Intelligent Multiagent Control System for Energy and Comfort Management in Smart and Sustainable Buildings

Lingfeng Wang, Zhu Wang, and Rui Yang

***Abstract*—Smart and energy-efficient buildings have recently become a trend for future building industry. The major challenge in the control system design for such a building is to minimize the power consumption without compromising the customers comfort. For this purpose, a hierarchical multiagent control system with an intelligent optimizer is proposed in this study. Four types of agents, which are switch agent, central coordinator-agent, local controller-agent, and load agent, cooperate with each other to achieve the overall control goals. Particle swarm optimization (PSO) is utilized to optimize the overall system and enhance the intelligence of the integrated building and microgrid system. A Graphical User Interface (GUI) based platform is designed for customers to input their preferences and monitor the results. Two sets of case studies are carried out and corresponding simulation results are presented in this paper.**

***Index Terms*—Smart and sustainable building, energy and comfort management, distributed energy resources, microgrid, multiagent control system, graphical user interface, heuristic optimization.**

I. Introduction

According to the results of the California Commercial End-Use Survey (CEUS), up to 85% of the energy usage in commercial buildings is consumed by heating and cooling, lighting, ventilation, and office equipment [1]. The operation of a building requires high energy efficiency to reduce energy consumption. However, the improvement of the indoor environment comfort demands more energy consumption. Thus, one of the most important issues on smart and energy-efficient buildings is to balance the requirements of the occupants' comfort and power consumption. The three basic factors which determine the occupants' quality of lives in a building environment are thermal comfort, visual comfort and air quality [2]. Intelligent control of the thermal comfort, visual comfort and air quality comfort are important for both energy efficiency and occupant's quality of living. Generally, temperature is used to indicate the thermal comfort in a building environment, and the auxiliary heating/cooling system is applied to maintain the temperature in a comfortable region. The illumination level is used to indicate the visual comfort in a building environment, which is measured in lux; and the electrical lighting system serves as actuators to control the illumination. CO_2 concentration is used as an index to measure the air quality in the building environment, and the ventilation system is utilized to achieve low CO_2 concentration [2]. The basic control objectives for a building energy management system are to maintain the high comfort level while reducing total energy consumption.

Microgrid is an important promising technology for meeting the increasing challenges faced by modern power systems such as environmental concerns, high requirements on power quality and reliability, growing social and industry demands, and aging infrastructure of the current power grid. A microgrid system is usually made up of distributed generators (DGs), distributed storage (DS), and controllable loads. Since generators and storage devices geographically locate close to the controllable loads, a variety of benefits can be achieved including improved reliability and reduced transmission losses. Furthermore, microgrid employs renewable resources as energy supplies, which meet the requirement of environmental friendliness. The overall microgrid system can be connected to and disconnected from the upstream utility grid according to the current condition in order to minimize the disruption to the loads [3]–[6].

Most, if not all, existing work in the field of energy and comfort management for building control and automation has been surveyed and discussed in [2]. However, no work has been done thus far to deal with the energy and comfort management for the integrated building and microgrid systems including distributed renewable energy resources. In particular, the task for energy and comfort management becomes more difficult for such building systems since multiple distributed energy resources need to be effectively coordinated, which are usually intermittent. In this study, the problem of energy and comfort management in an integrated building and microgrid system will be formulated and the proposed control method will be discussed.

The remainder of the paper is organized as follows. Section II describes the overall system architecture. The design of the multiagent control system is detailed in Section III, including all the agents and the particle swarm optimizer. Section IV gives the graphical user interface of the simulation platform. In Section V, case studies and simulation results are presented. The major implementation issues of the proposed building energy management system are discussed in Section VI. Finally, conclusion and future work are given in Section VII.

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The authors are with the Department of Electrical Engineering and Computer Science, University of Toledo, Toledo, OH 43606 USA (e-mail: Lingfeng.Wang@utoledo.edu).

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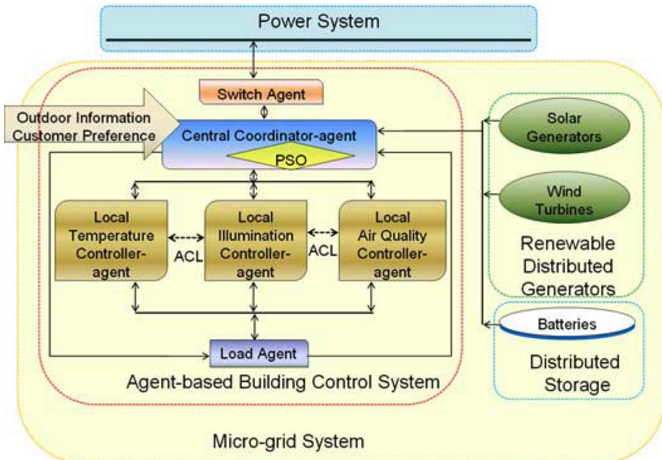

Fig. 1. Architecture of the multiagent control and management system.

II. System Architecture

The overall microgrid system includes the distributed renewable power supply, the distributed storage and the controllable loads. In this research, solar panels and wind generators are used for distributed renewable power supply. Here batteries are used as distributed storage for enhancing the reliability of the whole system through storing the surplus energy in the low demand periods and releasing the stored energy in the high demand periods. The smart building is integrated into the microgrid system and it is regarded as the controllable load. Fig. 1 shows the overall system architecture. The hierarchical multiagent system technology is applied to the control system for the smart building, and the agents are classified into four different layers based on their distinct functions. The first-layer agent is a switch agent, which is used to determine and monitor the energy flow between the power grid and the smart building system according to the customer preference and other relevant information. The central coordinator-agent and the multiple local controller-agents are considered to be the primary agents and locate in the second layer and the third layer respectively. A particle swarm optimizer (PSO) is embedded in the central coordinator-agent to optimize the set points. Multiple local controller-agents are used to control the devices which are related to the comfort factors. The three main comfort factors considered in this study include environmental temperature, illumination level, and indoor air quality (CO_2 concentration). Accordingly, the local controller-agents are classified into the temperature controller-agent, the illumination controller-agent, and the air-quality controller-agent. The fourth layer is the load agent, which controls all the interruptible loads. In this study, interruptible loads are those noncritical devices that have no direct connection with the three main comfort factors. When necessary, the load agent decides the amount and the order of the load shedding according to the customer preference to maintain the high-level comfort. Through the cooperation of these multilayered agents, the control goal, which is to maximize the customer comfort and minimize the energy consumption simultaneously, can be achieved [7].

Two communication modes in terms of direct communication and indirect communication are used for facilitating the communications between various agents in the proposed control framework. Direct communication mode can be utilized for the interagent communications in the same layer. This is accomplished through a direct information exchange between agents based on the Agent Communication Language (ACL). The indirect communication mode is used for enabling an information exchange between agents in different layers. A global database maintained by the coordinator-agent is needed for storing the incoming information from other agents including the local controller-agents, the switch agent, and the load agent. After the data is manipulated, the processed data or the resultant decisions will be sent back to the corresponding agents. By utilizing these two communication modes, each agent in the proposed control system will have sufficient real-time information to make correct decisions and thus exhibit the desired behaviors.

Due to the requirements of environmental friendliness in sustainable buildings, distributed renewable energy resources are considered as the primary energy supply and the utility grid is the backup energy supply in this study. All the devices in the building prefer consumption of renewable energy over utility power. The utility grid can be connected to the building in order to supply power when the available renewable energy cannot satisfy the building demands.

III. Multiagent Control System Design

Multiagent system (MAS) technology has been successfully utilized in various engineering fields. The fundamental element in an MAS is the agent, which can be a software or physical entity. In this work, a hierarchical multiagent based control system is designed for energy and comfort management in the smart building. All the agents are classified into multiple layers based on their different functions. Although agents exhibit distinct behaviors, they share some common properties. For instance, agents have a certain degree of autonomy enabling them to work properly without human intervention; they are able to communicate with each other; and they are capable of perceiving and reacting to the changes in the environment as well as determining the proper behaviors to achieve the final goal. All agents cooperate with one another to achieve the overall control goals [8]–[10]. In this section, an MAS-based control system designed for an integrated building and microgrid system will be discussed.

A. Switch Agent

The overall integrated building and microgrid system has two operation modes: grid-connected mode and islanded mode. The switch agent works with the central-coordinator agent to determine the switch status for connecting/disconnecting the microgrid to/from the utility grid. Fig. 2 shows the procedure for selecting the specific operation mode in different scenarios. If there is any disturbance in the utility grid or the electricity rate is not acceptable to the customers, the microgrid will be islanded from the main grid. The switch in these scenarios will be open and corresponding optimization or mitigation schemes will be adopted to maximize the overall comfort level using the available renewable energy resources. Otherwise, the microgrid is connected to the utility grid. However, the building will always

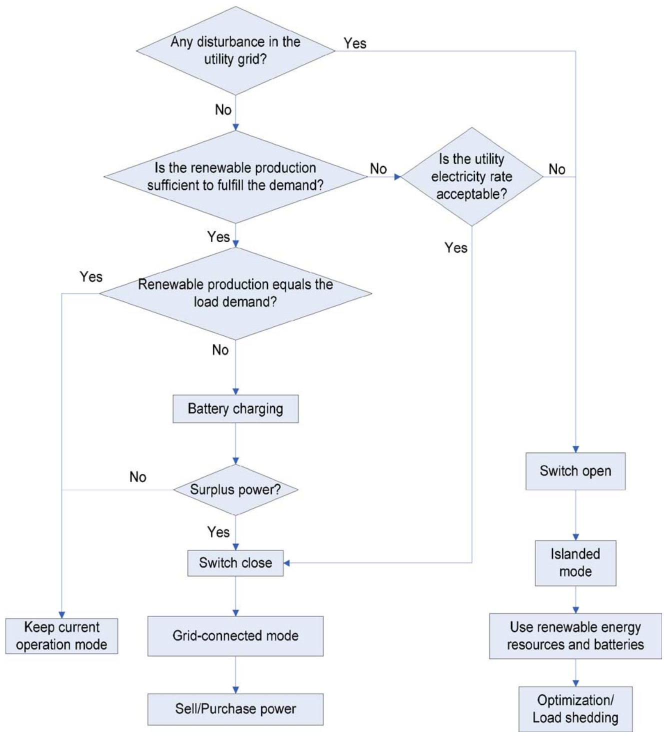

Fig. 2. The procedure for the choice of operation modes.

consume the available renewable energy first. If there is any surplus energy from the renewable resources, the batteries will be charged. If there is still energy remaining, the surplus energy will be sold back to the utility grid. Also if there is insufficient renewable energy from the microgrid and the utility electricity rate is acceptable, utility power will be purchased to fulfill the total load demands of the building.

B. Central Coordinator-Agent

For the central coordinator-agent, the primary task is to coordinate the power allocation and maximize the customer comfort. The central coordinator-agent bridges the energy sources and all the lower-level agents. It determines the power dispatch to the multiple local controller-agents and the load agent to maximize the overall comfort value according to the customer preference, the online energy production, and the environmental information. Since the control system is intended to be customer-centered, the customers will be given the flexibility to set their own preferences by configuring various user-defined parameters.

The task of the central coordinator-agent is to coordinate all the agents and the embedded optimizer for maximizing the composite comfort index, which can be defined in multiple ways based on the specific customer needs. In this study the overall comfort index is defined as follows:

$$\text{Comfort} = \mu_1\left[1-(e_T/T_{\text{set}})^2\right]+\mu_2\left[1-(e_L/L_{\text{set}})^2\right] +\mu_3\left[1-(e_A/A_{\text{set}})^2\right] \quad (1)$$

where:

Comfort is the overall customer comfort, which falls in the range of [0,1] and the control goal is to maximize its value.

μ_1, μ_2 and μ_3 are the user-defined weighting factors, which indicate the importance of three comfort factors and resolve the possible equipment conflicts as well. Customers can set their own preferred values in different situations through graphical user interfaces (GUIs). All the user-defined weighting factors fall into [0,1] and $\mu_1+\mu_2+\mu_3=1$. In some cases, a weighting factor can be zero. For example, μ_2 can be set zero if the users do not care about the indoor illumination level in certain conditions. Also a range can be imposed on any weighting factor if needed.

$T_{\text{set}}, L_{\text{set}}$, and A_{set} represent the set points of the temperature, the illumination, and the indoor air quality, respectively.

e_T, e_L, and e_A are the errors between the measured values and set points of the temperature, the illumination, and the indoor air quality, respectively.

Here in the definition of the overall comfort level, all three major environmental parameters are included. It is also possible that the air quality level is used as a constraint in the optimization problem. Here it is assumed that the set point of the air quality has been carefully selected by the users who are aware that the achievement of a lower CO_2 concentration level is at the expense of higher power consumption. Thus, in this optimization problem, the proposed control system is also designed to drive the CO_2 concentration to the set point.

C. Particle Swarm Optimizer (PSO)

Particle swarm optimization is inspired by the animal social behavior such as fish schooling and bird flocking, and it was first introduced as a novel stochastic, self-adaptive, and population-based algorithm by Kennedy and Eberhart in 1995 [11], [12]. As compared with other heuristic algorithms, PSO has several advantages. It has fewer parameters to adjust and it is easier to escape from the local optimal solutions. PSO has turned out to be an effective tool to solve highly complex problems such as large-scale nonlinear optimization.

In PSO, each possible solution is seen as a particle, which follows the current local optimal solution to fly through the whole multidimensional search space for approaching the global optimal solution. The particle includes location vector l and velocity vector v. The particle moves towards its best local position p_{best} by continuously adjusting the velocity vector and memorizing its own current location. Influenced by the randomly generated weights (α, r_1 and r_2) and acceleration constants (ω_1 and ω_2), the swarm finally moves towards the global best location g_{best}. The updating rules are described as follows:

$$v^{k+1} = \alpha v^k + \omega_1 r_1\left[p^k_{\text{bset}} - l^k\right] + \omega_2 r_2\left[g^k_{\text{best}} - l^k\right] \quad (2)$$

$$l^{k+1} = l^k + v^{k+1} \quad (3)$$

$$\alpha = \alpha_{\max} - (\alpha_{\max} - \alpha_{\min}) \times k_n/k_{\max} \quad (4)$$

where α is the inertia weight, $\alpha_{\max}$ and $\alpha_{\min}$ are the maximum value and minimum value of the inertia weight which can be set by customers, respectively; ω_1 and ω_2 are two positive acceleration constants; r_1 and r_2 are two randomly generated numbers from [0,1]; p^k_{best} is the local best position; g^k_{best} is the best global position; k is the iteration index, k_n is the current number of iterations, and $k_{\max}$ is the maximum number of iterations [13]–[15].

In this study, PSO is utilized to tune the set points according to the outdoor environmental information and the customer preference. As different customers have different preferences, a GUI simulation platform has been developed, which offers the flexibility to customers to set their different comfort zones $[T_{\min}, T_{\max}], [L_{\min}, L_{\max}]$, and $[A_{\min}, A_{\max}]$ for temperature, illumination, and CO_2 concentration, respectively. In the encoding scheme, each particle has three dimensions, which indicate the set point values of temperature, illumination, and air quality, respectively. Thus, there are three flight directions for each particle. This three-dimensional search space is restricted by the three corresponding comfort zones defined by the customers. The objective function is defined in (1), and the optimization goal is to maximize the objective function. Since the error between the measured value and set value determines the customer comfort level and power consumption, optimization of the set points plays an important role in achieving the control goal.

The implementation of the PSO is described as follows:

1) Randomly initialize the particles by assigning a location for each particle, and the initial location should be within the users-defined comfort zones. In this study, there are three flight dimensions which represent the T, L, and A, respectively.
2) Evaluate the fitness function of each particle based on (1).
3) Each particle remembers its fitness value and chooses the best value found so far as its best location p_{best}, which are $p_{\text{Tbest}}, p_{\text{Lbest}}$ and p_{Abest}, respectively. Set p_{best} as g_{best} in the first iteration.
4) Modify the velocity and position of each particle based on the updating rules.
5) Repeat steps 1)–4) until any stopping criterion is fulfilled. In our simulations, the stopping rule is whether or not the number of generations has reached 100 or the maximum comfort value 1 has been achieved.

Since heuristic algorithms such as PSO have no guarantee to find the global optimal solution within the limited iterations, in this study PSO runs 10 times in each time step to increase the possibility of achieving the global optimization [14], [15]. In principle, more runs of the optimization algorithm will lead to a higher probability of achieving better results, but it will inevitably take more computational time. After many trials, it was found that 10 is a reasonable number of runs for balancing the solution quality and computational cost.

D. *Local Controller-Agents*

Local controller-agents are implemented in three local subsystems to control thermal comfort, visual comfort and air quality, respectively. Fig. 3 shows the structure of the local subsystems. In the proposed building model, it is supposed that the indoor environment of the building under consideration is quite sensitive to the variation of the outdoor environment. It means that the indoor building environment will closely follow the change of outdoor environment if no control is applied. The local controller-agent takes the adjusted power from the central coordinator-agent and the error between real environmental parameters and the set points as inputs to the fuzzy controllers.

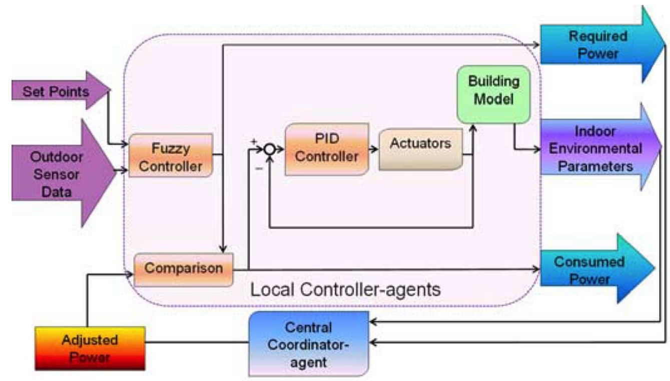

Fig. 3. Structure of local controller-agents.

Fuzzy rules are applied to calculate the required power in uncertain circumstances [16]. Comparison is carried out between the required power calculated and the adjusted power from the central coordinator-agent to determine the actual power to be used. It is used to drive the actuators to control indoor environmental parameters which decide the users' overall comfort level. The actuators are auxiliary heating/cooling, electrical lighting, and ventilating for controlling the thermal comfort, visual comfort, and air quality, respectively. Thus, the indoor environmental parameters can be controlled by the corresponding actuators in local subsystems.

1) Local Temperature Agent: To calculate the required power for maintaining the indoor thermal comfort, a fuzzy PD controller is developed for this subsystem. The input of this fuzzy controller includes the error error_T and the change of errors cerror_T. The change of errors cerror_T represents the difference between the previous and present errors. The membership functions of the inputs and output of the fuzzy PD controller are shown in Fig. 4. The membership functions of the inputs and outputs include the following values: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). The rules of the fuzzy controller are shown in Table I.

The output of the fuzzy controller is the required power which maintains the indoor temperature at the set point. A negative value indicates that the heating system is working while a positive value means the cooling system is working.

2) Local Illumination Agent: In the local illumination agent, illumination level is utilized as measured parameters to indicate visual comfort, which is measured in lux. The input of the local fuzzy illumination controller is the error between the outside illumination level and the indoor set point. The output is the required power to be consumed by the lighting system. The membership functions of the input and output of the local illumination controller are shown in Fig. 5. The rules of the local illumination controller are shown in Table II.

3) Local Air Quality Agent: CO_2 concentration is used as an index to indicate air quality in the building environment, which is measured in ppm. A fuzzy controller is implemented in the local air quality subsystem to calculate the required power for the ventilator. The input of the local fuzzy controller is the error between the CO_2 concentration and the indoor set point. The

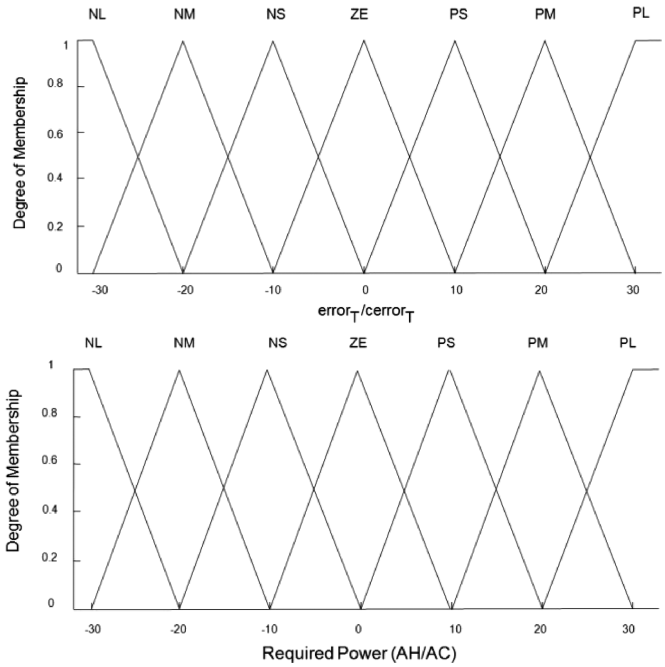

Fig. 4. Membership functions of local temperature controller.

TABLE I
FUZZY CONTROL RULES FOR LOCAL TEMPERATURE CONTROLLER

Required Power		$error_T$						
		NL	NM	NS	ZE	PS	PM	PL
$cerror_T$	NL	NL	NS	PS	PL	PL	PL	PL
	NM	NL	NM	ZE	PM	PM	PL	PL
	NS	NL	NM	NS	PS	PM	PL	PL
	ZE	NL	NM	NS	ZE	PS	PM	PL
	PS	NL	NL	NM	NS	PS	PM	PL
	PM	NL	NL	NM	NM	ZE	PM	PL
	PL	NL	NL	NL	NL	NS	PS	PL

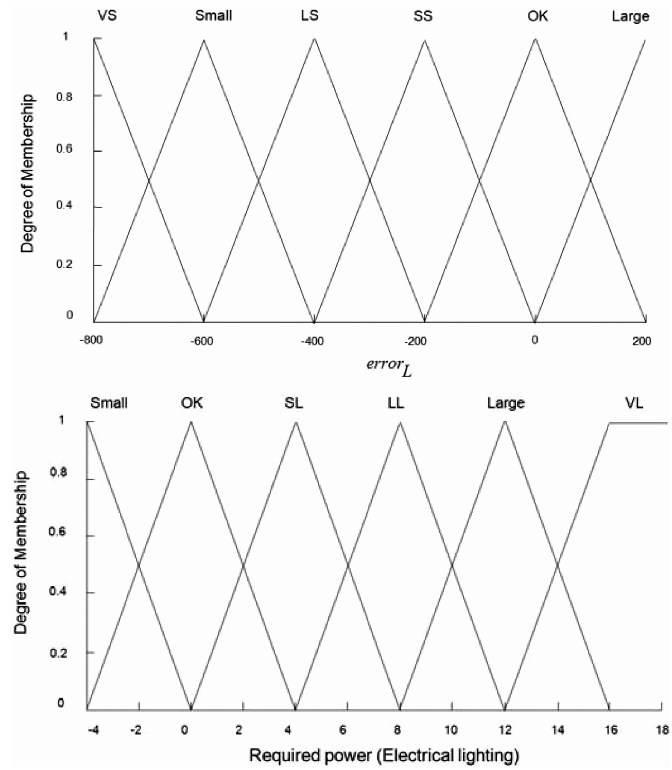

Fig. 5. Membership functions of local illumination controller.

TABLE II
FUZZY CONTROL RULES FOR LOCAL ILLUMINATION CONTROLLER

$error_L$	VS	Small	LS	SS	OK	Large
Required added power	VL	Large	LL	SL	OK	Small

output is the required power to be consumed in the ventilation system which helps maintain indoor air quality. The membership functions of the input and output of the fuzzy controller are shown in Fig. 6. The rules of the local ventilation controller are shown in Table III.

The output of the fuzzy controller will be compared to the adjusted power from the central coordinator-agent. If the adjusted power is sufficient, the power used for ventilation control equals the required power. Thus the indoor comfort will be maintained; otherwise, the indoor comfort will be compromised. The actual consumed power drives the actuators to control the indoor environmental comfort.

E. Load Agent

The load agent controls all the equipment which has no direct connection with the three main comfort factors. Considering the different functionalities of buildings and the variety of equipment, customers should be given the flexibility to manage the controllable loads according to their own preferences. Some load profiles are built and a GUI is designed for customers to configure corresponding parameters. Through the GUI-based platform, customers not only can define the load characteristics but also monitor the amount and the order of load shedding.

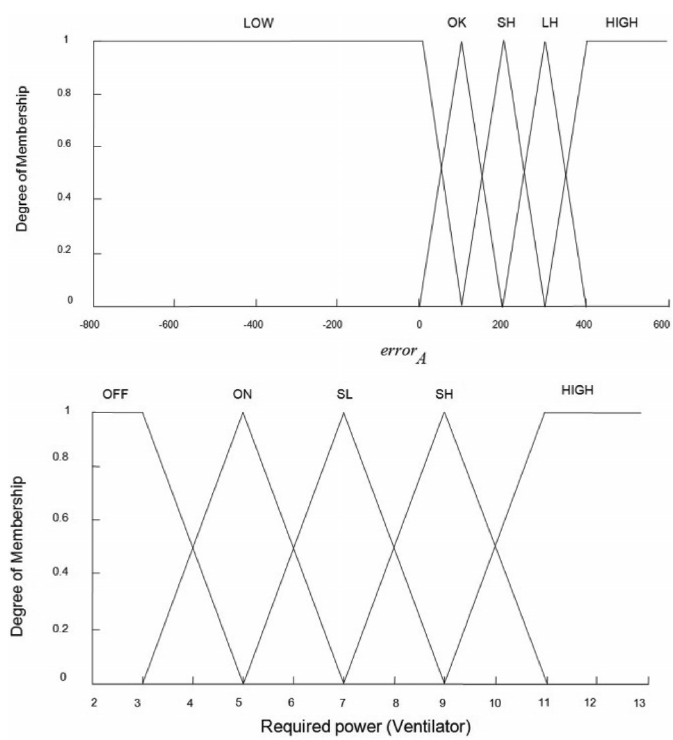

Fig. 6. Membership functions of local ventilation controller.

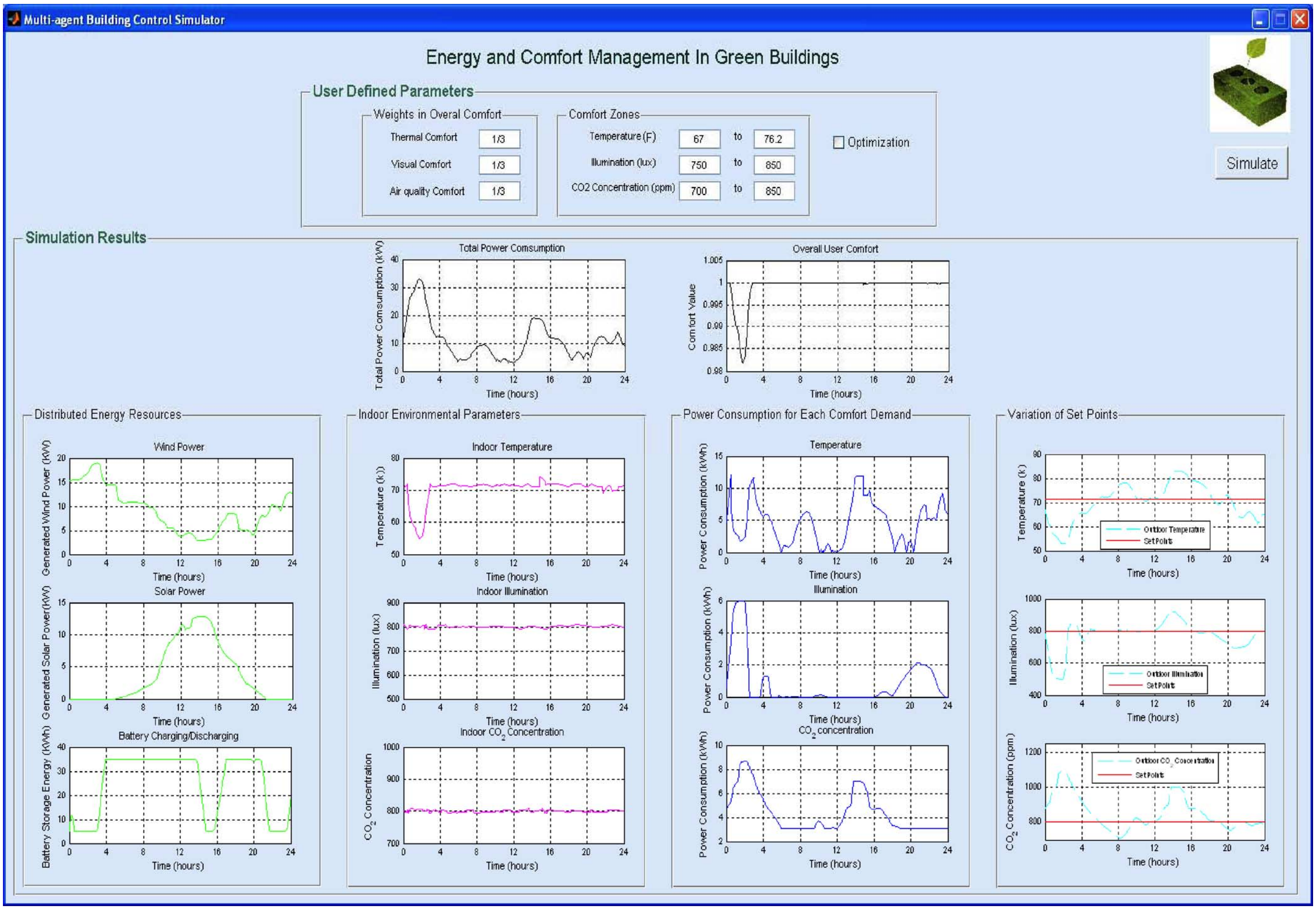

Fig. 7. GUI-based simulation platform for energy and comfort management in smart and sustainable buildings.

TABLE III
FUZZY CONTROL RULES FOR LOCAL VENTILATION CONTROLLER

Error	LOW	OK	SH	LH	HIGH
Required Power	OFF	ON	SL	SH	HIGH

Generally speaking, PSO is used to tune the set points for system optimization in both operation modes (i.e., grid-connected mode or islanded mode) according to the current situation and the customer preference. In the grid-connected mode, PSO is used to find the optimum set points in the comfort ranges to reduce the energy consumption. No load will be shed in this operating mode since energy can always be purchased from the utility grid. When the system operates in islanded mode, PSO is utilized to tune the set points first. If the overall comfort still cannot be maintained at the acceptable level after PSO is deployed, a certain amount of interruptible loads will be shed based on their priorities to ensure that more energy can be dispatched to the comfort-related equipment for maintaining the acceptable comfort level. These interruptible loads are related to the noncritical equipment which has no relationship with the overall comfort index defined.

IV. GRAPHICAL USER INTERFACE

In order to manage energy and comfort in a building environment, a GUI is designed using MATLAB GUIDE. An example GUI is shown in Fig. 7. The GUI-based simulation platform allows users to configure the control system parameters and observe system performance.

In the GUI, users can define several basic parameters including the weights for three individual comfort factors and the comfort zones. In the segment titled "*Weights in Overall Comfort*," the weights for three individual comfort objective μ_1, μ_2, and μ_3 can be defined by users. In the segment "*Comfort Zones*," users can define their own tolerable comfort ranges $[T_{\min}, T_{\max}]$, $[L_{\min}, L_{\max}]$, and $[A_{\min}, A_{\max}]$ for temperature, illumination, and CO_2 concentration, respectively. The "*Simulate*" button can be pressed to start simulation after all user-defined parameters have been configured. Users can observe the results for their chosen parameters through the second part of the interface, "*Simulation Results*." In this area, simulation results regarding overall power consumption and comfort value are shown. In addition, four separate segments individually display various results including "*Distributed Energy Resources*," "*Indoor Environmental Parameters*," "*Power Consumption for Each Comfort Demand*," and "*Variation of Set Points*."

The load agent manages all the other nonessential devices which are not related to those three comfort factors. Due to various functions of buildings, customers should be given the flexibility to choose the loads according to their own preferences. To

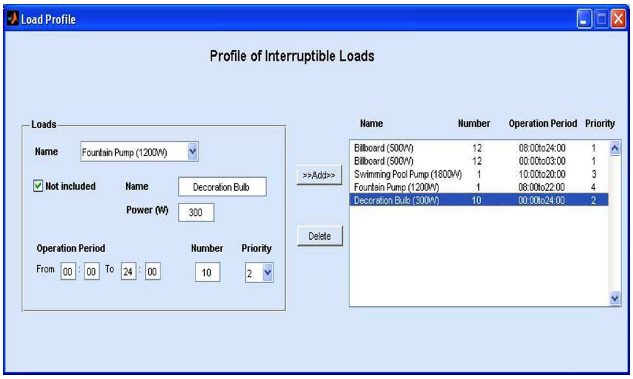

Fig. 8. GUI for configuring interruptible loads.

fulfill this need, a GUI is designed for the customers to define their own preferred load parameters as shown in Fig. 8.

In order to determine the amount and the proper order of shed loads, the detailed information about loads is required. The basic information for a specific load is its power consumption, operation periods in a day, and the priority among all the loads. The priority indicates the ranking of the loads by their importance. Loads in Priority 1 have the highest importance, which means that when the power supply is in a shortage, loads in Priority 1 will be shed at last. Detailed information about loads can be collected from users. Therefore, a GUI is built for users to define their own loads. As shown in Fig. 8, users can manage building loads by adding/deleting items to/from the load list. Basic properties of a load including load name, operation time, and priority can be configured through the panel.

V. Case Studies and Simulation Results

In this section, two case studies will be introduced. In the first case study, the impacts of different user-defined weighting factors and different comfort zones are examined. The second case study explores the control strategies and the effect of the two operation modes. Simulation results are presented.

A. Case Study 1

This case study is concerned about the islanded mode. Here three 4.5-kW solar panels and four 5-kW wind turbines are used for the renewable energy supply, and the simulation is carried out on a 24-h time scale [17], [18]. The batteries with total storable energy of 35 kW-h and a minimum storage threshold of 5 kW-h are selected for distributed energy storage. Fig. 9 shows the total power production from the distributed renewable energy resources.

1) Impact of User-Defined Weighting Factors: To illustrate the impact of user-defined weighting factors, two sets of weighting factors have been chosen. In the first group, $\mu_1 = 1/3$, $\mu_2 = 1/3$, $\mu_3 = 1/3$, and in the second one $\mu_1 = 0.3$, $\mu_2 = 0.5$, $\mu_3 = 0.2$. Here PSO is not applied, and the set points are $T_{\rm set} = 71.6$ $(°F)$, $L_{\rm set} = 800$ (lux), $A_{\rm set} = 800$ (ppm). Figs. 10 and 11 show the differences of the power consumption of each comfort demand using these two sets of weighting factors. The differences of the resultant indoor environmental parameters can be seen by comparing Figs. 12 and 13.

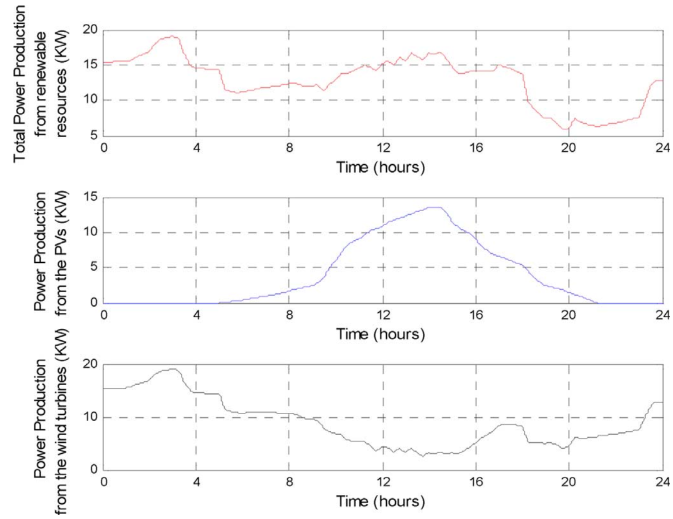

Fig. 9. Energy production from the distributed renewable supply.

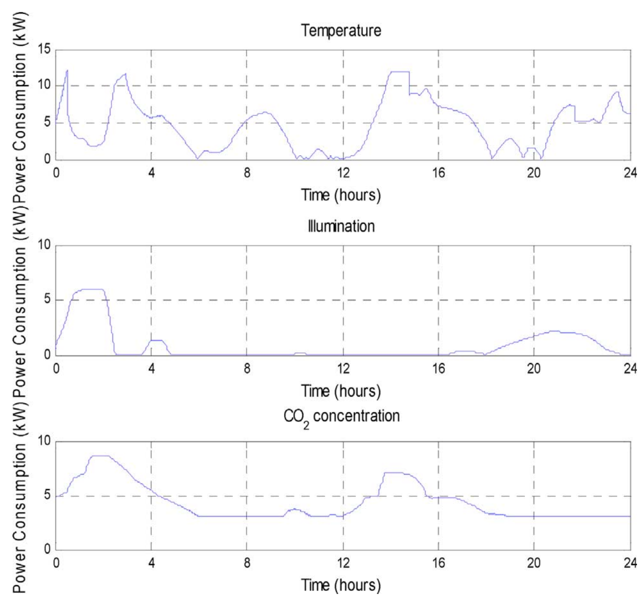

Fig. 10. Power consumption for each comfort demand using the first set of weighting factors without PSO.

Based on the online power production and user-defined weighting factors, the final power assigned to each local controller-agent is derived by the central coordinator-agent for controlling the corresponding indoor environmental parameter. The overall users' comfort is determined by all of the associated indoor environmental parameters. Fig. 14 illustrates the different overall user comfort levels using these two sets of different weighting factors.

2) Effect of Applying PSO: In the islanded mode, because of the possibility of power shortage in some time periods, the overall comfort cannot be maintained at the maximum value at all times. To enhance the comfort level and reduce the power consumption, PSO is applied to optimize the set points. The control system is tested using two scenarios with different comfort zones. The comfort zones of the first scenario are set as $[T_{\min}, T_{\max}] = [67, 76.2]$ $(°F)$, $[L_{\min}, L_{\max}] = [750, 850]$ (lux) and $[A_{\min}, A_{\max}] = [700, 850]$ (ppm). The comfort zones of the second scenario are $[T_{\min}, T_{\max}] = [64, 79.2]$ $(°F)$, $[L_{\min}, L_{\max}] = [720, 880]$ (lux) and

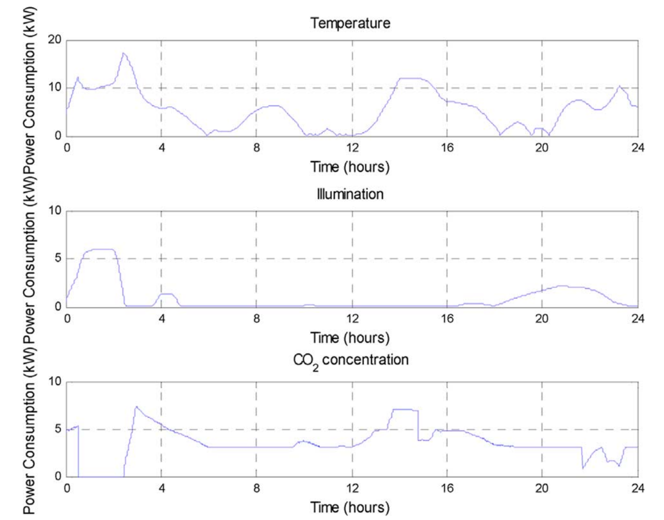

Fig. 11. Power consumption for each comfort demand using the second set of weighting factors without PSO.

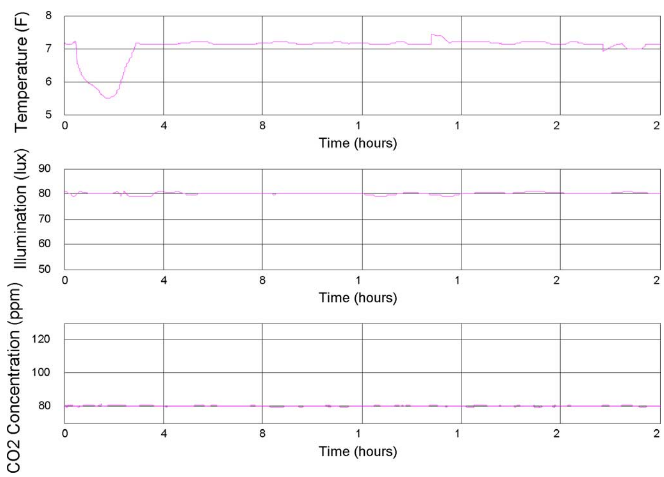

Fig. 12. Indoor environment parameters using the first set of weighting factors without PSO.

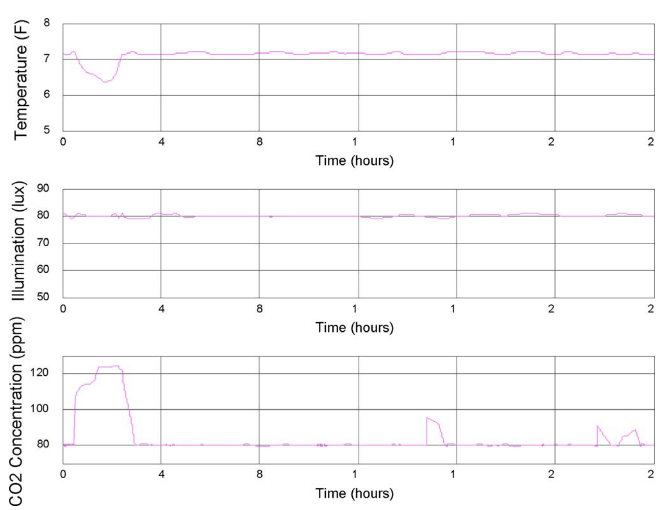

Fig. 13. Indoor environmental parameters using the second set of weighting factors without PSO.

$[A_{\min}, A_{\max}] = [700, 880]$ (ppm). These parameters are configured through the GUI of the simulation platform. The variations of the set points in the two scenarios, which can be monitored from the GUI-based platform, are shown in Figs. 15 and 16, respectively.

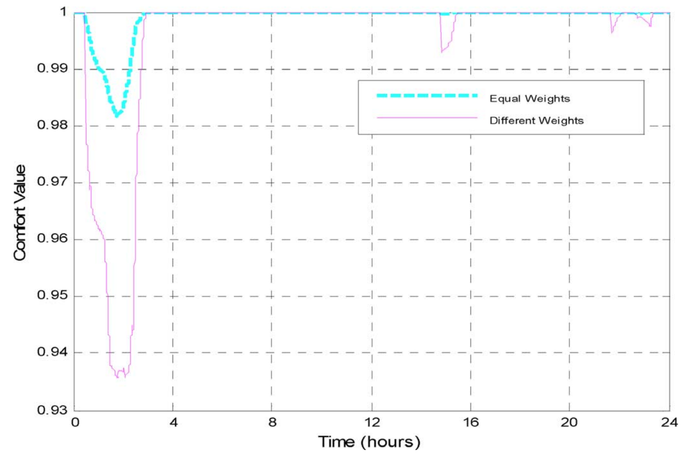

Fig. 14. Comfort values using different sets of weighting factors without PSO.

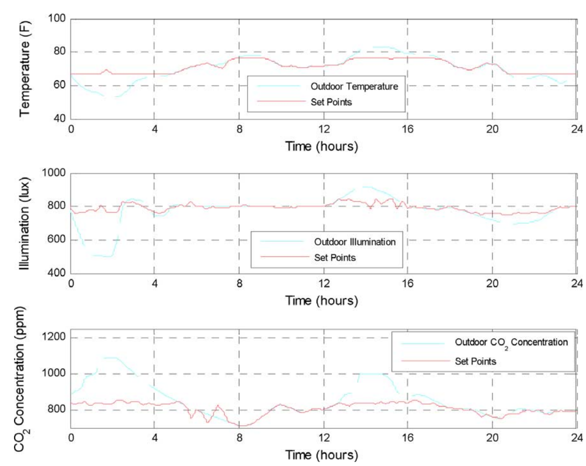

Fig. 15. The variation of set points in the first scenario.

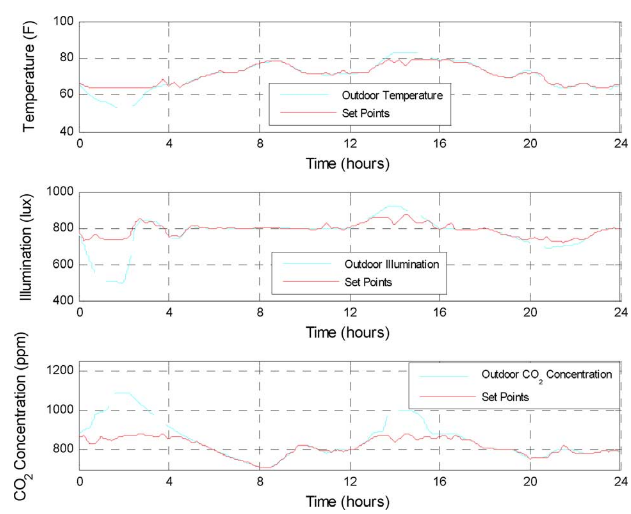

Fig. 16. The variation of set points in the second scenario.

Figs. 17 and 18 indicate the effects of the PSO. The variation pattern of the set points becomes different, and the overall comfort level is improved with the reduced total power consumption. It can also be seen that different comfort zones have different impacts on the system behaviors. Larger comfort zones

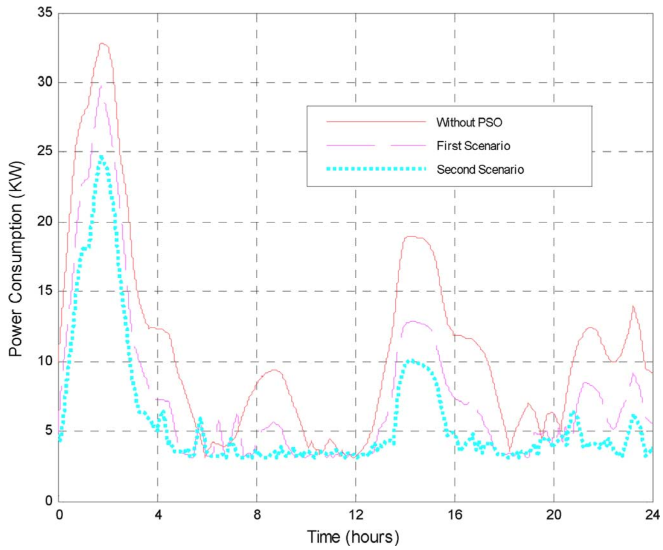

Fig. 17. Changes of total power consumption without and with PSO using different comfort zones.

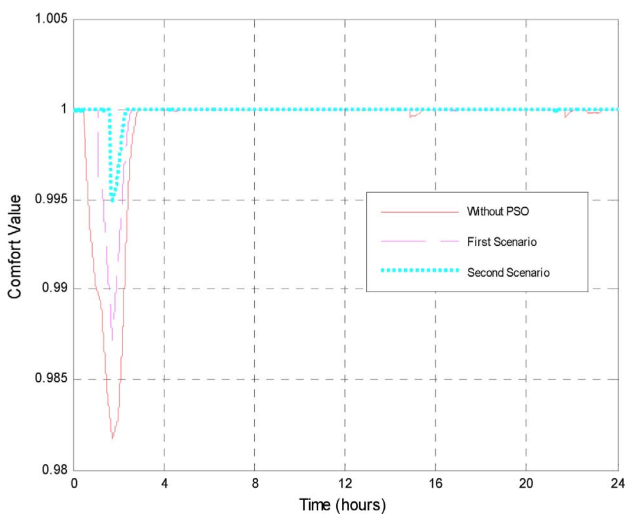

Fig. 18. Changes of overall user comfort without and with PSO in different comfort ranges.

lead to lower power consumption and higher comfort values if other conditions are identical.

B. Case Study 2

In this case study, five 4.5-kW solar panels and four 5-kW wind turbines are used, and the battery is the same as that used in the first case study. Fig. 19 illustrates the total energy production from all the renewable resources. Table IV shows the interruptible loads selected in this case study [19]. Customers determine the amount, the operation periods, and the priority of each selected load. Fig. 20 illustrates the total energy demand of the building in a day.

1) Grid-Connected Operation Mode: When the utility grid interconnection is in the normal condition and the electricity rate is acceptable to customers, the switch can be closed to connect the building system to the power grid. The switch agent determines and monitors the energy exchanges between the building system and the power grid. As shown in Fig. 21, the dark areas represent the energy exchanges. The positive area indicates that

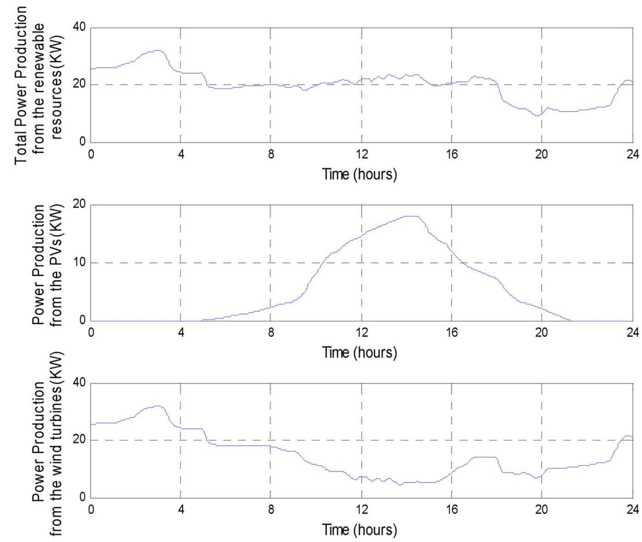

Fig. 19. Energy production of the renewable resources.

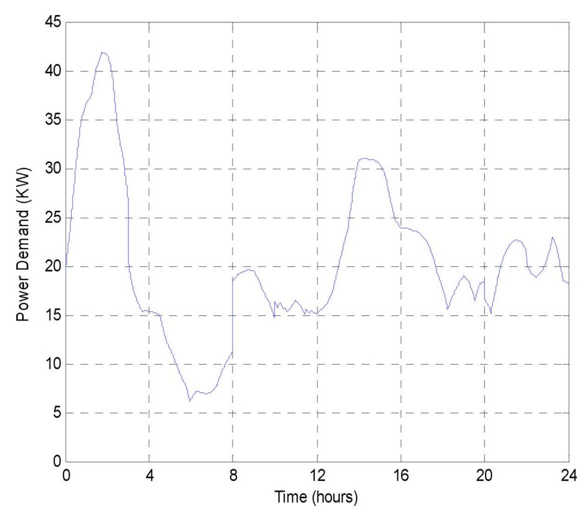

Fig. 20. Total energy demands of the smart building.

TABLE IV
INTERRUPTIBLE LOAD PROFILES

Load	Power	Number	Operation Periods	Priority
Fountain Pump	1200W	1	8:00-22:00	4
Electronic Billboard	500W	12	0:00-3:00, 8:00-24:00	1
Decoration Bulb	300W	10	0:00-24:00	2
Swimming Pool Pump	1800W	1	10:00-20:00	3

the energy is being injected into the building system from the power grid. On the contrary, the negative area means that the energy is being sent back to the power grid from the building system. Zero value indicates there is no energy exchange between the building and the power grid during that period, while the building demand is still fulfilled by renewable energy production coupled with the batteries. It is obvious that customers can gain some economic benefits through selling the surplus power back to the power grid. Fig. 22 illustrates the energy flow when PSO is used in the first scenario. The energy extracted

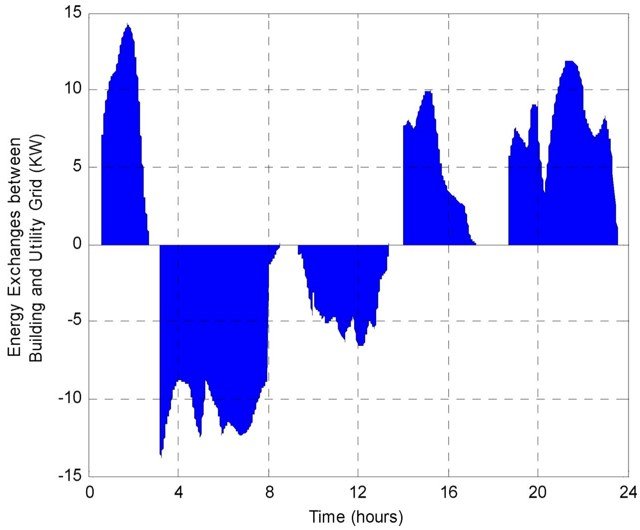

Fig. 21. Energy exchanges between the building and utility grid without PSO.

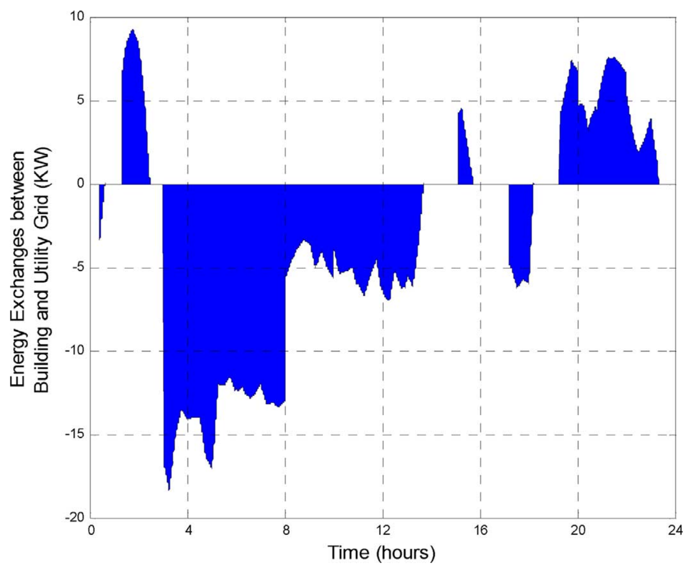

Fig. 22. Energy exchanges between the building and utility grid with PSO.

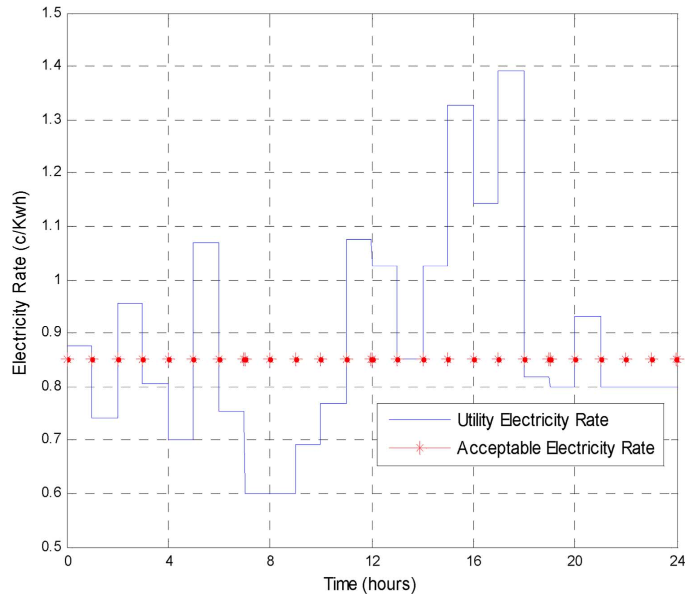

Fig. 23. The utility electricity rate and the customers' acceptable rate.

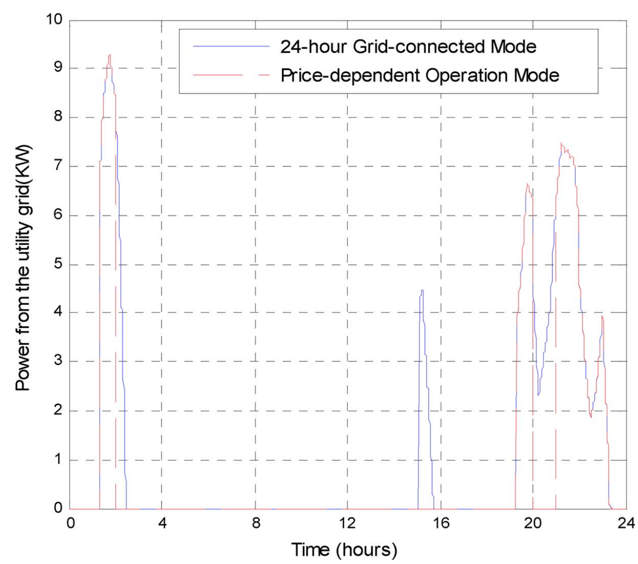

Fig. 24. Power purchases of 24-h grid-connected mode and price-dependent operation mode.

from the utility grid decreases while the energy sold back to the grid increases. By comparing Figs. 21 and 22, we can see that in the grid-connected mode, the economic benefit can be improved using PSO.

In the grid-connected mode, since energy is sufficient to feed the building loads at all times, the overall comfort can always be maintained at the highest level of "1."

2) Islanded Operation Mode: Let us first consider the scenarios where no disturbances occur in the grid interconnection and the utility grid itself. In this case, the building operating strategy is dependent on the real-time utility electricity rate. Fig. 23 shows the variation of the utility electricity rate in a sample day (April 2, 2011) [20] as well as the acceptable electricity prices set by the customers. But certainly the acceptable electricity rate of customers can also be variable in different time periods. The electricity rate profile shown in Fig. 23 is used in our simulation study. In the presence of insufficient renewable energy production, the building will operate in the islanded mode if the utility electricity rate is higher than the acceptable rate; otherwise, the building will operate in the grid-connected mode. Moreover, the building only purchases energy from the utility grid when the renewable energy production coupled with battery discharge cannot fulfill the customer demands. As shown in Figs. 19 and 20, the total renewable energy available is higher than the demands during hours 7 to 10. Although the electricity rate is lower than the customer's acceptable rate during hours 7 to 10, the building does not purchase any energy from the utility because the renewable energy production is sufficient to fulfill all the demands during that period.

Compared to the 24-h grid-connected mode with optimization, the power purchase considering the acceptability of the real-time electricity price is shown in Fig. 24. The resultant overall comfort is illustrated in Fig. 25.

When any unacceptable disturbances such as poor power quality and voltage distortion occur in the grid interconnection

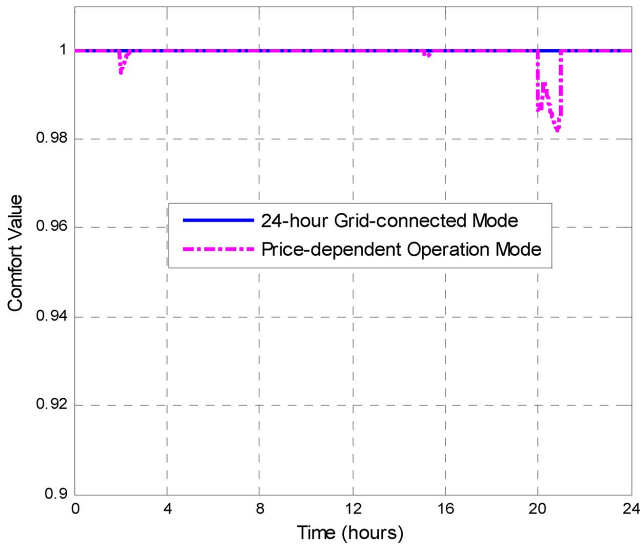

Fig. 25. Overall comfort values of 24-h grid-connected mode and price-dependent operation mode.

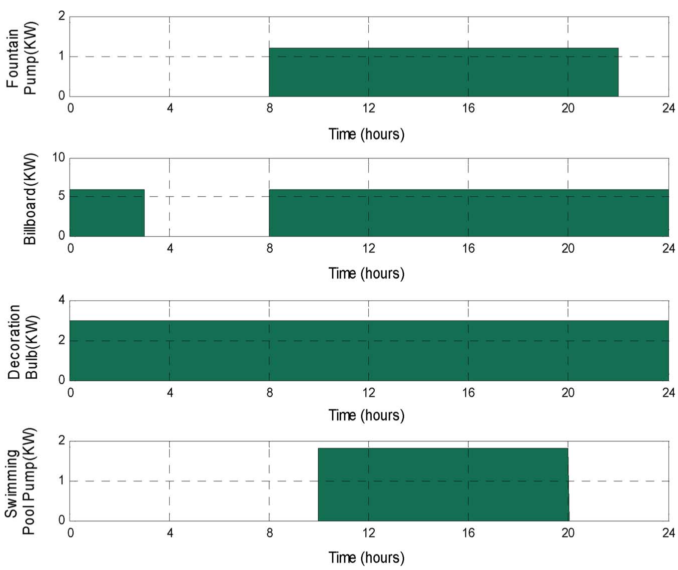

Fig. 26. Energy consumption of each interruptible load in the normal condition.

or the utility grid, the building will operate in the islanded mode. Here the islanded operation mode without optimization will be first examined and then the effect of the PSO will be demonstrated. The overall customer comfort is expected to be improved after PSO is applied, but there is still a possibility that optimization itself is not adequate to maintain the highest comfort level in all time periods. Thus, if desired, load agent can be activated to improve the overall customer comfort by shedding some interruptible loads. Fig. 26 illustrates the energy consumption of each interruptible load based on Table IV in the normal condition, while Fig. 27 illustrates the power consumption of each interruptible load when load shedding is applied to improve the overall comfort level. The drops shown in the figures indicate that these loads are shed in some time periods.

Figs. 28–30 show the changes of the overall customer comfort in the islanded mode using different operating strategies. Fig. 28 depicts the overall customer comfort in islanded mode

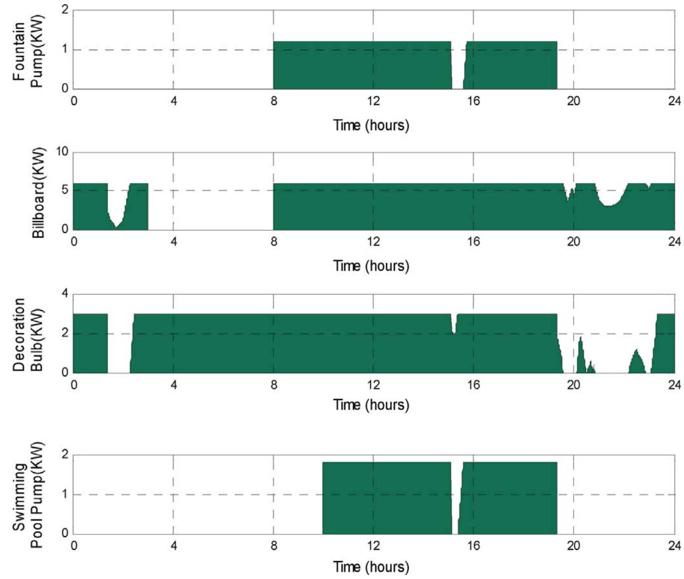

Fig. 27. Energy consumption of each interruptible load with load shedding.

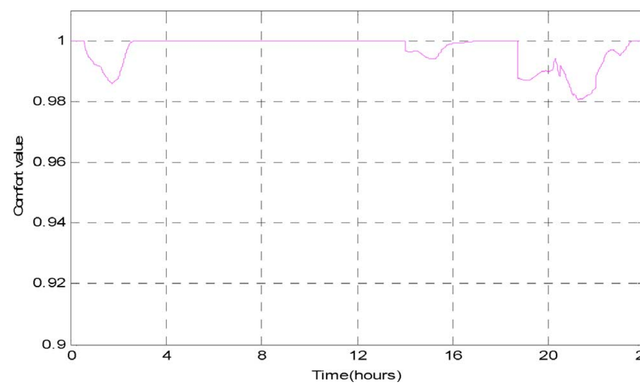

Fig. 28. Overall customer comfort in islanded mode without optimization.

without optimization. Fig. 29 shows the overall customer comfort in islanded mode after PSO is applied to tune the set points but load agent is not activated. It can be observed that overall comfort level is somehow improved with optimization. If desired, load shedding can be used to further improve the overall comfort level. Fig. 30 shows the overall customer comfort in islanded mode with both optimization and load shedding. It can be seen that the overall comfort level is maximized using the optimizer coupled with load shedding.

VI. Implementation Issues of the Proposed System

The proposed control system can be integrated with the building energy management system (BEMS) and the required hardware facilities such as sensors, microprocessors, actuators, and communication devices should be installed in the building. To implement the proposed multiagent control system in a physical building, a two-level control structure can be utilized to enable the interagent communication and collaboration. In the high-level control layer, various system configuration and agent coordination tasks are performed. At the low-level control layer, environmental parameters are measured and controlled directly by corresponding sensors, microprocessors, and actuators. Communication devices can be used in the control network for enabling data exchanges.

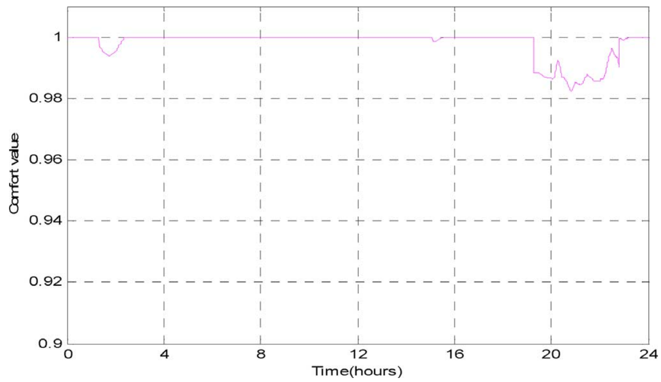

Fig. 29. Overall customer comfort in islanded mode with optimization.

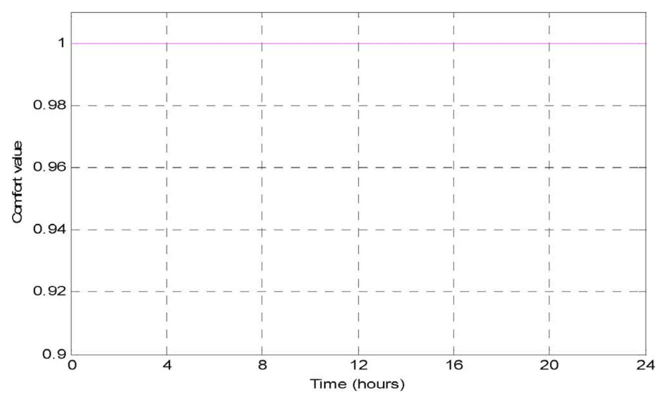

Fig. 30. Overall customer comfort in islanded mode with optimization and load shedding.

The central coordinator-agent lies in the high-level control layer. It is responsible for overseeing the behaviors of the entire building control system as well as making final decisions for all other agents. This agent can be embedded in the BEMS as a piece of application software. The building manager or operator is in charge of configuring the required parameters including comfort and economic preferences of customers through the GUI-based BEMS panel for enabling informed decision making. Switch agent and load agent also lie in this layer. They are implemented as software entities in distributed microprocessors and communicate with the central coordinator-agent through the control network during system operations.

Sensors, actuators and local controller-agents lie in the low-level control (field) level. The devices in this level interact directly with the physical environment. They are responsible for data acquisition, preliminary control manipulation, and actuation operations for controlling the physical environment. Various sensors are distributed and embedded in the building environment to continuously collect the ambient environmental parameters. Sensors for environmental parameter measurement include thermometers, photometers and IAQ meters. Different fuzzy control laws can be implemented in the distributed microprocessors of local controller-agents. Under the control of local controller-agents, actuators act on the physical building environment. Field actuators include environmental parameter actuators (e.g., air conditioners, lighting systems, and ventilators), load shedding actuators, and energy flow switch.

Building Automation and Control network (BACnet) can be utilized as the protocol for facilitating interagent communications as well as linking the heterogeneous devices together. This standard protocol is developed specifically to meet the requirements set forth by ASHRAE for building automation and control.

In practically implementing the proposed building control system, there are a couple of major issues that engineers should pay attention to. First, the user-defined parameters such as set points, weights, and comfort zones should be able to reflect the true preferences of the occupants in the building. These can be collected in multiple ways such as questionnaires and online surveys. The final parameters can be keyed into the BEMS by the building operator/manager based on the survey results. Second, all the space in the building which shares the same comfort ranges can be seen as a "building zone" which can be controlled by a set of corresponding local controller-agents. If a building has multiple function zones with different comfort ranges, the building should be appropriately divided into different "building zones". Multiple sets of local controller-agents with distinct parameters can be employed for all these zones.

VII. Concluding Remarks

The integrated building and microgrid system has some salient advantages such as environmental friendliness. In this study, an intelligent multiagent control system with heuristic optimization is designed, and it has been shown to be capable of achieving the control goals by coordinating the multiple agents and the optimizer. A GUI-based simulation platform is also developed to provide the flexibility to customers to control the integrated building system based on their own preferences. The control system behaviors can also be observed through the platform. In the future study, quantitative analysis is needed for the optimization of economic benefits in system operations. Different objective functions can be defined as the overall comfort index in the control system design. Also, since frequent changes of operating mode will reduce the lifetime of the related components, the maximum number of operation mode changes during a day will be imposed as a constraint in the model to ensure the lifetime of the components. In addition, optimal sizing of the microgrid including PV panels, wind turbines, and battery storage will be investigated in the future work.

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