Modeling and Simulation of MAS-based Management System for Smart Grid with Smart Homes

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Keywords: MAS, NSGA-II, Operation Optimization, Smart Home, Smart Grid.

Abstract: Traditional power system is undergoing revolutionary changes. Concepts like Smart Grid and Smart Home have come into practice due to high penetration of distributed generation and advanced information technologies. This paper incorporates Smart Home and Smart Grid. It focuses on a community where houses are equipped with photovoltaic panels, energy storage system and smart appliances. A new management system is proposed based on multi-agent technology. Agents are designed to be intelligence, autonomous and with high plug-and-play capability. System control architecture has three levels corresponding to management of devices, houses and community. A two-level operation optimization scheme is proposed, in which operation optimization problem is decomposed into five constrained multi-objective problems, mutual supply mechanism is deployed to efficiently coordinate Smart Homes and NSGA-II is introduced to obtain Pareto-optimal solutions. Simulation results validate the effectiveness of proposed management system.

1 INTRODUCTION

Over the last decade, rising awareness of energy crisis and environmental deterioration has led to a revolution in electricity industry. Novel technologies like distributed generation (DG) and smart electrical appliances have been brought into daily life and new concepts as Smart Home and Smart Grid have been introduced to facilitate the transformation of traditional power system.

Smart Grid is seen as the energy infrastructure for future electric power system. Through the incorporation of advanced control strategies and information technologies, Smart Grid is endued with capability to rapidly collect and assess large amounts of data, to smoothly integrate renewable energy sources and controllable loads (CLs) and to efficiently coordinate numbers of units towards the economic, reliable and secure running of power system (Gungor et al., 2011).

Sensors and smart meter brings smart grid concept into households. Smart Home is an energy-aware household equipped with smart electrical appliances, residential DG and energy storage system (ESS). Such home is expected to adjust its energy profile in accordance with dynamic pricing, DG output and grid operation to cut energy bill (Komninos et al., 2014).

Significant research work has been done regarding the implementation and control of Smart Grid. Multi-agent technology is widely proposed as an effective tool to manage Smart Grid since McArthur et al. (2007a, 2007b) discovered its capability to satisfy the demand of distributed control, autonomous operation and flexible framework. Dimeas and Hatziargyriou (2005) developed a MAS-based infrastructure of management system as well as an energy exchange optimization algorithm. Mao et al. (2014) proposed a hybrid architecture for MAS-based energy management system by combining hierarchical and central architecture. Foo Eddy, Gooi and Chen implemented agent models and energy management system framework based on Simulink, JADE and MACSimJX. Scheduling of air conditioning incorporating customer's convenience in home energy management system (HEMS) is discussed by Jo, Kim and Joo (2013). Cost-effective energy management system with hierarchical agents for Smart home is studied by Jiang and Fei (2015).

The work reported in the literature focuses on either Smart Home or Smart Grid while the consequences of integration of Smart Homes into Smart Grid as well as the establishment of

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correspondent management system is seldom discussed. To address this issue, this paper proposes a management system for a community where each household has its own photovoltaic (PV) panels, ESS and smart appliances. The management system is MAS-based with three-level hierarchical control architecture. System framework is formed by intelligent agents assigned to PV, ESS, load and house. A two-level operation optimization scheme is proposed to schedule ESS and CL. Mutual supply mechanism is deployed to coordinate household agents. NSGA-II is used to solve constrained multi-objective problems. The effectiveness of the proposed system is investigated by numerical simulation.

The rest of this paper is organized as follows. Section 2 describes structure of studied community and proposed management system. Section 3 presents operation optimization scheme. Section 4 is contributed to simulation and results analysis. Part 5 concludes this paper.

2 SYSTEM ARCHITECTURE AND CONFIGURATION

In this section, the structure of studied community is presented first, followed by detailed presentation of structure and design of proposed management system.

2.1 System Scheme

Structure of the studied community is illustrated in Figure 1. Community comprises of more than 20 households, but only four households are considered in this paper for simplicity. Community is connected to utility grid by Point of Common Coupling (PCC). A public ESS (PESS) is installed near PPC for stability. In islanded mode, PESS discharges as standby power supply.

Figure 2 depicts individual household structure. Each household has its own PV panels and ESS. Load demand is divided into two categories: CL, namely smart appliances, and fixed load (FL) which groups the rest of electrical appliances in the house. FL is usually presented by a curve, which corresponds to residents' living habits and daily schedule. With advanced information technologies like smart meter, households can sell electricity when energy generation exceeds consumption.

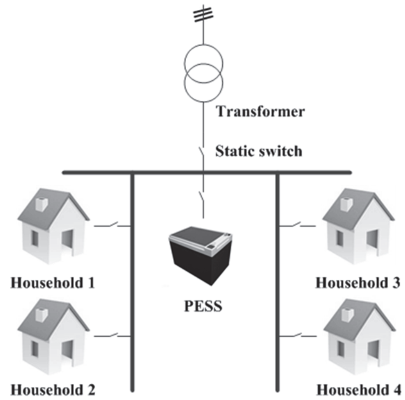

Figure 1: Structure of studied community.

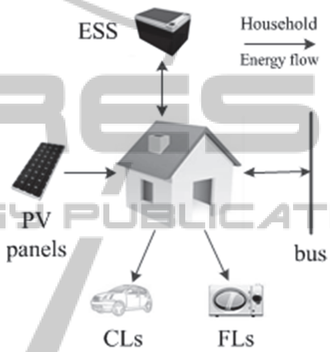

Figure 2: Structure of individual household.

2.2 Management System Design

Control architecture of proposed management system consists of three levels: local control level, coordinated control level and central control level. System framework is based on multi-agent technology. Agents are assigned to each PV unit, ESS, load demand, household and PCC for better plug-and-play capability. Each agent has a certain degree of intelligence and autonomy. Provided with a set of function modules, agents interact and exchange information with others to attain local and global objectives. Scheme of proposed management system is depicted in Figure 3.

Local Control level is the interface between management system and physical entities. It is comprised of PV agent, ESS agent and Load agent. Each agent has Data Acquisition module which collects real-time data, Control module which adjusts devices' operation state and Communication module which permits data exchange with Household agent. Forecast module of PV agent and Load agent provides a one-day-ahead forecast of PV output and FL profile.

Coordinated Control level corresponds to Smart

Home management system. Receiving generation and load demand data coming from Local Control Level as well as information of utility grid and neighbouring households coming from Central agent via Communication module, Household agent analyses power flow of house circuit to detect device malfunction (Power Flow Analysis module), compares real and forecast data to modify scheduled plan in case of huge difference (Real-time Adjusting module), calls optimization algorithm to provide optimal operation plan for the following day (Operation Optimization module). Communication module then transmits scheduled plan to ESS and Load agent and electricity selling/consuming data to Central agent.

Central Control level is equivalent to Smart Grid management. It has only one agent: Central agent assigned to PCC. Electricity surplus/demand information of Smart Home and operation data of PESS are gathered for processing. Operation Optimization module schedules PESS and coordinates households for the following day. Power Flow Analysis module monitors the operation states of community network. Real-time Adjusting module changes PESS state when forecast deviates from real data. Bidirectional power exchange with utility grid is monitored by PCC Control module.

3 OPERATION OPTIMIZATION FORMULATION

As householders are not willing to pay extra for the sake of others' interest, operation optimization of Smart Grid with Smart Homes is decomposed into two levels. Optimization of community network is performed after individual household optimization. Otherwise, it may occur that the optimal operation plan of whole community is not necessarily optimal for one household.

In this section, individual household optimization is formulated at first, followed by community operation optimization. Solving algorithm is presented at end.

3.1 Individual Household Optimization

The objective is to cut energy bills by scheduling CL and ESS. Energy bill of individual household is quantified by Equation 1.

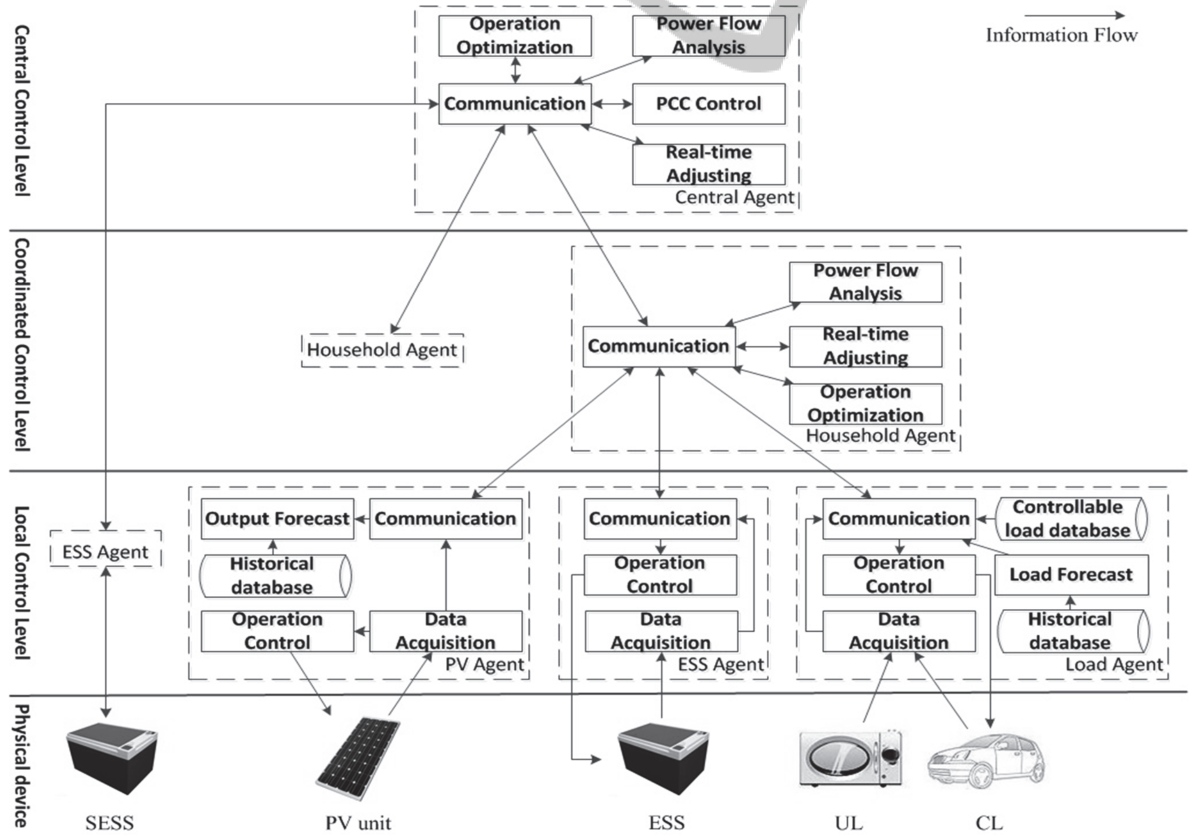

Figure 3: Scheme of three-level MAS-based management system.

$$F_{bill} = C_{install} + C_{pollu} + C_{main} + C_{depre} + C_{ce} - P_{se} \quad (1)$$

$C_{install}$, C_{pollu} and C_{main} signify respectively installation cost, pollution charge and maintenance charge, which are regarded as constant in short-time scheduling problem. C_{depre} is the depreciation charge, which is proportional to the energy charged and discharged. C_{ce} is the total cost of electricity purchase while P_{se} signifies the profit earned by selling electricity back to grid. Energy bill of household is rewritten as Equation 2.

$$F_{bill} = k_d \int_T |P_{ESS}|\, dt + PR_c \times \int_T P_c dt - PR_s \times \int_T P_s dt$$
$$P_{ESS} = \begin{cases} P_{ESSd}, & \text{when discharging} \\ -P_{ESSc}, & \text{when charging} \end{cases} \quad (2)$$

where T is studied period, k_d is depreciation coefficient, P_{ESSd} and P_{ESSc} are discharging or charging power of ESS, P_c and P_s are purchasing or selling power of household, PR_c and PR_s are retail price and selling price.

It should be noted that frequent charge-discharge harms ESS unit and decreases battery life, charge-discharge cycle of ESS, denoted as η_{cycle}, should be minimized during optimization.

Constraints related to operation of different agents are listed below.

a) Power balance constraint

$$P_{PV} + P_{ESS} + P_h = FL + CL_j$$
$$P_h = \begin{cases} P_c, & \text{when purchasing electricity} \\ -P_s, & \text{when selling electricity} \end{cases} \quad (3)$$

where P_{PV} is PV output power and CL_j is the jth controllable load.

b) ESS operation constraint

$$SOC_{\min} \le SOC_{ESS} \le SOC_{\max} \quad (4)$$

$$SOC_0 \times (1-\beta) \le SOC_{ESSfinal} \le SOC_0 \times (1+\beta) \quad (5)$$

where SOC_{ESS} is current state of charge (SOC), SOC_{min} and SOC_{max} are lower and upper limit of SOC, SOC_0 and $SOC_{ESSfinal}$ are SOC at the beginning and end of studied period, β is variation coefficient.

c) User's satisfaction constraint

$$T_{lj} \le T_{CLj} \le T_{uj} \quad (6)$$

where T_{CLj}, T_{lj} and T_{uj} are respectively execution time, lower and upper limit of preferred execution period of task j.

To summarize, optimization problem of individual household is formulated by Equation 7.

$$\min F = [F_{bill}, \eta_{cycle}]^T$$
$$\text{subject to } (3)-(6) \quad (7)$$

3.2 Community Network Optimization

Community network optimization schedules PESS and coordinates Smart Homes to curtail operation cost. Operating cost of community network is illustrated by Equation 8.

$$F_{ocost} = C_{install} + C_{pollu} + C_{main} + C_{depre} + C_{ce} - P_{se} + C_{loss} \quad (8)$$

$C_{install}$, C_{pollu}, C_{main}, C_{depre}, C_{ce} and P_{se} are treated as mentioned in 3.1. C_{loss} is cost of transmission loss. Transmission loss is related to power, which is fixed as energy demand of households is given, and transmission distance, which is reduced when and only when households deliver excess energy directly to nearby household in need instead of selling it back to utility grid. PESS won't influence transmission distance since PESS is near PCC. With the aim to avoid time-consuming loss calculation and to reduce transmission loss, mutual supply mechanism is proposed to detect energy surplus/demand pair and to coordinate households accordingly.

Equation 8 is then rewritten as

$$F_{ocost} = k_{dP} \int_T |P_{PESS}|\, dt + PR_c \times \int_T P_c dt - PR_s \times \int_T P_s dt$$
$$P_{PESS} = \begin{cases} P_{PESSd}, & \text{when discharging} \\ -P_{PESSc}, & \text{when charging} \end{cases} \quad (9)$$

where k_{dP} is depreciation coefficient, P_{PESSd} and P_{PESSc} are discharging or charging power of PESS.

Grid operation constraints are listed below. Operation constraints of PESS are described by Equation 4 and 5.

a) Power balance constraint

$$P_{PESS} + P_{PCC} = \sum_i P_{hi} \quad i = 1, ..., 4 \quad (10)$$

where P_{PCC} is power of PCC.

b) Power flow constraint

$$P_{l\min} \le P_{line} \le P_{l\max} \quad (11)$$

where P_{line}, P_{lmin} and P_{lmax} are respectively real-time power, minimum power and maximum power of transmission line.

c) Transmission capability constraint

$$P_{p\min} \le P_{PCC} \le P_{p\max} \quad (12)$$

where P_{pmin} and P_{pmax} are lower and upper limit of allowed exchange power of PCC.

Operation optimization problem is thus formulated as

$$\min F = [F_{\text{ocost}}, \eta_{cycle}]^T \\ \text{subject to } (4), (5), (10) - (12) \quad (13)$$

3.3 Solving Algorithm

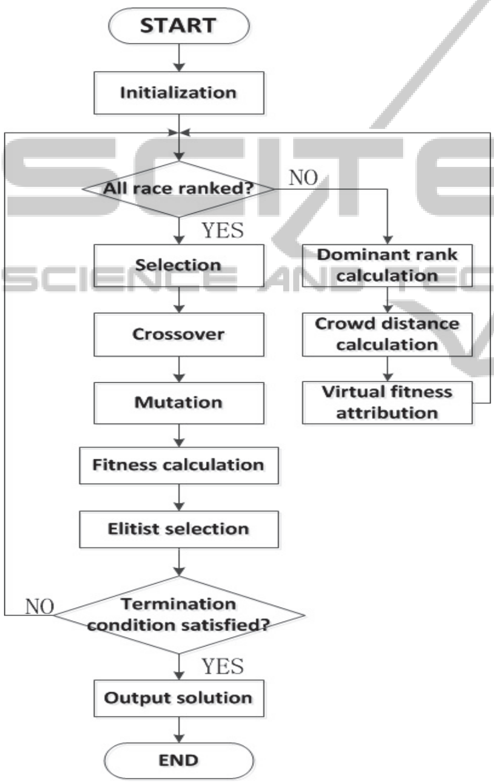

Figure 4: Flow chart of NSGA-II.

Operation optimization of studied community is formulated as five constrained multi-objective problems.

Proven to be effective in search of Pareto optimal solutions of constrained multi-objective problem, Non-Dominated Sorting Genetic Algorithm II (NSGA-II) is deployed as solving algorithm in this paper. Flow chart of NSGA-II is illustrated in Figure 4 (Deb et al., 2002).

4 SIMULATION AND RESULTS ANALYSIS

To validate the effectiveness of proposed system, simulation studies for a typical day were carried out.

4.1 Parameters Specification

The simulation platform is implemented with Matlab R2011a. The community illustrated in Figure 1 and 2 is modelled in Simulink while optimization algorithm is programmed using Matlab script. The program is run on Intel Core i5-3.2GHz PC with 4G RAM.

Suppose each day starts at 6 a.m. and ends at 6 a.m. of the next day. Time slot is set as 30 minutes. A tiered electricity pricing mechanism quantified in Table 1 is used.

Table 1: Tiered electricity tariff.

Period	Peak	Valley
	06h00-22h00	22h00-06h00
PRc /¥/kWh	0.617	0.320
PRs /¥/kWh	0.540	0.307

Each household is configured with its own PV, ESS, FL and CL. For simplicity, we assume that PV panels and ESS are identic for all four households. PV generation data provided by Ding and XU (2011) and typical FL profile provided by Rudion et al. (2006) are utilized and shown in Figure 5-8. Three CLs are considered, whose parameters are listed in Table 2. With reference to Rahbar, Jie and Rui's work (2015), ESS is modelled by Equation 14. ESS parameters are summarized in Table 3.

$$SOC_{N+1} = SOC_N + (\eta_c \int_{\Delta T} P_{ESSc} dt - \int_{\Delta T} P_{ESSd} dt / \eta_d) / C_{nom} \quad (14)$$

where η_c and η_d are charge and discharge efficiency, C_{nom} is nominal capacity of ESS.

As to optimization algorithm, roulette-wheel selection method is used. Mutation and crossover rate are respectively 0.1 and 0.9, population size is 100 and iteration number is set as 1000.

Table 2: Parameters of controllable load.

Task name	Load /kW	Duration /hour	Preferred period
Washing clothes	0.4	0.5	09h00-18h00 22h00-05h00
Drying clothes	1	0.5	09h00-18h00 22h00-05h00
Charging EV	4	6	Before 06h00

Table 3: Parameters of energy storage system.

Parameter	ESS	PESS	Unit
η_c	88.2	88.2	%
η_d	98.0	98.0	%
SOC_{max}	95	90	%
SOC_{min}	10	20	%
SOC_0	80	70	%
C_{nom}	20	80	kWh
k_d	0.1	0.1	¥/kWh

4.2 Results and Analysis

Figure 5-8 illustrate simulation results of individual household optimization.

Analyse the optimization result of Household 1 in detail. Due to the solar radiation limitation, PV generates electricity only from 7 a.m. to 4:30 p.m.

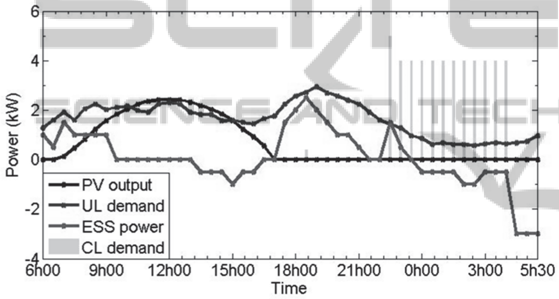

Figure 5: Optimal operation plan for Household 1.

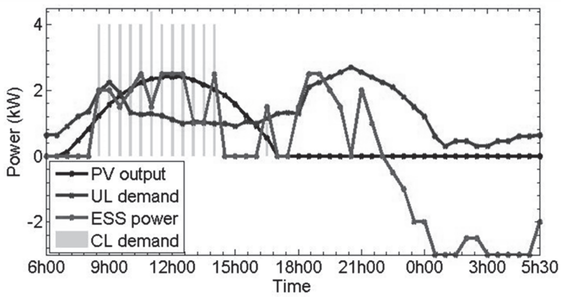

Figure 6: Optimal operation plan for Household 2.

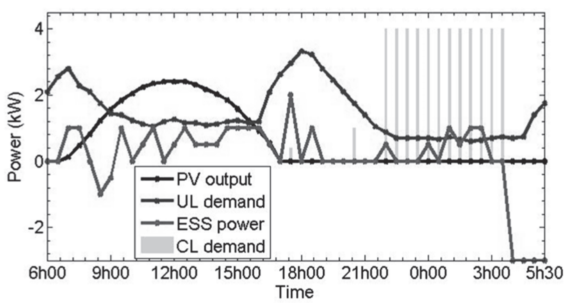

Figure 7: Optimal operation plan for Household 3.

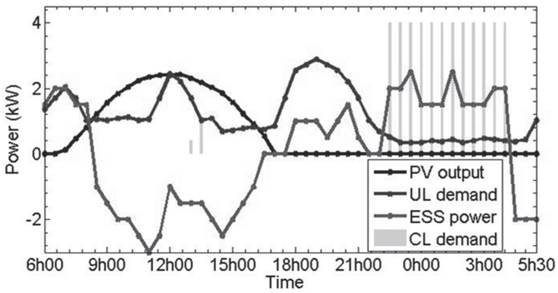

Figure 8: Optimal operation plan for Household 4.

Energy generation satisfies fixed load demand and charges ESS. From 5:30 p.m. to 8:30 p.m., ESS discharges to curtail electricity purchase. ESS recharges from 23:30 in order to regain initial SOC level. Charging EV and drying clothes are scheduled after 22:00 which coincides with valley hours.

Simulation results are compared with traditional system. Without ESS and load demand scheduling, energy bill is only related to purchasing/selling electricity. Minimal cost is achieved when all PV generation is used to supply power and all CLs are scheduled in valley period. It is worthy to mention that, judging from the difference between FL and PV output, these two assumptions cannot be simultaneously true.

Table 4: Comparison of proposed and traditional system.

House	η_{cycle}	F_{bill} /¥ proposed system	F_{bill} /¥ traditional system
1	3	15.2416	17.4017
2	1	12.3656	14.0022
3	3	13.2813	16.8225
4	3	12.1592	14.3193

Objective function value of two systems is shown in Table 4. As can be seen, the application of optimization algorithm cuts the electricity bill of individual household by about 12%.

Figure 9 shows exchange power between households and community network.

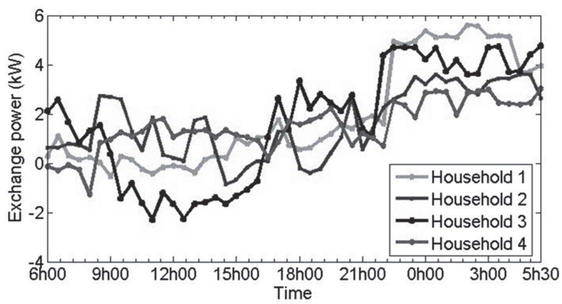

Figure 9: Exchange power of four households.

It is observed that some households have excess energy while others is in need of electricity at a given time slot k. At 9:30 a.m., Household 3 has a surplus of 1.4354kW while Household 4 demands 1.2526kW. Household 3 should deliver 1.2526kW directly to Household 4 if mutual supply mechanism operates properly. Results of coordination among households are shown in Figure 10. Each bar marks one mutual supply instruction between neighbouring houses.

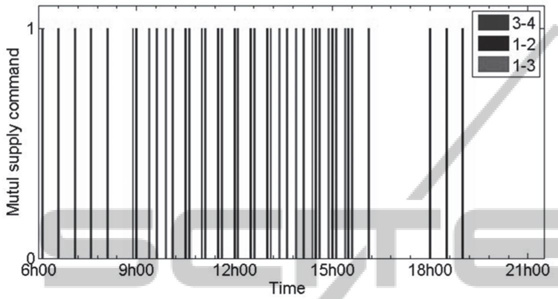

Figure 10: Mutual supply instructions.

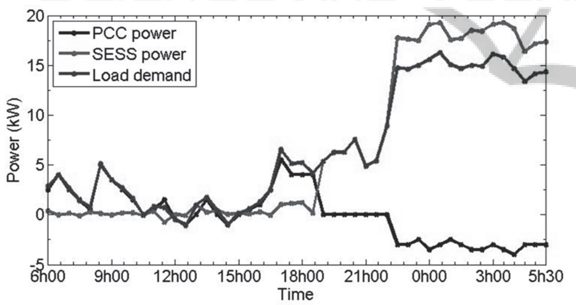

Figure 11: Scheduled PESS and PCC power.

Figure 11 illustrates PESS scheduling and calculated PCC power. We can see that PESS discharges at peak hours and charges at valley hours. PCC power is close to 0 during peak hours, which signifies that the proposed system has successfully shifted peak load.

Value of objective function F_{ocost} of proposed system and traditional system are shown in Table 5. It is noticed that the application of proposed optimization scheme curtails operation cost of community network by 11.5%.

Table 5: Value of F_{ocost} of proposed and traditional system.

Method	F_{ocost} /¥
proposed system	59.1742907
traditional system	66.8606358

It can be concluded from aforementioned analysis that the performance of proposed two-level optimization scheme is satisfying.

5 CONCLUSIONS

This paper integrates Smart Homes into Smart Grid. A three-level MAS-based management system is proposed to manage a community with smart homes. MAS-based framework, hierarchical control architecture as well as information flow of the proposed system is described in detail. In the presented two-level optimization scheme, optimization problem is formulated as constrained multi-objective problems and solved by NSGA-II while coordination of Smart Homes is realized by mutual supply mechanism. Simulation results show that the proposed optimization scheme is able to curtail energy bill by over 10% for householders and grid owner and to shift peak load. Based on agents with high plug-and-play capability, the proposed management system is of universal applicability and practicability. Extension to other communities is achieved by adding correspondent agents. Nevertheless, as NSGA-II provides more than one recommended operation plan, methods to automatically obtain one optimal solution should be investigated in further studies.

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