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Two-stage Energy Management of Residential Microgrid Community using Pairing Strategy

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***Abstract*—A generalized two-stage energy management model in the context of interconnected microgrid (MG) community is proposed in this paper. Total operational cost minimization of the community and benefits of MG partners are both investigated. In the lower stage, based on the detailed model of individual MG with multiple energy sources and loads, the distributed MG-level EMS solves the optimization problem to decide the optimal energy dispatch based on the interest of MG owners. In the upper stage, a pairing strategy is proposed in the community-level EMS to explicitly determine the power flow between MGs and with the upstream distribution grid. The profit by minimized energy exchange with the distribution grid is fairly shared by participants in the MG community. With the proposed structure and control algorithm, the user preference of each MG is reserved and user privacies are well preserved. Simulation studies successfully demonstrate the effectiveness that the proposed two-stage energy management model can effectively allocate the power flow among different MGs while the minimal operational cost of the community is achieved.**

***Index Terms*—Energy Management, microgrids, hierarchical control.**

I. Introduction

Increasing investment on renewable energy sources (RES), rapid development on demand side management and massive integration of energy storages (ES) in microgrid (MG) have brought opportunities for economic efficient and reliable operation [1]–[5]. The paradigm of MG community, which clusters several MGs in adjacent feeders, brings new opportunities for economic and reliability concerns [6]. MG community can provide additional benefit to individual members by resource sharing with minimizing dependency and effect and operate as an autonomous entity to enhance power system reliability under extreme events.

Centralized and decentralized energy management system (EMS) to optimization problems have been thoroughly investigated in the context of MG community. Centralized controller gathers full information from dispatchable components and makes operating decisions for all individual MGs [7]–[10]. However, centralized EMS may lead to several impractical outcomes. Individual MGs are regarded as self-interested entities whose optimization objectives may be inconsistent with the centralized EMS and other MGs. Size expansion makes centralized EMS problematic to handle computational burden for massive variables. Full observability results into MG security and privacy issues. Various infrastructures and geographic locations of MGs also bring new challenges to centralized EMS in the sense of complexity on control strategies. On the other hand, decentralized EMS has also gained a lot of attention considering distributed infrastructures for power sharing [11]–[13] and economic operation [14]–[16] for MG community. However, the distinct power flow inside the MG community has not yet been addressed, and iterative algorithm may result into intensive computation stress and convexity issues, especially for the MG community with a large number of MG partners.

In order to address these problems, we focus on a generalized two-stage energy management model for an interconnected residential community with multiple MGs. Minimization problems of total operational cost and impacts of the MG community on the upstream distribution grid are both investigated. The distributed EMS is integrated in the MG level. Based on the detailed model of individual MG with ES, electric vehicle (EV), RES and controllable loads, the distributed EMS solves the optimization problem in each individual MG to decide the optimal energy dispatch based on the interest of MG owners. In the upper stage, the community-level central EMS is implemented to explicitly determine the power exchange between MGs and with the upstream distribution grid. A non-iterative pairing strategy is proposed so that the energy exchange with the distribution grid is minimized that MG owners can adjust the scheduling freely to determine their participation levels. Private confidential information such as specific scheduling inside MGs is well preserved, as public information for communication only involves energy exchange values of each MG.

The remainder of this paper is organized as follows. In Section II, the system model and formulation of individual MG is presented, and the pairing strategy for the MG community is proposed. Case studies and results are discussed in Section III. The conclusion are summarized in Section IV.

II. System Model and Problem Formulation

A. Structure of Regional MG Community

The schematic diagram of the MG community is illustrated in Fig. 1. The regional MG community can be regarded as a distributed smart power system comprising of one community-level central EMS and several MGs sited on different locations. Each MG has a bidirectional power link with the distribution grid across the point of coupling (PCC) so that the power transmission between MGs and the distribution grid are allowed. Additionally, several connections between

MGs have been also established to allow energy exchange between MGs. Each MG includes local EMS, PV, ESs, EVs and different types of critical and controllable loads. The generalized MG model can be easily modified and utilized to specify different system frameworks by changing the above components. The local EMS in each individual MG aims to its self-interested operation. MG owners can schedule the device usage in order to optimize strategies, fulfilling their energy requirements either in the grid-tied mode or as an islanded grid. Grid-tied operation is mainly discussed in the following study since we focus to investigate interactive mechanisms of MGs inside the community. Hence, the power consumed by a MG may be procured by the distribution grid or other regional MGs by selling their excessive energy under supervision of the central community-level EMS.

B. Problem Formulation of Individual MG

As the self-interested entity, the objective of each individual MG is to minimize the total operational cost in a finite period of time in the MG level. The modeling of different components and their constraints introduce different operation requirements. The generalized optimization model of the individual MG_k can be formulated as follows:

$$\min \sum_{t\in T} \left\{ \begin{array}{l} p^k_{M,b}(t)c_b(t)\Delta t + p^k_{M,s}(t)c_s(t)\Delta t \\ + \sum\limits_{i\in N_G, i\neq k} [p^{k,i}_{C,b}(t)\varepsilon^{k,i}_{C,b} + p^{k,i}_{C,s}(t)\varepsilon^{k,i}_{C,s}]\Delta t \\ + \sum\limits_{i^k_{ES}\in N^k_{ES}} [p^k_{ES,b}(i^k_{ES},t) - p^k_{ES,s}(i^k_{ES},t)]c^k_{i^k_{ES}}\,\Delta t \end{array} \right\} \quad (1)$$

subject to

$$\begin{array}{l} p^k_{M,b}(t) + p^k_{M,s}(t) + p^k_{PV}(t) \\ + \sum\limits_{i\in N_G,\, i\neq k} (p^{k,i}_{C,b}(t) + p^{k,i}_{C,s}(t)) \\ + p^k_{ES,b}(t) + p^k_{ES,s}(t) \\ + p^k_{EV,s}(t) + p^k_{EV,s}(t) = p^k_{L1}(t) \\ \qquad + p^k_{L2}(i^k_{L2},t)\lambda^k(i^k_{L2},t) \\ \qquad + p^k_{L3}(i^k_{L3},t)\lambda^k(i^k_{L3},t) \end{array} \quad (2)$$

$$0 \le p^k_{M,b}(t) \le p_{M,\max}u^k_M(t) \quad (3)$$

$$p_{M,\min}(1-u^k_M(t)) \le p^k_{M,s}(t) \le 0 \quad (4)$$

$$0 \le p^{k,i}_{C,b}(t) \le p_{C,\max}u^{k,i}_C(t) \quad (5)$$

$$p_{C,\min}(1-u^{k,i}_M(t)) \le p^{k,i}_{C,s}(t) \le 0 \quad (6)$$

$$\begin{array}{l} E^k_{ES}(i^k_{ES},t+1) = E^k_{ES}(i^k_{ES},t) \\ \qquad + \eta^k_{ES}(i^k_{ES})p^k_{ES,b}(i^k_{ES},t)\Delta t \\ \qquad - p^k_{ES,b}(i^k_{ES},t)\Delta t \end{array} \quad (7)$$

$$E^k_{ES,\min}(i^k_{ES}) \le E^k_{ES}(i^k_{ES},t) \le E^k_{ES,\max}(i^k_{ES}) \quad (8)$$

$$0 \le p^k_{ES,b}(i^k_{ES},t) \le p_{ES,\max}u^k_{ES}(i^k_{ES},t) \quad (9)$$

$$p_{ES,\min}(1-u^k_{ES}(i^k_{ES},t)) \le p^k_{ES,s}(i^k_{ES},t) \le 0 \quad (10)$$

$$\begin{array}{l} E^k_{EV}(i^k_{EV},t+1) = E^k_{EV}(i^k_{EV},t) \\ \qquad + \eta^k_{EV}(i^k_{EV})p^k_{EV,b}(i^k_{EV},t)\Delta t, \\ \qquad - p^k_{EV,b}(i^k_{EV},t)\Delta t,\ t\in T_p(i^k_{EV}) \end{array} \quad (11)$$

$$E^k_{EV,\min}(i^k_{EV}) \le E^k_{EV}(i^k_{EV},t) \le E^k_{EV,\max}(i^k_{EV}), t\in T_p(i^k_{EV}) \quad (12)$$

$$0 \le p^k_{EV,b}(i^k_{EV},t) \le p_{EV,\max}u^k_{EV}(i^k_{EV},t), t\in T_p(i^k_{EV}) \quad (13)$$

$$p_{EV,\min}(1-u^k_{EV}(i^k_{EV},t)) \le p^k_{EV,s}(i^k_{EV},t) \le 0, t\in T_p(i^k_{EV}) \quad (14)$$

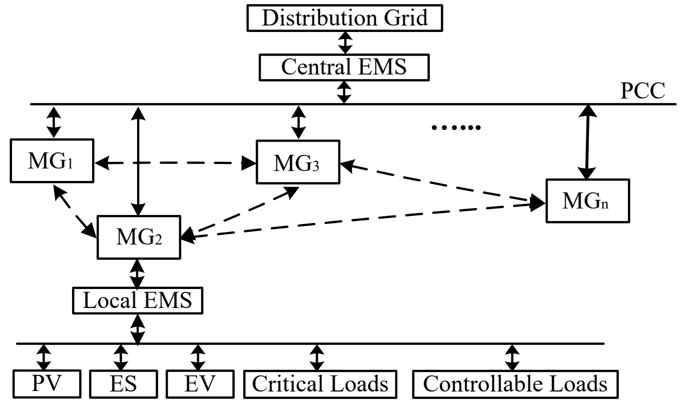

Fig. 1. Power of load, PV and wind turbine in 48 hours.

$$\sum_T p^k_{L2}(i^k_{L2},t)\lambda^k(i^k_{L2},t) = P^k_{L2}(i^k_{L2}) \quad (15)$$

$$\sum_T \lambda^k(i^k_{L2},t) = H^k_{L2}(i^k_{L2}) \quad (16)$$

$$\sum_T p^k_{L3}(i^k_{L3},t)\lambda^k(i^k_{L3},t) = P^k_{L3}(i^k_{L3}) \quad (17)$$

$$\sum_T \lambda^k(i^k_{L3},t) = H^k_{L3}(i^k_{L3}) \quad (18)$$

$$\sum_{T-1} \mu^k_s(i^k_{L3},t) = 1,\ \mu^k_s \in \{0,1\} \quad (19)$$

$$\sum_{T-1} \mu^k_e(i^k_{L3},t) = -1,\ \mu^k_e \in \{-1,0\} \quad (20)$$

$$\begin{array}{r} \lambda^k(i^k_{L3},t+1) - \lambda^k(i^k_{L3},t) = \mu^k_s(i^k_{L3},t) + \mu^k_e(i^k_{L3},t), \\ t\in\{1,\cdots,T-1\} \end{array} \quad (21)$$

The appropriate time horizon T is determined by each MG owner, which may not be necessarily correspondent with the central EMS in the community level. In (1), the first line of the objective function represents the grid-tied electricity tariff, in which the buying price $c_{in}(t)$ is higher than the selling price $c_s(t)$ to prevent energy arbitrage from a dynamic electricity market. Such a price difference provides economic incentives to MGs by bilateral transaction schemes. The second line represents the transmission loss induced by energy exchange in the community with loss factors $\varepsilon^{k,i}_{C,b}$ and $\varepsilon^{k,i}_{C,s}$. The degradation costs of ESs are presented in the third line with a fixed degradation cost $c^k_{i^k_{ES}}$ to address the effect on lifetime by daily usage. It is noted that investment cost of other appliances such as EV and PV are not considered since the proposed strategy is focused on operational optimization of the MG.

The objective function is subject to several constraints from (2) to (21). (2) claims the power balance requirements. (3)-(6) provides the constraints on power flows to the distribution grid and in the community, respectively. The binary variables $u^k_M(t)$ and $u^{k,i}_C(t)$ enforce the directions at each time interval. (7)-(10) describes the state dynamics of ESs in terms of power and capacity limits to avoid over-charging and over-discharging, in which $u^k_{ES}(i^k_{ES},t)$ is added to determine the power flow direction in each time interval. (11)-(14) claim the similar constraints for EVs. Additionally, $T_p(i^k_{EV})$ denotes the parking time region, meaning that EV can be scheduled only if it is parked in the MG of its owners.

The loads in MGs are classified into critical and controllable loads. Critical loads represent the basic non-controllable electricity consumption that is fixed and hardly shifted over time, since critical loads stand for the most fundamental requirements. The critical loads can be aggregated as a single a time-dependent variable $p_{L1}^k(t)$. Controllable loads represent the electrical appliances that can be flexibly dispatched. Based on the operation modes, two categories of controllable loads are defined as interruptible and non-interruptible types. Interruptible loads include appliances which can be scheduled into several nonconsecutive time intervals, such as mashing machine that does wash and spin at different times. The model are formulated in (15)-(16) by using the binary variable $\lambda^k(i_{L2}^k, t)$ to indicate the on/off status. On the other hand, non-interruptible loads represent those appliances which must be scheduled during consecutive times under users discretion. It is formulated in (17)-(21) with the binary variable $\lambda^k(i_{L3}^k, t)$. Additionally, two auxiliary integral variables $\mu_s^k(i_{L3}^k, t)$ and $\mu_e^k(i_{L3}^k, t)$ are modeled in (19)-(21) to address the feature of consecutive operation.

C. Pairing Strategy in MG Community

The utilization of dynamic real-time pricing scheme offers uniform price to all MG partners, concentrating demand response that the load profile of MGs would be adverted altogether [15]. Considering the diversity of MGs, however, with the integration of PV and demand response program, it is not always the case that most of MGs would purchase as much power as possible during hours when the electricity price is low. At some hours in daytime, some MGs may have excessive energy produced by PV, while at the same time other MGs may purchase electricity from the main grid due to the relatively low price. Frequent energy transmission between the MG community and the upstream network would induce additional energy loss and stress the economic operation. To this end, The central EMS in the MG community deploys the pairing strategy to minimize the energy exchange between the community and the distribution grid, and provides additional economic benefit for MG owners.

The pairing strategy attaches the unique identification to power flow between a pair of MGs representing supply and load. It is used to determine the pattern of MGs exchanging surplus and deficit energy inside the MG community so that the pattern of MGs exchanging energy surplus and deficit inside the MG community can be established.

In order to represent the geographical location of MGs accordingly, a 2-D Cartesian coordinate system is formulated. The location of each MG can be presented by a 2-D coordinate vector . The Euclidean distance between every two MGs in the 2-D Cartesian coordinate system can be presented as follows:

$$w_{ij} = ||d_i - d_y|| = \sqrt{(x_i - x_j)^2 + (y_i - y_i)^2} \tag{22}$$

Since geographical locations of MGs can be approximately modeled to relate with transmission losses, we use the Euclidean distance matrix W_d to describe the weighting coefficient values of the MG community, which can be formulated as follows:

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1N_G} \\ w_{21} & w_{22} & \cdots & w_{2N_G} \\ \vdots & \vdots & \ddots & \vdots \\ w_{N_G 1} & w_{N_G 2} & \cdots & w_{N_G N_G} \end{bmatrix} \tag{23}$$

To this end, the Euclidean distance W_{ij} is implemented to determine the priority sequence of the energy exchange sequence inside the MG community. If there is no physical connection between MG i and j, then the corresponding weighting coefficient W_{ii} is set as zero. It can be easily recognized that the diagonal element is zero and W is a $N_G \times N_G$ symmetric matrix.

To this end, the corresponding row $r_i = [w_{i1}, w_{i2}, \ldots, w_{iN_G}]$ in W is the weighing coefficients to other MGs of MG i. Next, it is proven that there always exists a pairing for each MG whose distance to each other is the minimum among those to all other MGs.

Theorem 1. *A pairing for each MG can be always found whose distance to each other is the minimum among those to all other MGs.*

Proof: We denote $m \in N_G$ and $n \in N_G$ to be the indices of rows and columns, respectively. The minimum value of each row in W can be expressed as follows:

$$W_{R_{min}} = \min_{n \in n_G} w_{m,n} = \left[w_{1,c_1}, w_{2,c_2}, \cdots, w_{n,c_{N_G}} \right]^T \tag{24}$$

where $\{c_1, c_2, \cdots, c_{N_G}\}$ are the column indices of the minimal element in W.

We firstly make a counter-assumption that there does not exist such the pairing for at least one MG. In other words, The elements in $W_{R_{min}}$ are all different with each other. For signal simplicity, we denote $k_m = c_{k_{m-1}}$ for $\forall m \in N_G$ in the following discussion. Since W is a symmetric matrix, starting from the k_0 th row, we can get its minimum elements as follows:

$$w_{k_0, c_{k_0}} = w_{c_{k_0}, k_0} = w_{k_1, k_0} \tag{25}$$

In the k_1 th row, since $w_{k_1, c_{k_1}}$ is the minimum element in this row and all the elements are different, we have:

$$w_{k_1, k_0} = w_{c_{k_0}, k_0} > w_{k_1, c_{k_1}} = w_{k_2, k_1} \tag{26}$$

Sequentially, we can get the following equation:

$$w_{k_0, c_{k_0}} > w_{k_1, c_{k_1}} > \cdots > w_{k_{N_G - 1}, c_{k_{N_G - 1}}} > w_{k_{N_G}, c_{k_{N_G}}} \tag{27}$$

It has been recognized that $\{c_1, c_2, \cdots, c_{N_G}\}$ are all different, thus $\{k_0, k_1, \cdots, k_{N_G - 1}\}$ are also all different. Therefore, In the last term in the above formulation, k_{N_G} must be one element in the K set. As a consequence, the last element $w_{k_{N_G}, c_{k_{N_G}}}$ must be equal to at least one element in $W_{R_{min}}$, which is contradictory to the counter-assumption. Hence, such the pairing for each MG can be always found. ■

With the implementation of the proposed pairing strategy, the appropriate allocation for MGs with energy deficit and surplus can be always detected. Self-pairings and pairings between two MGs with both surplus/deficit can be automatically excluded, since they are unable to make a valid energy flow loop. The detailed procedure of the proposed two-stage control is presented as in Fig. 2.

Initialize $t = 1$
for $t = 1$ **to** T, **do**
  for each MG $i = 1$ **to** N_{MG}, **do**
    Make PV and load forecast locally and acquire electricity price forecast, and set $p_{C,b}, p_{C,s}$ to zero.
    solve the optimization problem locally, and submit the initial power surplus/deficit to the central EMS.
  end for
  The central EMS calculates the total energy surplus or deficit in the community, and form the weighting coefficient matrix W in which rows and columns with same power flow directions of MGs are excluded..
  while both of total energy surplus/deficit are nonzero, **do**
    The central EMS executes find the pairing with maximum elements and sends the reference $p_{C,b}, p_{C,s}$ back to MGs.
    Calculate the total residue energy surplus or deficit of MGs and exclude the corresponding rows and columns of the MG without any residue.
  end while
end for

Fig. 2. Algorithm of control strategy for two-layer EMS.

TABLE I
MICROGRID CHARACTERISTICS

Microgrid	house 1	house 2	apartment	RES station
ES				
Capacity (kWh)	8	8	12	12
Maximum power (kW)	-4/4	-4/4	-4/4	-4/4
Initial SOC (%)	20.9	33.1	33	31
SOC range (%)	17.0-84.1	17.5-83.5	16.9-82.1	18.7-89.0
Cost ($/kWh)	0.04	0.04	0.04	0.04
Efficiency (%)	95	95	95	95
EV				
Capacity (kWh)	16	16	N.A.	N.A.
Maximum power (kW)	-1.44/3.6	-1.44/3.6		
Initial SOC (%)	52.63	33.1		
available charge hour (h)	0-4.88, 19.09-24	0-7.65,18.93-24		
Efficiency (%)	95	95		
SOC range (%)	15.8-83.7	19.9-81.6		
Min depart SOC (%)	51.45	61.58		
Cost ($/kWh)	0.03	0.03		
PV				
Capacity (kW)	2	2	16	16
Unified Geo location				
(x, y)	(0.12, 0.13)	(0.16, 0.79)	(0.83, 0.11)	(0.09, 0.26)

TABLE II
CONTROLLABLE LOADS

Appliance	Power(kW)	Operating range	Operating duation(h)	type
Washing machine	0.7	0-19,23-24	1	1
Cleaner	0.6	0-4,6,24	4	1
Air conditioner	1.2	0-7,18-24	3	1
Lighting	0.15	6-7,18-23.5	5	1
Oven	1.16	11-13	0.5	1
Toaster	1.2	7-9	0.25	2
Dish washer	1	0-4,9-11,14-17,20-24	1	2

III. CASE STUDY

A. Input Data and Benchmarks

A MG community with 4 MGs is considered including two individual houses, an apartment building involving 10 homes and a small-scale PV station. The specifications are detailed in TABLE I. For each house in individual houses and apartment buildings, home appliances are regarded as controllable loads listed in TABLE II with predefined operation time ranges. The electricity price of the MG community is adopted from Energy Market Company of Singapore [17], as depicted in Fig. 3. The selling price is set to be 60% of the buying price. The community-level EMS resolves the optimization problem by

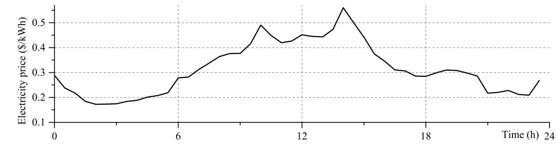

Fig. 3. Electricity price of MG community.

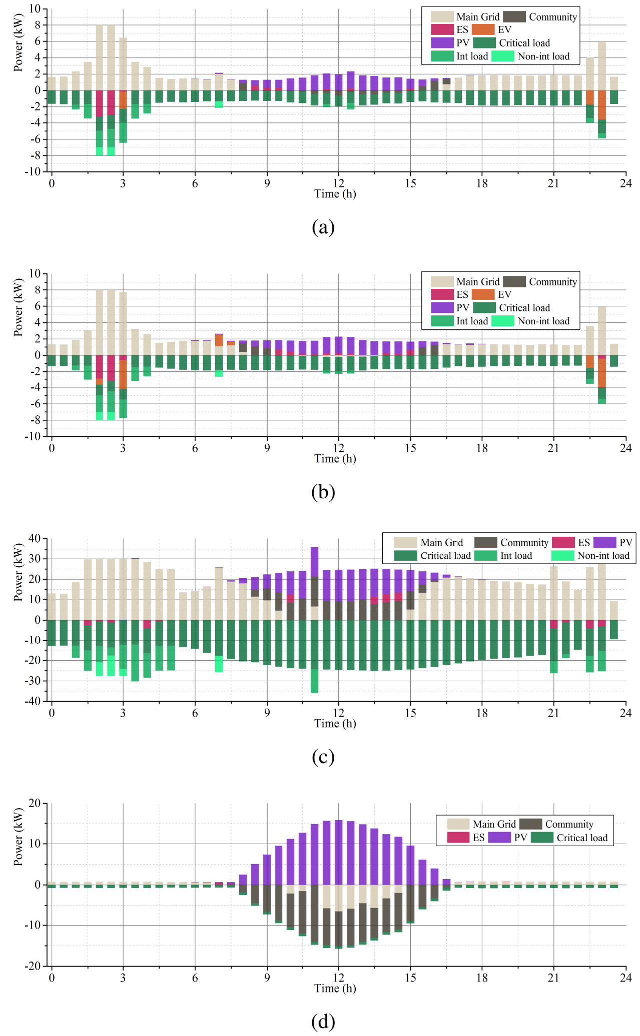

Fig. 4. Energy scheduling in (a) house 1; (b) house 2; (c) apartment; and (d) RES station.

using the proposed pairing strategy, and the MG-level EMS is solved by using CPLEX. The simulation is conducted for a 24h scheduling horizon.

B. Results and Discussion

The hourly energy scheduling for four MGs is presented in Fig. 4. Two houses can cover most of electricity demand by the PV in daytime, while the PV cannot fully cover the apartment need. The home appliances in the houses and apartment show similar pattern load profiles. Controllable loads are scheduled within off-peak hours due to the relatively low electricity price. The ES and EV are charged until the required energy levels are reached at hours with low electricity prices (e.g., at hour 2 and 23). However, the ES can effectively respond the high price signals in daytime whereas the EV does not participate

TABLE III
ENERGY FLOW RESULTS IN 24 HOURS

Time(h)	1-2	1-3	1-4	2-3	2-4	3-4
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	-1.0834	-3.3408
10	0	0	0	0	0	-8.8575
11	0	0.1525	0	0	0	-10.4862
12	0	0.337	0	0	0	-9.0195
13	0	0.2086	0	0	0	-8.8794
14	0	0.5046	0	0	0	-7.2953
15	0	0.2985	0	0	0	-9.1176
16	0	0	-0.51	0	-0.9753	-4.0017
17	0	0	-0.654	0	0	0
18	0	0	0	0	0	0
19	0	0	0	0	0	0
20	0	0	0	0	0	0
21	0	0	0	0	0	0
22	0	0	0	0	0	0
23	0	0	0	0	0	0
24	0	0	0	0	0	0

TABLE IV
OPERATION COST OF EACH MG COMMUNITY WITH 4 MGS

Cost ($)	house 1	house 2	apartment	RES station	total
original	5.7806	5.8503	72.2331	-10.5057	71.9217
from grid	5.4494	4.9494	56.3267	-1.1935	65.532
from community	-0.1216	0.3934	11.5099	-13.0596	-1.2779
total	5.3278	5.3428	67.8366	-14.2531	64.2541
percentage %	7.8331	8.6748	6.0865	35.6701	10.661

since it is already departed. Particularly, when the electricity price increases at hour 7, the EV in house 2 starts to charge to lower the electricity consumptions of the distribution grid.

TABLE III shows the energy flow in the MG community. MG1 (house 1) has the higher priority to export the energy surplus to MG3 (apartment) due to its smaller weighing coefficient, even when both houses have excessive energy from the PV at daytime. Similarly, when the RES output is insufficient at hour 17, MG1 has the higher priority to take energy from MG4 (RES station) than MG3. With the implementation of the proposed pairing strategy, the total operational cost hase been decreased for each MG and the whole MG community, as shown in TABLE IV. Compared with direct interaction with the distribution grid, the total operational cost of the MG community is reduced by 10.66%, while the operational cost of each MG is reduced by starting from 6.08% to at most 35.67%. Therefore the MG owners can increase their electricity sale profits reduce their purchases through the local electricity market, which would potentially attract other community customers to participate into the interaction schemes inside the MG community.

IV. CONCLUSION

A generalized two-stage EMS model in the context of interconnected MG community is proposed. Minimization problems of total operational cost and the impact of the community on the upstream distribution grid are both investigated. The distributed MG-level EMS is integrated in the lower stage to solve the optimization problem in each individual MG based on the interest of MG owners. A pairing strategy is proposed in the community-level EMS to explicitly determine the power flow between MGs and with the upstream distribution grid. The profit by the minimized energy exchange with the distribution grid is fairly shared by participants in the MG community. Since the central EMS does not account for the individual optimization problem, the user preference of MG is reserved that MG owners can adjust the schedules to determine their participation levels, and user privacies are also well preserved. Simulation studies successfully demonstrate the effectiveness that the proposed method can effectively allocate the power flow among different MGs while the minimal operational cost of the community is achieved.

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