Cooperative Scheduling of Smart Community Based on Electric Energy Router

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Abstract. Aiming at the ever-increasing trend of distributed energy resources (DER), this paper proposes a home/community integrated energy management model based on electric energy routers (EER). Firstly, based on the modeling of energy storage and controllable load in home energy Local Area Network (LAN), a home-level collaborative scheduling model is proposed. Then, considering the power interaction between homes, a community dispatching model is established to minimize the electricity charge and improve the utilization ratio of renewable energy. Cplex18.0 is used to solve the daily optimal electricity plan. Finally, the results of the case study verify the effectiveness and economy of the proposed model by comparing community’s cost under different modes.

1. Introduction

With development of energy crisis, DER has received extensive attention. However, disadvantages such as decentralization, intermittent, and volatility prevent it from applying on a large scale. With the view of fully realize the potential of DER, a new structure called energy internet has emerged [1-5].

The concept, key technologies, and major technical features of the energy internet have been refined in [6]; References [7-10] focus on the architecture and key equipment of the Internet-based power grid. Furthermore, the concept and topological structure of the Special Energy Internet are introduced in [11]. References [12] and [13] introduce the demand response mechanism into the home energy LAN’s optimal scheduling. However, the researches above use the load side absorption technology without energy storage equipment. Considering the source/charge/load cooperative operation strategy, [14] adopts the dynamic operating mechanism which releases energy in peak and store energy in low based on time-of-use(TOU) price mechanism. Furthermore, constraints about user comfort are added in [15] to achieve the balance between economy and comfort. Although there are quite a lot of researches about EER and home energy management, few of them have considered the issue of power interaction between homes based on EER.

The remainder of this paper is organized as follows. The architecture of Special Energy Internet based on EER is introduced in Section 1; Section 2 establishes the optimal models in the home and community level; Simulation is discussed in section 3; Conclusions are summarized in Section 4.
2. The Architecture of Novel Energy Internet Based on EER

As the core component of energy internet, EER can realize many functions such as energy quality monitoring, energy deployment, and communication security relying on advanced power electronics and other key technologies.

This paper proposes a novel energy internet architecture based on community EER and home EER [16]. As shown in figure 1, multiple home energy LAN can be regarded as a collection of many physical nodes, including photovoltaic (PV), battery (BAT) and loads, which are connected through a community EER. The home EER transmits the family's PV historical output, load forecasting data, and basic information of BAT to the community EER. With these information, the community EER can calculate a plan to minimize the electricity cost of the community and release it to home EERs to schedule internal BAT and various types of loads.

![Figure 1. The architecture of novel energy internet](image)

3. Home/Community Cooperative Scheduling Model

3.1. Component model of home energy LAN

3.1.1. BAT model. The BAT model mainly considers the change of BAT state of charge (SOC) which is shown in equation (1):

\[
E_{bat}(i,t+1) = E_{bat}(i,t) + P_{ch}(i,t)\eta_{ch}\Delta t - \frac{P_{dis}(i,t)}{\eta_{dis}}\Delta t, t = 1, 2, \ldots, T - 1
\]

Where \( i \) refers to the \( ith \) home, \( t \) refers to the current time, \( E_{bat}(i,t+1) \) and \( E_{bat}(i,t) \) refer to the next SOC and current SOC, \( P_{ch} \) and \( P_{dis} \) refer to the charge power and discharge power, respectively. \( \eta_{ch} \) and \( \eta_{dis} \) are the charging and discharging efficiencies, respectively. \( \Delta t \) refers to the simulation horizon.

3.1.2. Model of Controllable load. According to controllability, loads in the home energy LAN can be divided into uncontrollable loads (UCL), transferable loads (TL) and interruptible loads (IL). Among them, UCL lacks flexibility in using time. Based on the completion of work, TL including regular rice cooker and electric vehicle (EV) can participate in load dispatching by shifting working period. IL represented by air conditioners can participate in load dispatching within the range of user’s comfort. According to the simplified equivalent thermal parameter model in [17], the room temperature \( T \) in the \( ith \) home can be calculated by equation (2) and (3):

\[
T_i^{t+1} = T_o^{t+1} - (T_o^{t+1} - T_i^{t})e^{-\Delta t/RC}, s = 0
\]

\[
T_i^{t+1} = T_o^{t+1} - \eta P_i^t R - (T_o^{t+1} - \eta P_i^t R - T_i^{t})e^{-\Delta t/RC}, s = 1
\]
Where $T_{e,i}^{j}$ refers to the outside temperature in the next time, °C; $C$ refers to the equivalent heat capacity, $J/°C$; $R$ refers to the equivalent thermal resistance, $°C/W$; $s$ refers to the status variable of air conditioner, 1 means start and 0 means stop.

3.2. The centralized dispatching model in community

3.2.1. Objective function. For the communities that implement PV, the economy of energy management is mainly reflected in the reduction of electricity cost. Therefore, the minimum cost is adopted as the objective function, as shown in equation (4).

$$\min C_{total} = \sum_{t=1}^{T} P_{grid}(t) \text{price}(t)$$  \hspace{1cm} (4)

$$\begin{cases}
P_{grid}(i,t) = 0 & P_{grid}(i,t) \leq 0 \hspace{1cm} (5) \\
P_{grid}(i,t) = P_{grid}(i,t) & P_{grid}(i,t) \geq 0
\end{cases}$$

Where $C_{total}$ is the electricity cost in community, $\text{price}(t)$ refers to power tariff at time $t$, $P_{grid}$ indicates the purchasing power bought from the grid. When the PV output is large, $P_{grid}(t)$ may be negative and the community will send power to the grid. Since the back-fed energy may adversely affect distribution network power flow and power quality, this paper discards the surplus PV output.

3.2.2. Constraint conditions. The function of power balance constraint in Home LAN is as follows:

$$P_{i}(i,t) = P_{buy}(i,t) - P_{sell}(i,t)$$  \hspace{1cm} (6)

$$P_{j}(i,t) = P_{L}(i,t) - P_{PV}(i,t) - P_{dis}(i,t) + P_{ch}(i,t) \hspace{1cm} (7)$$

$$P_{c}(i,t) = P_{a}(i,t) + P_{b}(i,t) + P_{c}(i,t)$$  \hspace{1cm} (8)

Where $N$ is the total number of homes, $P_{buy}(i,t)$ and $P_{sell}(i,t)$ refer to the purchasing power and selling power, $P_{L}(i,t)$ is the total load, $P_{PV}(i,t)$ refers to the PV output, $P_{a}(i,t)$ and $P_{b}(i,t)$ and $P_{ch}(i,t)$ refer to the power consumption of UCL, TL and IL, $P_{c}(i,t)$ refers to the net load which is used to judge whether the electricity status is surplus or deficit. When the net load power is positive, the household needs to purchase electricity and vice versa.

In the optimal model, the supply-demand balance needs to be satisfied at any time. Therefore, the active power balance constraints within the community is as follows:

$$P_{grid}(t) = \sum_{i=1}^{N} P_{buy}(i,t) - \sum_{i=1}^{N} P_{sell}(i,t)$$  \hspace{1cm} (9)

Assuming the price of electricity trading between homes equals the TOU price, the following power-constraints between households are established:

$$\begin{cases}
\rho_{sell} + \rho_{buy} < 1 \\
0 \leq P_{sell}(i,t) \leq P_{sell}^{max} \rho_{sell}(i,t) \\
0 \leq P_{buy}(i,t) \leq P_{buy}^{max} \rho_{buy}(i,t)
\end{cases}$$  \hspace{1cm} (10)

Where $P_{sell}^{max}$ and $P_{buy}^{max}$ are the maximum selling and buying active power, which are generally equal to the maximum operating power of the home EER, $\rho_{sell}$ and $\rho_{buy}$ which are Boolean variables (0/1) are the status of buying and selling.

BAT needs to meet charging and discharging power constraints shown in equation (11) and the residual energy constraint is shown in equation (12):
\[
\begin{align*}
0 \leq P_{ch}(i,t) & \leq P_{ch}^{\max} D_{ch}(i,t) \\
0 \leq P_{dis}(i,t) & \leq P_{dis}^{\max} D_{dis}(i,t) \\
D_{ch}(i,t) + D_{dis}(i,t) & < 1 \\
E_{bat}^{\max} \times 20\% & \leq E_{bat}(i,t) \leq E_{bat}^{\max} \times 100\% \tag{12}
\end{align*}
\]

Where \(P_{ch}^{\max}\) and \(P_{dis}^{\max}\) are upper limits of charging and discharging active power, \(D_{ch} + D_{dis} \leq 1\) prohibits the simultaneous charging and discharging, \(E_{bat}^{\max}\) is the maximum energy of the battery. Taking the life of the BAT into account, its actual use range is set to 20% to 100%.

Constraints of the controllable load is set to ensure that the transfer of using time does not affect normal use. Constraints for TL and IL are shown in equations (13), (14) respectively:

\[
\begin{align*}
\begin{cases}
P_b^{\min} \leq P_b(t) \leq P_b^{\max} & \forall t \in [t_{b}^{\text{start}}, t_{b}^{\text{end}}] \\
P_b(t) = 0 & \forall t \notin [t_{b}^{\text{start}}, t_{b}^{\text{end}}] \\
Q_b^{\min} \leq \sum_p p(t) & t \in [t_{b}^{\text{start}}, t_{b}^{\text{end}}] \\
0 < p(t) < p_c^{\max} & \forall t \in [t_{c}^{\text{start}}, t_{c}^{\text{end}}] \text{ and } T(t) > T_{\text{min}} \\
p_c^{\min} \leq p(t) \leq p_c^{\max} & \forall t \in [t_{c}^{\text{start}}, t_{c}^{\text{end}}] \text{ and } T(t) \leq T_{\text{max}} \\
p_c(t) = 0 & \forall t \notin [t_{c}^{\text{start}}, t_{c}^{\text{end}}] \tag{14}
\end{cases}
\end{align*}
\]

Where \(P_b^{\max}\) and \(P_b^{\min}\) are upper and lower active power limit of TL, \(P_c^{\max}\) and \(P_c^{\min}\) are upper and lower active power limit of IL, \(Q_b^{\min}\) refers to the minimum energy consumption of IL to accomplish the mission, \(t_{b}^{\text{start}}\) and \(t_{b}^{\text{end}}\) indicate the start time and end time of TL, \(t_{c}^{\text{start}}\) and \(t_{c}^{\text{end}}\) indicate the start time and end time of IL, \(T_{\text{max}}\) and \(T_{\text{min}}\) are upper and lower temperature requirements of IL. During the operation of IL, the minimum power consumption may be 0 when satisfying temperature demand. Otherwise, the power consumption is the rated power of IL.

4. Case Studies

4.1. Basic parameters

A community is taken as a simulation case, where the PV capacity per house is 3 kW, the average number of air conditioners and rice cookers per house is one, and the residential EV ownership rate is 67%. In order to ensure normal dining, the scheduled timetable of regular rice cookers is 09:00-12:00 and 13:00-19:00. Similarly, the general traffic pattern of EV is: Travel after 07:00 and charge after 19:00. Besides, to ensure users’ comfort, the indoor temperature needs to be maintained at 22-26°C. It is presumed that the price within peak period (07:00-12:00 and 17:00-21:00) is 1.0752 RMB/kWh, the price in flat period (12:00-17:00 and 21:00-24:00) is 0.6451 RMB/kWh and the price in valley period (00:00-07:00) is 0.315 RMB/kWh. Taking three homes in the community as an example, the prediction of PV, total load, and outdoor temperature are presented in figure 2. The total net load reaches the minimum (-2.6822 kW) at 10:15, which means the PV is not completely absorbed. In addition, the net load between 7:00-9:30 and 18:00-24:00 within peak period is relatively large.

4.2. Simulation study

Assuming that the test interval is 24h and the simulation step length is 15min, the optimized simulation results are shown in figure 3. The total net load is always positive which means the PV output is completely consumed. Besides, the total net load is relatively large at 0:00-5:00, 7:00-7:30, 16:00-17:30 and 21:15-21:45 when the energy tariffs are low mostly.

Taking Home 1 as an example, the optimized power consumption plans are shown in figure 4, figure 5, figure 6, and figure 7. The using time of regular rice cookers and EV can be adjusted to the period when the PV is abundant or the electricity price is relatively low. Meanwhile the air conditioner
also shortens the using time through optimization. Besides, the BAT can make profit through arbitrage. The plan can be provided to users through interactive terminal, and users have the right to decide whether to perform it.

It can be seen in figure 8 that the surplus power of each house will be traded according to the energy tariff through the community EER, thus the community reduce to purchase electricity from the grid. Figure 9 shows that the decrement is significant when the PV output is relatively large.

![Figure 2. Predicted cave](image1)

![Figure 3. Scheduled results](image2)

![Figure 4. Rice cooker power diagram](image3)

![Figure 5. Electric vehicle power diagram](image4)

![Figure 6. Air-conditioning power diagram](image5)

![Figure 7. Energy storage power diagram](image6)

![Figure 8. Electricity trading between households](image7)

![Figure 9. Power bought by the community](image8)
For simplicity of following discussion, we define Scenario 1 as the case without EER, Scenario 2 as the case with home EER and Scenario 3 as the case with both home EER and community EER. Cost of three scenarios is compared in table 1.

Comparing to scenario 1, the total electricity charge drops by 44.22% in scenario 2 and drops by 45.61% in scenario 3. Thus, the joint scheduling of two EER can minimize the total electricity charge of the community.

Table 1. Analysis of simulation results

| Scenario | Charge/RMB | Home1 | Home2 | Home3 | Total |
|----------|------------|-------|-------|-------|-------|
| 1        | 55.77      | 56.99 | 18.94 |       | 132.69|
| 2        | 33.71      | 33.99 | 6.33  |       | 74.02 |
| 3        | 33.90      | 33.97 | 4.29  |       | 72.17 |

5. Conclusion
Considering the power interaction and home energy management, this paper establishes an optimal scheduling model whose objective function is the lowest electricity charge. The results show that home energy scheduling based on home EER promotes the consumption of PV and sharply drops the user's electricity cost by utilizing demand response and BAT’s peak-shaving, valley-filling function. What’s more, community EER provides a platform for transactions between households to further reduce the cost of electricity.

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