Research for Control Strategy of Smart Home Energy Management System with Distributed Photovoltaic Generation and Application Practice

Jinfeng Li, Kai Jiang, Zhixin Wang, Xiaozhuo Xu, Liang Wang, and Chao Zhang

***Abstract*—To combine the PV generation and household appliances and realize the energy management for the whole resident, a smart home energy management system (HEMS) which contributes to both the utility grid in load shifting and the customers in cutting electricity bill is proposed. A household appliances network on the base of ZigBee technology is designed to realize remote control and monitoring as well as electricity consumption information gathering. In this system, home appliances are divided into two types based on their operation feature and a mathematic model of resident energy consumption is built, dividing the time of a day into 480 time slots. Combined with varying electricity price in Shanghai as well as the real-time power supply from the PV system, the optimal schedule of appliances operation can be figured out taking situations both with and without a storage battery into consideration. A simulation is carried out in MATLAB environment and the result shows a good performance and a considerable economic benefit in different situations..**

***Index Terms*—Appliances scheduling, distributed PV generation, electricity consumption information gathering, home energy management system (HEMS).**

I. Introduction

Nowadays the energy industry is facing a series of problems such as rising demand for electricity, growing peak-to-valley ratio of energy demand and environment pollution due to energy generation [1], [2]. To solve these problems, renewable energy, like distributed photovoltaic generation, has been proven to be effective. To the grid, distributed photovoltaic generation can efficiently cut the peak demand by offering solar power to the customers. To the customers, the PV generation system can reduce the energy cost. Besides, installing the PV generation is a good investment now since the government announced in 2013 an encouraging policy that customers who install the PV generation system will get a subsidy according to the amount of PV generation and the grid company will buy the excessive energy from residents at a certain price.

However, related energy management system and control strategy have not been carried out yet. Customers who install a household PV generation can only benefit from the PV output but not the energy management for the household appliances.

At noon, when it is the peak time and the electric tariff is high, the output power of the PV generation system is huge since the solar radiation is strong. By scheduling the appliances to shift their operation time from the peak period, such as the noon, to the off-peak period, such as the morning or the evening, the total energy cost can be reduced. To cut the household electricity bill, the paper proposes a home energy management system which can collect the electric information and shift the operation time of the appliances.

II. Home Energy Management System with a Distributed PV Generation

Smart home is a newly-developing appliances energy management platform combined with network communication, electric information of appliances, and devices automation. It contains system, structure, service and management to ensure the efficiency, comfort, safety and convenience of the home environment [3]. Based on a home communication network, the system can collect the operating condition and electric information of the appliances, which makes it convenient and intelligent to monitor and control the appliances in long distance [4]. On this platform, we can take a further research of household energy consumption model and find the optimal plan or schedule of using appliances. Smart home energy management system can also control the appliances according to the optimal schedule automatically to minimize the electricity bill.

A. The Structure of Smart Home Energy Management System with a PV Generation

A smart home with a distributed PV generation system consists of a solar PV panel, an energy storage system, an inverter, electricity meters, both sing directional and bi-directional, home communication network and appliances. References [5]-[7] present the main technologies of micro-grid. Fig. 1 shows a structure of the smart home energy management.

The solar PV panel generates DC energy, which is connected to the storage battery through a DC-DC converter with MPPT function. If the PV output is sufficient and the

Manuscript received May 22, 2015; revised September 23, 2015. This work was supported in part by the Natural Science Foundation of China (No.51377105), National 863 Program (No.2014AA052005), Lian Meng Program of Shanghai (No.2015LM11), Science and Technology Program of Jiaxing (No.2014BZ15002) and Science and Technology Program of Minhang District, Shanghai (2014MH103).

Jinfeng Li, Xiaozhuo Xu, and Liang Wang are with Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: lijinfengdanny@163.com).

Kai Jiang is with the Shanghai Municipal Electric Power Company, Shinan Supply Company, Shanghai 200110, China (e-mail: jimmy_kate@sina.com).

Zhixin Wang is with the Dept. of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China; he is also with the Jiaxing Renewable Power Electrical Co., Ltd., Jiaxing, Zhejinag 314031, China (e-mail: wangzxin@sjtu.edu.cn).

Chao Zhang is with Shanghai Naijie Electric Unit Ltd., China.

doi: 10.18178/jocet.2016.4.6.320

battery power is insufficient, the battery will be charged by the PV output. On the contrary, if the PV output is insufficient and the battery power is sufficient, the battery will supply the appliances along with the PV generation [8]. The inverter output is precisely 220V and 50Hz and the amount of PV generation can be measured by a smart meter to calculate the subsidy. The grid is connected to the house through a bidirectional meter to measure energy trading between the grid and the resident in both directions. Both the grid and the PV generation offer power supply to the appliances.

The communication network within the house can be used to collect the real-time electric information of each appliance, including operating time and rated power. Technology of ZigBee becomes a mainstream when it comes to smart home communication network because the high capacity and convenience to be installed and expanded. In this system, every single appliance is connected to a module which can collect and send the electric information of the appliance to the central PC with a RF function. Meanwhile, the module can realize the remote controlling and energy management to every appliance. The PV generation system can also be considered as an appliance so we can get the PV output using the module and all this information is used to calculate the optimal schedule of appliances operation.

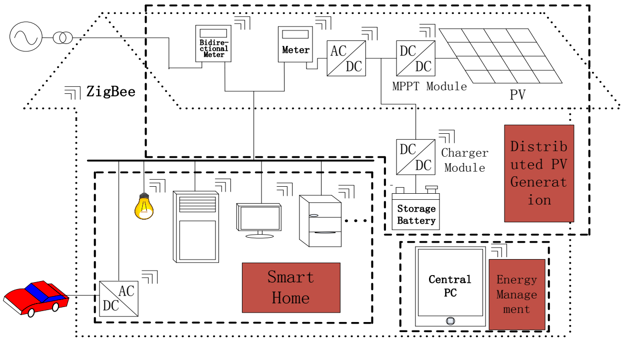

Fig. 1. Structure of smart home energy management.

In this paper, we propose a home energy management system based on ZigBee technology to connect all the appliances into a communication network. Within the ZigBee network, every appliance is a nod point and the central PC is a coordinate point. Nod points will collect electric information and send it to the coordinate point through ZigBee transmission and the coordinate point will send the information to the central PC, which will analyze the electric information, the PV output and the tariff to obtain the optimal schedule of using appliances. According to the schedule, the coordinate point will send control signal to every nod point, scheduling every appliance to operate in a set period [9], [10].

B. Hardware Design of Home Energy Management System

Fig. 2 shows the hardware circuit for communication network that consists of coordinate point and nod points.

A high accuracy electric energy measurement chip ADE7755 is the core of electric energy metering module and a CC2530 manufactured by TI company with a high performance RF transceiver is the core of wireless communication module. With the combination of these two modules the electric information can be collected and sent to the central PC.

The plug is connected to the energy measurement module through a relay with an photo-coupling isolation and the output of the measurement module offers power supply to the appliance. The electric information obtained by the measurement module is displayed on the screen of 1602LCD. Meanwhile, ADE7755 is connected to CC2530 nod point through serial port to transfer electric information, which will then be transferred to CC2530 coordinate point through ZigBee. CC2530 coordinate point is connected to the central PC through serial port to transfer the electric information so the central PC can obtain all the information for appliances scheduling. After calculation for the optimal schedule is finished, the control signal will be transferred reversely through the network channel described above to turn on or turn off the appliances by controlling the relays. Fig. 3 shows the system diagram.

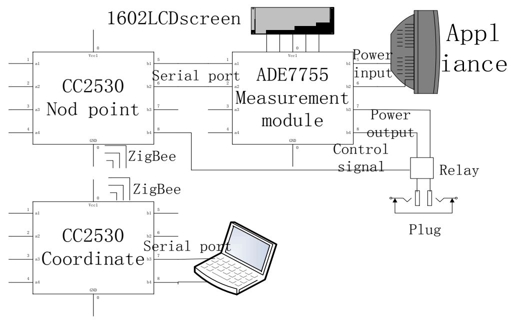

Fig. 2. Hardware circuit for communication network.

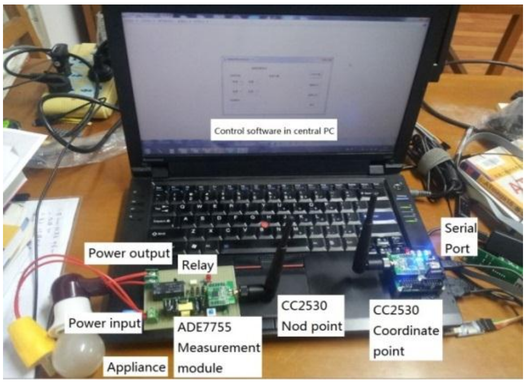

Fig. 3. System diagram.

C. Software Design of Central Controller

The software system is built in the environment of VISUAL STUDIO C++ MFC, including functions of information display, long distance control, energy efficiency analysis and energy management. Fig. 4 shows the software interface.

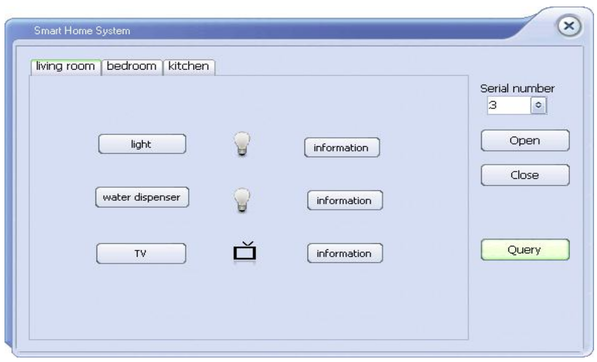

Fig. 4. Software interface.

III. Mathematic Model of Household Electricity Consumption

The smart home energy management system makes it possible to figure out the optimal appliances' operation schedule by building a mathematic model for household energy consumption. To convert continuous issue into discrete, we need to divide 24 hours of a day into several time zones with the same duration and the precision can be promised as long as the resolution is high enough. We have therefore introduced the concept of time slot, which represents a small period of time. Mark the time slots from 1 to H and every slot lasts T. We have $TH = 24h$. t represents the tth time slot, namely $[(t-1)T, tT]$. When H is set large enough, it makes the duration of $[(t-1)T, tT]$ very short and we can suppose that within a time slot electric information and operating feature of every appliance stay unchanged. With the PV output data and the electric information of appliances, a mathematic model of home energy management can be built.

A. Prediction of PV Output

PV output is necessary for home energy management. We can get the predictive data of the next day based on the data and the type of weather of the previous day as well as the type of weather of the next day using the BP neural network predictive model [11]. We use $\overline{P_{PV}(t)}$ to represent the PV output in time slot t of the previous day and $P_{PV}(t)$ to represent the data of the next day. Similarly, $\overline{\partial_a}$ and ∂_a represent respectively the type of weather of the previous day and the next day, where $a = 1, 2, 3$ means sunny, cloudy and rainy. We can get $P_{PV}(t)$ with $\overline{P_{PV}(t)}$, $\overline{\partial_a}$ as well as ∂_a and then replace $\overline{P_{PV}(t)}$ and $\overline{\partial_a}$ with the data of the next day.

B. Classification of Household Appliances

In general, appliances can be categorized into two types, deferrable and non-deferrable, depending on their operation features. For example, cookers, TVs should be activated in a certain time and are non-deferrable because their operating time can't be deferred in order to ensure the comfort of the user. Others, such as washing machines and water heater, are deferrable since the delay of their operation won't cause any inconvenience. This kind of appliances is flexible and can be shifted to valley period to reduce the tariff.

We consider the situation of a house with a set of P_{Lt} devices and the number is N, including a set of deferrable devices and a set of non-deferrable devices. i is the ID of the appliances, $i = 1, 2, \cdots, N$, and $P_{Lt}(i)$ refers to the i th appliance. To non-deferrable appliances, their rated power, time to be activated and the duration of operation are all determined by the feature of their operation. To deferrable appliances, their rated power, possible time region for operation and the duration of operation are already determined by their feature, while the time to be activated is undetermined yet. The precise start time of the set of deferrable appliances determines the total electricity bill so the task of home energy management is to find the optimal scheduling for start time of every deferrable appliance.

C. Mathematic Model of Home Energy Management

Mathematic model of home energy management is on the base of real-time power balance. The total energy demand for the appliances is satisfied by the sum of the PV output, the storage battery output and the utility grid supply. The real-time power balance can be expressed as:

$$P_{pv}(t) + P_b(t) + P_g(t) = \sum_{i=1}^{N} P_{Lt}(i,t) \tag{1}$$

where $P_g(t)$, $P_{PV}(t)$, $P_b(t)$, $\sum_{i=1}^{N} P_{Lt}(i,t)$ refers respectively to the grid supply, the PV output, the storage battery output and the total household electrical power demand for all its appliances in time slot t and they are all quantified in W.

Use $price(t)$ to represent the tariff in time slot t and the minimum electricity bill can be expressed as:

$$\begin{aligned} &\min \sum_{t=1}^{H} price(t) \bullet P_g(t) \bullet T \\ &= T \min \sum_{t=1}^{H} price(t) \bullet (\sum_{i=1}^{N} P_{Lt}(i,t) - P_b(t) - P_{pv}(t)) \\ &= T \min [\sum_{t=1}^{H} price(t) \bullet (\sum_{i=1}^{N} P_{Lt}(i,t) - P_b(t)) - \sum_{t=1}^{H} price(t) \bullet P_{pv}(t)] \end{aligned} \tag{2}$$

Since the PV output and the tariff are already determined, the second part of the formula is a known quantity. So the total bill is only determined by the scheduling of appliances and the strategy of charging the storage battery.

We assume a house with the following appliances and every detail of the appliances are shown in Table I, including the duration of operation, the time zone possible to be activated and the rated power.

When $D_i > C_i$, the i th appliance is deferrable and its operation can be deferred for s_i. So the start time is $T_i + s_i$ and the terminal time is $T_i + C_i + s_i$. In time slot t, the power of the i th appliance can be expressed as:

$$P_{Lt}(i,t) = \begin{cases} P_L(i) & T_i + s_i \le t < t+1 \le T_i + C_i + s_i \\ 0 & t+1 < T_i + s_i \ \text{ or } \ t > T_i + C_i + s_i \end{cases}$$

where $P_L(i)$ is the rated power of the i th appliance.

To simplify the model, we first assume the situation without a storage battery and (2) is equal to:

$$\begin{aligned} &\min \sum_{t=1}^{H} price(t) \sum_{i=1}^{N} f(t) P_L(i) T \\ &s.t. \quad 0 \le s_i \le D_i - C_i \end{aligned} \tag{3}$$

where $f(t) = \begin{cases} 1 & T_i + s_i + 1 \le t \le T_i + s_i + C_i \\ 0 & \text{others} \end{cases}$

In consideration of the features of the storage battery, we can make a charging strategy to pursue the optimal output. During off-peak period we charge the battery with grid supply and discharge it during the peak period [12]. Assume that the depth of discharge is B, namely:

$$\sum_{t=N_{st}}^{N_{fh}} P_b(t)T = B \tag{4}$$

where $[N_{st}, N_{fh}]$ represents the peak period.

Besides, the battery output has a limitation, namely:

$$P_b(t) \le P_{b\max} \tag{5}$$

Ignoring the constant section, the model is equal to:

$$\min \sum_{t=1}^{H} price(t)\left[\sum_{i=1}^{N} f(t)P_L(i) - P_b(t)\right]T \tag{6}$$

$$\begin{aligned} s.t.\quad & 0 \le s_i \le D_i - C_i \\ & \sum_{t=N_{st}}^{N_{fh}} P_b(t)T = B \\ & P_b(t) \le P_{b\max} \end{aligned} \tag{7}$$

We assume that when the output of PV is sufficient, the excessive power will be sold to utility grid company at the same price as the tariff when resident user absorbs the power from the grid. In that situation, we have $P_g < 0$.

IV. Simulation and Analysis

For electricity tariff, we adopt the varying electricity price of Shanghai. The peak tariff is 0.617 RMB/kWh and the off-peak tariff is only 0.307 RMB/kWh. For household appliances, refer to electric information shown in Table I. For PV output, we adopt the data given by new energy research center of Huazhong University of Science and Technology in [13]. Table II shows the PV output data.

Simulation is carried out in the environment of MATLAB and comparison of 3 different conditions is made, including optimization with a storage battery, optimization without a storage battery and non-optimization. Fig. 5 illustrates the electricity bills for all the conditions. X axis represents the number of time slot. $H = 480$, $T = 3\text{min}$. Y axis represents the electricity bill.

In Fig. 5, the rising of the curves indicates that the resident absorbs power from the grid so the bill keeps increasing when the electricity demand of the house cannot be fully supported by the PV and the storage battery. On the contrary, the falling of the curves indicates the output of the PV and the storage battery is sufficient and the system sells the excessive power to the grid and earns profit. Curve C represents the bill of a house with distributed PV generation but without a home energy management system. For condition C, when the PV output is inadequate and increasing appliances are activated at 7:30 am, the curve begins to ascend. At 10:00, the solar radiation is strong enough and the PV output starts to increase and exceed the electricity demand, the curve begins to descend. At 17:30, the PV output is almost zero and the resident electricity demand encounters the evening peak with the curve ascending again. At the end of the day the bill is close to 0, showing that the PV generation can satisfy the basic demand of the household appliances. For condition A, the curve shows the real-time electricity bill of a house with the PV generation as well as the home energy management. The curve shows that the operation of some certain appliances have been limited during peak period at noon and shifted to off-peak period in the evening.

TABLE I: Information of Household Appliances

ID	Duration of operation C_i	Start time T_i	Deferrable Range D_i	Rated Power P_i/W	Appliances N_i
1	15	60	480	280	Washing machine
2	30	0	140	1200	Dish-washing machine
3	15	380	30	1500	Water heater
4	260	140	260	55	Water fountain
5	480	0	480	35	Smart house system
6	180	180	180	25	Air humidifier
7	480	0	480	30	Refrigerator
8	10	220	10	750	Cooker 1
9	10	390	10	750	Cooker 2

TABLE II: PV Output Data

Time	t	PV output/W
9:00-10:00	181-200	200
10:00-11:00	201-220	1280
11:00-12:00	221-240	2500
12:00-13:00	241-260	2700
13:00-14:00	261-280	2300
14:00-15:00	281-300	1950
15:00-16:00	301-320	2050
16:00-17:00	321-340	1150
17:00-18:00	341-360	350

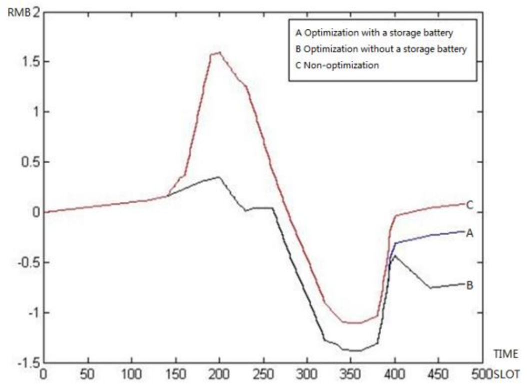

Fig. 5. Illustration of electricity bills.

This kind of scheduling can both shave the peak load of the utility grid and decrease the resident electricity bill. In this paper, the amount of money saved by the home energy management is small since we only take a few appliances into consideration. However, it will be of great significance with an incentive varying electricity price policy which is very likely to be carried out to encourage the social public to conserve energy and reduce emission in the future. For condition B, the curve shows the real-time electricity bill of a house with the PV generation and a storage battery as well as the home energy management. Analysis shows that a storage battery, which costs a lot, can bring a great profit on the other hand. Therefore residential users should decide whether to install a storage battery or not according to their individual situation.

REFERENCES

[1] Y. Zhang, P. Zeng, Z. Li *et al*., "A multi-objective optimal control algorithm for air conditioning system in smart grid," *Power System Technology*, vol. 38, pp. 1819-1826, July 2014.

[2] Y. Wang, S. Yue, and M. Pedram, "A hierarchical control algorithm for managing electrical energy storage systems in homes equipped with PV power generation," presented at the IEEE Green Technologies Conference, Tulsa, OK, America, April 19-20, 2012.

[3] H. Peng, "Research of architecture and key technologies of the intelligent home," M.S thesis, School of Electrical Engineering, Beijing Jiao Tong University, Beijing, 2012.

[4] L. Deng, Z. Wang, J. Shen *et al*., "Smart distribution technology and its application," *Power System and Clean Energy*, vol. 28, pp. 10-15, March 2012.

[5] C. Wang, B. Jiao, L. Guo *et al*., "Optimal planning of stand-ablong microgrids incorporating reliability," *Journal of Modern Power System and Clean Energy*, vol. 2, pp. 195-205, March 2014.

[6] L. Qing and X. Zhao, "Recent advancements on the development of microgrids," *Journal of Modern Power System and Clean Energy*, vol. 2, pp. 206-211, March 2014.

[7] Y. Li and N. Farzam, "Overview of control, integration and energy management of microgrids," *Journal of Modern Power System and Clean Energy*, vol. 2, pp. 212-222, March 2014.

[8] Z. Liao and X. Ruan, "Energy management control strategy for stand-alone photovoltaic power system," in *Proc. the CSEE*, July 2009, vol. 29, pp. 46-52.

[9] C. Adika and L. Wang, "Autonomous appliance scheduling for household energy management," *IEEE Transactions on Smart Grid*, vol. 5, pp. 673-682, Feb. 2014.

[10] Z. Zhao, W. Lee, Y. Shin *et al*., "An optimal power scheduling method for demand response in home energy management system," *IEEE Transactions on Smart Grid*, vol. 4, pp. 1391-1400, March 2013.

[11] X. Yuan, J. Shi, and J. Xu, "Short-term power forecasting for photovoltaic generation considering weather type index," in *Proc. the CSEE*, Dec. 2013, vol. 33, pp. 57-64.

[12] T. Tazoe, J. Mstsumoto, D. Ishi *et al*., "Novel scheduling method to reduce energy cost by cooperative control of smart houses. In: Power System Technology (POWERCON)," presented at the IEEE International Conference, Auckland, New Zealand, Oct. 30-Nov. 2, 2012.

[13] C. Chen, S. Duan, and J. Yin, "Design of photovoltaic array power forecasting model based on neutral network," *Transactions of China Electro-Technical Society*, vol. 24, pp. 153-158, May 2009.

Jinfeng Li was born in Zhanjiang, Guangdong, China, in 1989.

Mr. Jinfeng Li obtained his master degree from Shanghai Jiao Tong University of Electrical Engineering in 2015. His main research field is distributed PV generation and home energy management.

Kai Jiang was born in Shanghai, China, in 1982. Mr. Kai Jiang obtained his B.Sc degree from Shanghai Jiao Tong University China in 2005. His main research field is distributed PV generation and power system operation management.

Zhixin Wang was born in Shanghai, China, in 1964. Prof. Zhixin Wang obtained his PhD from Zhejiang University China in 1994. His main research field is distributed PV generation and home energy management.

Xiaozhuo Xu was born in Zhangjiakou, Hebei, China, in 1993. Mr. Xiaozhuo Xu obtained his B.Sc. degree from Zhejiang University of Electrical Engineering in 2014. His main research field is distributed PV generation and home energy management.

Liang Wang was born in Jingzhou, Hubei, China, in 1991. Mr. Liang Wang obtained his B.Sc. degree from Tianjin University of Electrical Engineering in 2013. His main research field is distributed PV generation and home energy management.

Chao Zhang was born in Huzhou, Fujian, China, in 1982. Mr. Chao Zhang obtained his B.Sc. degree from Fuzhou University in 2003. His main research field is distributed PV generation and home energy management.