Energy Management of Cooperative Microgrids with P2P Energy Sharing in Distribution Networks

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***Abstract*—To handle the mismatch problem between local demand and local generation in microgrids (MGs), the paradigm of peer-to-peer (P2P) energy sharing among neighboring MGs has been considered as a promising solution for improving the utilization of local distributed energy resources and saving the energy bills for all MGs. Existing works on cooperative MGs usually consider the high-level energy sharing and trading strategies but little about the physical constraints (e.g. voltage tolerance and power flow constraints) in the underlying distribution network. Hence, their solutions may not be applicable to practical power systems. This paper proposes an optimization problem that aims at minimizing the overall energy cost and the P2P energy sharing losses in a distribution network consisting of multiple MGs and explicitly incorporates the practical constraints (e.g., power balance and battery's operational constraints). The proposed optimization problem is difficult to solve directly due to the non-convex constraints. Nevertheless, motivated by the very recent result in radial distribution networks, the proposed non-convex optimization problem can be relaxed to a second-order cone programming (SOCP) problem without incurring any loss of optimality. We apply the proposed problem to a radial distribution network testbed and obtain the corresponding optimal energy management strategy, which exploits the diversified energy consumption profiles to dynamically coordinate multiple MGs and reduces the total energy bill of all MGs. Moreover, an interesting observation from the simulation results is that the cooperation scheme in the P2P sharing network is significantly affected by the MGs' relative locations in the distribution network.**

I. Introduction

Microgrid (MG), which accommodates a variety of distributed energy resource (DER) units and different types of energy users, has been considered as a promising approach to improve the utilization of DER and the users' benefits [1]. However, due to the intermittent nature of the output of the DERs (e.g., the solar panels and wind turbines), there could be a significant mismatch between the power supply and demand in an MG, especially when the MG is operated in the islanded mode disconnected with the main grid. Therefore, seeking the help of distributed storage (DS) units is a typical solution for the MG to deal with its energy surplus and deficiency. However, the usage of DS units suffers from two drawbacks, i.e., i) a huge capital investment, and ii) significant transfer energy loss due to the inefficiency of the charging and discharging processes.

Fortunately, the peer-to-peer (P2P) energy sharing and trading among the geographically correlated MGs has been conceived as a promising yet economical approach to tackle with the supply-demand mismatch problem [2]. In particular, in a P2P energy sharing network, an MG, if it has surplus energy beyond its internal demand, can directly transfer energy to some other ones in short of supply via dedicated transmission lines. By exploiting the diversified energy generation and consumption profiles of the MGs at different geographical locations, the P2P sharing network gains many advantages. For instance, the energy transmission loss can be reduced for the short distance transmissions between neighboring MGs. Moreover, with a well-designed trading scheme, each individual MG can benefit from the P2P energy network, e.g., each MG will enjoy a lower purchase price and a higher selling price in the P2P network, in comparison with the external main grid [3].

The coordinated energy management with networked MGs have been warmly discussed in the literature [4]–[8]. Specifically, Lakshminarayana *et al.* [4] analyzed the tradeoff between the use of storage and the cooperation by energy sharing among DG resources. In [4], the objective was to minimize the time average cost of the energy exchange within the grid. However, the energy transfer losses were not taken into account. Zhu *et al.* in [5] proposed a structure wherein nearby homes explicitly shared energy with each other to balance the local energy harvesting and demand in MGs. And they developed an energy sharing and transmission allocation approach to minimize the system-wide efficiency losses or electricity cost. However, one problem of both these prior works was that the transmission losses associated with energy sharing were either ignored or simplified by a linear model, which is not realistic in practical systems. Towards this end, [8] studied the cooperative MGs' problems with transmission losses, in which the energy transmission loss function was defined to be quadratic in the energy transferred.

In spite of the aforementioned works [4]–[8] dealing with the energy sharing issue in cooperative MGs, seldom of them have considered the underlying distribution network. In fact, MGs are indeed connected with the main grid at the point of common coupling (PCC) through *the distribution network*, which has its own power flow constraints and system operational constraints and consequently influences the corresponding energy managements [9]–[11]. As a result, the physical conditions (or limits) of the underlying distributed network should be carefully taken into account, such that the designed P2P energy sharing scheme is applicable to real power systems and can truly benefit the users in MGs.

Motivated by the above considerations, in this paper, we consider the energy management of multiple networked MGs under a distribution network in the day ahead market using the time-of-use (TOU) price. We assume that the local area operator (LAO) constructs the dedicated transmission lines for direct P2P energy sharing among different MGs and determines the topology of this P2P network, since these dedicated transmission lines yield lower losses than in an AC distribution network and reduce the power conversion losses [5]. Therefore, combined with the conventional AC distribution network, a hybrid transmission system can be established. The LAO decides scheduling strategies for DG and DS units, energy sharing, and interaction with the main grid. To take advantages of RES, we consider photovoltaic (PV) generators and wind turbines (WTs) as DG units, and the predicted generation and load profiles are adopted for our day-ahead scheduling. Then, the LAO aims at minimize the total cost that includes: i) the money paid for the power fed into this network, ii) the power loss in the distribution network, iii) the P2P energy transmission cost, and iv) the battery's operational cost. Our proposed model not only guarantees the transmission feasibility and the battery's operation feasibility in the high-level P2P energy network, but also takes into account the power flow constraints and the voltage tolerance in the bottom-level distribution network.

The problem is formulated as an optimization problem. Since we consider the P2P transmission losses and resistive power losses in the distribution network to make our model more realistic with respect to the practical system, the resulting energy management problem is a non-convex optimization problem, which is difficult to solve efficiently. To tackle with the non-convexity, we exploit the recent results of *the exact relaxation method* from [12]. In particular, the relaxation method matches the property of our model very well, which thus enables us to equivalently transform the original non-convex problem into a second-order cone programming problem and determine the optimal solution successfully (without suffering from any relaxation loss). We apply our model on a 34-bus test radial distribution system and perform extensive numerical tests. The results show that different MGs can cooperate with each other according to their distinct and/or complementary consumption profiles to minimize the total cost of the system. Furthermore, the results demonstrate that the cooperation scheme is significantly affected by the MGs' relative locations in the distribution network. To the best of our knowledge, this is the first work coping with the energy management problem of MGs incorporating direct P2P energy sharing and distribution network constraints simultaneously.

The rest of the paper is organized as follows. In Section II, the MGs P2P network and distribution network are modeled. The problem formulation as well as its relaxed version is discussed in Section III. Numerical results are presented in Section IV followed by conclusions in Section V.

II. System Model

A. MGs P2P Network Model

We consider a set of N MGs in a distribution system, denoted by $\mathcal{N} := \{MG_n : n \in \mathcal{W}\}$, where $\mathcal{W} := \{1, 2...N\}$ is the index set of MGs. The time horizon is discretized, and $t \in \{1, 2 \cdots H\}$ denotes the time slot $(t, t + \Delta]$, where H is the total number of time slots of interest. Each MG_n is connected to a bus of the underlying distribution network by the PCC. Moreover, MGs are equipped with storage devices (e.g., batteries) as well as RES (e.g., PV generators and WTs). These MGs are also connected by a P2P network. Fig. 1 is an example of a three MGs P2P network. At each time slot t, if MG_m transfers $T_{m,n,t}$ amount of power to MG_n, then the power received by MG_n is [8]:

$$T_{m,n,t} - \frac{r_{m,n} T_{m,n,t}^2}{U_{m,n}^2} \quad \forall\, t, m, n, m \neq n, \tag{1}$$

where $r_{m,n}$ denotes the resistance of the transmission line, and $U_{m,n}$ denotes the transmission voltage. See the example in Fig. 1 between MG_1 and MG_2.

Furthermore, our model is applicable to any network topology because we focus only on the amount and the direction of the energy transferred on each line in arbitrary topology. To be more specific, as the example shown in Fig. 1, if $T_{1,3,t}$ is 15 KW and $T_{3,2,t}$ is 10 KW, then it means that at time slot t, 10 KW of the power is transferred from MG_1 to MG_2 passing by MG_3, while 5 KW is supplied to MG_3. Obviously, MG_1 can transfer energy through a direct line to MG_2. So our model can cover all the possible paths between every two MGs. Note that $T_{m,n,t}$ is different from $T_{n,m,t}$, and they represent the energy transferring in two different directions.

B. DS Device Model

We use $ES_{n,t}$ to denote the remained energy level in the battery of MG_n at time slot t, and its evolution can be given as follows:

$$ES_{n,t+1} = ES_{n,t} + (\eta_c P_{n,t}^{ESC} - \frac{1}{\eta_d} P_{n,t}^{ESD})\Delta \quad \forall\, m, t, \tag{2}$$

where $P_{n,t}^{ESC}$ (or $P_{n,t}^{ESD}$) denote the charging (or discharging) power during time slot $(t, t + \Delta]$, and η_c, $\eta_d \in (0, 1]$ are the charging and discharging efficiencies, respectively. Note that the charging and discharging rates are respectively limited by the power ratings $\overline{P_{n,t}^{ESC}}$ and $\overline{P_{n,t}^{ESD}}$, and they cannot be nonzero at the same time, which are given as follows:

$$0 \leq P_{n,t}^{ESC} \leq \overline{P_n^{ESC}} \qquad \forall\, n, t, \tag{3}$$

$$0 \leq P_{n,t}^{ESD} \leq \overline{P_n^{ESD}} \qquad \forall\, n, t, \tag{4}$$

$$P_{n,t}^{ESC} \cdot P_{n,t}^{ESD} = 0 \qquad \forall\, n, t. \tag{5}$$

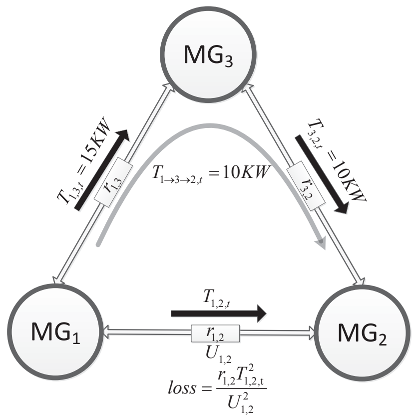

Fig. 1. An example of the P2P network topology comprising 3 MGs.

The storage level should be within a range at each time slot:

$$\underline{ES_n} \leq ES_{n,t} \leq \overline{ES_n} \qquad \forall\ n,t, \tag{6}$$

where $\underline{ES_n}$ and $\overline{ES_n}$ denote the lower and upper bound of the permitted storage levels, respectively. Also, the battery's operational cost $C^{ES}_{n,t}$ is modeled by its conversion loss, i.e.,

$$C^{ES}_{n,t} = (1-\eta_c)P^{ESC}_{n,t} + (\frac{1}{\eta_d} - 1)P^{ESD}_{n,t} \qquad \forall\ n,t. \tag{7}$$

Moreover, the storage level at the end of the time horizon must be higher than a predefined level $\gamma_n \in (0,1]$,

$$ES_{n,T} \geq \gamma_n \overline{ES_n} \qquad \forall\ n, \tag{8}$$

so that MG_n can have enough energy for future use.

C. Renewable Energy Generation and Demand Models

1) Renewable Energy Generation: Each MG is equipped with a PV generator and a WT for renewable energy supply. In our day-ahead scheduling problem, we use $P^{RE}_{n,t}$ to denote the renewable energy generation of MG_n at time slot t, and assume that it can be predicted for the next 24 hours. We emphasize here that our problem mainly focuses on understanding the tradeoff between energy storage, P2P energy sharing and the interaction with the main grid in a day-ahead manner, thus the detailed prediction methods of the renewable energy generation is beyond the scope of this paper. In particular, our model allows the MG to buy energy from the main grid for the purpose of energy sharing as long as the overall system cost can be reduced. The incentive for an MG doing so can be a lower purchase price from the main grid and/or a higher remuneration from the P2P network, however the pricing mechanism is not discussed in this work.

2) Demands: The load demands of MGs and other pure load buses can have active and reactive parts, which can be denoted by

$$S^L_{i,t} = P^L_{i,t} + jQ^L_{i,t}. \tag{9}$$

The demands of MGs can be met by either self renewable generation, battery discharging, P2P energy sharing or purchasing from the main grid.

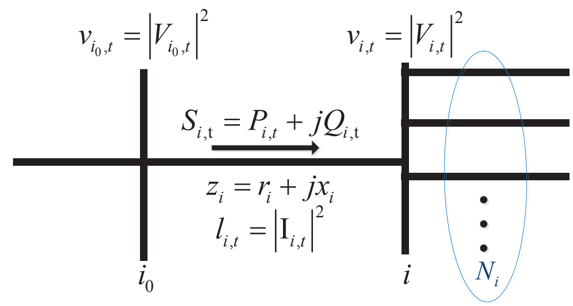

Fig. 2. Branch flow model from bus i_0 to i.

D. Distribution Network Model

A distribution network in most cases is a radial network and can be represented by a tree $\mathcal{T} = (\mathcal{K}, \mathcal{E})$, where $\mathcal{K}$ and $\mathcal{E}$ denote the node set and the branch set, respectively. Each node (bus) indexed by $i \in \mathcal{K} := \{0,1,2,3,\cdots K\}$ is either a pure load or an MG, and $|\mathcal{E}| = K$ is the cardinality of branch set $\mathcal{E}$. The tree is rooted at the substation bus indexed by $i = 0$. In a radial network, every node $i \in \mathcal{K}\backslash\{0\}$ has a unique parent bus denoted by i_0. Thus, we can simplify the notation index of variables on directed branches (i_0, i) to be i. In Fig. 2, for instance, at time slot t, the complex power flow from node i_0 to node i can be defined as

$$S_{i,t} = P_{i,t} + jQ_{i,t} = V_{i_0}I^*_{i,t}, \qquad \forall\ t, i \in \mathcal{K}\backslash\{0\}, \tag{10}$$

where $P_{i,t}$ and $Q_{i,t}$ are active and reactive parts of the power flow, respectively. We denote z_i, x_i and r_i as the branch impedance, reactance, and resistance, respectively and we use $v_{i,t}$ and $l_{i,t}$ to denote the squared magnitude of the bus voltage $V_{i,t}$ [1] and the branch current $I_{i,t}$, respectively. Therefore, based on the branch flow model [14], the relationship among these parameters can be summarized as follows:

$$P^A_{i,t} = P_{i,t} - r_{i,t}l_{i,t} - \sum_{k\in N_i} P_{k,t}, \tag{11}$$

$$Q^A_{i,t} = Q_{i,t} - x_{i,t}l_{i,t} - \sum_{k\in N_i} Q_{k,t}, \tag{12}$$

$$v_{i,t} = v_{i_0,t} + (r_i^2 + x_i^2)l_{i,t} - 2(r_iP_{i,t} + x_iQ_{i,t}), \tag{13}$$

$$l_{i,t} = \frac{P^2_{i,t} + Q^2_{i,t}}{v_{i_0,t}}, \quad \forall\ t, i \in \mathcal{K}\backslash\{0\}, \tag{14}$$

where $P^A_{i,t}$ and $Q^A_{i,t}$ denote the active and reactive power drawn from bus i, respectively. $N_i = \{j \in \mathcal{K} : j_0 = i\}$ is the set of branches connecting with i, excluding its parent bus. Equations (11) and (12) are the power conservation equations, where $r_{i,t}l_{i,t}$ represents the power loss on branch i. Equation (13) comes from the combination of Kirchoff's law and Ohm's law after simple derivation. Equation (14) is from (10) after squaring. The voltage at each bus needs to be restricted in an

[1]The bus voltage $V_{i,t}$ and the transmission voltage $U_{i,j}$ are independent with each other in the P2P network.

allowable range to ensure the system stability and security:

$$\underline{v_i} \leq v_{i,t} \leq \overline{v_i} \qquad \forall\, t, i \in \mathcal{K}\backslash\{0\}, \tag{15}$$

where $\underline{v_i}$ and $\overline{v_i}$ are the lower and upper bound of the squared magnitude of bus voltage, respectively. Note that at the root bus ($i = 0$), the voltage $V_{0,t} \equiv V_0$ (i.e., $v_{0,t} \equiv v_0$) across the total time horizon considered, where V_0 is the rated voltage. Another boundary condition is as follows:

$$-S^A_{0,t} = -(P^A_{0,t} + jQ^A_{0,t}) = \sum_{i \in \{i \in \mathcal{K}: i_0 = 0\}} S_{i,t}, \tag{16}$$

which represents the total complex power injected into the distribution network. The total energy purchase cost is defined as:

$$C^P_t = PR_t \cdot (-P^A_{0,t}) \qquad \forall\, t, \tag{17}$$

where PR_t is the TOU price given by the main grid.

We must emphasize that our model has a two-level network structure, in which the P2P energy sharing network is isolated and separated from the distribution network and our energy sharing scheme only affects the amount of net power ($P^A_{n,t}, n \in \mathcal{W}$) injected (drawn) into (from) the distribution network. Therefore, the radial structure of the distribution network is not changed and thus the branch flow model is indeed applicable to our problem.

III. Problem Formulation and Exact Relaxation

The objective of our energy management problem is to minimize the total cost of the distribution network including the payoff for buying power from the main grid, the battery's operational cost, and the power losses in the distribution network and the P2P network, with corresponding weighting factors $\omega_i, i \in \{1, \cdots 4\}$. In the constraints, we take into account the power balance constraints (i.e., e.q.(18)-(20), system operational constraints on the power flow (i.e., e.q.(11)-(14)) and voltage (i.e., e.q.(15)) as well as the battery's operational constraints (i.e., e.q.(2)-(6) and (8)). Mathematically, the optimization problem is as follows:

Problem $\mathscr{P}$

$$\min_{\boldsymbol{X_t}} \quad \sum_t \Bigg(\omega_1 \cdot PR_t \cdot (-P^A_{0,t}) + \omega_2 \sum\nolimits_{i=1}^{K} r_i l_{i,t} + \omega_3 \sum_{n \in \mathcal{W}} [(1-\eta_c)P^{ESC}_{n,t} + (\frac{1}{\eta_d} - 1)P^{ESD}_{n,t}] + \omega_4 \sum_{m \in \mathcal{W}\backslash\{n\}} \sum_{n \in \mathcal{W}} \frac{r_{m,n}T^2_{m,n,t}}{U^2_{m,n}} \Bigg)$$

$$\text{s.t.} \quad P^A_{n,t} + P^{RE}_{n,t} + \sum_{m \in \mathcal{W}\backslash\{n\}} (T_{m,n} - \frac{r_{m,n}T^2_{m,n,t}}{U^2_{m,n}}) + P^{ESD}_{n,t} \geq P^L_{n,t} + P^{ESC}_{n,t} + \sum_{m \in \mathcal{W}\backslash\{n\}} T_{n,m,t}, \quad \forall\, t, n \in \mathcal{W}, \tag{18}$$

$$P^A_{i,t} \geq P^L_{i,t}, \qquad \forall\, t, i \in \mathcal{K}\backslash\mathcal{N}, \tag{19}$$

$$Q^A_{i,t} \geq Q^L_{i,t}, \qquad \forall\, t, i \in \mathcal{K}\backslash\{0\}, \tag{20}$$

and (2)–(6), (8), (11)–(15),

where $\boldsymbol{X_t} = (P_{i,t}, Q_{i,t}, v_{i,t}, l_{i,t}, P^A_{n,t}, Q^A_{n,t}, P^{ESC}_{n,t}, P^{ESD}_{n,t}, T_{m,n,t})$ are the set of decision variables, $\forall t \in \{1, 2, \cdots H\}$. Equations (18)–(20) are the active and reactive power balances for pure load buses and MGs. $\mathcal{K}\backslash\mathcal{N}$ denotes the pure load bus set excluding the set representing those MGs. Problem $\mathscr{P}$ is non-convex because of the non-convex equality constraint (5) and (14). As to the constraint (5), we can see that the objective involves both the charging and discharging rates in the cost, so at the optimal solution of our minimization problem, they should not be nonzero at the same time. Thus we can relax this non-convex constraint and it has actually been incorporated into the structure of our formulation implicitly. In order to tackle with the difficulty brought by the constraint (14), we relax it to the following inequality constraint:

$$l_{i,t} \geq \frac{P^2_{i,t} + Q^2_{i,t}}{v_{i_0,t}} \qquad \forall\, t, i \in \mathcal{K}\backslash\{0\}. \tag{21}$$

Using (21), a relaxed problem $\mathscr{P} - relaxed$ is formulated as follows:

Problem $\mathscr{P} - \boldsymbol{relaxed}$

$$\min_{\boldsymbol{X_t}} \quad \sum_t \Bigg(\omega_1 \cdot PR_t \cdot (-P^A_{0,t}) + \omega_2 \sum\nolimits_{i=1}^{K} r_i l_{i,t} + \omega_3 \sum_{n \in \mathcal{W}} [(1-\eta_c)P^{ESC}_{n,t} + (\frac{1}{\eta_d} - 1)P^{ESD}_{n,t}] + \omega_4 \sum_{m \in \mathcal{W}\backslash\{n\}} \sum_{n \in \mathcal{W}} \frac{r_{m,n}T^2_{m,n,t}}{U^2_{m,n}} \Bigg)$$

s.t. (2)–(4), (6), (8), (11)–(13), (15) and (18)–(21).

The relaxation is said to be *exact* if the inequality constraint (21) is binding at the optimal solution of problem $\mathscr{P} - relaxed$. Some sufficient conditions for the exactness of the relaxation are referred to in [12], which have been verified in many real and standard distribution network testbeds. Roughly speaking, if the bus voltage is kept around the nominal value and the power injection at each bus is not too large, then the relaxation is exact [9]. Here, we assume those sufficient conditions hold in our problem since our distribution network topology is also radial and we illustrate the exactness by numerical results (in Sec. IV). The problem $\mathscr{P} - relaxed$ is convex, since it is in nature a *second-order cone programming* (SOCP) problem. It can be seen more clearly if we transform constraint (21) into the standard form of a second-order cone:

$$\text{constraint (21)} \Longleftrightarrow \left\| \begin{pmatrix} 2P_{i,t} \\ 2Q_{i,t} \\ l_{i,t} - v_{i_0,t} \end{pmatrix} \right\|_2 \leq l_{i,t} + v_{i_0,t} \tag{22}$$

Through this transformation, this SOCP problem can be solved by convex optimization solvers like CVX.

IV. Numerical Results

We apply our energy management model on a 34-bus radial distribution network, as shown in Fig. 3. This radial network has a main feeder and 4 laterals with a rated voltage of 18

KV and an allowed voltage range of $\pm 5\%$. Details and load data can be found in [13] with some slight modifications.[2] We assume that 3 MGs (N=3) are located at nodes 4, 8, and 19, respectively. All the other nodes are pure loads (for $i \in \{2, 3 ... 34\} \backslash \{4, 8, 19\}$, $K = 34$) except node 1, which is a slack bus. For the P2P MGs network, each MG connects to each of the others, and the line resistances ($MG_1 \leftrightarrow MG_2$, $MG_1 \leftrightarrow MG_3$, $MG_2 \leftrightarrow MG_3$) are 2.5Ω, 2.5Ω, 0.075Ω, respectively. The P2P transmission voltage $U_{i,j} = 1.58\ KV$, $\forall i, j \in \{1, 2, 3\}, i \neq j$. Time is slotted into 48 intervals for 24 hours ($H = 48$), so $\Delta = 0.5$h. $\overline{ES_n}$=100 KWh and $\underline{ES_n} = 0.2\overline{ES_n}$ for each MG. The charging and discharging efficiencies are $\eta_c = 0.95$ and $\eta_d = 1$, respectively, and the predetermined battery's end-of-day level is $\gamma_n = 0.8$. The charging and discharging rates limit are 30 KW and the weighting factors $\{\omega_i,\ i = \{1, 2, 3, 4\}\}$ are $\{0.1,\ 0.5,\ 0.3,\ 2\}$. Load profiles for different buses are some typical consumption profiles from Slovenian distribution companies [15] and the TOU price PR_t is the *Summer Rate* obtained from the website of *PG&E Company* [16], shown in Fig. 4 and Fig. 5, respectively.[3] The renewable energy generation profiles (Fig. 4) are from *California Independent System Operator* [17] and the generation capacity is set as 80 KW, 150 KW and 150 KW for $\{MG_n,\ n \in \{1, 2, 3\}\}$, respectively.

From Fig. 4, we can see that different MGs have different consumption profiles during the day. More specifically, MG_1 behaves like an industrial user who has a continuous high demand during the day. MG_2 is a typical residential user with low power consumption during working hours while the peak demand appears during the night. On the contrary, MG_3 shows a complementary behavior compared to MG_2, which is common for commercial users. Their renewable energy generation profiles are similar, because of the fact that they are not too far away from each other and correlations are assumed to exist among MGs. WT generates a relatively uniform power throughout the day, while for PV generators, peaks always occur around noon. Therefore, facilitated by the cooperation, the P2P sharing network can take advantages of the diversified profiles among MGs.

After verifying that the constraint (21) is binding at the optimal solution of problem $\mathscr{P} - relaxed$ with numerical results, which means that the solution is also optimal for original problem $\mathscr{P}$, we demonstrate the optimal energy management strategies for MGs in Fig. 6 and Fig. 7. In Fig. 6, the positive bars represent receiving energy from different sources while the negative bars represent offering energy to others. We can see that all MGs choose to discharge at around 10 a.m. when the electricity price starts to rise. This reduces

[2]Note that the lengths of the branches have been increased by 3 times to better illustrate the trade-off between different losses. The load data in [13] is used as the maximum/peak load of a day and the load profiles are given afterwards. Also, the peak load data from node 20 to 27 and from node 30 to 34 are multiplied by a factor of 0.5 and 1.5, respectively.

[3]Fig. 4 only shows the active power of load while reactive power is related to active power by a power factor specified in [13].

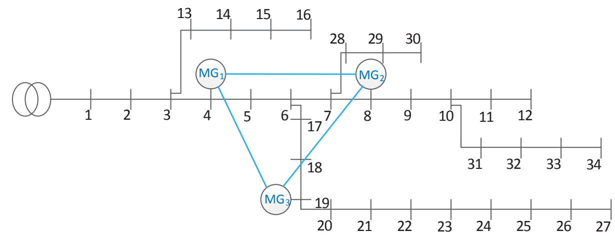

Fig. 3. A 34-bus radial distribution network.

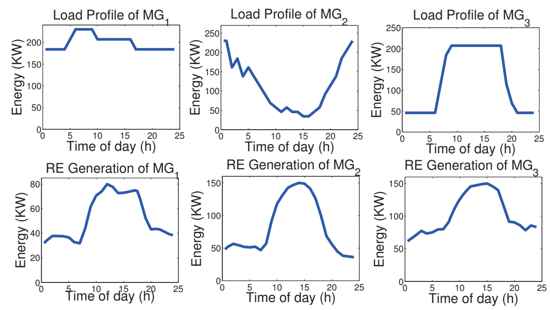

Fig. 4. Load (active power) and generation profiles of different MGs (Load profiles of MG_1, MG_2 and MG_3 are the typical consumption behaviors of industrial, residential and commercial users in summer).

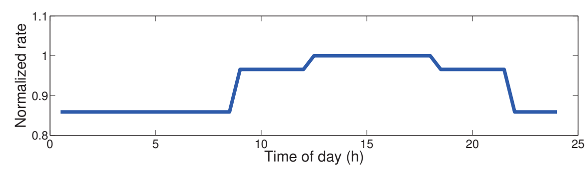

Fig. 5. Normalized time-of-use price (Summer Rate from PG&E Company).

energy purchase from the main grid. They recharge at midnight when the price is the lowest. Furthermore, it can be observed that although MG_1 does not have energy surplus for the whole day, it always buys energy from the main grid not only for meeting its own demand, but also for supplying to the other two MGs. This can reduce the overall cost by utilizing the P2P sharing network, alleviating the energy burden on the distribution network. By comparison, generally, when MG_2 and MG_3 do not have enough renewable energy supplies, they will buy energy from the main grid and satisfy the remaining demand through the P2P sharing network. Moreover, they balance the energy through selling to the main grid and the P2P network, when they have surplus energy. Therefore, Fig. 6 shows the coordination of different MGs with heterogeneous load profiles and storage capacities to minimize the system-wide cost.

Fig. 7 shows the detailed energy transmissions in the P2P sharing network. It can be seen that MG_1 always transmits energy to the other two MGs, because MG_1 is closer to the feeding entry (*Bus 1*) of the distribution network, and a mass of power flows by MG_1 to feed the downstream part of the distribution network. Therefore, it is reasonable to transmit energy by *short path* from MG_1 to the other two MGs. However, the inverse transmission is not preferable, because it is opposite to the main power flow direction. Another result is that the energy transmission between MG_2 and MG_3 changes directions alternatively. We can see that during morning (from

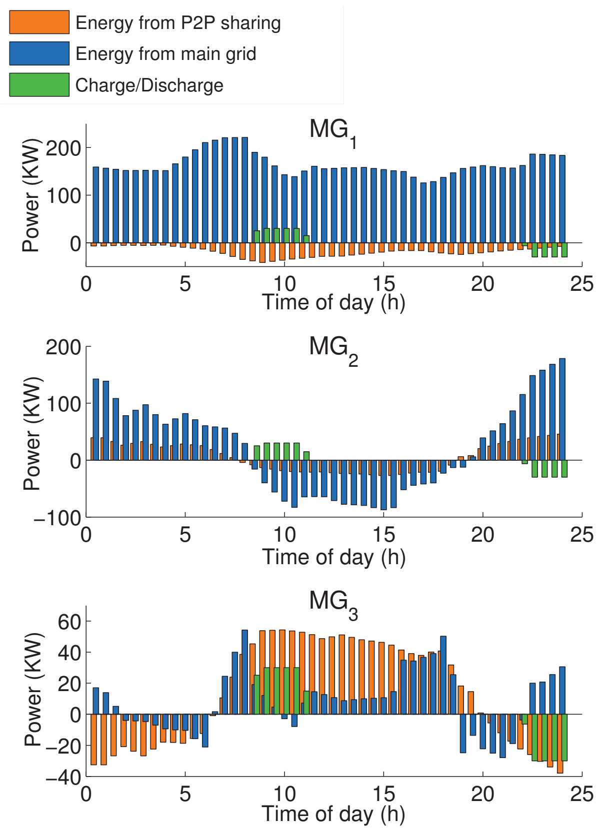

Fig. 6. Optimal energy management strategies of different MGs.

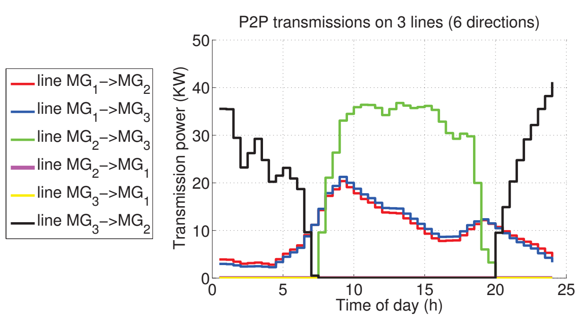

Fig. 7. P2P energy sharing strategies among different MGs.

00:00 to 06:00) and night (from 20:00 to 24:00) periods, MG_3 has an energy surplus while MG_2 has an energy deficiency. In this case, MG_3 acts as a supplier during this period, while it becomes a receiver during working hours. In summary, Fig.7 demonstrates the dynamic interaction among MGs according to their distinct energy consumption behaviors and their relative geographical locations in the distribution network.

V. Conclusion

In this work, we studied the energy management for cooperative MGs with P2P energy sharing under the distribution network. We formulated the energy management problem as a practical yet non-convex optimization problem to minimize the total system cost including those of the MGs, the distribution network, the P2P energy network as well as the battery's operational cost. After exploiting an exact relaxation of the non-convex constraint, we equivalently transformed this problem into a *SOCP* problem and thus solved it efficiently. By applying our model to a 34-bus distribution network testbed, we found a cooperation of energy storage devices and the P2P network among heterogeneous MGs, instead of solely relying on the main grid to satisfy their load demands. Another finding is that the MG that is closer to the upstream part of the distribution network has a tendency to act as an energy supplier in the P2P network, which can bring a lower cost.

This work can be further extended in two directions. First, we will take into account the intermittency of renewable generation and demand, for which the current deterministic methods are no longer applicable. Second, we will investigate the detailed internal trading mechanism such as how to control the pricing in the P2P network to encourage the energy sharing among different MGs.

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