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ECONOMIC OPERATION PLANNING OF COMBINED HEAT AND POWER SMART DISTRIBUTION SYSTEM

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Abstract

Optimal planning of the combined heat and power (CHP) smart distribution system increases the energy efficiency of the system effectively and decreases the overall operating and environmental cost. This paper proposes an optimal planning approach to minimize the combined total operating and environmental cost of the distribution grid based CHP. The proposed optimization problem is formulated as an interval mixed-integer quadratic program (IMIQP) in a unit commitment (UC) multi-objective optimization approach. The UC strategy is developed to respond to both the power and heat energy output of the CHP. The emission cost of greenhouse gases is converted to the monetary concept, and emission level limitation constraints are taken into account in the model of the problem. This converts the multi-objective function to a single function that can be solved and the single solution is obtained. Further, a set of comprehensive constraints was taken into consideration when formulating the problem. To verify the applicability of the proposed system, the proposed approach is applied to the low voltage distribution grid. The results reveal that the total cost is minimized. Thus, the proposed multi-objective optimization approach can help to obtain the optimal planning strategy of the CHP grid to minimize the total operating and emission cost.

Keywords: Combined heat and power, Emission cost, Microgrid, Mixed integer quadratic programming, Multi-objective optimization.

1. Introduction

Combined heat and power (CHP) units exploit the waste heat to supply electrical and heat power simultaneously to the consumers. Employing the CHP with renewable energy resources increases the overall efficiency of the power grids and reduces the operating cost. Recently, wind, and solar energy have been used widely in electrical systems, where solar energy is utilized in many applications apart from the generation of electricity [1-4]. Utilizing renewable energy reduces the emission of greenhouse gases. This leads to tackle global warming and environmental pollution. Recently, the low voltage distribution grid has been developed to include different types of generators, renewable energy resources, storage devices, and CHP. This developed distribution grid supplies the end-users with electricity and heat in a smart approach. The optimal management of this system draws more attention to the researchers due to its economic benefits for both users and the environment. Therefore, many sophisticated algorithms and approaches are proposed in the literature to formulate and solve the optimization problems [5-12]. However, the CHP is not taking into account in these works.

Motevasel et al. [13] proposed an optimization approach to minimize the operating cost and emission level of a Microgrid (MG) including micro-turbine and fuel cell as CHP and electrical and thermal storage devices with the wind, and solar energy resources. Li and Li [14] presented an optimization approach to minimize operating and emission cost. They employed the same system of reference [13]. However, they did not consider any constraints in their optimization problem. Gambino et al. [15] addressed the economic dispatch of a MG based CHP to minimize the running cost, where the problem is formulated as a mixed-integer linear program (MILP). Authors in [16] suggested an optimal energy scheduling to minimize the operating cost of a MG and satisfy the electrical and thermal loads, where the MG includes photovoltaic panels, wind turbine, CHP, storage battery, and electric vehicles. Liu et al. [17] presented optimal energy management to minimize the operating cost for a connected MG that includes renewable energy sources, CHP, and electrical and thermal energy storage. Jafari et al. [18] addressed the optimal generation planning strategy to maximize the profit of a MG that consists of wind turbines, PV, fuel cell, CHP units, and the tidal steam turbine are addressed. Dong et al. [19] proposed an optimal management system to minimize the operating and carbon dioxide emission cost for a MG that contains CHP, wind turbine, PV panels, and storage battery. The optimization problem was formulated as MILP, which can be solved easily.

In this paper, a developed energy management strategy is proposed for a smart low voltage distribution grid that consists of CHP, fuel cell (FC), micro-turbine (MT), diesel generator (DG), wind turbines (WTs), Photovoltaic panels (PV), electric and heat storage devices, gas boiler, and electric heater. The problem is formulated as multi-objective optimization, where this function is transformed into a single objective by converting the emission cost of greenhouse gases (GHG) to the monetary concept and considering the emission limitation constraints. This function can be solved directly and a single solution can be found. The proposed approach involves the model of a cost function which includes the operating cost of different energy resources, exchanging heat and power with the utility grid. The interaction between the electric and heat systems also are modelled comprehensively and taken into consideration when formulating the optimization problem. Besides, the emission costs of carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxide (NOx) and particulate matter (PM) are considered in the proposed approach. Further, a set of realistic constraints with emission limitation constraints is considered as well. Furthermore, the unit commitment strategy is employed and developed to respond to both the electrical and heat loads. All the afore-mentioned models of the proposed problem include in one optimization problem so that the proposed approach is much closer to the real scenario.

2. Structure of Smart Distribution Grid-Based CHP and Mathematical Model

Figure 1 shows the structure of the proposed CHP distribution grid. It includes MT-based CHP, FC, DG, storage devices, gas boiler, electric heater, WTs, and PV units. Besides, the grid can exchange electrical and heat energy with the utility grid. To optimize the operation of the proposed grid, each component of the system should be modelled. The modeling of these components is as follows:

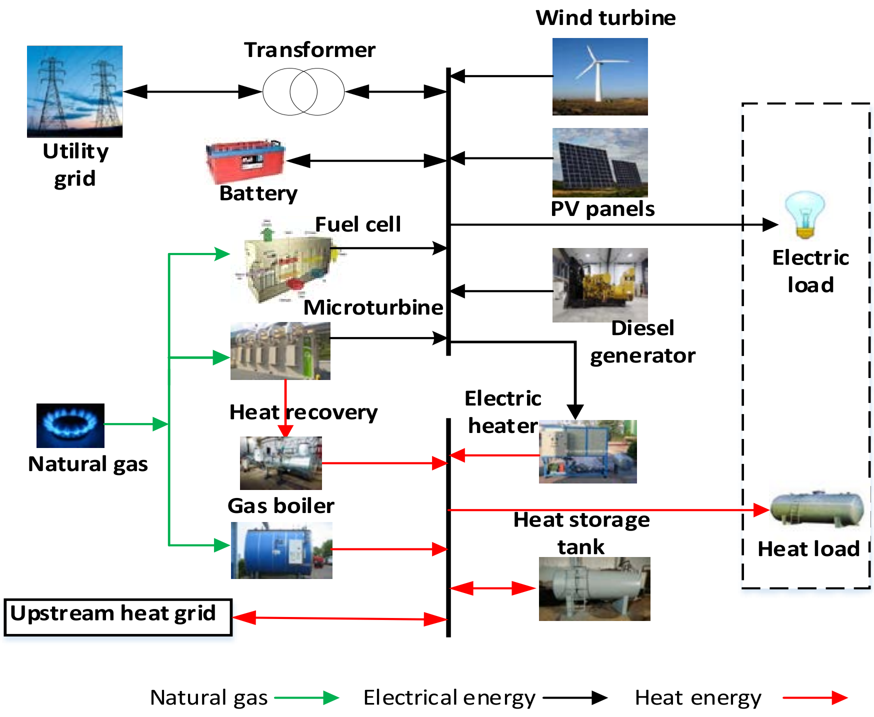

Fig. 1. Schematic diagram of the CHP distribution grid.

2.1. MT-based CHP model

In this paper, the MT-based CHP unit provides electricity and heat to the consumers. Micro-turbine Capstone C200 is utilized as a CHP unit. It is driven by natural gas, where employing the nanoparticles [20-22] with fuel reduces the emission of greenhouse gases. The gas consumption is calculated by the following equation [23]:

$$gc_{MT}(t) = (\delta_{MT}(t).P_{MT}(t))/(L_{NG,MT}.\eta_{MT}) \quad (1)$$

where $P_{MT}(t)$ is the output electrical power of the MT (kWh), $L_{NG,MT}$ is a low heating value (LHV) of natural gas (kWh/m^3), η_{MT} is the efficiency of CHP, $\delta_{MT}(t)$ is the on/off state of the CHP at each sampling time.

The CHP produces heat when generating electrical power. The produced heat is determined as follows:

$$H_{MT}(t) = (\delta_{MT}(t).P_{MT}(t).[1-\delta_{MT}(t)-\delta_1].\delta_{hr})/\delta_{MT} \quad (2)$$

where δ_1 is the heat loss factor of MT and δ_{hr} is the efficiency of heat recovery. The cost of fuel consumption of the CHP is expressed as follows:

$$C_{MT}(t) = gc_{MT}(t).p_g \quad (3)$$

where $p_g$is the price of natural gas($/m^3).

2.2. Diesel generator model

The cost function of the diesel generator is formulated as a quadratic equation as follows [24]:

$$C_{DG}(t) = a.\delta_{DG}(t) + a_1.\delta_{DG}(t).P_{DG}(t) + a_2.\delta_{DG}(t).P_{DG}(t)^2 \quad (4)$$

where , a_1 , and a_2 are the coefficients of the cost function, $\delta_{DG}(t)$ is the on/off state of the DG at each time interval.

2.3. Fuel cell model

The proton membrane fuel cell is used in this paper, where the fuel consumption is calculated by using the following equation [23]:

$$gc_{FC}(t) = (\delta_{FC}(t).P_{FC}(t))/(L_{NG,FC}.\eta_{FC}) \quad (5)$$

where $P_{FC}(t)$ is the output electrical power of FC (kWh), η_{FC} is the efficiency of the FC, and $\delta_{FC}(t)$ is the on/off state of the FC at each time interval. The cost of fuel consumption of the FC is expressed as follows:

$$C_{FC}(t) = gc_{FC}(t).p_g \quad (6)$$

2.4. Storage battery

The equations that describe the operation of battery (BAT) are formulated as follows [25]:

$$W_b(t) = W_b(t-1) - \Delta t.\left(\frac{P_{bdis}(t)}{\eta_{dis}}\right) + \Delta t.P_{bch}(t).\eta_{ch} \quad (7)$$

where $W_b(t)$, $W_b(t-1)$ are the state of charge of the BAT at the current, and previous time respectively. $P_{bch}(t)$ and $P_{bdis}(t)$ are the BAT charging and discharging power respectively. η_{ch} and η_{dis} are the efficiencies. Δt is the sampling time. The cost of battery degradation due to its operation is calculated as follows:

$$C_b(t) = C_d \,. P_b(t). \Delta t \tag{8}$$

where C_d is the BAT degradation cost ($/kWh), $P_b(t)$ is either charging or discharging power.

2.5. Interacting power with the utility grid

The cost of exchanging power with the upstream grid is formulated as follows:

$$C_{U,P}(t) = P_U(t). p_{U,P}(t) \tag{9}$$

where $P_U(t)$ is the trading power with the upstream grid, (+) for purchasing power (-) for selling power. $p_{U,P}(t)$ is the exchanging power price ($/kWh).

2.6. Gas boiler model

The fuel consumption by a gas boiler (BO) is calculated as follows:

$$gc_{bo}(t) = H_{bo}(t)/(L_{NG,bo}. \eta_{bo}) \tag{10}$$

where $H_{bo}(t)$ is heat generated by BO and η_{bo} is the efficiency of the BO. The cost of fuel consumption by the BO is formulated as follows [19]:

$$C_{bo}(t) = gc_{bo}(t). p_g \tag{11}$$

2.7. Electric heater model

The electric heater (EH) provides heat to the thermal loads, where the output heat is expressed as:

$$H_{eh}(t) = P_{eh}(t). \eta_{eh} \tag{12}$$

where $P_{\boldsymbol{eh}}(t)$ is the consumed electric power, η_{eh} is the efficiency of EH.

2.8. Heat storage model

The following equation describes the operating of heat storage (HS) [26].

$$W_{hs}(t) = W_{hs}(t-1).(1-\rho_{hs}) - \Delta t. \left(\frac{H_{hs,dis(t)}}{\eta_{hs,dis}}\right) + \Delta t. H_{hs,ch(t)} \,. \eta_{hs,ch} \tag{13}$$

where $W_{hs}(t)$ and $W_{hs}(t-1)$ heat storage state at the current and previous intervals. $H_{hs,dis}(t)$ and $H_{hs,ch}(t)$ heat power released and stored of the HS (kWh).

2.9. Interacting heat with the upstream grid

The cost of exchanging heat with the upstream grid is formulated as follows:

$$C_{U,H}(t) = H_U(t).\,p_{U,H}(t) \tag{14}$$

where $H_U(t)$ is the trading heat with the utility grid, (+) for purchasing power (-) for selling power. The $p_{U,H}(t)$ is the exchanging heat price ($/kWh).

2.10. Operating and maintenance cost

The following equations are employed to calculate the maintenance cost of the different generators of the system:

a. The maintenance cost of the MT:

$$C_{om,MT}(t) = \eta_{MT}(t).\,K_{om,MT}.\,P_{MT}(t) \tag{15}$$

b. The maintenance cost of the FC:

$$C_{om,FC}(t) = \eta_{FC}(t).\,K_{om,FC}.\,P_{FC}(t) \tag{16}$$

c. The maintenance cost of the BO:

$$C_{om,bo}(t) = K_{om,bo}.\,H_{bo}(t) \tag{17}$$

d. The maintenance cost of the EH:

$$C_{om,eh}(t) = K_{om,eh}.\,H_{eh}(t) \tag{18}$$

where $K_{om,FC}$, $K_{om,MT}$, $K_{om,DG}$, $K_{om,bo}$, $K_{om,eh}$ ($/kWh)are the coefficients of maintenance cost of the FC, MT, DG, BO, and EH.

2.11. Environment damage cost

The emission of CO_2, SO_2, NOx, and PM which are caused by burning fossil fuel leads to damage to the environment. This damage to the environment is converted to the monetary concept by using the following equations:

a. Environment cost of the MT

$$C_{E,MT}(t)=\sum_{j=1}^{M} E_{j,MT}\,.\,C_j.\,P_{MT}(t) \tag{19}$$

b. Environment cost of the FC

$$C_{E,FC}(t)=\sum_{j=1}^{M} E_{j,FC}\,.\,C_j.\,P_{FC}(t) \tag{20}$$

c. Environment cost of the DG

$$C_{E,DG}(t)=\sum_{j=1}^{M} E_{j,DG}\,.\,C_j.\,P_{DG}(t) \tag{21}$$

where $E_{j,MT}$, $E_{j,FC}$ and, $E_{j,DG}$ (kg/kWh) are the emission amount of j^{th} GHG from the MT, FC, and DG respectively, C_j (€/kg) is an expense of emission of j^{th} GHG.

2.12. Cost of on/off generators

These costs of the generators are determined by the following equations [27]:

$$SU(t) = S_c\,.(\delta(t) - \delta(t).\delta(t-1)) \quad (22)$$

$$SD(t) = S_d\,.(\delta(t-1) - \delta(t).\delta(t-1))$$

where S_c and S_d ($/kWh)are the price of the start-up and shutdown cost of the FC, MT, and DG ($/kWh).

3. Objective Function of the Proposed System

The proposed multi-objective function aims to minimize the total operating and emission cost. This function includes all the aforementioned cost functions in the previous sections. The cost function is formulated as follows:

$$F = Min\ \sum_{t=1}^{T}\{C_{MT}(t) + C_{FC}(t) + C_{DG}(t) + C_b(t) + C_{bo}(t) + SU_{MT}(t) + SU_{FC}(t) + SU_{DG}(t) + SD_{MT}(t) + SD_{FC}(t) + SD_{DG}(t) + C_{om,MT}(t) + C_{om,FC}(t) + C_{om,DG}(t) + C_{om,bo}(t) + C_{om,eh}(t) + C_{E,MT}(t) + C_{E,FC}(t) + C_{E,DG}(t) + C_{U,P}(t) + C_{U,H}(t)\} \quad (24)$$

4. Modeling of Constraints

The following proposed constraints should be met when solving the optimization problem.

4.1. Energy balance constraints

The electrical and heat demands should be satisfied at each time intervals.

a. Electrical power constraint

This constraint is as follows:

$$\sum_{t=1}^{T}\{P_{MT}(t) + P_{FC}(t) + P_{DG}(t) + P_w(t) + P_{PV}(t) + P_{b,dis}(t) + P_{U,p}(t) = P_L(t) + P_{b,ch}(t) + P_{U,s}(t)\} \quad (25)$$

where $P_w(t)$ and $P_{PV}(t)$ are the wind turbine and PV panels power, $P_{\boldsymbol{U,p}}(t)$ and $P_{\boldsymbol{U,s}}(t)$ are purchasing and selling power from/to the utility grid, and $P_L(t)$ is the electrical load.

b. Heat power constraint

This constraint is formulated as follows:

$$\sum_{t=1}^{T}\{H_{MT}(t) + H_{bo}(t) + H_{eh}(t) + H_{hs,dis}(t) + H_{U,p}(t) = H_L(t) + H_{hs,ch}(t) + H_{U,s}(t)\} \quad (26)$$

where $H_{\boldsymbol{U,p}}(t)$ and $H_{\boldsymbol{U,s}}(t)$ are the purchasing and selling heat from/to the utility grid, and $H_L(t)$ is the heat load.

4.2. Generators operating constraints

a. Capacity constraints

$$P_{min} \leq P(t) \leq P_{max} \tag{27}$$

where $P(t)$ is the output power of the MT, FC, and DG.

b. Ramp rate constraint

The generation level of any DG at each time interval ΔT should not increase more than a ramp-up limit (UR_i) or less than ramp-down limit (DR_i). This constraint should be met when the optimization problem is solved [28]. This constraint is expressed as follows

$$-DR.\Delta t \leq P(t+1) - P(t) \leq UR \tag{28}$$

where DR and UR are ramp up and down of the generators.

c. Minimum time up and down constraints

These constraints are formulated as follows [29]:

$$\delta(t) - \delta(t-1) \leq \delta(\tau) \quad \text{(off/on)} \tag{29}$$

$$\delta(t-1) - \delta(t) \leq 1 - \delta(\tau) \text{ (on/off)} \tag{30}$$

Where, in case of minimum uptime

$$\tau = t + 1 \ldots \ldots \min\left(t + T_i^{up} - 1, T\right) \tag{31}$$

Otherwise

$$\tau = t + 1 \ldots \ldots \min\left(t + T_i^{down} - 1, T\right) \tag{32}$$

where $\delta(t)$ is on / off state of the generator.

4.3. Storage battery constraints

a. State of charge constraint

$$W_{b,min} \leq W_b(t) \leq W_{b,max} \tag{33}$$

b. Charging and discharging power

$$\delta_{bch}(t).P_{bch,min} \leq P_{bch}(t) \leq \delta_{bch}(t).P_{bch,max} \tag{34}$$

$$\delta_{bdis}(t).P_{bdis,min} \leq P_{bdis}(t) \leq \delta_{bdis}(t).P_{bdis,max} \tag{35}$$

$$\delta_{bch}(\mathrm{t}) + \delta_{bdis}(t) \leq 1 \tag{36}$$

where $\delta_{bch}(\mathrm{t})$ and $\delta_{bdis}(\mathrm{t})$ are binary variables that are employed to determine the storage battery operations status.

4.4. Heat storage constraints

a. State of charge constraint

$$W_{hs,min} \leq W_b(t) \leq W_{hs,max} \quad (37)$$

b. Charging and discharging power

$$\delta_{hs,ch}(t).H_{hs,ch-min} \leq H_{hs,ch}(t) \leq \delta_{hs,ch}(t).H_{hs,ch-max} \quad (38)$$

$$\delta_{hs,dis}(t).H_{hs,dis-min} \leq H_{hs,dis}(t) \leq \delta_{bdis}(t).H_{hs,dis-max} \quad (39)$$

$$\delta_{hs,ch}(\mathrm{t}) + \delta_{hs,dis}\,(t) \leq 1 \quad (40)$$

where $\delta_{hs,ch}(\mathrm{t})$ and $\delta_{hs,dis}(\mathrm{t})$ are binary variables that are employed to determine the heat storage operations status.

4.5. Boiler constraint

$$H_{bo,min} \leq H_{bo}(t) \leq H_{bo,max} \quad (41)$$

4.6. Electric heater constraint

$$H_{eh,min} \leq H_{eh}(t) \leq H_{eh,max} \quad (42)$$

4.7. Emission limitation constraints

The constraints of the emission of greenhouse gas from DGs are formulated as follows:

$$E_{MT,CO2}.P_{MT}(t) + E_{FC,CO2}.P_{FC}(t) + E_{DG,CO2}.P_{DG}(t) \leq L_{CO2} \quad (43)$$

$$E_{MT,NO_X}.P_{MT}(t) + E_{FC,NO_X}.P_{FC}(t) + E_{DG,NO_X}.P_{DG}(t) \leq L_{NO_X} \quad (44)$$

$$E_{MT,SO2}.P_{MT}(t) + E_{FC,SO2}.P_{FC}(t) + E_{DG,SO2}.P_{DG}(t) \leq L_{SO2} \quad (45)$$

$$E_{MT,PM}.P_{MT}(t) + E_{FC,PM}.P_{FC}(t) + E_{DG,PM}.P_{DG}(t) \leq L_{PM} \quad (46)$$

where L_{CO2}, L_{NO_X}, L_{SO2}, L_{PM} are the maximum allowable emission level of CO_2, NO_X, SO_2, PM in the area of the grid.

4.8. Isolated mode operation constraint

This constraint should be satisfied at each time interval. This constraint is considered to make sure that the grid can supply its load at any time if the connection with the utility grid is lost. This constraint is formulated as follows:

$$P_{MT,max}(t) + P_{FC,max}(t) + P_{DG,max}(t) + P_{b,disc,max}(t) \geq P_L(t) \quad (47)$$

5. The solution of the optimization problem

The proposed optimization problem is formulated as MIQP. The branch and bound method usually applied to solve this type of problem. The main merit of this algorithm is when the solution is reached, the solution is global optimal [10]. In this paper, ILOG CPLEX version 12.6 is used to solve the optimization problem, which is an efficient solver based on the branch and bound algorithm.

This optimization problem is for the operation stage and the proposed system should be operated according to the optimization program because the proposed system is much more complicated than the conventional power grid. The conventional system can be operated without optimization and the generation level of the energy resources is according to their rating. While operation the proposed system without optimization is quite difficult and lead to considerably high operating cost. This is because the system can exchange heat and power with the utility grid according to the pricing system. In addition, using electric and heat storage devices. Moreover, the interaction between the electric and heat system. In the case of operation of the proposed system without optimization and according to the rating values of the devices, the total operating cost is 5465.3 $ per scheduling day. This value is much higher than the total cost based on the optimization program, which is 893.6 $. It can be observed that the employing of the optimization approach results in a massive reduction in the total operating cost.

The results of the proposed optimization approach are verified and validated by applying the considered approach in this research on the modeling of papers [10, 30, 31], where the obtained results almost followed the results in these papers.

6. Case Study

To verify the applicability and effectiveness of the proposed optimization approach, it is tested on the CHP low voltage distribution grid which is shown in Fig. 1. The hourly electrical and heat loads, the price of exchanging electrical and heat power, and the generation of PV and WT are illustrated in Table 1. These values are taken from reliable papers [23, 32]. The rated charging and discharging power of BAT is 90 kWh. The rated and minimum energy of the BAT are 300 kWh and 90 kWh, respectively. The rated and minimum stored energy of heat storage are 300 kWh and 90 kWh, respectively. The rated of gas boiler and the electric heater is 100 kWh and 500 kWh respectively. The ramp rate of CHP, FC, and DG is set at 100 kW, 20 kW, and 100 kW respectively. The ramping rate is taken 50% of the maximum generation of each generator to prevent the generators from damage and makes the cause study close to the real scenario. The maximum and minimum output power of the CHP, FC, DG, BO, EH, and exchanging power and heat with the utility grid are listed in Table 2.

Table 1. Hourly loads, prices, and renewable generation [23, 32].

Time (h)	E. load kW	H. load kW	E. price $/kWh	H. price $/kWh	WT kW	PV kW
1	192	466.88	0.01	0.162	55	0
2	177.6	481.82	0.018	0.1332	61	0
3	132	489.29	0.02	0.1368	65	0
4	122.4	481.82	0.018	0.1476	58	0
5	117.6	489.29	0.025	0.1008	58	0
6	110.4	451.94	0.045	0.054	24	0
7	162	443.22	0.1	0.0432	40	0
8	213.6	428.28	0.28	0.0972	34	6
9	258	382.22	0.45	0.1152	40	25

10	220.8	343.62	0.519	0.144	46	31
11	295.2	336.15	0.4	0.1116	30	34
12	368.4	290.09	0.25	0.09	31	40
13	442.8	252.74	0.48	0.054	25	46
14	421.2	217.88	0.3	0.0504	25	45
15	406.8	244.02	0.25	0.0792	36	33
16	368.4	282.62	0.1	0.126	30	31
17	327.6	367.28	0.035	0.1476	46	27
18	339.6	428.28	0.045	0.1152	36	25
19	361.2	520.41	0.08	0.1008	52	9
20	420	573.95	0.12	0.0972	46	0
21	405.6	559.01	0.025	0.1584	52	0
22	421.2	555.27	0.015	0.1476	46	0
23	375.6	539.09	0.012	0.108	46	0
24	370.8	520.41	0.01	0.288	52	0

Table 2. Related parameters.

Type	Minimum power (kW)	Maximum power(kW)
CHP	20	200
FC	10	40
DG	20	200
BO	0	100
EH	0	500
P_U	10	200
H_U	10	200

7. Results and Discussion

Figures 2 to 4 show the optimal electrical power schedule of the generators and exchange power with the battery and the utility grid. It can be observed from Fig. 2 that the CHP is committed during the entire scheduling period to satisfy both the electrical and heat demand. It also can be seen that the FC is committed over the whole scheduling horizon to supply the electrical demand. Further, the DG is not operated until hour 12 because it has the highest operating cost, where other generators and battery can supply the electric demand and satisfy the isolated mode constraint when the DG is off. Furthermore, the DG is committed between 12 and 17 and from 17 to the end of the day when the electric load has the highest values and the exchanging price with the utility grid has high values. The DG is operated to supply load and satisfy the isolated mode constraints when the demand has the highest values and other generators could not satisfy the isolated mode constraint. It can be observed that the UC of the CHP is responded to both electrical and heat demands.

Figure 3 shows that the battery is discharged when the electricity price has high values and is charged when the price has low values to reduce the operating and emission cost of the system. Besides, the battery is discharged the highest power at hour 10 and 13 when the price has the highest values during the scheduling day, where the grid sells the highest power to the utility grid at hour 10 to reduce its cost.

It can be noticed from Fig. 4 that the distribution grid purchases power from the utility grid to supply the electric demand and electric heater when the price has low values to reduce its operating and emission cost. For the same reasons, the system sells power to the utility grid when the price has high values.

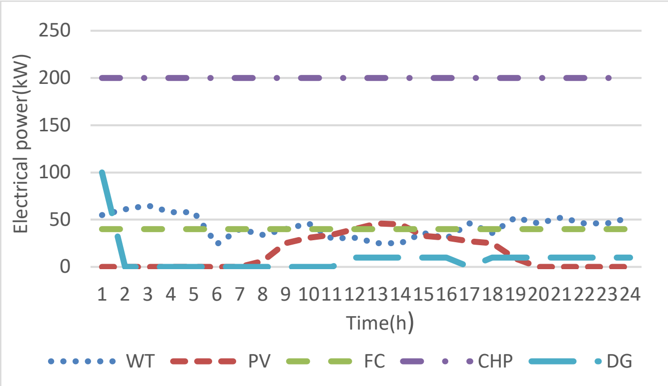

Fig. 2. Optimal power schedule of the generators.

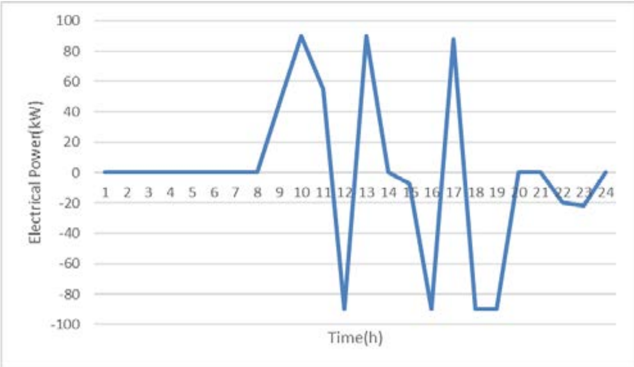

Fig. 3. Optimal power schedule of the battery.

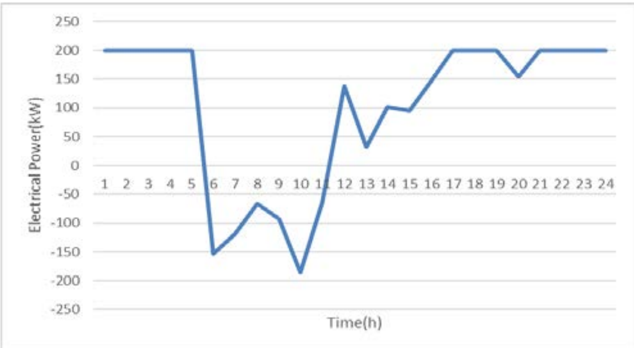

Fig. 4. Optimal exchange power with the utility grid.

Figures 5 to 7 show the heat schedule of generators and exchanging heat with the upstream grid and heat storage. It can be seen from Fig. 5 that the EH provides high output heat at hours 1 to 5 to satisfy the heat demand and sells heat to the utility grid because the heating price has high values at these hours. Besides, the BO is committed over the whole scheduling horizon because it has the lowest operating cost.

Figure 6 reveals that the heat storage device discharges when the heat price high has value and charges when the price has low value to reduce the operating cost of the CHP grid.

Figure 7 shows that the distribution grid sells heat to the utility grid when the price has high values and the heat demand has low value, while purchases heat from the utility grid when the heat demand has high values.

Figure 8 depicts the hourly electric and heat systems costs, emission, and total cost, where the hourly values are listed in Table 3. It can be observed that the highest electric system emission and total cost occurs at hour 1 because the generators provide the maximum power to supply the electric and heat demand, where the CHP supplies the heat and the CHP with other generators provided electric power to the electric heater. This is because the heat load has a high value at this hour. It also can be noticed that the heat system cost has negative values. This means revenue to the distribution grid. Since the heating price has the highest value at these hours, therefore, the distribution grid sells the possible highest heat to the utility grid to reduce its operating cost.

In addition, the lowest cost occurs at hour 10 because the exchange electric and heat prices have high values and the distribution grid sells power to the utility grid and the electric and heat loads have low values. Moreover, the emission cost has positive value during the whole scheduling day because the FC, and the CHP are committed over the entire scheduling horizon. The total cost is 893.6 $ per scheduling day.

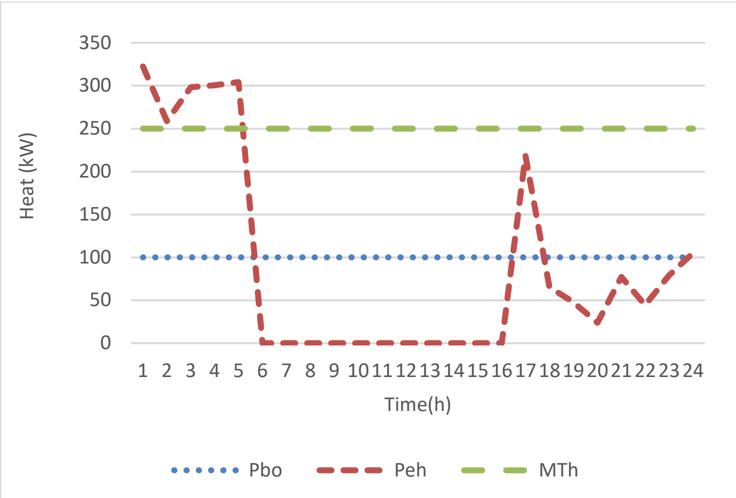

Fig. 5. Optimal heat power schedule of heat generators.

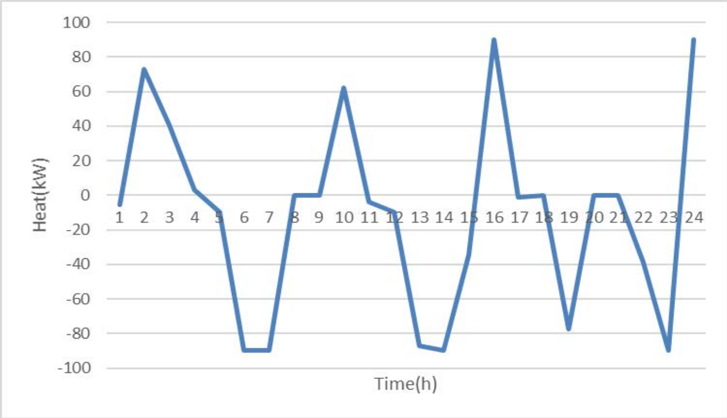

Fig. 6. Optimal heat power schedule of heat storage.

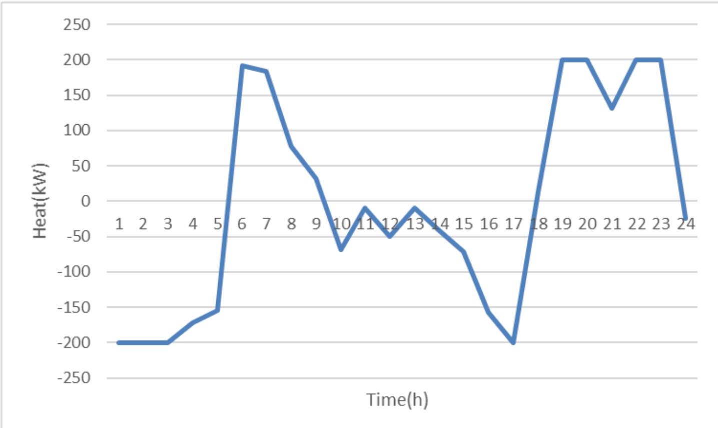

Fig. 7. Optimal exchange heat power with the utility grid.

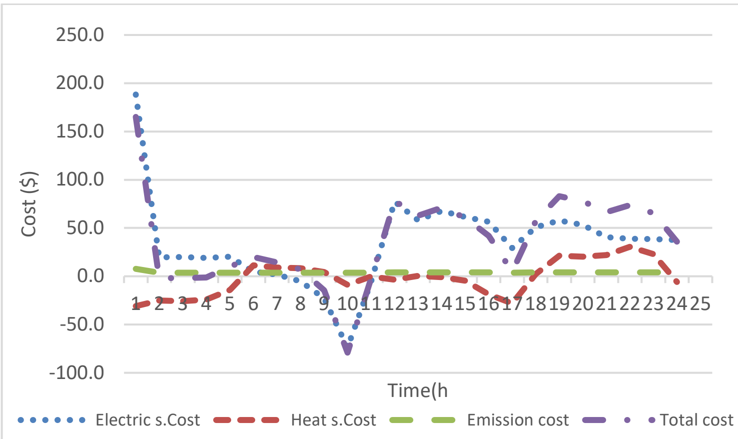

Fig. 8. Costs of electrical and heat systems, emission, and total cost.

Table 3 Hourly costs of electrical and heat systems, emission, and total cost

Time (h)	Electric system cost	Heat system cost	Emission cost	Total cost
1	188.3	-30.9	7.7	165.1
2	19.5	-25.1	3.7	-1.8
3	20.1	-25.8	3.7	-2.0
4	19.0	-24.0	3.7	-1.3
5	20.4	-14.2	3.7	9.9
6	4.8	11.5	3.7	20.0
7	1.7	9.0	3.7	14.4
8	-5.1	8.4	3.7	7.0
9	-22.8	4.5	3.7	-14.6
10	-73.9	-8.9	3.7	-79.1
11	-6.3	-0.3	3.7	-2.9
12	77.4	-3.6	4.1	77.9
13	58.1	0.6	4.1	62.8
14	67.9	-1.0	4.1	71.0
15	61.5	-4.7	4.1	60.9
16	56.5	-18.7	4.1	41.9
17	29.4	-28.2	3.7	4.8
18	51.0	2.5	4.1	57.5
19	57.7	21.3	4.1	83.1
20	53.3	20.3	4.1	77.7
21	40.5	21.9	4.1	66.4
22	38.9	30.5	4.1	73.6
23	38.5	22.9	4.1	65.4
24	37.5	-5.8	4.1	35.8

8. Conclusion

This paper proposes a multi-objective optimization approach to minimize the total operating and emission cost of the smart distribution grid based CHP. The emission cost is converted to the monetary concept and the emission limitation constraint is considered to convert the objective function to a single function that has one solution. The UC technique is employed to reduce the operating and emission cost, where the UC is developed to accommodate both the electric and heat output of the CHP. The results reveal that one feasible solution is obtained from the solution of the problem. Besides, the battery and heat storage are scheduled to minimize the operating and emission cost and to satisfy the constraints. The UC manages the electrical and heat output of the CHP to meet the electrical and heat demands and to reduce the operating and emission cost of the system. Further, the proposed approach helps the operators to design the scheduling strategy to minimize the total operating cost.

Nomenclatures

a , a_1, a_2	Coefficients of the cost function
C_d	Battery degradation cost, $/kWh
C_j	The expense of emission of j^{th} GHG, €/kg
$E_{j,DG}$	Emission amount of j^{th} GHG from the DG, kg/kWh

Nomenclatures

$E_{j,FC}$	Emission amount of j^{th} GHG from the FC, kg/kWh
$E_{j,MT}$	Emission amount of j^{th} GHG from the MT, kg/kWh
$H_{bo}(t)$	The heat generated by BO, kWh
$H_{eh}(t)$	The heat generated by EH, kWh
$H_{hs,ch}(t)$	Heat stored, kWh
$H_{hs,dis}(t)$	Heat discharged, kWh
$H_L(t)$	Heat load, kWh
$H_U(t)$	Trading heat with the utility grid, kWh
$K_{om,DG}$	Coefficients of maintenance cost of DG, \$/kWh
$K_{om,FC}$	Coefficients of maintenance cost of FC, \$/kWh
$K_{om,MT}$	Coefficients of maintenance cost of MT, \$/kWh
$K_{om,bo}$	Coefficients of maintenance cost of BO, \$/kWh
$K_{om,eh}$	Coefficients of maintenance cost of EH, \$/kWh
$L_{NG,MT}$	The low heating value of natural gas, kWh/m^3
L_{CO2}	The maximum allowable emission level of CO_2, kg
L_{NOX}	The maximum allowable emission level of NO_x, kg
L_{SO2}	The maximum allowable emission level of SO_2, kg
L_{PM}	The maximum allowable emission level of PM, kg
$P_b(t)$	Power of battery, kWh
$P_{bch}(t)$	Charging power of the battery, kWh
$P_{bdis}(t)$	Discharging power of the battery, kWh
$P_{FC}(t)$	Electrical power of FC, kWh
$P_L(t)$	Electrical load, kWh
$P_{MT}(t)$	Electrical power of MT, kWh
$P_{U,P}(t)$	Trading power with the upstream grid, kWh
$P_w(t)$	PV panels power, kWh
$P_w(t)$	wind turbine power, kWh
p_g	Price of the natural gas, \$/m^3
$p_U(t)$	Exchanging power price with the utility grid, \$/kWh
$p_{U,H}(t)$	Exchanging heating price with the utility grid, \$/kWh
S_c, S_d	Price of the start-up and shutdown cost of the DG, FC, and MT, \$/kWh
$W_b(t)$	State of charge of the battery at time t, kWh
$W_{hs}(t)$	State of charge of the heat storage at time t, kWh

Greek Symbols

$\delta_{DG}(t)$	On/off state of the DG
$\delta_{FC}(t)$	On/off state of the FC
$\delta_{MT}(t)$	On/off state of the MT
η_{bo}	Efficiency of BO
η_{eh}	Efficiency of EH
η_{ch}	The efficiency of charging power of the battery
η_{dis}	The efficiency of discharging power of the battery

Nomenclatures

$\eta_{hs,ch}$	The efficiency of charging heat
$\eta_{hs,dis}$	The efficiency of discharging heat
η_{FC}	Efficiency of FC
η_{MT}	Efficiency of MT
δ_1	The heat loss factor of MT
δ_{hr}	The efficiency of heat recovery

Abbreviations

CHP	Combined Heat and Power
IMIQP	Interval Mixed-Integer Quadratic Programming

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