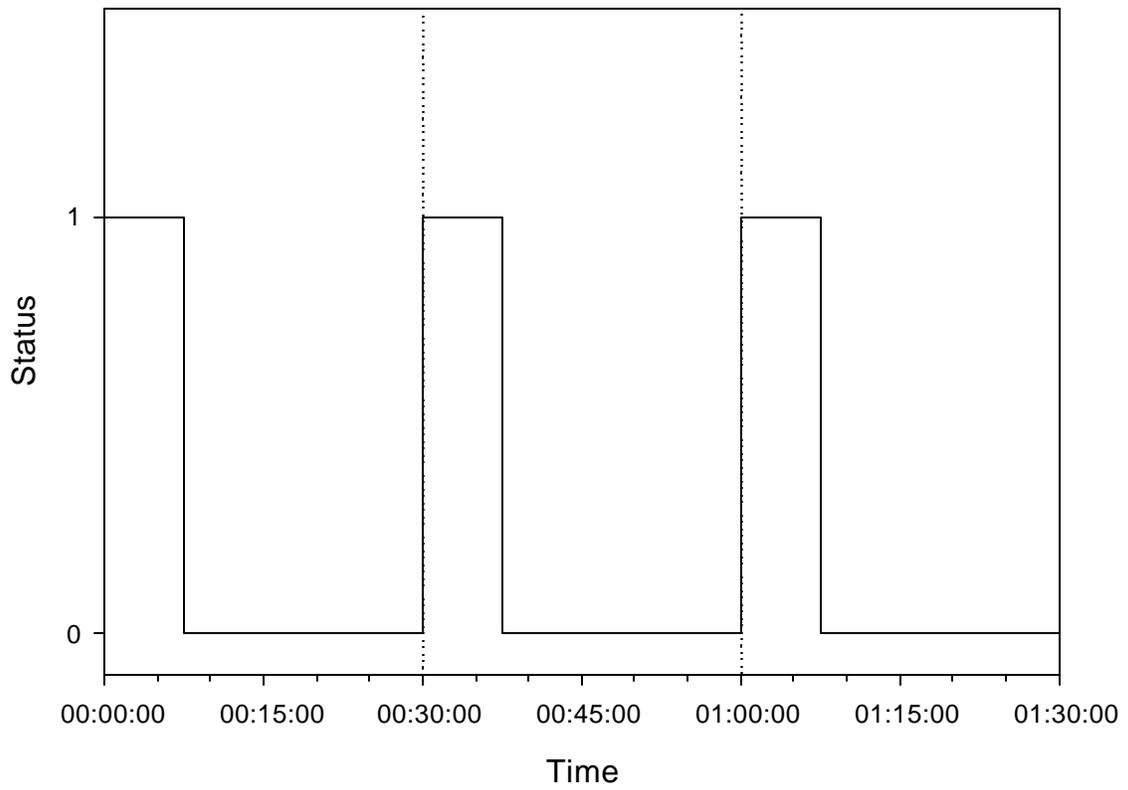


Figure 3-1: PWM signal with 30 minute period, 25% duty cycle and zero phase.

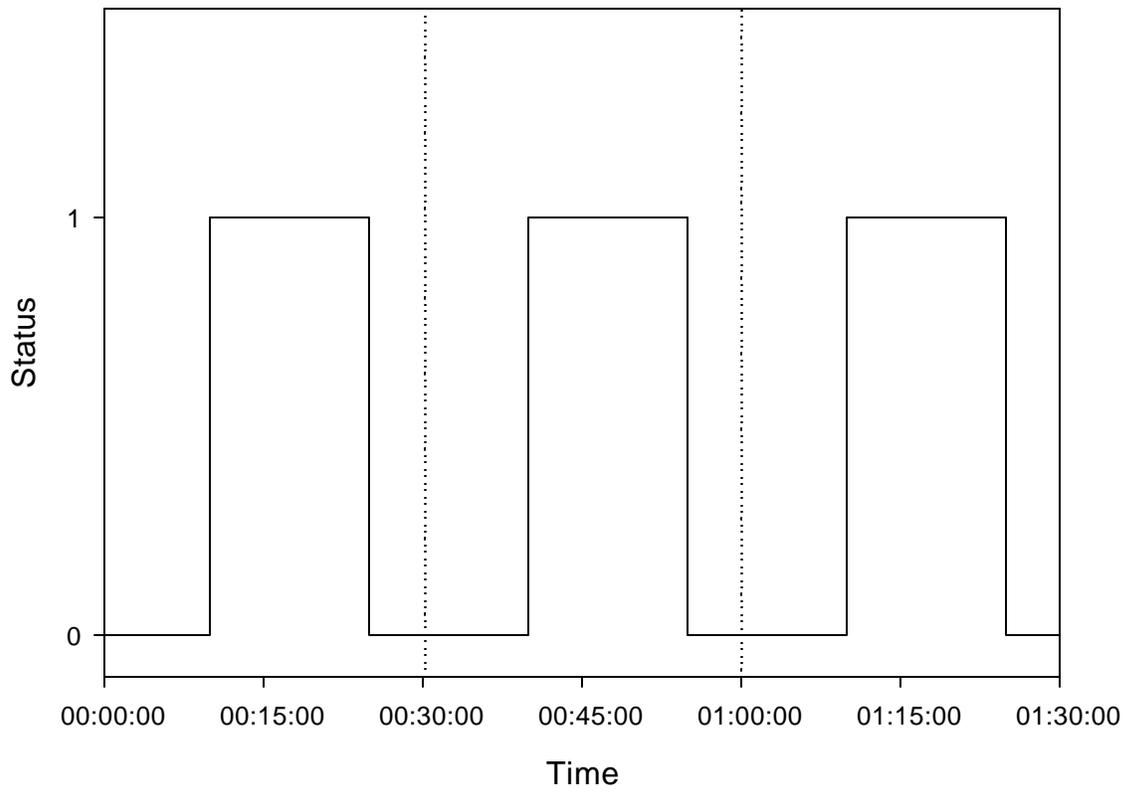


Figure 3-2: PWM signal with a period of 30 minutes, a duty cycle of 50%, and a phase of 10 minutes.

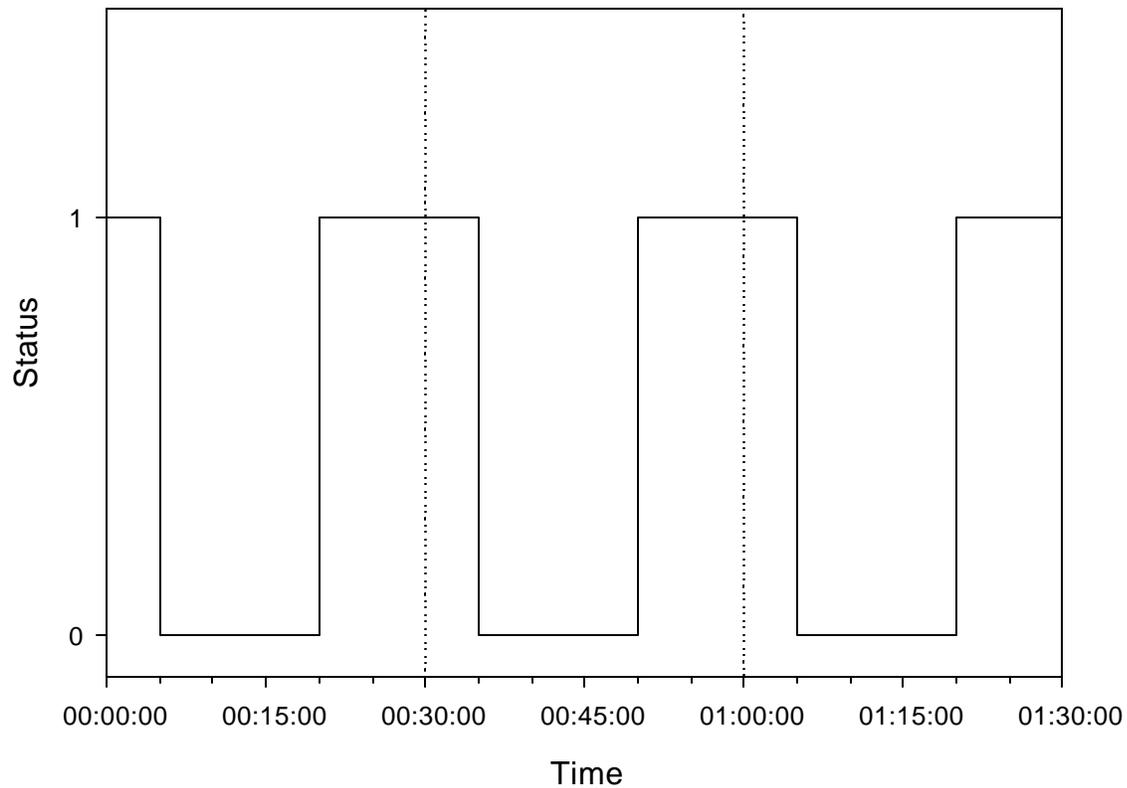


Figure 3-3: PWM signal with a period of 30 minutes, a duty cycle of 50%, and a phase of 20 minutes.

3.1.2 State Charts

Figure 3-4 shows the state chart for the multi-stage HVAC system. The definitions of the states and the state transitions are shown in Table 3-1 and Table 3-2. Cool States 1 and 2 have all four heaters off and the outdoor air damper closed. The two cooling coils are turned on and off determined by the duty cycle from the PID controller and the state. In Cool State 2, the first air cooler is turned on at 100% duty cycle, while the second air cooler is turned on with a variable duty cycle from the PID controller. Cool State 1, keeps one of the air coolers completely off, while the other is turned on with a variable duty cycle.

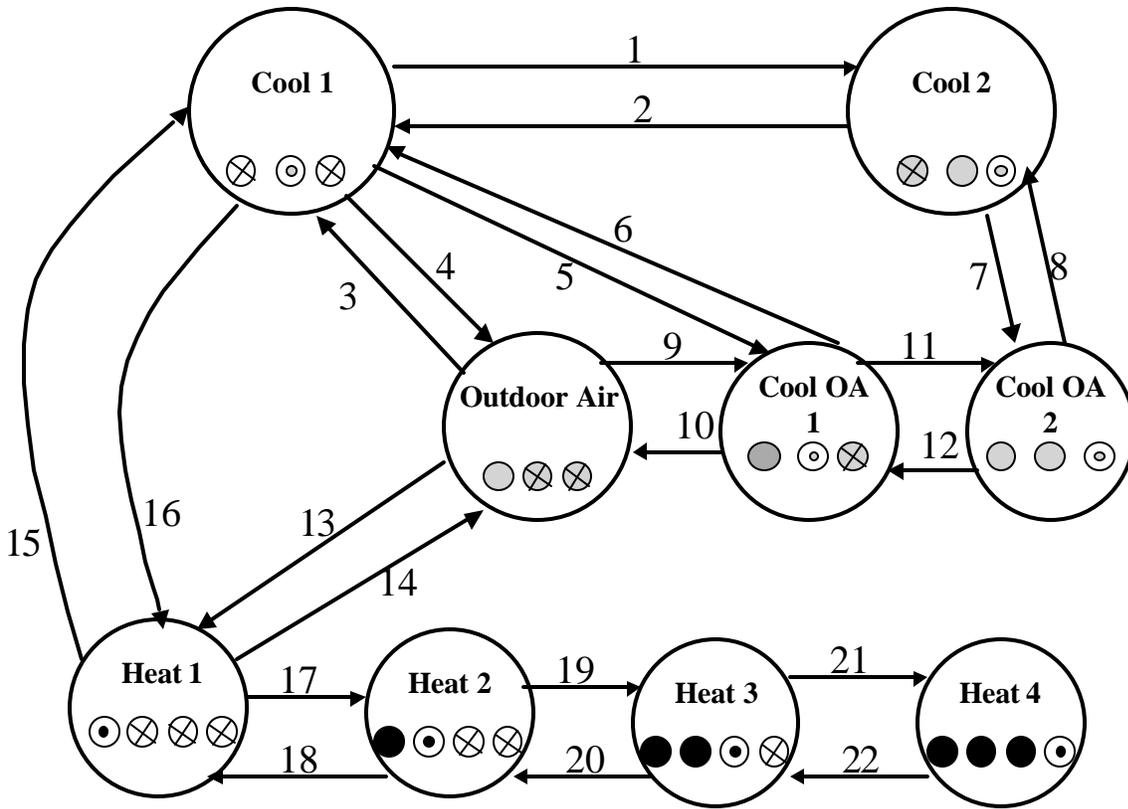


Figure 3-4: State transition diagram

Table 3-1: State definitions.

State	Equipment On
Cool 1	Compressor 1 cycling
Cool 2	Compressor 1 on, Compressor 2 cycling
Outdoor Air	Outdoor air damper open
Cool1 OA	Outdoor air damper open, Compressor 1 cycling
Cool2 OA	Outdoor air damper open, Compressor 1 on, Compressor 2 cycling
Heat 1	Heater 1 cycling
Heat 2	Heater 1 on, Heater 2 cycling
Heat 3	Heater 1 and 2 on, Heater 3 cycling
Heat 4	Heater 1, 2, and 3 on, Heater 4 cycling

Table 3-2: State transition definitions.

Number	Condition
1	Cool 1 saturated at 100%, Outdoor air above threshold
2	Cool 2 saturated at 0%, Outdoor air above threshold
3	Cool 1 saturated at 0%, Outdoor air temperature below threshold
4	Outdoor air is above threshold
5	Outdoor air is above threshold
6	Outdoor air is below threshold
7	Outdoor air is below threshold
8	Outdoor air is above threshold
9	Outdoor air damper fully open, Outdoor air is below threshold
10	Cool 1 saturated at 0%, Outdoor air is below threshold
11	Cool 1 saturated at 100%, Outdoor air is below threshold
12	Cool 2 saturated 0%, Outdoor air is below threshold
13	Outdoor air damper is fully open
14	Heat 1 saturated at 0%, Outdoor air is below threshold
15	Heat 1 saturated at 0%, Outdoor air is above threshold
16	Cool 1 saturated at 0%, Outdoor air temperature is below threshold
17	Heat 1 saturated at 100%
18	Heat 2 saturated at 0%
19	Heat 2 saturated at 100%
20	Heat 3 saturated at 0%
21	Heat 3 saturated at 100%
22	Heat 4 saturated at 0%

The outdoor air states work the same way as the cooling states, however they include the use of an outdoor air damper that allows outdoor air to enter and cool the building when the outdoor air temperature is low. Outdoor air states are enabled and disabled by a separate state machine.

Heating States 1-4 keep the air compressors off, the air damper closed, and control how many of the heaters are on or off. For each of the states, some of the heaters are either 100% on or off, while the PID controller starts and stops one of the heaters at a certain duty cycle determined every period.

The state transitions occur when the controller for the equipment in a certain state becomes saturated for three periods. A saturated controller will determine the duty cycle to be either 100% or 0%. If the controller is saturated at 100%, the transition will go to a state of higher power. If the controller is saturated at 0%, the transition will go to a state of lower power. The state, temperature, and outdoor temperature are monitored every fifteen minute period. Transitions can only occur when a controller has been saturated for two consecutive periods, thus giving some hysteresis to the system and limiting wear and tear on the equipment.

3.2 Computer Simulations

We used the component models described above to compare the energy performance of systems that use pulse-width modulation as a means to start and stop equipment with the energy performance of systems

that use level-crossing logic (e.g., a common thermostat). The basis of comparison was energy consumption, peak demand for power, deviation of space temperature from setpoint, and the number of start-stop operations.

Table 3-3 shows how the three start-stop strategies compare on the basis of the five performance metrics. The first metric is the mean absolute deviation of the temperatures of the three systems from the setpoint. The second metric is the total number of starts and stops of the three systems during the simulation. The third metric is the total energy consumption of the set of three systems. The fourth metric is the standard deviation of the power. It is computed by averaging the variances of the three systems for each start-stop method. The fifth metric is the peak demand of the set of three systems.

Table 3-3: Performance of the three start-stop methods.

	Optimized phase	Constant-Delayed Phase	Level-Crossing
MAD of error, C	1.44	1.39	1.30
# starts and stops per hour	2.15	2.38	1.69
Average Power, kW	36.1	38.8	37.2
Std of Power, kW	2.3	10.5	12.4
Peak Power, kW	40.0	49.8	44.5

Although Table 3-3 indicates that the optimal-phase strategy uses less energy than the other strategies, the differences are small. The table shows that the optimal-phase strategy used 7% less energy than the constant-delay phase strategy and 3% less energy than the level-crossing strategy. Considering the large variation in the power consumption of the constant-delay phase and level-crossing strategies, these differences are not considered significant.

Table 3-3 shows that the optimized phase strategy reduces the peak demand for power by 10% in comparison to the level-crossing logic and by 20% in comparison to the constant-delayed phase strategy. The table also shows that the reduction in peak demand is achieved by reducing the variance of the total power consumption. The standard deviation of the power consumption of the optimal phase strategy is just 19% of the standard deviation of the power consumption of the level-crossing strategy and just 22% of the power consumption of the constant-delayed phase strategy. Figure 3-5 shows the power consumption of the three strategies during the simulation period. The reduced variation and reduced peak demand of the optimal-phase strategy is evident from the graph.

The coordinator increases the mean absolute deviation of the temperature and the number of start stop operations slightly in order to reduce peak demand and reduce the variance of the power consumption. Relative to the level-crossing logic, the coordinator increases the mean absolute deviation of the control error by 11% and increases the number of starts and stops per hour by 27%.

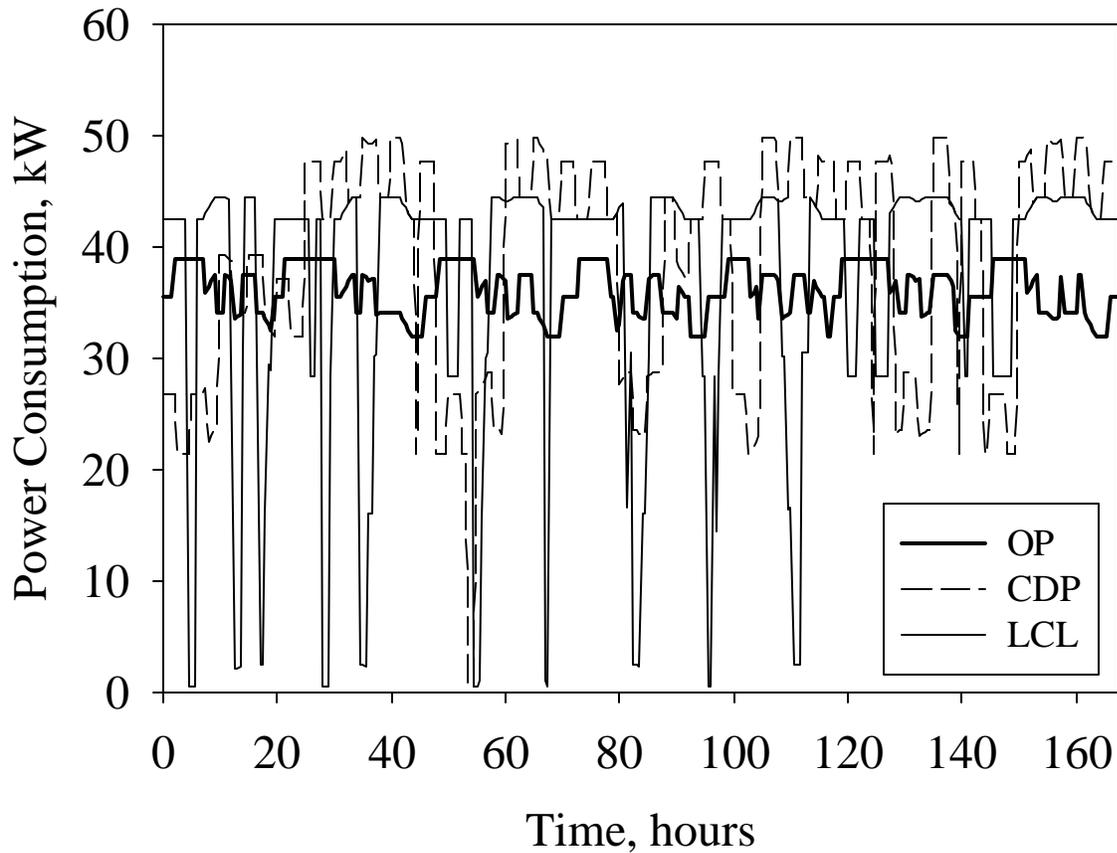


Figure 3-5: Power consumption comparison.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The results of Section 3 indicate that the new control strategy can outperform level-crossing logic on the basis of energy performance. When the PWM logic and state machine were combined with an optimized coordinator, the new strategy reduced peak demand by 20% relative to level-crossing logic.

The results also demonstrated that there is a comfort and maintenance penalty for the improved energy performance. The new strategy increased the mean absolute deviation of the space temperature from the setpoint by 11% relative to the level-crossing logic. This was only 0.14 °C, so that penalty may not cancel the energy benefit. However, the new strategy also increased the number of start-stop operations by 27% relative to the level-crossing logic. If the number of start-stop operations is proportional to the mean time to failure, then this penalty may be significant.

4.2 Commercialization Potential

The new control strategy has the potential to reduce energy costs for end users. Commercialization would involve primarily control software development. The existing code would have to be adapted to a particular platform, but no hardware would be required as long as there was an existing control communication system in place so that a coordinator running on a networked computer could supervise a number of HVAC control units.

Equipment manufacturers may be resistant to commercializing the new strategy because of the increase in start-stop operations. Equipment manufacturers are sensitive to warranty risks. Control system vendors may be less sensitive to warranty risks in some cases.

4.3 Recommendations

Additional work is needed to investigate whether or not it is possible to maintain the energy benefits of the new strategy while reducing the maintenance penalty. It is possible that by operating the PWM signals asynchronously and at different frequencies the maintenance penalty could be reduced. Asynchronous operation may also yield additional energy benefits. Asynchronous operation would increase the complexity of the design of the control logic, though not necessarily the complexity of implementing it.

4.4 Benefits to California

If the new control strategy were widely deployed in California, end users would benefit by paying less for electrical power. The reduction would be derived primarily from the reduction in the peak demand for power. The amount of cost reduction would depend on specific details of the end user's utility contract. The greatest cost savings would be derived during part-load months when coordination of the loads can have the greatest impact on the peak demand.

5 DEVELOPMENT STAGE ASSESSMENT

Table 5-1 shows the overall development effort in terms of the Stages and Gates process. The development status for each cell is shown as percent complete. A description of the status of each row is given in the following subsections.

Table 5-1: Project Development Stage Activity Matrix

Stages	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop- ment	5 Product Develop- ment	6 Demon- stration	7 Market Transfor- mation	8 Commer- cialization
Marketing	0%	0%	0%	0%	0%	0%	0%	0%
Engineering / Technical	100%	50%	100%	20%	0%	0%	0%	0%
Legal/ Contractual	0%	0%	0%	0%	0%	0%	0%	0%
Risk Assess/ Quality Plans	50%	50%	50%	0%	0%	0%	0%	0%
Strategic	0%	0%	0%	0%	0%	0%	0%	0%
Production. Readiness/	0%	0%	0%	0%	0%	0%	0%	0%
Public Benefits/ Cost	100%	50%	50%	0%	0%	0%	0%	0%

5.1 Marketing

There has been no activity in this area other than investigating opportunities for continued funding. To date, efforts to secure additional funding have been unsuccessful.

5.2 Engineering/Technical

The idea generation was fairly mature when the proposal was first written. Additional ideas extending the original technical concepts include considering asynchronous coordination, where units do not cycle on and off at a fixed period. This approach may solve some of the drawbacks of the approach that was tested including increased temperature variance and increased number of starts and stops.

There was no market analysis of the proposed innovation, only technical analysis. The technical analysis is described in detail in previous sections of this report.

We researched the proposed innovation, both by reviewing the open literature for related innovations and by testing the concept with computer simulation methods.

The technical analysis and research resulted in graphs and software that could serve as the starting point for technology development.

5.3 Legal/Contractual

There has been no activity in this area.

5.4 Risk Assessment/Quality Plans

At the idea generation stage we recognized the need to study the impact of the innovation on temperature control performance (variation from setpoint), and on start-stop frequency. Our technical analysis and research included these metrics because they will be important to facility managers and equipment manufacturers.

5.5 Strategic

There has been no activity in this area.

5.6 Production Readiness

There has been no activity in this area.

5.7 Public Benefits/Costs

The idea generation related to public benefits and costs were fairly mature when the proposal was first written. Technical analysis and research demonstrated that the innovation could reduce peak demand by 10-15%.

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