Optimization of the Power Flow in a Smart Home

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Abstract. With the IT technology, the traditional power grid is being upgraded to the smart grid (SG) with two-way communication and power flow between utilities and customers. In addition, SG includes new technologies in distributed energy generation (DEG) and distributed energy storage (DES), advanced measurement and sensing, controls, cyber security, consumer-side energy management, and environment protection. Thus, it shows the advantages in efficiency, reliability, and security. A smart home is a mini power system with the renewable energy resources and the local energy management. Therefore, the emission and the power consumption can be reduced while the system efficiency will be improved. In this paper, particle swarm optimization is used to manage the power flow in a smart home with the objectives in the minimum cost and maximum comfort. Results from two homes with different size of PV systems are compared and discussed. The PV size for a stand-alone home is determined.

Keywords: Demand response · Distributed generation · Electric vehicle

1 Introduction

With the IT technology, the traditional power grid is being upgraded to the smart grid (SG) with two-way communication and power flow between utilities and customers. In addition, SG includes new technologies in distributed energy generation (DEG) and distributed energy storage (DES), advanced measurement and sensing, controls, cyber security, consumer-side energy management, and environment protection. Thus, it shows the advantages in efficiency, reliability, and security. DEG plays a more and more important role in SG through peak demand reduction, congestion alleviation, and reliability. It is mainly from solar, hydro, wind, biomass, and geothermal renewable energy, and 13% of electricity was from the renewable energy in 2015. In the U.S., 37% of electricity is consumed in residences, where the heating and cooling account for about 48% of the utility bill in the home [4]. Similar to power grid, the residential buildings are being upgraded to smart homes with incorporated devices to achieve the goals of the homes, such as energy consumption, comfort, security, and home-based health care [1]. A smart home typically includes HVAC system, electrical vehicles (EVs), home backup battery, and other appliances. It also includes the DEGs with renewable energy except hydro and biomass. Due to the possible noise of the wind turbines and particular regions required by the geothermal, they both show the restriction for the installation close to residential buildings. Solar energy, the only one left, is clean and sustainable with little maintenance for the

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photovoltaic (PV) system. Although the PV panels are not effective in cold regions, their advantages still make them as a viable source of electricity generation. Furthermore, with the technology development and consumer awareness, the cost of the residential installed PV project fell from $5.71/W in 2010 to $3.09/W in 2015 and the national residential PV capacity increased from 250 MW in 2010 to 2,250 MW in 2015 [2–4].

Besides the development in renewable energy, there is a significant change in the transportation. Today, more than 180, 000 electric vehicles (EVs) are on the roads worldwide and they are attractive to the families due to their high efficiency and low or zero emission. On the market, there are Tesla Model S, Honda Fit, Ford Focus, and Nissan Leaf and their miles per gallon equivalent (MPGe) rating is around 100 according to the U.S. Environmental Protection Agency [5–7]. These EVs can be Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV), and pure Battery Electric Vehicle (BEV) [8]. With the enough spare generating capacity in the current power grid infrastructure, the EV number is expected to be over 20 million by 2020 [9, 10]. At a smart home, EV charging in the night is convenient and doesn't need to go to the gas station. A vehicle-to-grid (V2G) car with fully charged batteries (85 kWh as the capacity) could provide the 10 kW grid for 4.25 h for 50% discharge. Thus, a large amount of DES can supply power to the critical facility in response to power shortage due to storms and other disasters [11].

For the residential DEG, the outputs from the stochastic PV systems strongly depend on the weather and have significant negative impacts on grid voltage and frequency stability. Therefore, the PV system has no scheduling freedom. In order to compensate for the negative impact of DEG on the grid, techniques in DES have been developed to mitigate this variability for short periods. DES includes rechargeable battery, super capacitor, and hot water tank technologies. They have different ratings for power and discharge time [12, 13]. For a smart home, home backup batteries are possible choices to mitigate the power-quality related issues by scheduling the batteries' charging and discharging. On the market, the home backup batteries available is $3,500 for a 10 kWh batteries and $25,000 for a 100 kWh [11]. When combined with rooftop photovoltaic (PV) system, the utility cost can be completely eliminated. In addition, the vehicles stay in garages for most of time and the EVs' large batteries can also be used as distributed energy storage (DES) to smooth out the fluctuating production of electricity and to improve stability of the power system. Similar to DEG, DES has its own behavior pattern and the control strategies for DES are based on such behavior as well as the energy conversion efficiency. For instance, to charge rechargeable battery at constant current, the charge voltage increases and its capacity is affected by ambient temperature, etc.

The power from the grid, DEG, or DES will be consumed by different devices and appliances at a smart home. Their demand on electricity is a random variable with a probability distribution in an operation time window and it can be categorized into different types or patterns based on whether it is can be separated, shifted, interrupted, decreased, or cancelled [14]. However, such pattern of a demand may change. For example, the charging of an electrical vehicle can be interruptible and shiftable with in the midnight. But this charging can be non-interruptible and non-shiftable if a long distance trip is planned for the next early morning. With the advanced sensing and metering, residential energy management systems can adjust consumption levels as demand response to respond the electricity price, correct voltage sags and flickers, or to help stabilize the system frequency [15]. This energy management can also help utility companies and power plants reduce cost through reductions in peak demand.

In this paper, Sect. 2 is focused on the physical and mathematical model of a smart home and the details in the optimization of the power flow are provided. Section 3 shows the simulation results and the discussion of the power flow and Sect. 4 includes the conclusion.

2 Physical and Mathematical Models

The structure of a smart home is shown in Fig. 1. This home consists of several rooms. In addition, there are a roof-top PV system, a set of home backup battery, an AC system, and an electric vehicle in the garage. One central control panel is used for the energy management in the house.

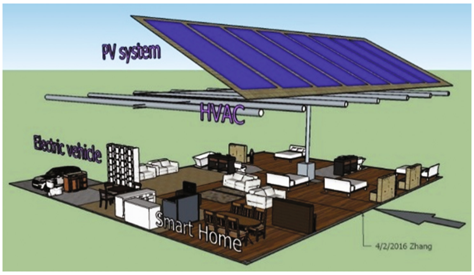

Fig. 1. The structure of a smart house

For the temperature control in each room, there are at least one electronic grill damper, a thermometer, a motion detector, and one RF transceiver. The damper is a valve or plate that regulates the flow of air inside a duct to the room. Thus, there are multiple zones in a smart home.

Among different devices, heating, cooling, and lighting counts for over 50% of the utility bill. While a 2.5 ton central unit (about the size for a typical 1,500 to 2,000 square foot home) uses about 8.7 kW. For a 5 ton, the power is around 17 kW. Two stage cooling, Two-stage cooling means the air conditioner or heat pump has a compressor with two levels of operation: high for hot summer days and low for milder days. Comfortable summer room temperature 25 °C and the winter room temperature 23 °C.

Zoning allows resident to precisely control the temperature in every room of the home. With a thermometer in each room, an automatic air vent grill damper in the duct is used to control airflow to that room. Motion detectors will help the central controller to determine whether the room is occupied or not. Thus, the temperature is differentiated and energy is saved. Most large homes feature multi-zone heating and air conditioning systems with one single furnace or one central air conditioner. With electronic dampers and thermostats, the rooms will be maintained at different temperatures. Thus, the energy is saved as unoccupied parts of the home are kept at a temperature setback. In fact, most traditional multi-zone duct systems don't save energy and their reliability is low. If the residents are away, the heating or ac should not be shut down in order to maintain the temperature and control humid to minimize the damage to furniture and the wall compounds in Sheetrock.

2.1 Dynamic Price

The house is connected to the power grid and there are two-way information and power flows between the home and the grid. The information only includes the dynamic electricity prices: one is on the grid and the other one from the house. Figure 2 shows the day-ahead hourly price on the grid and it should be higher than the one from the house due to the extra cost in power transmission and distribution. In order to minimize the cost, the two-way power transmission should below.

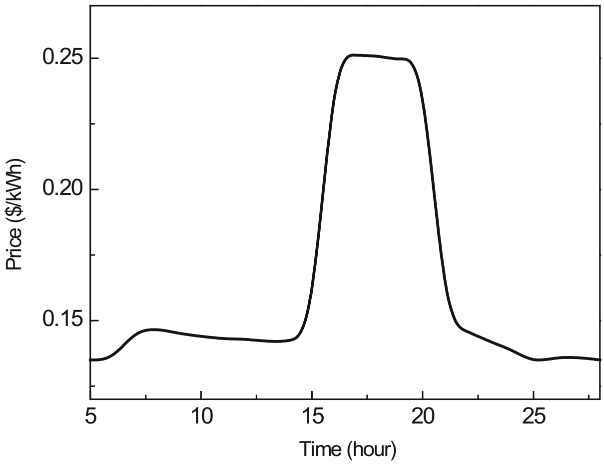

Fig. 2. The price of the electricity from the grid

2.2 Loads

In this model, there are two types of loads: flexible and fixed. The power supplied to the fixed load is guaranteed but not to the flexible load. Thus, the flexible loads can be reduced or completely cancelled and its original profile is shown in Fig. 3. In this work, there are two kinds of the fixed loads implemented, one is also shown in the Fig. 3 and it is due to the devices, such as router and home security system, which always run. The second one is shiftable loads and it can be regarded as separated and fine-grained tasks. Each task will be completed in one time slot. This kind of loads includes the dish washer, washer, and dryer. The EV battery is also a shiftable load for charging with a specific time window. In out calculation, the daily total usage is around 27.8 kWh, which is close to the average daily American home electricity consumption [20]. There are two peaks in the load profile at 7AM and 6PM similar to ref [21].

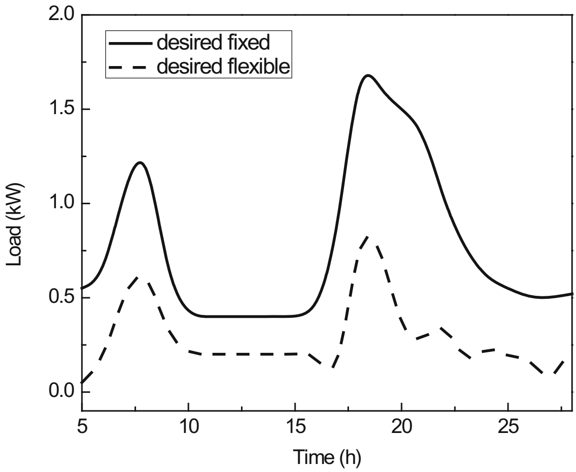

Fig. 3. The daily profiles of the fixed and flexible loads

In this work, only AC unit operation is discussed in the summer but not household heating in winter because nearly half of houses use natural gas [22]. Power demand from the AC unit is a combination of the fixed and flexible loads. If the room is occupied, the temperature has to be maintained as the desired temperature and this demand is fixed. For the room unoccupied, the temperature can be kept at a little bit higher than the desired temperature and this load is flexible.

2.3 Energy Management

In order to evaluate the performance with the consideration of electricity price, and comfort, the comfort is converted to uncomfortableness and an overall performance index Q is the weighted total of cost index, C, and discomfort index U [27, 28]:

$$Q = w_1 C + w_2 U \tag{1}$$

Here, C is calculated through the price and the power flow between the grid and the home. This power can be positive if it flows from the grid to the home and negative if it flows from the home to the grid. U is proportional to the shortage of the power supplied to the flexible loads. w_1 and w_2 are weighting factors and the sum of them is 1. The objective of the control is to minimize the Q and the room temperature settling time.

In this paper, an optimal energy management strategy, through particle swarm optimization (PSO), is to minimize Eq. (1) for the most cost-effective and comfort-aware service to a residential consumer. In the implementation, there are one array for the response of the flexible loads, one array for the power flow between the home and the grid, and two arrays for charging and discharging strategy of the home backup battery and the EV battery. The particles, a potential solution to the problem, consist of these four arrays as the positions. In case there is no home backup battery, the element in the corresponding array is set to be zero.

3 Results and Discussion

Figure 4 shows the load profiles on the summer solstice. Compared with the Fig. 3, there is difference between the scheduled fixed load and the real load on the summer solstice because of the extra power for the central AC unit for cooling. The peak values in both cases are around 3.25 kW, which is 1.5 kW higher. While the real flexible loads are the same in the day time but not in the night time. More power is supplied to the flexible load at the home with 100 m^2 PV system.

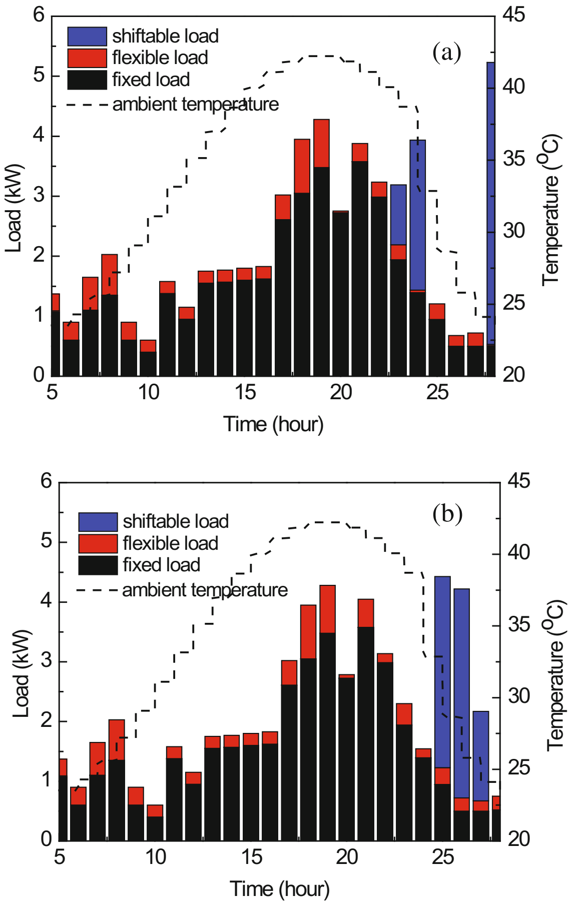

Fig. 4. Loads and the ambient temperature on the summer solstice for the houses with 50 m^2 (a) and 100 m^2 (b) PV systems

In the summer, the temperature of the occupied rooms is set as 23 °C. Otherwise, it is set as 27 °C. In Fig. 5, the power for cooling to the bed rooms and the other rooms is the same before 20 O'clock in both cases. Since the size and the heating properties of the rooms are close, the temperature is maintained at 27 °C. With the same dead band as 1 °C, the temperature of the rooms fluctuate simultaneously. After 20 O'clock, the living rooms and the kitchen are occupied, the temperature is kept at 23 °C, the power increases. However, the temperature of the bed rooms are still maintained 27 °C. After 21 O'clock, the temperature set point of the bed rooms are changed to 23 °C and the temperature in the other rooms is set at 27 °C.

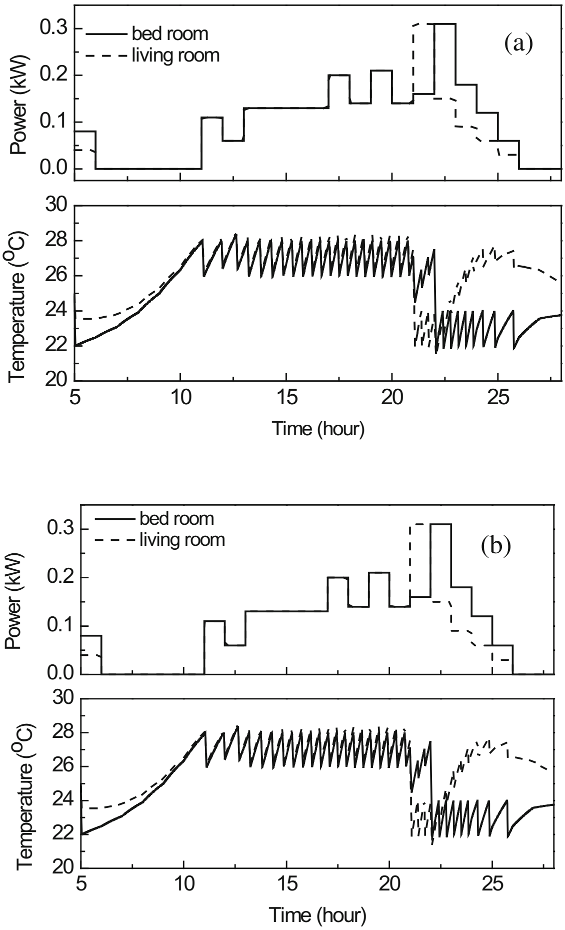

Fig. 5. The power and the temperature in the bed room and the living room 50 m^2 (a) and 100 m^2 (b) PV system

Figure 6 shows the power flow from the homes with a 50 m^2 and 100 m^2 PV system on the summer solstice. This day is the longest with the sunrise at 5 o'clock and sunset at 18 o'clock. The PV system generates electricity from 5 o'clock to 18 o'clock. Since the ambient temperature is high, the peak power is only 5 kW and 10 kW for the two cases. The power from the PV system is supplied to the loads and the backup battery. For the home with a 50 m^2 PV System, the PV output power is supplied to the loads and the EV battery after 15 o'clock. Between the sunset at 18 O'clock and 21 O'clock, battery starts to be discharged. Then, power from the grid, with the peak between the prices of \$0.136/kWh and \$0.139/kWh, is the only source to meet the demand of the home. For the home with a 100 m^2 PV system, the peak PV output power is 10 kW between 10 and 15 O'clock and the power flow is similar to that in the home with 50 m^2 PV system. After sunset, the backup battery is discharged and the power flows to the load and the EV battery. Different to the first case, there is no power needed from the grid. Thus, a home with a 100 m^2 PV system can be a stand-alone system.

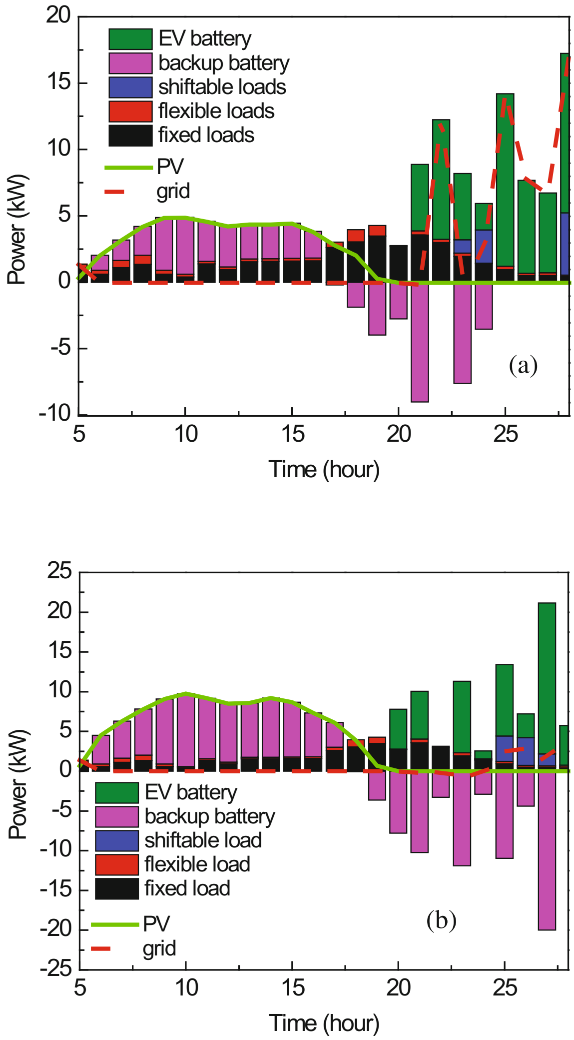

Fig. 6. The power profiles on summer solstice with the PV size as 50 m^2 (a) and 100 m^2 (b)

4 Conclusions

In this paper, particle swarm optimization is used to manage the power flow in a smart home with the objectives in the minimum cost and maximum comfort. Results from two homes with different size of PV systems are compared and discussed. The fixed loads are guaranteed with the power supply and the temperature of the occupied room is maintained. The PV size for a stand-alone home is determined.

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