Short Time Planning and Allocation of Cost Saving in Industrial Microgrids

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***Abstract*- Industrial microgrids consist of many factories with distributed energy resources (DERs) and local electric loads that rely heavily on combined heat and power (CHP) systems. In this paper, a unit commitment (UC) for industrial microgrids is formulated to minimize the cost of generating electricity and heat via CHP systems and boilers. As each DER and boiler may have an individual owner, an approach is also presented to fairly allocate the cost saving among factories participating in the generation process. The proposed methods are implemented in an industrial microgrid consisting of 12 factories divided into three groups according to their levels of participations in the energy generation. Simulation results are analyzed to show the effectiveness of the proposed approaches.**

***Index Terms*-industrial microgrids, short time planning, CHP, distributed energy resource and allocation of cost saving.**

I. INTRODUCTION

Microgrids consist of distributed energy resources (DERs) and electrical loads connected together via a distribution network. They can operate in both grid-connected and stand-alone modes [1]. From the distribution network operator (DNO) point of view, microgrids can enhance system reliability. While from the end user point of view, they offer various advantages including local reliability enhancement, efficiency increment through acquisition of waste heat, improvement of voltage profile, local voltage support, facilitating energy without interruptions, and improvement of power quality [1]. Different types of DERs are used in microgrids including solar photovoltaic (PV) systems, wind energy conversion systems (WECS), small-scale hydroelectric generators, and combined heat and power (CHP) systems.

CHP systems have important role in industrial regions as they facilitate energy-efficient power generation by capturing waste heat. These systems maintain the heat acquired from power generation and utilize it for domestic and industrial heating purposes [1]. Heat produced at moderate temperatures (100-180 ^{o}C) can also be used in absorption chillers for cooling. Simultaneous production of electricity, heat and cooling is known as trigeneration or polygeneration [1].

Among various types of CHP systems, gas turbine, natural gas engine and some micro turbines have major roles in industrial regions and industrial factories since:

- They require lower investment costs as compared to other technologies.
- Unlike large thermal generators, they do not have complicated constraints such as minimum up/down time, ramp rate, etc.
- Unlike WECS and PV systems, they are dispatchable DERs with the ability to generate energy in all times.

Short term planning in microgrid is easier than the conventional power systems since i) there is rarely a congestion problem as loads are mostly located nearby the generators, ii) it is possible to use units with fewer constraints, and iii) most generators are designated to support their own local electric loads with high priorities.

There is miscellaneous research work available in the area of microgrid [2, 3]; however, less attention has been focused on the short term planning of industrial microgrids. This relatively new research definitely needs more work and deliberation.

The first aim of this paper is to propose an approach for short term planning in industrial microgrids within the 24 hours period. The essence of an industrial microgrid is that any factory with a DER has an electric load nearby and most factories require heat for their manufacturing process. Therefore, the proposed short term planning considers the waste heat which can be captured from generators for thermal needs; and if captured heat is less than thermal needs, boilers will start to compensate the dearth of the heat. On the other hand, because each factory has an individual owner, there should be some remuneration mechanism to encourage them to participate in generating the requested electric and heat power. The second aim of the paper is to allocate the cost saving (profit) among all factories that have cooperated in procurement of electric and heat loads.

Section II provides information on the concepts of CHP systems. Section III formulates the short term planning problem in industrial microgrids. Sections IV and V present the case study, simulation results and discussion. Section VI describes cost saving allocation in industrial microgrid followed by the conclusion.

II. COMBINED HEAT AND POWER (CHP) SYSTEMS

The average efficiency of producing electricity by gas turbines and natural gas engines is around 45 percent. By utilizing CHP systems, the efficiency can be increased to more than 80 percent. In this method, exhaust waste heat can be used for serving the thermal loads around the generator. Figure 1 shows the typical fuel input needed to produce 35 units of electricity and 50 units of heat using conventional separate heat and power. Compared with the typical electrical and thermal efficiencies, CHP system is nearly twice as efficient [4].

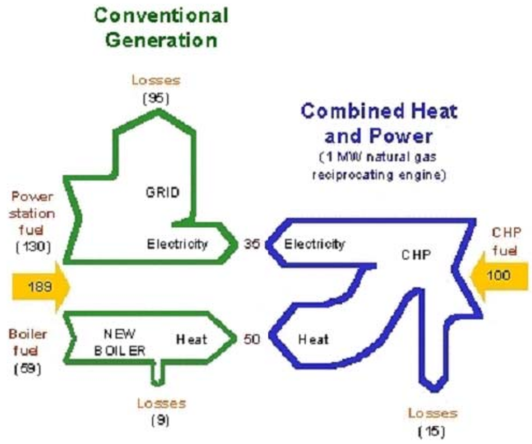

Figure1. CHP versus separate heat and power energy flows

The thermodynamic parameters used for characterizing CHP systems are presented below [5]:

- ***Heat Rate***-describes how much fuel is required to produce a unit of electric energy. Heat rate values are in kilojoules per kilowatt hour (kJ/kWh). The electric efficiency of a generation device can be determined by converting heat rate to KJ/kJ (divide the heat rate by 3600 kJ/kWh) and taking the inverse of it to give electric energy produced per fuel energy consumed.
- ***Waste Heat Factor: Alpha (α) -*** is a dimensionless ratio of energy terms that describes how much useful heat energy is generated per electric energy produced by a given generation technology.

III. Problem Formulation

A typical industrial microgrid is formed by the corporation of a few large and small factories with DERs. In this paper, DERs are assumed to be gas turbines, natural gas engines and micro turbines. Each factory has a forecasting electric load and some factories need heat for their procreative processes. The required heat can be obtained from CHP systems or from boilers. In this paper, it is assumed that the microgrid is in a stand-alone mode and must support all electric loads with its own generators. On the other hand, because of existing distances between factories, thermal requirements of various factories cannot be served via all of thermal resources. In other words, only the factories in the vicinity of each other can cooperate to procure thermal needs. Of course, some factories may not have thermal requirements.

Each factory must submit its forecasted electric and heat loads for the next 24 hour period to the microgrid controller (MGC). Consequently, MGC will summarize all received data and run the short term planning problem. The ultimate objective is to find an optimal electrical and thermal unit commitment schedule which can minimize the total production cost of the industrial microgrid for a 24 hour horizon while satisfying constraints. This optimization problem can be formulated as follows:

$$\mathrm{Min}\sum_{i\in elec}\sum_{h\in\tau}\left(\mathrm{Cost}_{elec_{i,h}}\right)+\sum_{i\in th_j}\sum_{h\in\tau}\left(\mathrm{Cost}_{boiler_{i,h}}\right) \quad (1)$$

where:

$$\mathrm{Cost}_{elec_{i,h}}=\frac{P_{i,h}}{\mathrm{eff}_{elec_i}}*gp \quad (2)$$

$$\mathrm{eff}_{elec_i}=\frac{1}{\frac{HR_i}{3600}} \quad (3)$$

$$\mathrm{Cost}_{boiler_{i,h}}=\frac{b_{i,h}}{\mathrm{eff}_{b_i}}*gp \quad (4)$$

while "$Cost_{elec_{i,h}}$" and "$Cost_{boiler_{i,h}}$" are costs of generating electricity and heat of factory i at hour h, respectively; "$elec$" represents all factories cooperating in the generation of electricity; "th_j" is Group #j of factories which can exchange heat; "τ" is the schedule period (in this paper 24 hours); "$P_{i,h}$" is the electricity generation of factory i at hour h; "eff_{elec_i}" is the electric efficiency of generator of factory i; "gp" is the gas price; "HR_i" is the heat rate of generator of factory i; "$b_{i,h}$" is the heat generation via boiler of factory i at hour h; and "eff_{b_i}" is the efficiency of boiler of factory i.

The optimization problem is subjected to the following constraints:

- Electric load balance constraint

$$\sum_i P_{i,h}=D_h \quad (5)$$

- The generated heat in each thermal group

$$\sum_i \alpha_i * P_{i,h}+\sum_i b_{i,h}\geq D_{th_{j,h}}\ \forall i\in th_j \quad (6)$$

- Electricity output limits

$$P_{min_i}\leq P_{i,h}\leq P_{max_i} \quad (7)$$

- Heat output limits for boilers

$$b_{i,h}\leq b_{max_i} \quad (8)$$

Where "D_h" is the electric demand at hour h; "$D_{th_{j,h}}$" is the heat demand in group #j at hour h; "P_{min_i}" and "P_{max_i}" are the minimum and maximum electric output of generator i, respectively; and "b_{max_i}" is the maximum output of boiler i.

The optimization problem presented above is a mixed integer linear programming (MILP) which can be solved with most optimization software. In this paper, we use General Algebraic Modeling System (GAMS), a commercial software package for solving optimization problems [6].

IV. Case Study

The test system is an industrial microgrid with 12 factories. DER's data for all factories are given in Table 1 [7]. All factories cooperate for generating electricity but only neighboring factories can cooperate in acquiring the required heat. It is assumed that factories #1, #3, #7, #9 and #11 are in the same neighborhood and heat can be transferred between group members (Group1). Also, factories #2, #4, #6 and #8 constitute another group with heat transfer ability (Group2). Factories #2, #10 and #12 don't need any heat for their processes and can cooperate for generating electricity. Table 2 summarizes the above statements. Boiler's data are given in Table 3.

As mentioned in the previous section, each factory must submit its forecasted electric and heat loads to MGC. MGC will summarize all received data. Tables 4, 5 and 6 represent electric demand and heat demand in each group.

TABLE 1. GENERATOR DATA

Factory	Factory Type	Pmin (KW)	Pmax (KW)	OMVAR* ($/KWh)	Heat Rate (KJ/KWh)	Alpha
1	Gas Turbine	500	5000	0.0059	13284	1.84
2	Natural Gas Engine	300	3000	0.009	10286	1.2
3	Natural Gas Engine	300	3000	0.009	10286	1.2
4	Natural Gas Engine	100	1000	0.009	10588	1.36
5	Gas Turbine	100	1000	0.0096	16438	2.45
6	Gas Turbine	100	1000	0.0096	16438	2.45
7	Natural Gas Engine	30	300	0.013	11613	1.85
8	Natural Gas Engine	30	300	0.013	11613	1.85
9	Natural Gas Engine	30	300	0.013	11613	1.85
10	Natural Gas Engine	10	100	0.018	12000	2.05
11	Natural Gas Engine	10	100	0.018	12000	2.05
12	Micro turbine	10	100	0.015	13846	1.71

*OMVAR: Operation and Maintenance Variable Cost

TABLE 2. CALSSIFICATION OF FACTORIES IN GROUPS

	Cooperating factories	
Electric energy	All of factories (electrical)	
Thermal energy	Group#1 (th1, Eq. 1)	1, 3, 7, 9, 11
	Group#2 (th2, Eq. 1)	2, 4, 6, 8
	Group#3 (no heat requirement)	5, 10 ,12

TABLE 3. BOILER DATA

Unit	1	2	3	4	6	7	8	9	11
Efficiency	0.8	0.83	0.85	0.90	0.90	0.85	0.80	0.85	0.83
Pmax (KWth)	2000	1000	1000	500	500	200	200	200	200

TABLE 4. ELECTRICAL DEMAND OF MICROGRID

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load (KW)	7000	7000	7000	7000	7000	7500	8000	9000	9000	10000	10500	10500
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load (KW)	12000	12500	14000	14000	13000	12000	11000	11000	9000	8000	7500	7000

TABLE 5. HEAT DEMAND OF GROUP #1

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Thermal Load (KWth)	7000	7000	7000	7000	7000	8500	8500	9500	9500	10500	10000	10000
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Thermal Load (KWth)	10500	13000	13000	13000	12000	11000	10000	9000	9000	8000	7000	7000

TABLE 6. HEAT DEMAND OF GROUP #2

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Thermal Load (KWth)	5000	5000	5000	5000	6000	6500	6500	6500	7000	7000	7000	7500
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Thermal Load (KWth)	7500	8500	8500	8500	8000	7000	7000	6000	5000	5000	5000	5000

V. SIMULATION RESULTS

The unit commitment (UC) problem in industrial microgrid is solved with GAMS. Figure 2 shows the electric generation schedule for each factory. Units #5 and #12 will be off at all hours and units #4, #7, #8 and #9 will be in maximum power generation mode. Figure 3 shows the boiler generation schedule for each factory. It can be seen that boilers #1 and #11 will be off at all hours while boiler#8 will be on only at 2 p.m.

Consequently, the cost of producing heat and electricity is 25278$, and 353.793MWh thermal energy will be saved by microgrid within the 24 hour period because of using CHP systems and capturing waste heat of the generators. Figure 4 shows heat demands in microgrid and the role of CHP systems and boilers in generating them. It can be seen that about 90 percent of heat demand can be achieved via waste heat and only a small part of that heat would be generated via boilers.

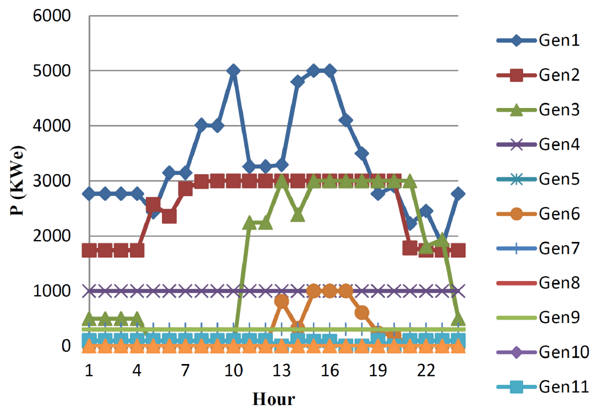

Figure 2. Electric generation schedule

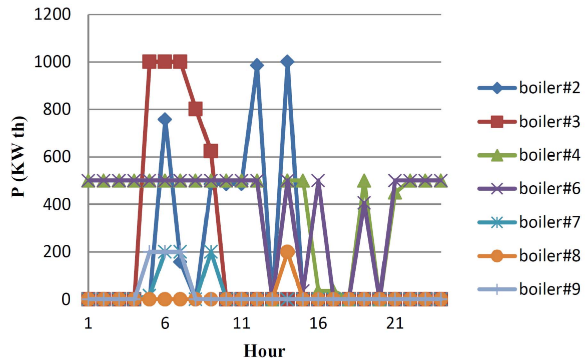

Figure 3. Heat generation schedule

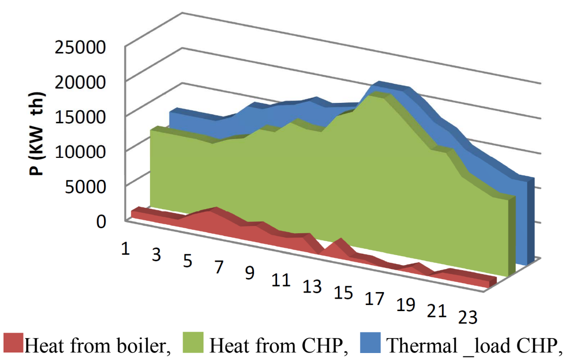

Figure.4: Heat demand, CHP and boilers heat generation

VI. COST SAVING ALLOCATION

The structure of a microgrid is very similar to a traditional power system; however, there are some basic differences. For example, in a power system, a security constrained unit commitment would result in a schedule for generators which have the same owner (e.g. government); hence, generation or no generation for each of them doesn't have any influence on their profit or cost. On the other hand, in an industrial microgrid consisting of several individual factories with individual owners, commitment/non-commitment of a unit would influence the profit or cost. Thus, each factory involved in the generation process should earn its costs and each factory which receives energy from microgrid must pay for its demand and all factories which cooperate in this method should earn a reward.

Electric or heat producers earn their cost on the basis of their generator's data and boiler's data, and electric or heat consumers pay on the basis of marginal cost, the cost is calculated based on whether the factories have independently generated their demands. Also, because of the cooperation among all factories in the coalition, there is some cost saving which must be allocated to all factories. This cost saving is the difference between "summation of cost of all factories if they generate all of their demand independently (without coalition)" and "cost of UC (resulting from coalition of all factories)".

In other words, the worst strategy is that each factory supplies its demand with its own generator and boiler. The best strategy is that all factories participate in coalition while the UC problem is solved by MGC. Between these two strategies several other approaches also exist which are developed from the coalition of some (but not all) factories. This middling strategy results in the costs lower than worst strategy but more than grand coalition (best strategy). Indeed the above statements show that all factories in microgrid can have a cooperative game for minimizing the total cost of microgrid; hence, cost saving must be fairly allocated to each of them.

A. Fair Allocation of Cost Saving in Industrial Microgrids Based on Cooperative Game Theory

Since all factories in microgrids are involved in a cooperative game to minimize the total cost, the resulting cost saving should be allocated among them. This paper uses game theory [8-11] to fairly allocate the resulting cost saving after solving the UC problem.

There are several methods for allocating cost saving (or profit) between members of a coalition [8, 9]. The Shapley value is an applicable fair method used in many references including [9-12].

Shapley value of a factory is defined as the weighted average of its marginal contributions to the cost savings in all possible coalitions in which the factory may participate. It is expressed mathematically as

$$\varphi_i = \frac{(m-1)!(n-m)!}{n!}\{v(S) - v(S - \{i\})\} \qquad (9)$$

Where "m" is number of coalition S; "n" is number of all members in grand coalition N; "$S - \{i\}$" is the coalition of not including member i; "$\{v(S) - v(S - \{i\})\}$" is the incremental gain of coalition brought by factory joining the coalition; and "φ_i" is the expected pay off to factory #*i*. For example [10], in the case of three factories cooperating with each other to form coalitions, the expected cost saving (profit) allocated to factory #2 is:

$$\phi_2 = \frac{1}{3} * \{V_2 - V_\varphi\} + \frac{1}{6}\{V_{21} - V_1\} + \frac{1}{6}\{V_{23} - V_3\} + \frac{1}{3}\{V_{123} - V_{13}\}$$

B. Cost Saving Allocation for the Case Study

There are 12 factories in the studied case; hence, n=12. The number of possible coalitions are 2^{12}; however, only 71 coalitions are feasible because not all coalitions can satisfy the constraints. The problem is solved in GAMS and data are transferred to MATLAB to perform the Shapley value calculations.

Table 7 shows the marginal cost of each factory for the case of independent generation (no coalition). The sum of all costs is 25601.2$ and grand coalition of all factories in the microgrid (calculated using the UC) is 25278$. Thus, the cost saving from cooperation is 323.2$ that must be allocated to factories. Table 8 shows cost savings allocated to each factory. As expected, the sum of all allocated cost savings is equal to total profit. It can be seen that factories earned different portions of the total cost saving according to their levels of participations in the generation process.

TABLE 7. MARGINAL COST OF EACH FACTORY (NO COALITION)

Factory	Cost ($)	Factory	Cost ($)
1	8840.90	7	500.10
2	4309.00	8	499.40
3	4309.00	9	500.10
4	1474.50	10	178.90
5	2222.90	11	345.80
6	2222.90	12	197.70

TABLE 8. COST SAVING (PROFIT) ALLOCATION

Factory	Cost ($)	Factory	Cost ($)
1	51.23	7	13.37
2	51.23	8	26.37
3	51.23	9	13.37
4	51.23	10	0.45
5	11.10	11	2.08
6	51.23	12	0.32

VII. CONCLUSION

In this paper, the unit commitment problem in an industrial microgrid is formulated to minimize the cost of generating electricity and heat via CHP systems and boilers. Furthermore, the cost saving due to the participations of some factories in the generation process is fairly allocated to each one of them. The proposed methods are tested in an industrial microgrid with 12 factories divided into three groups according to their levels of participations in the energy generation. Simulation results confirm the effectiveness of the proposed scheduling technique, as well as fair allocation of resulted cost saving to individual factories.

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