An Optimization Strategy of Smart Home Energy Management System

Si-cong Wang¹, Jiong Yan¹, Xiao Xu², Zi-xia Sang¹, Mao-song Zheng³, Yun-fei Zheng¹, Xiao-qin Xu¹ and Zhu Chen¹

¹ State Grid Laboratory for Hydro-thermal Power Resources Optimal Allocation & Simulation Technology, Wuhan 430077, China
² State Grid Electric Power Research Institute Efficiency Evaluation Company Limited, Wuhan, 430077, China
³ State Grid Xiaogan Electric Power Supply Company, Xiaogan, 432000, China
*Corresponding author’s e-mail: hustwangsc@qq.com

Abstract. Optimization of energy use is an important concept in providing solutions to lots of the energy challenges in our world nowadays. Large hydraulic, mechanical, chemical, electrical and pneumatic systems require energy efficiency as one of the significant aspects of operating systems. This paper presents a smart home energy management system (SHEMS) with distributed generations, energy storages and smart domestic appliances, as well as its typical structures. According to the power consumption characteristics of household appliances and the users’ dependence, the residential loads are classified into four types. An optimization strategy of SHEMS is proposed to minimize customer electricity expenditure and maximize demand satisfaction simultaneously. Simulation results demonstrate that the proposed strategy can make users of smart home have a comfortable and economical life.

1. Introduction
With the increasing demand and tremendous usage of electrical energy around the whole world, energy shortage and global warming are attracting more and more attention recently [1]. To deal with the current situation, people gradually focus on the demand side energy management, especially on the user side [2]. And Smart Home Energy Management System (SHEMS) is a typical application example of the user side energy management system [3].

Generally, Smart Home Energy Management System (SHEMS) refers to provide comfortable, safe, energy efficient, economical and environment-friendly living environment for users with a range of communication networks, home automation equipment and other functions [4-6]. According to the user’s habit, SHEM copes with the real-time supervisory and arranging of various domestic appliances, through an intelligent set of systems controlled by a human–machine interface in smart home [7]. Several studies have been done in recent years such as home energy storage system [8], smart sensor technologies [9] and home area network [10].

The demand to improve power supply stability of the grid has resulted in discovering additional power supply sources such as distributed energy resources like solar energy and distributed energy storage like battery. Off-peak power consumption is considered to be a better method among traditional implementing schemes of load management for the purpose of reducing electricity cost and improving energy utilization efficiency, for the whole energy production will not change no matter
how load rate increases. Moreover, the difference between peak and valley load reduces and peak load reduces. As a result, the users' load characteristics are able to be re-adjusted without power off, and the generation cost can be reduced at the same time.

The proposed optimization strategy of smart home energy management system is based on the power flow, and the optimal objective is to use the least cost to make the maximum use of the energy. The rest of the work is organized as follows. Several typical structures are presented in Section 2, while the load characteristics and classifications are presented in Section 3. The optimization strategy of the SHEMS is in Section 4. Section 5 constructs the model and discusses the simulation results while Section 6 contains the conclusion of the work.

2. SHEMS Configuration
As described in [11], a typical SHEMS consists of power sources (including local generations and utility grid), smart gateway grid (distribution), load, energy storage unit and intelligent power and energy management system (IPEMS), thus it can be treated as a reduced model of a public smart grid. Fig. 1 illustrates the structure of the SHEMS on which the proposed optimal strategy is applied.

As shown in Fig. 1, the power sources of the SHEMS include regular utility grid and distributed generators (e.g. PV). The loads may be AC loads or DC loads. The storage is a very important unit in the SHEMS since it makes the electric power supply flexible. This structure also makes vehicle-to-home easy and efficient. The bidirectional converter which connects the distribution grid and the bus, can achieve the dealing including buying electricity at the low price and selling electricity at the high price. The bidirectional converter between the energy storage and the bus makes charging and discharging of the battery possible, furthermore, it can reduce the weight of the system and prevent the battery from being damaged by controlling its charging and discharging current. Therefore, the system is able to work in different states due to the different working modes of the converters, and the energy flow of the system can be managed effectively. The possible energy flow directions are also depicted
in Fig. 1. Furthermore, a new demand response strategy can be performed with the residential consumers’ active participation since the local DGs and battery are available.

3. Load Characteristics and Classifications

Typical residential loads include lights, air conditioner, water heater, refrigerator, washing machine, dryer, cooking appliances, dishwasher, TV, computer and other electronic equipments, which have different electrical characteristics. In this paper, the residential appliances are characterized by the power consumptions. Hence, most residential appliances are in binary status: the ON state where the appliances work under their nominal power and the OFF state where the appliances pause (still during service/usage period) or stop running (out of service/usage) and no power consumption occurs. The appliances only transit between ON and OFF states. It should be noted that there is a difference between pausing and stopping. In the former case, the appliance will returns to an ON period after an OFF period, while in the latter case, the load will be switched off [12]. Fig. 2 shows the possible state transitions of the household appliances.

![State transition of residential loads](image)

(a) Case I                                 (b) Case II                          (c) Case III

Figure 2. State transition of residential loads

The load of SHEMS can be classified into four categories from the viewpoint of controlling load consumptions.

Type A includes non-reschedulable hard loads. Certain residential appliances have strict scheduling requirement and constant usage or service interval, such as refrigerator, and cooking appliances. Cases I and II shown in Fig. 2 depicts their state transitions. Fig. 3 shows the simplified power characteristic curve of the refrigerator. Although the refrigerator is turned on 24 hours a day, the power consumption is intermittent. Generally speaking, Type A includes uncontrolled loads.

![Simplified characteristic curves of refrigerator (Type A load) in a day](image)

Figure 3. Simplified characteristic curves of refrigerator (Type A load) in a day

Type B includes non-reschedulable soft loads. This category also has strict scheduling requirement but the usage of such loads can be reduced, such as lights, TV and computer. Fig. 4 shows some typical power characteristic curves of these loads.
Type C includes reschedulable hard loads. This category may need consume an amount of electricity continuously for a limited amount of time with flexible scheduling, such as washing machine, dishwasher, and clothes dryer. Their starting time can be postponed without impact on the service. Fig. 5 depicts a typical power characteristic curve of such load.

Type D includes reschedulable soft loads. This category may require a fixed amount of electricity with discrete scheduling, such as air conditioner and water heater. The appliances of this type start to work when the temperature reaches a fixed value, and they stop working when the temperature reaches another fixed value. The typical power characteristic curves are shown in Fig. 6.
Table I gives the comparison on different types of loads, including type A, B, C and D.

| Non-reschedulable                        | Reschedulable                        |
|------------------------------------------|--------------------------------------|
| **Hard**                                 | **Soft**                             |
| Type A: Certain time & Certain Consumption | Type B: Certain time & flexible consumption |
| e.g. Refrigerator, Cookers               | e.g. Lights, TV, Computer             |
| Type C: Flexible time & Certain consumption | Type D: Flexible time & Flexible consumption |
| e.g. Washing machine, dish washer, Dryer | e.g. Air conditioning, water heater   |

The electric vehicle (EV) is different from regular home appliances and is special for SHEMS because it has three states throughout the duration in the residence where it may charge, discharge, or remain idle. The overall load profile of the SHEMS may change by introducing EV into the system. The energy storage almost has the same function as the EV, except for it has more flexible scheduling capability. Hence, the EV and energy storage will be treated as a flexible load for simplification, such as Type D load.

The lead acid battery is usually used as energy storage device in small and medium size power systems due to its low cost. The state of charge (SOC) is an important indicator of the battery, and can be calculated by a discrete method according to the following equations (1) and (2).

\[
SOC_{t+1} = SOC_t + k\Delta SOC
\]

\[
\Delta SOC = \frac{\Delta E}{E_{cap}} = \frac{P_n \times T_{step}}{P_{rated} \times T_{rated}}
\]

where \( k \) is charging and discharging coefficient, \( k=1 \) when battery is charging, \( k=-1 \) when battery is discharging, \( T_{step} \) is simulation step size, and \( T_{rated} \) is rated time when the battery is charging under rated power \( P_{rated} \).

Type B, C and D loads can be controlled to provide leverage for energy and cost savings. However, any optimization strategy should not degrade the quality of users’ living. Thus, the residents’ daily lives should not be limited by controlling residential loads. So Type B load is not considered to be regulated in the paper.

It is not enough for SHEMS to know which loads are controllable. To solve this problem, the concept of load priority is introduced to gather information about load condition. In the concept, each appliance will have different priority and the priority will change with time because people rely on different appliances at different time, which is dominantly influenced by consumer behavior, obviously.

4. The Proposed Optimization Strategy
The application of the proposed optimization strategy is realized in SHEMS by the IPEMS in Fig.1. There are some basic rulers should be complied with which are shown as follow.

1) PV power has the top priority to reduce the power amount drawn from the utility.
2) It is permitted that the SHEMS supply power to the grid.
3) Every source and load could be switched on and off independently.
Since the main aim of the proposed optimization strategy is to reduce the user's electricity fee as much as possible, not only the reschedulable load can be controlled as required, but also the battery should be flexible utilized. When the strategy is performed, it firstly checks whether the PV supply can fullfill the need of load consumption. If the PV supply can fullfill the need of load consumption and the SOC of the battery is lower than a certain value (e.g. 80%), the PV will charge the battery. If the PV supply can no longer fullfill the need of load consumption, it will then check the electricity price. When the price is high and the SOC is higher than a certain value (e.g. 40%), the battery will then provide DC or AC voltage to loads. When the price is low and the SOC is lower than a certain value (e.g. 80%), the battery will be charged by the grid. In this case, the grid supply parts of the energy. Otherwise, the battery neither charge nor discharge.

The work hours of actual power consumption controlled appliances and the capacity of battery provide the potential of the optimization. Thus, it is a multi-variable optimization problem that can be solved using particle swarm optimization algorithm (PSO) [13-15]. The objective function is shown in the following equations (3).

$$\min C = C_{pv} + C_{bat} + \sum_{0}^{24} C_{grid} \cdot P_{grid}$$

where $C_{pv}$ is the cost of the power generated by PV, $C_{bat}$ is the cost of battery, $C_{grid}$ is the electricity price of the grid in a period of time, and $P_{grid}$ is the power supplied by the distribution grid during that time.

The constraint conditions include power balance constraints and numerical limit of the work hours of actual power consumption controlled appliances and the capacity of battery, as shown in equations (4):

$$P_{load} = P_{bat} + P_{pv} + P_{grid}$$

where $P_{load}$ is all appliances’ consumption, $P_{bat}$ is the power provided by the battery, and $P_{pv}$ is the PV output power.

The load power consumption can be expressed as in the following equations (5) and (6):

$$P_{load} = \lambda_{i,t} \cdot P_{i,t}$$

$$\lambda_{i,t} = \lambda_{i,t-1} + T_{S_{i,t}} - T_{E_{i,t}}$$

where $\lambda_{i,t}$ is a bit that denotes if the ith appliance is on or off, $T_{S_{i,t}}$ is a bit equaling to 1 when appliance is on, 0 otherwise, and $T_{E_{i,t}}$ is a bit equaling to 1 when appliance is off, 0 otherwise.

5. Modeling and Simulation

To evaluate the proposed optimization strategy, a simulation model was developed in Matlab/Simulink. In the model, the maximum output power of PV is 400W at noon, the power supply of the grid is available all the time. The real-time electricity price has peak and valley, as shown in Fig.7. According to Fig.3-Fig.6, the total load in a day can be calculated.
The optimization variables in the strategy include the work hours of actual power consumption controlled appliances and the capacity of battery, which both have a certain scale. The initial state of charge is 40%. The simulation results are shown in Fig. 8-10.
The comparison with the simulation results in Fig. 8 shows that the electricity cost of smart home users in a day is reduced significantly with the proposed optimization strategy. And it can be seen from Fig. 9 and Fig. 10 that the load curve flattens, and the battery utilization has increased. Therefore, the proposed optimization strategy can be effective for SHEMS.

6. Conclusion
In this paper, three typical SHEMS structures including AC type, DC type and AC/DC hybrid type have been proposed, as well as an optimal strategy for the Smart Home Energy Management System. In the proposed strategy, the household appliances are classified into four types of loads by their working characteristics, and given different priority level during different time sections according to users’ demands. Thus, the Smart Home Energy Management System has flexible loads to achieve electric price response to reduce the users’ cost. Furthermore, this strategy can be coordinated with the direct load control to achieve fully responsive control. The results obtained from simulation verify that the strategy can make the electricity cost reduction of smart home users significant, as well as improve the load curve and the battery utilization by choosing the optimal work hours for actual power consumption controlled appliances and capacity for battery.

Acknowledgment
This research was supported in part by the State Grid Hubei Electric Power Company Science and Technology Project (521538170010).

References
[1] Bimal K. Bose. (2000) Energy, Environment, and Advances in Power. IEEE. Trans. Power Electron, 15: 688–701.
[2] Conopask J V. (2004) Public service obligations: U.S. experience and evolution. In: Licensing/Competition Committee Meeting. Tirana, Albania.
[3] Wei Wang, He Guangyu, and Wan Junl. (2012) Preliminary Investigation on User Energy Management System. Automation of Electric Power Systems, 36: 10–15.
[4] Minkyoung Kim, Hyun Kim. (2006) Behavior Coordination Mechanism for Intelligent Home. In: the 5th IEEE/ACIS International Conference on Computer and Information Science.
[5] Abhishek Roy, Soumya K. Das Bhaumik, Amiya Bhattacharya etal. (2003) Location Aware Resource Management in Smart Homes. In: the First IEEE International Conference on Pervasive Computing and Communications.
[6] Eric D. Manley, Jitender S. Deogun. (2007) Location Learning for Smart Homes. In: 21st International Conference on Advanced Information Networking and Applications Workshops.
[7] Collotta M., Pau G. (2017) An Innovative Approach for forecasting of Energy Requirements to improve a Smart Home Management System based on BLE. IEEE Trans. Green Commun. Netw.

[8] Pascual J., Sanchis P., Marroyo L..(2014) Implementation and Control of a Residential Electrothermal Microgrid Based on Renewable Energies, a Hybrid Storage System and Demand Side Management. Energies, 7: 210–237.

[9] Ahmed M.A., Kang Y.C., Kim Y.-C.. (2015) Communication Network Architectures for Smart-House with Renewable Energy Resources. Energies, 8: 8716–8735.

[10] Collotta M., Pau G. (2015) A Novel Energy Management Approach for Smart Homes Using Bluetooth Low Energy. IEEE J. Sel. Areas Commun., 33: 2988–2996.

[11] D. Wang and F. Z. Peng. (2012) Smart Gateway Grid: A DG-Based Residential Electric Power Supply System. IEEE Transactions on Smart Grid, 3: 2232-2239.

[12] J. S. Vardakas, N. Zorba, and C. V. Verikoukis. (2014) Scheduling policies for two-state smart-home appliances in dynamic electricity pricing environments. Energy, 69: 455-469.

[13] Eberhart R.C, Shi Y. (2001) Particle Swarm Optimization: Developments, Applications and Resources. In: The 2001 Congress on Evolutionary Computation. Piscataway. pp. 81-86.

[14] V. Roberge, M. Tarbouchi, and G. Labonte. (2013) Comparison of Parallel Genetic Algorithm and Particle Swarm Optimization for Real-Time UAV Path Planning. Industrial Informatics, IEEE Transactions on, 9: 132-141.

[15] H. Lou, C. Mao, J. Lu, D. Wang, and W. J. Lee. (2009) Pulse width modulation AC/DC converters with line current harmonics minimisation and high power factor using hybrid particle swarm optimisation. IET Power Electronics, 2: 686-696.