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The network-based energy management system for convenience stores

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Abstract

Convenience stores generally consume energy higher than other retailing merchants. As the problem of energy shortage becomes more serious during summer, almost all convenience stores sign a contract with power plants, which provides for fines if demand limiting occurs in Taiwan and many other countries. Therefore, a reliable and effective method to reduce their utility consumption is required for modern business and industry. This research integrates the remote sensors, the control network, and the embedded system technologies to construct a distributed energy management control system for dedicated convenience stores. Energy consumption can thus be reasonably managed with demand limits by measuring and analyzing the power consumption sources in four major subsystems of convenience stores, namely, (1) air-conditioning, (2) lighting, (3) heating, and (4) refrigeration. By applying the proposed demand prediction and control method, the demand limiting condition can be properly predicted, and the possible peak load can thus be eliminated via the network control mechanism. Moreover, by integrating the LonWork fieldbus and the WinCE operating system (OS), the proposed system has been successfully applied to a convenience store. The experimental results indicate that the proposed distributed energy management system suitably predicts the peak loading condition and successfully prevents its occurrence by switching the air-conditioning system without affecting the indoor temperature regulation.

Keywords: Convenience store; Load distribution; Demand prediction and control; Distributed energy management system

1. Introduction

In tropical countries, business activities account for about 11% of the total electricity consumption. Convenience stores, which consume 1757 kWh/m^2 per year on the average with their 24 h operation, are ranked at the top of all retailing merchants in Taiwan [1]. Their energy consumption index is four times higher than those of general department stores and 1.6 times higher than those of supermarkets based on the same scale [1–3]. Their total electricity consumption is considerably huge especially during summer, and several potential management methods for convenience stores to save energy have been developed [4–8]. Basically, an appropriate management, monitoring, and control system cannot only enhance individual equipment utilization but also optimize the total energy usage. The energy monitoring and control network requires both an operational experience and an energy-saving policy with a well-organized execution platform.

This research focuses on energy management, monitoring, and control activities for convenience stores. Moreover, the pioneering system is implemented in a convenience store to evaluate its performance. The structure of the energy management system and the software and hardware design for the energy management controller of the convenience store will be introduced in detail in the following sections. The experimental results and analysis for real data will also be provided in order to prove the feasibility of the proposed system.

2. The structure of the energy management system

The network-based energy management system, which is based on a distributed concept, is shown in Fig. 1.

This system consists mainly of three major parts [9,10]:

(1) The network-based distributed energy-saving management and control system

This subsystem contains a network-based energy management controller and multiple distributed sensors. It is designed as a generic platform for both residential and commercial energy management systems and can be customized to

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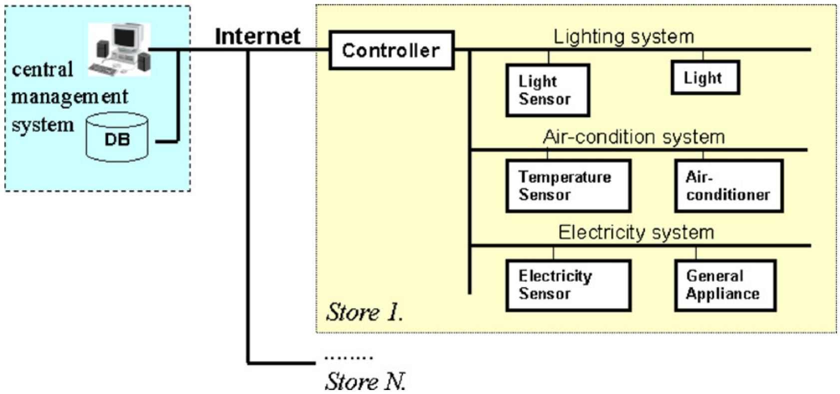


Fig. 1. The energy management system structure of convenience stores.

implement the designed control functions for electricity, air-conditioning, lighting, and the like.

(2) The chain store central energy saving and management system

This subsystem includes the link management, database system, energy management analysis/decision software, proprietary/customer application, and value-added application interface. Through the backbone of the network, the store group management, decision-making analysis, and convenience store-specific add-on functions can be integrated.

(3) The convenience store-specific energy saving and management application systems

In convenience stores, the air-conditioning, lighting, and electric power saving and control policy are analyzed and integrated with the two previously mentioned systems in order to establish a customized and proprietary energy-saving management system aimed at enhancing the total energy-saving efficiency.

The network-based energy management controller is the pivot of the whole system. It must be designed with special considerations toward the needs of convenience stores. The control system block diagram is shown in Fig. 2, where

- RISC: reduced instruction set computing,
- DOC: disk on-chip solid-state storage,
- EMS: energy management system,
- UART: universal asynchronous receiver/transmitter,
- RTC: real-time clock,
- ADC: analog-to-digital converter,
- LAN: local area network,
- DIO: digital input/output,
- I/F: interface.

The core of the present main controller is a 32-bit RISC CPU containing appropriate peripherals. With a serial port to the LonWorks bridge interface [11], the controller can communicate with distributed sensors via power-line or twist-pair cable. The important equipment status and operation parameters can be read out, such as electric power, refrigeration, air-conditioning, and lighting. The data can then be shown on an LCD display, saved in a disk on a chip (DOC) as historical

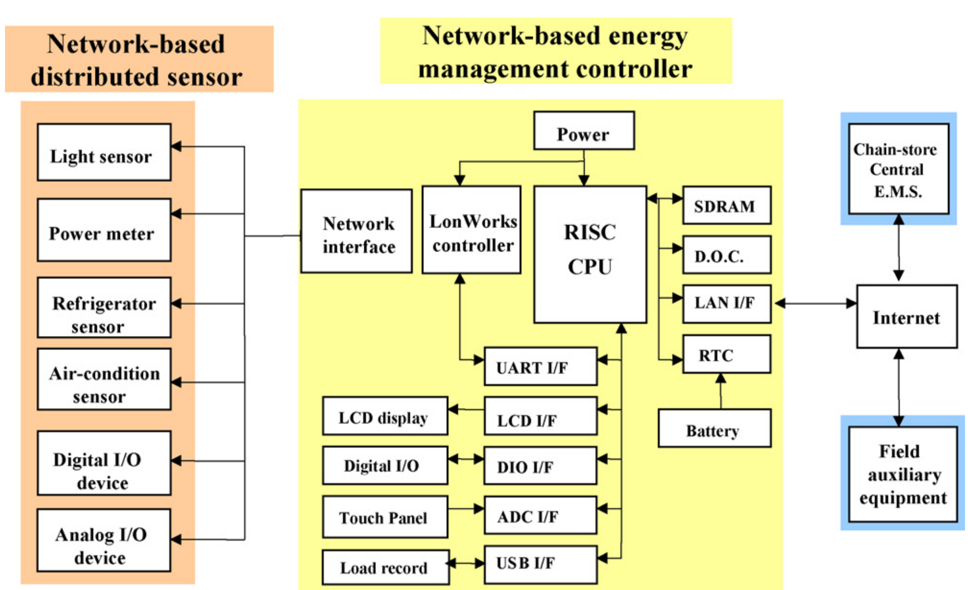


Fig. 2. The block diagram of the network-based energy management system.

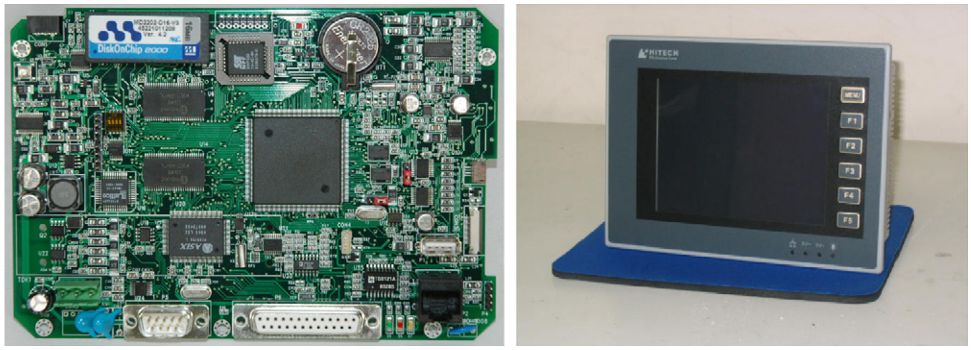


Fig. 3. The main controller of the management system.

records, and exported to other portable storage media via the USB port. The energy management policy and decision can be executed by the CPU. Then through fieldbus communication, the control can be activated to drive the I/O interface and the energy-saving control action. The main controller also has a built-in embedded http/FTP server, which can be linked with the chain store through the Intranet or Internet.

3. Hardware design

3.1. Main controller

The major parts of the present management system and their functions are introduced as follows:

(1) Main control circuit

An embedded RISC CPU [12] is adopted for this controller, as shown in Figs. 2 and 3, with the following specifications:

- CPU: 32-bit RSIC, SH7727-160 MHz,
- RAM: 64 Mbytes SDRAM,
- Flash: 32 Mbytes NOR type,
- DOC or CF Card: optional 32 Mbytes,
- Ethernet: 10/100 Mbps,
- UART: 2 ports (Debug port, LonWorks interface),
- USB: host 1, slave 1,
- RTC: battery back-upped,
- I/O port: reserve GPIO for extension,
- VGA: on-chip LCD controller,
- Audio CODEC interface.

(2) LonWorks module

Based on a LonTalks standard, a LonWorks host is designed with LonWorks to an UART (RS232) gateway function. Its major features are as follows:

- ECHELON 3150 CPU,
- Twist-pair Transceiver,
- Free Topology,
- LonWorks to RS232 Gateway interface.

3.2. Distributed sensors and network-based power communication

Sensor nodes such as electric power, lighting, temperature, humidity, and generic I/O are required in a real convenience store environment. Their general properties are the following:

(1) The LonTalks fieldbus communication interface of a sensor node can be linked with the network-based energy management controller. The physical network media can either be a power-line or a twist-pair cable, which will support pier-to-pier communication up to 5 and 50 kbps, respectively.
(2) Usually, the precision of an electric power sensor should be better than 3%. The lighting, temperature, and humidity sensor operation ranges should be chosen according to the specific equipment.
(3) Generic I/O nodes can be made up of a digital I/O interface with isolated contacts, and all the nodes are expandable when necessary.
(4) All sensors have internal power modules and accept 110/220 VAC or 24 VDC.

The network-based power communicator is a distributed power sensor and meter possessing fieldbus communication ability, as shown in Fig. 4. It is designed to measure the single-loop accumulated electric power (kWh) of the power plate, power distribution box, and individual electric equipment. It can be applied to various electric appliances such as lights, ice-boxes, refrigerators, and the like. The electric power consumption and electric line signal degrading conditions can be monitored to achieve long-term energy management and control.

4. Software design

4.1. Windows CE.NET operation system

Windows CE is an important real-time operation system designed by Microsoft [13]. For dedicated equipment and embedded applications, Windows CE provides flexible, versatile, and allocable configurations. In addition, with its many application programs and rich design resources, Windows CE helps users to quickly achieve necessary products and solutions.

The .NET operation framework of Microsoft's new generation computing environment is a virtual machine (or execution engine) applied as a middleware [14]. This structure can further reduce the interface communication between the operating system and applications. The new common language runtime (CLR) concept is also provided to make runtime cross-language execution possible. Moreover, many advanced functions such as just-in-time compilation and automatic

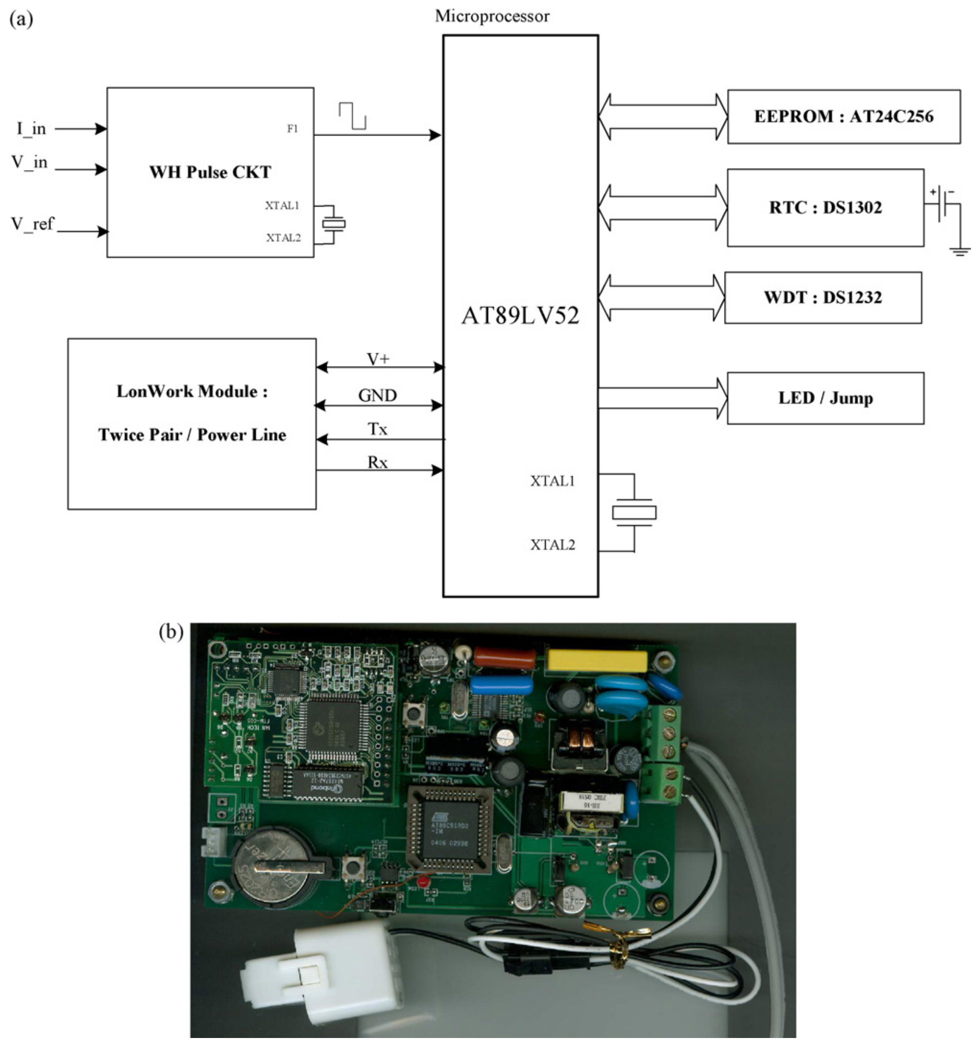


Fig. 4. The electric power sensor module. (a) The block diagram and (b) the hardware.

memory garbage collection constitute an up-to-date and important software-developing environment. The .NET platform in Windows CE is called .NET compact framework (NETCF). It is a simplified form of the complete set of the whole .NET platform designed to cope with the highly limited computation resource in small-embedded systems. Fig. 5 shows the architecture of Windows CE and NETCF. Owing to the function simplification in NETCF, the flow control in the system integration between the high-level applications and the low-level control networks must be carefully handled.

In ordinary supervisory control and data acquisition applications [15], there are two main categories, namely, monitor and control. In a monitor or supervisory operation, events and data flow toward the controller, while in a control or command operation, commands and messages flow toward the plant (equipment or process). On the other hand, viewing with the control flow, the controller presents both an active and passive operation status. The active operation is user-given, or the default operation flows with sequential commands or procedures; the passive operation is the pre-defined process driven by the plant status change or the external event excitation. Owing to the simplification in NETCF, the delegation, which is the event-driven mechanism in .NET, is not supported. This limitation leads to the inability of low-level network events to directly trigger the high-level procedures. Therefore, a more active polling or scanning in the program is required to compensate for the control and network access time.

4.2. Application program design

Based on the control network and operation system, the application program module structure of the energy management system can be shown as in Fig. 6, where the sensors are the electric power sensor, the light sensor, the temperature and humidity sensor, generic I/O device, and the like.

The user interface of the proposed system is shown in Fig. 7. The application program of the energy management system is developed in VB.NET, and it provides a user interface between the user and the controller for basic parameter setting, sensor data reading, display, saving, graphical display, and the like. Furthermore, according to the control policy, it also provides the following functions:

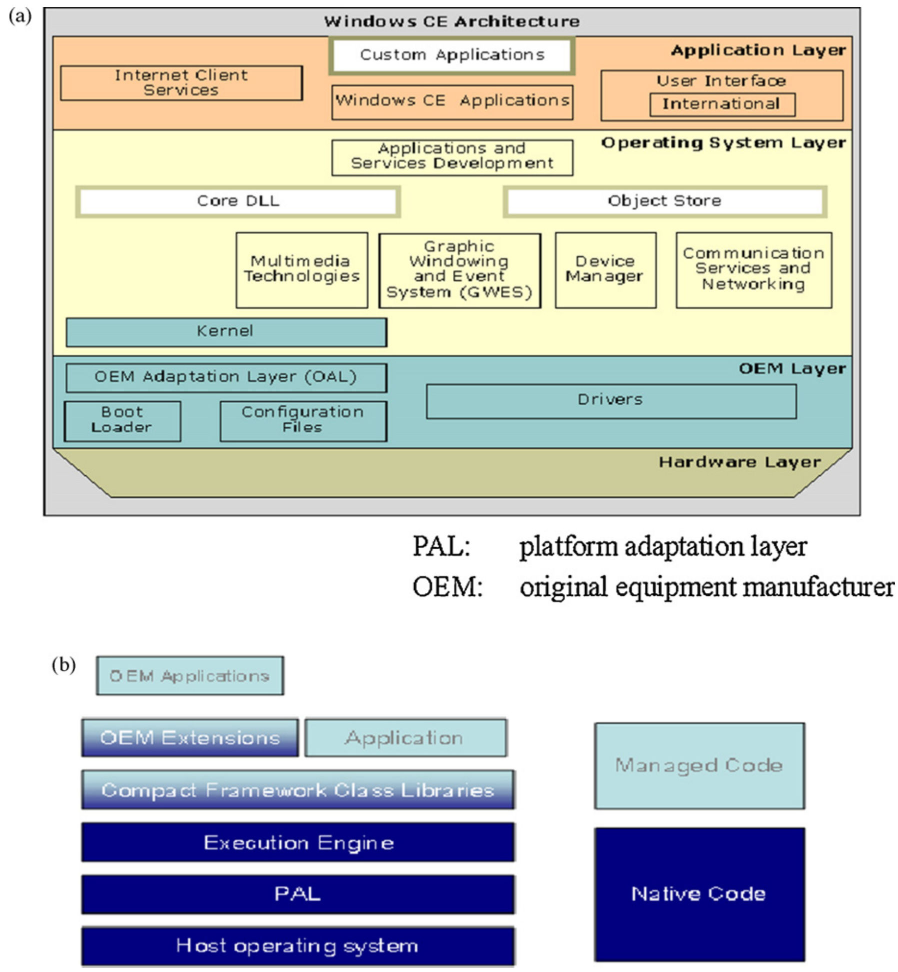


Fig. 5. The Windows CE architecture (a) and .NET compact framework (b).

- System setting: sensor profile setting, sample period, unloading mechanism setting, and the like.
- Data acquisition and recording: electricity, temperature, humidity, CO_2, data process, collection, and record saving.
- Remote data access: link remote SQL server and perform database operation (new, modify, delete, etc.) via ADO.NET.
- Demand control: monitor electric power demand and control equipment loading and unloading.
- Alarm function: provide warning or alarm via I/O and network devices.
- Data display: provide real-time and historical data display and tendency analysis.

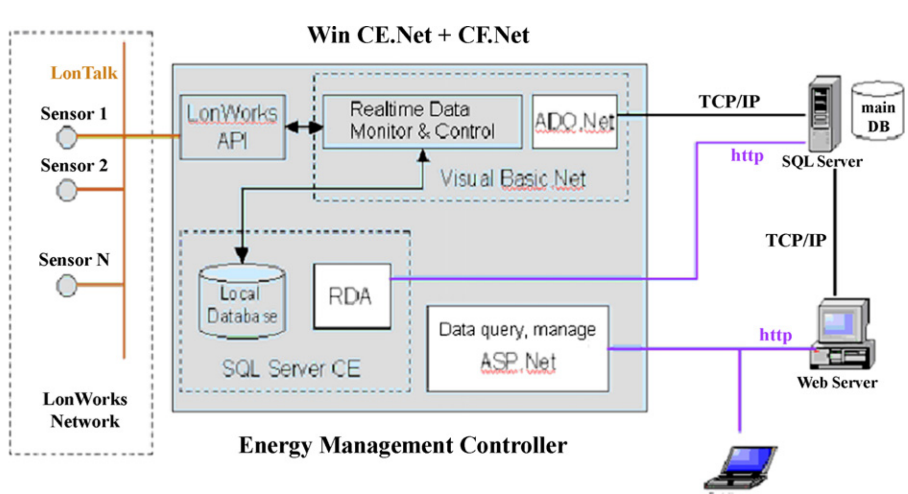
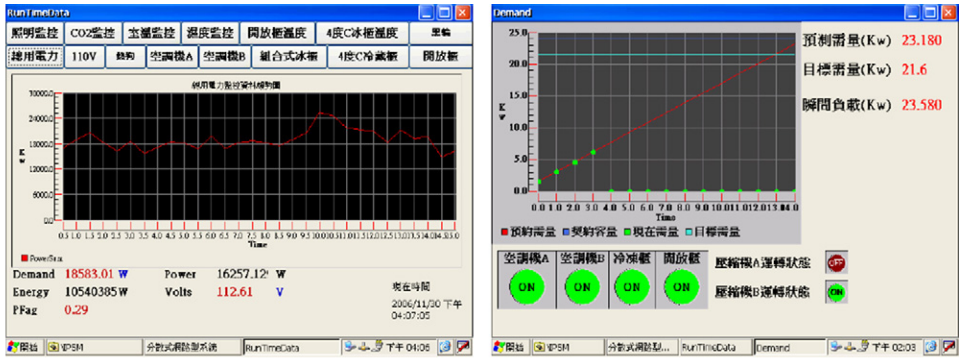


Fig. 6. The application program module of the network-based energy management system.



(a) (b)

Fig. 7. Examples of the controller user interface. (a) Real-time electric power data display and (b) demand trend prediction.

- Control network: provide LonWorks API and communication applications.

4.3. Demand management

Power demand refers to the average effective power value in a specific time period. For example, the demand period in Taiwan is computed every 15 min. By monitoring the electric power consumption of convenience stores, the demand control system can predict whether the utility demand will violate the contract between users and the power plant. When the control system executes the demand control, the subsystem will be switched to the unloading status if the predicted value goes over the contract capacity. Thus, fines for contract violation can be reduced.

The parameters of the proposed prediction method, as shown in Fig. 8, are as follows:

- Δt: sample period (1 min).
- T: demand period (15 min).
- Q_s: target electric energy or contract capacity (kWh).
- Q_t: $0 \sim t$ electric energy (kWh).
- P_t: current demand (kWh): $P_t = \frac{Q_t}{T}$.

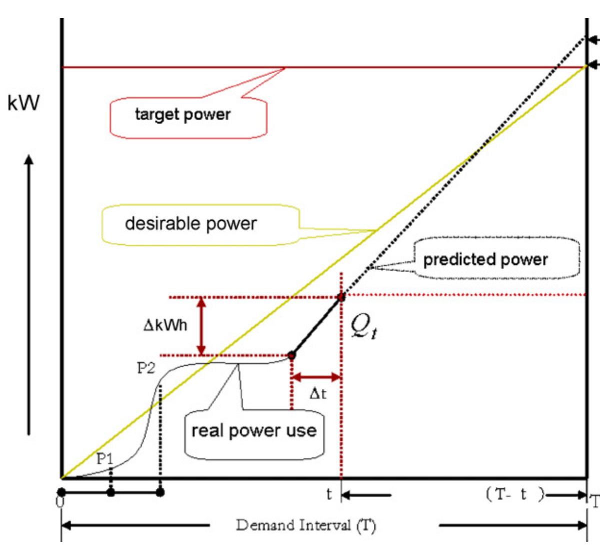


Fig. 8. The demand prediction curve.

- P_i: instantaneous load (kW): $P_i = \frac{dQ_t}{dt} = \frac{Q_t - Q_{t-1}}{\Delta t}$.
- Q_u: predict electric energy (kWh): $Q_u = Q_t + P_i(T - t)$.
- P_u: predict demand (kW): $P_u = \frac{Q_u}{T} = \frac{1}{T}\left[Q_t + \frac{dQ_t}{dt}(T - t)\right]$.

If $Q_u > Q_s$, the prediction demand is higher than the target or contract demand, and thus the demand limiting condition will occur in this demand period. The electric loading must be arranged so as not to violate the contract. Thus, the strategy of the present demand management system will unload the appliances according to a given priority sequence, which can simply be assigned by a user according to the power consumption amount for an individual appliance. In the convenience store, the air-conditioner is the most obvious power consumer, so it is usually assigned the highest priority to be unloaded. For example, as shown in Fig. 7(b), when the power unloading operation is required, the control system will inactivate the compressor A to avoid the violation of the contract. After the peak demand period

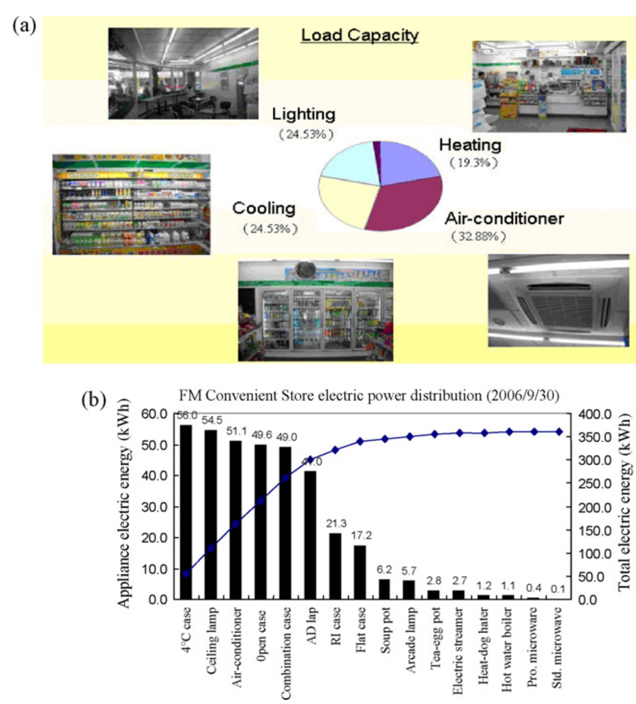


Fig. 9. The electric power consumption analysis results. (a) Load capacity share and (b) appliance distribution.

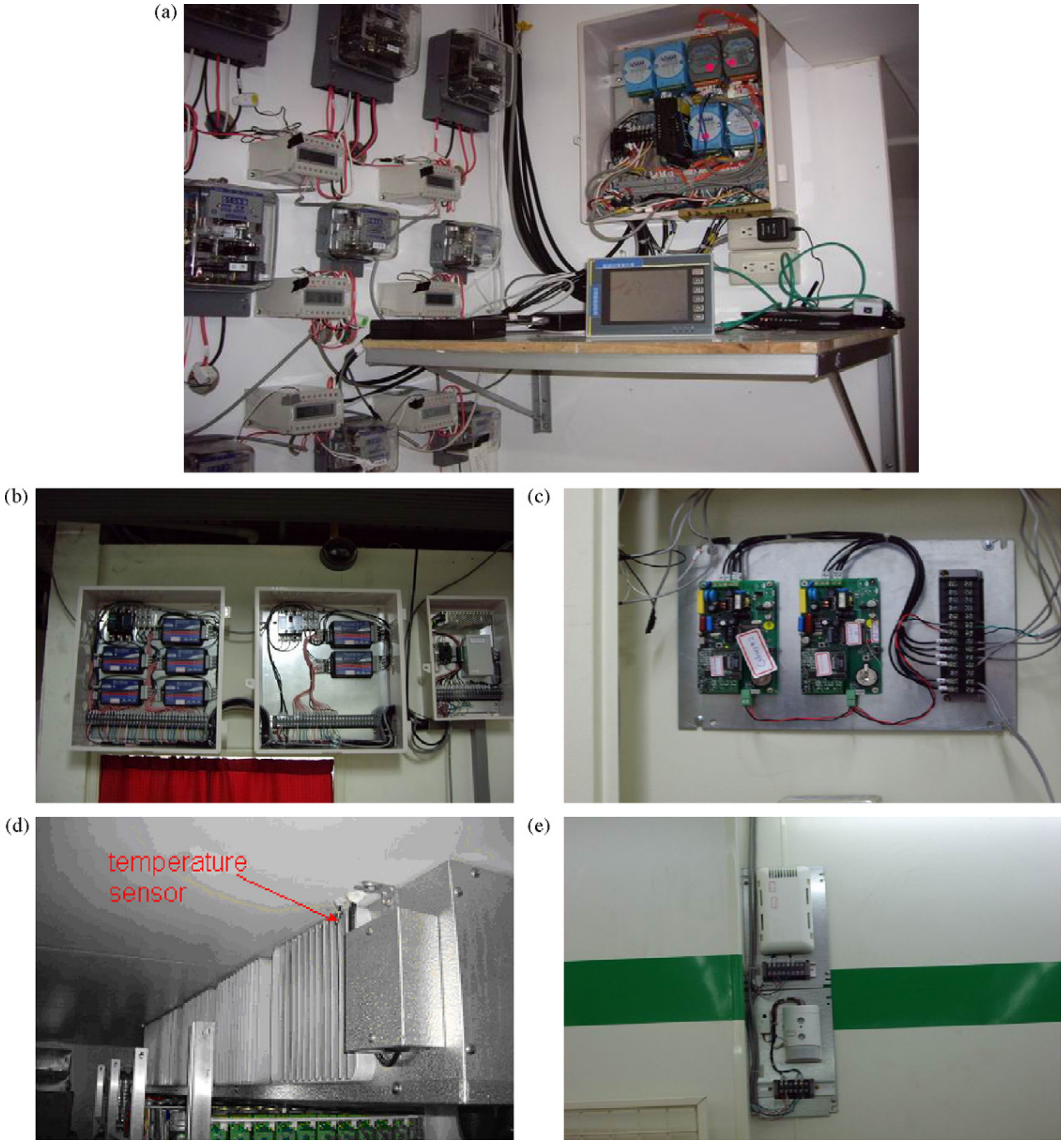


Fig. 10. The convenience store energy management system: (a) overview; (b) 220 V power meter and DIO module; (c) 110 V power meter; (d) low-temperature sensor in combination case; (e) indoor temperature, humidity, CO_2, and illumination sensor.

is passed and the demand is back to a normal value, the compressor A is reloaded again.

5. Experimental setup

In order to test and verify the proposed approach, the developed energy management systems have been implemented in several convenience stores to examine its functions and feasibility. The basic energy-consuming facilities of convenience stores are the air-conditioning equipment, the refrigerator and freezing equipment, the lighting and heating equipment, and the cooking appliances. Fig. 9(a) presents the statistical results of the capacity of the major energy-consuming equipments. The air-conditioner, refrigerator, and lighting equipment hold the largest share of the total energy consumption. According to a sampled 1-day power consumption chart shown in Fig. 9(b), the energy consumption amount is mainly sorted as air-conditioner (2 sets), the 4 °C refrigerator, the ceiling lamp, the open case, the combination case, the advertisement lamp, the rear-in (RI) case, and the flat case.

Considering the practical energy-saving policy, because convenience stores usually adopt brighter lamps in order to attract customers, it is not feasible to promote energy saving in lighting. The present management system practically focuses mainly on the measurement and control of the air-conditioner and the refrigerator. In addition, temperature, humidity, and illumination data are recorded for further cross-analysis to formulate a better energy-saving policy.

This demonstration system measures the following parameters:

- Main meter: average voltage and current, power factor, instantaneous power, power demand, and the like.

- 110 V meter: average voltage and current, power factor, instantaneous power, power demand, and the like.
- Air-conditioner A: instantaneous power and accumulated power.
- Air-conditioner B: instantaneous power and accumulated power.
- Open case: instantaneous power and accumulated power.
- 4 °C case: instantaneous power and accumulated power.
- Combination case: instantaneous power and accumulated power.
- RI case: instantaneous power and accumulated power.
- Tea-egg pot: accumulated power.
- Soup pot: accumulated power.
- Indoor: temperature, humidity, illumination, and CO_2 concentration.
- Outdoor: temperature and illumination.

The system also provides the following applications:

- Power monitor: electric power record of the individual payload.
- Power quality monitor: measures and records electric information such as voltage, current, power factor, and the like.
- Status monitor: alarm/warning points can be set on critical equipment.

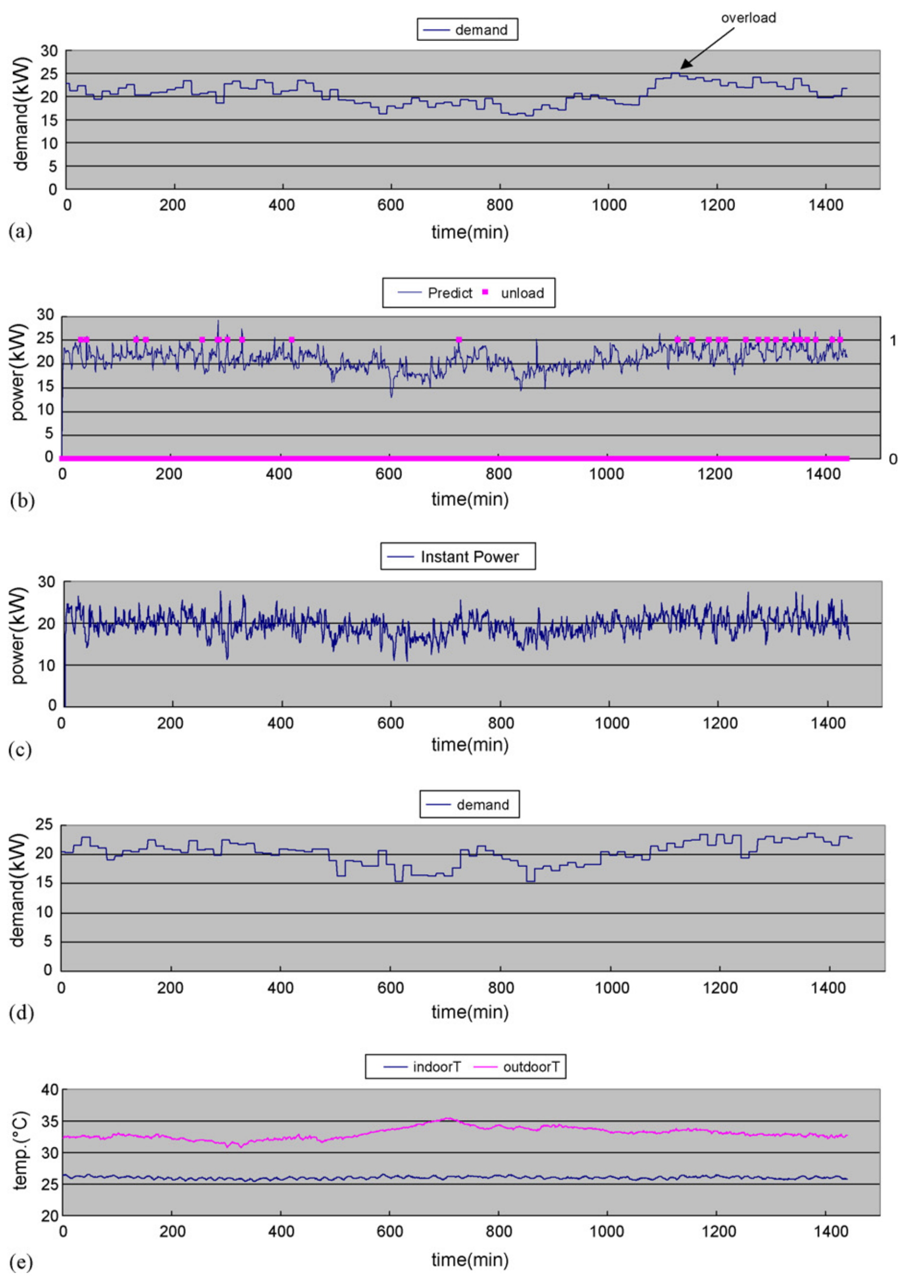


Fig. 11. Experimental results. (a) The averaged power consumption (without the demand control), (b) the power prediction of demand limiting (without the demand control), (c) the instant power recording (with the demand control), (d) the averaged power consumption (with the demand control), and (e) the stable indoor and outdoor temperatures (with the demand control).

- Demand monitoring and control to predict the limiting condition and provide the unloading function when the power violates the contract capacity, thus reducing the power demand and avoiding penalty.
- Air-quality monitor: measures indoor CO_2 concentration and provide alarm.
- Refrigeration monitor: measures temperatures in the refrigerators to provide automatic temperature control or alarm function.
- Statistics and analysis: with long-term data collection, the results can be applied to optimize the energy-saving policy.

During the implementation process, each power loop is measured with the power meter, and the power information and load variation are also collected. The data are then analyzed, and the appropriate sensor nodes and control policies are arranged for long-term monitoring and control. In the shop floor, proper measure locations also need to be decided to install the sensors. Finally, system integration and test are performed to execute the long-term data collection and analysis for future modifications of the decision policy. The real system implementation of the present design is shown in Fig. 10.

6. Experimental results

The experimental results are automatically recorded for 24 h. One example on 26 August 2006 is shown in Fig. 11(a). There are two air-conditioners in the present experimental store. Without applying the present management system, the results indicate that the store's energy consumption may exceed the contact value of 25 kW, as shown in Fig. 11(b). Based on the predicted value of electrical energy, the assigned high-priority air-conditioner (number 1) is unloaded first and then number 2 is also unloaded when it is necessary. By implementing the present management system, the prediction mechanism and unloading controls effectively limit the demand from running over the contract demand of 25 kW as shown in Fig. 11(d). Meanwhile, the room temperature, which is also appropriately regulated as shown in Fig. 11(e), is not affected by the on/off status of the air-conditioners. The contract violation condition can thus be successfully avoided by turning off the two air-conditioners sequentially as required, even with a maintained room temperature.

7. Conclusion

In order to reduce power consumption in the widely located convenience stores, this research successfully completes the development and establishment of a distributed energy management and control system through the Internet. The developed system has been successfully integrated and verified in a remote convenience store to confirm the designed system performance not only by reducing the peak load but also by ensuring that the indoor temperature regulation is not significantly affected.

This research results can enhance the concept and technology of energy saving in order to improve energy utilization efficiency in real applications. Further operation research on integration with the store's business model in order to optimize electric power usage in a local area through the Internet should be of great potential.

Acknowledgments

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