ENERGY OPTIMIZATION MANAGEMENT OF COMBINED COOLING AND POWER DISTRIBUTED ENERGY SUPPLY SYSTEM WITH MICRO TURBINE

Mengxuan LIU  
Tianjin University – China  
mengxuanliu@tju.edu.cn

Chengshan WANG  
Tianjin University – China  
cswang@tju.edu.cn

Li GUO  
Tianjin University – China  
liguo@tju.edu.cn

ABSTRACT

This paper proposes a reasonable integrated Energy Management System (EMS) for Combined Cooling and Power System (CCPS). Four kinds of operation modes listed as: (1) Determining cooling load by electricity consumption (DC Mode), (2) Determining Electric Load by Cooling Consumption (DE Mode), (3) the Optimal Cost (OC Mode) and (4) the Optimal Prime Energy Ratio (PER) (OP Mode) are integrated in EMS. The (1) and (2) realize real-time power adjustment of Micro turbine (MT) depending upon the electric and Cooling load (CL) demand and the (3) and (4) are realized depending upon the minimum operation cost of the whole system or maximum PER and are used for cooling capacity of Lithium Bromide Double-effect Absorption Refrigerator (LBDEAR) and MT power adjustment in real time. Integrated factors such as the cooling and Electric Load (EL), the generation possibility to grid, electricity price of MT for sale and the price of natural gas and electricity are considered into these four modes. The effectiveness of the algorithm is verified through typical experiments.

NOMENCLATURE

\[ p_f \]  
Price of natural gas (Yuan/Nm³);

\[ p_e \]  
Purchased power price from external grid (Yuan/kWh);

\[ p_{MT} \]  
Sell power price to external grid (Yuan/kWh);

\[ P_{Grid} \]  
The tie-line power of CCPS (kW);

\[ P_{MT} \]  
Output power of MT (kW);

\[ P_{set} \]  
The power reference of \( P_{Grid} \) (kW);

\[ Q_{ac} \]  
Cooling power of LBDEAR (kW);

\[ Q_{fuel} \]  
The total fuel thermal power consumption of MT (kW);

\[ Q_r \]  
Cooling power of demonstration system (kW);

\[ Q_{air} \]  
Cooling power of electric-driven air conditioning (EAC) (kW);

\[ Q_{ac-max} \]  
Cooling capacity of MTs with full power output (kW);

\[ LHV \]  
Lower heating value (MJ/m³);

\[ V_{COP} \]  
Refrigeration coefficient of EAC;

\[ V_{fuel} \]  
The amount of fuel thermal power consumption in unit time (Nm³/h), \( V_{fuel} = 3.6Q_{fuel}/LHV \)

\[ t \]  
Time (h)

INTRODUCTION

Combined Cooling Heating and Power (CCHP) system converts the primary energy such as natural gas and fuel oil into secondary energy such as cooling, heating or electricity with high PER [1][2]. The selection for operation modes determines the system operating cost and energy consumption. Meeting heating/cooling load preferentially or meeting electric load preferentially are two types of conventional operation modes. Based on these modes, the Oak Ridge National Laboratory (ORNL) implements one optimization software named “CHP manager” into its research program called ‘Modular Integrated Energy System’. Minimum of annual operating costs is the optimal objective. The system operating mode was determined by the combination of cooling/electric load, electricity price, equipment features and weather changes. Compared with the mode of determining electric load by cooling/heating consumption, the simulation results show that 6% of annual operating cost is saved [3]. In Ref. [4], a new energy optimization and management model aiming at minimum operating costs of CCPS is proposed, and a generation plan could be determined according to the forecast curves of EL and CL. At present, most of operation modes in CCPS are simple in China, integrated operation optimization theory and energy management strategies remain to be discussed in depth.

This paper is supported by one of the China Southern Power Grid Company undertook national 863 plan, which is called as “The key technology and demonstration project of grid-connecting issue for a MW level CCP distributed energy MicroGrid” [5-7]. A reasonable integrated EMS including four types of operation mode is proposed, as well as corresponding control strategies. The effectiveness of different modes is approved by experiment results.

FOUR TYPES OF OPERATION MODES

Figure 1 Energy supply system

The energy supply flow of real demonstration system is shown as Figure 1. In order to meet the requirements of EL and CL, CCPS makes use of purchased natural gas preferentially, when it is not sufficient, CCPS also purchases electricity from external grid.
wiring and operating modes can be found in Ref. [4]. The operation mode of CCPS is determined by integrated factors such as EL and CL, the generation possibility to grid, electricity price of MT for sale and the price of natural gas and electricity. Considering of the demonstration system’s characteristic, this paper proposes 4 operation modes as follows:

**OC Mode:** The minimum of purchase expenses for electricity, nature gas and the revenue from electricity sales is the objective, with the prerequisite of meeting the cooling and electrical demand of demonstration system.

**OP Mode:** The maximum PER is the objective, with the prerequisite of meeting the cooling and electrical demand of demonstration system.

**DE Mode:** The control objective is to balance CL demand of demonstration system. In the words, CCPS will supply CL if cooling capacity is enough. Otherwise, EAC will supply the remaining CL.

**DC Mode:** The control objective is to balance the EL demand of demonstration system. In the words, CCPS will supply the EL if electricity capacity is enough. Otherwise, external grid will supply the additional EL.

**MATHEMATICAL MODEL AND CORRESPONDING CONTROL STRATEGIES**

**OC Mode**
The control objective is to obtain the lowest operating costs, the mathematical model can be found in Ref. [7]. The simplified objective function is,

\[ C_t = \min(C_f + C_e) = \min(p_f V_{fuel} + k_e P_{Grid}) \]

\[ \text{if } P_{Grid} > 0, \quad k_e = p_e; \quad \text{else } P_{Grid} < 0, \quad k_e = p_{MT}. \]

The open-loop control schedule is shown in Figure 2(a). Base on the measurements of CL and EL demand in real-time, the optimal schedule of \( P_{MT} \) can be calculated. To avoid frequent adjustments, the system uses delay control, which means only when the operating cost difference between last instructions and operating instructions exceeds the threshold for more than \( T \triangleq \) time, the power of MT is adjusted.

**OP Mode**
The control objective is to obtain the maximum PER, and the objective function is,

\[ C_t = \max(\text{PER}) = \max((P_{MT} + Q_{ac})/Q_{fuel}) \]

The constrains are same as Mode 1. The control strategy is similar with OC Mode and only uses “operating PER” to replace “operating cost”.

**DE Mode**
The control objective is to meet CL demand of demonstration system preferentially, and the objective function is,

\[ Q_{ac} = Q_r - Q_{air} \]

The control schedule is shown in Fig.2(b). It also uses delay control method. If the \( Q_r > Q_{ac-max} \) is true for \( T \triangleq \), MT will be set to full power status and LBDEAR will generate the greatest cooling capacity; Otherwise, only when the \( Q_r \) difference between last instructions and operating instructions exceeds the threshold for more than \( T \triangleq \) time, the power of MT is adjusted.

**DC Mode**
The control objective is to keep the power purchased from external grid around \( P_{set} \), and the objective function is,

\[ \left| P_{Grid} - P_{set} \right| < YD \]

where \( YD \) (kW) is the threshold.

The control strategy is similar with OC Mode and the difference is to change comparison condition into “Compare \( P_{Grid} \) with \( P_{set} \)”. In order to reach new balance point, MT will not be adjusted during the period of \( T \) after last adjustment.

**MODEL PARAMETER ADJUSTMENT**

In standard operating conditions, the relationship between \( Q_{fuel} \) and \( P_{MT} \), \( Q_{fuel} \) and exhaust temperature \( T_0 \) and exhaust flow of MT \( (V_{ex0}) \) can be approximated by a linear equation [4]. The maximum \( Q_{ac} \) has approximate linear relationship with \( T_0 \) and \( V_{ex0} \). So the relationship between \( P_{MT} \) and \( Q_{ac} \) can be also approximated by a linear equation.

In the case of two operating MTs, according to the table given by manufacturers about MT and LBDEAR, the results of linear fitting is as follows,

\[ Q_{ac} = 18.919 \times P_{MT} + 246.22 \]

To improve the accuracy of the model, based on more...
practical experiment results, Equation (5) can be modified as,

\[ Q_{ac} = 13.738P_{MT} + 174.33 \quad (6) \]

Both the revised and old curves of the linear function are shown in Figure 3.

ANALYSIS OF EXPERIMENTAL RESULTS

In this paper all the experiments were conducted in September. The experimental condition was -- the maximum number of operated MT was two. Set \( p_e \approx 1.0136 (¥ / kWh), p_{MT} = 0.77(¥ / kWh), p_f = 3.85(¥ / m^3), LHV = 37.36(MJ/m^3), V_{COP} = 3. \)

OC Mode

Figure 4 shows some selected data from 11:06 to 11:53 of one day in Sept. When \( Q_r \) increases, the corresponding \( PMT \) increased. When \( Q_r \) began to increase at 10:09:10, only one MT was operated. The increase of \( Q_r \) leaded to start another MT until 11:09:55. After that the \( PMT \) instructions and \( PMT \) was increasing with the continuous growth in \( Q_r \).

Figure 4 the results of OC Mode

The economical analysis was made for the sampled data in one stable period from 12:00 to 13:00. The actual and theoretical EL, \( Q_r, V_{fuel} \) are shown in Table 1. The actual cost and theoretical cost can be calculated by Equation (1). The theoretical \( Q_{fuel} \) can be calculated by the linear equation between \( Q_{fuel} \) and \( PMT \). If the CL is only supplied by EAC (without CCPS), the cost is expressed as \( C_l = (k_e P_{Grid} + Q_{ac} / V_{COP}) \). The difference between the theoretical and the cost is less than 10 ¥ / h in this specific hour. The cost of CCPS is ¥ 732.94 and without CCPS is ¥ 784.85.

OP Mode

The new experiments were carried out in some another day in Sept. The experimental results (17:00 to 18:00) are shown in Figure 5. \( P_{MT} \) was almost stable during this period and \( P_{Grid} \) followed the changes of EL. \( Q_r \) was in a volatile state during the experiment because that LBDEAR pump keeps opening and closing constantly during this period.

Figure 5 the results of OP Mode

<table>
<thead>
<tr>
<th>Time</th>
<th>( Q_r ) (kW)</th>
<th>EL (kW)</th>
<th>Actual ( V_{fuel} ) (Nm3/h)</th>
<th>Theoretical ( V_{fuel} ) (Nm3/h)</th>
<th>Actual ( PMT ) (kW)</th>
<th>Theoretical ( PMT ) (kW)</th>
<th>Actual cost (¥/h)</th>
<th>Theoretical cost (¥/h)</th>
<th>Cost without CCP (¥/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:00</td>
<td>439.97</td>
<td>703.13</td>
<td>104.34</td>
<td>102.23</td>
<td>301.85</td>
<td>300</td>
<td>808.45</td>
<td>802.20</td>
<td>861.34</td>
</tr>
<tr>
<td>12:15</td>
<td>435.92</td>
<td>642.32</td>
<td>103.82</td>
<td>102.23</td>
<td>303.03</td>
<td>300</td>
<td>767.43</td>
<td>740.56</td>
<td>798.34</td>
</tr>
<tr>
<td>12:30</td>
<td>452.08</td>
<td>621.01</td>
<td>103.51</td>
<td>102.23</td>
<td>299.82</td>
<td>300</td>
<td>724.07</td>
<td>718.96</td>
<td>782.20</td>
</tr>
<tr>
<td>12:45</td>
<td>435.11</td>
<td>584.55</td>
<td>103.36</td>
<td>102.23</td>
<td>296.02</td>
<td>300</td>
<td>690.39</td>
<td>682.01</td>
<td>739.51</td>
</tr>
<tr>
<td>13:00</td>
<td>444.46</td>
<td>609.33</td>
<td>103.79</td>
<td>102.23</td>
<td>299.82</td>
<td>300</td>
<td>714.03</td>
<td>707.12</td>
<td>767.79</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>( Q_r ) (kW)</th>
<th>( P_{Grid} ) (kW)</th>
<th>Actual ( PMT ) (kW)</th>
<th>Theoretical ( PMT ) (kW)</th>
<th>Actual PER (%)</th>
<th>Theoretical PER (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17:00</td>
<td>288.96</td>
<td>498.32</td>
<td>153.57</td>
<td>152</td>
<td>83.3</td>
<td>83.0</td>
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<tr>
<td>17:15</td>
<td>293.05</td>
<td>362.79</td>
<td>155.87</td>
<td>152</td>
<td>84.5</td>
<td>83.8</td>
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<tr>
<td>17:30</td>
<td>257.36</td>
<td>356.52</td>
<td>153.06</td>
<td>152</td>
<td>77.1</td>
<td>76.9</td>
</tr>
<tr>
<td>17:45</td>
<td>258.54</td>
<td>343.42</td>
<td>148.93</td>
<td>152</td>
<td>76.5</td>
<td>77.1</td>
</tr>
<tr>
<td>17:00</td>
<td>293.36</td>
<td>328.95</td>
<td>151.21</td>
<td>152</td>
<td>83.7</td>
<td>83.9</td>
</tr>
</tbody>
</table>
The actual and theoretical EL, $Q_r$, $V_{fuel}$ are shown in Table 2. The PER of CCPS is calculated by Equation (2). The actual average of PER in this period is 80.1%, and the theoretical average of PER is 79.8%.

**DE Mode**

Some experimental results (15:47 to 16:37) are shown in Figure 6. Before 15:48:55, $P_{MT}=300kW$ and $Q_r=410kW$ were almost stable. At 15:51:45, $Q_r$ began to reduce and went down to 266kW at 16:37:55, and at this time $P_{MT}$ was 283.5kW, and $P_{MT}$ instruction is 285kW.

As the experimental results shown, when $Q_r$ decreases, $P_{MT}$ will be decreased, and changes of $Q_r$ can be traced timely according to the requirements of this mode.

**DC Mode**

Some experimental results (17:19 to 17:22) are shown in Figure 7. While two MTs running at 17:19:00, the $P_{MT}$ instruction was 205kW, $P_{MT}=201.9kW$, $P_{Grid}=22.17kW$, $EL=204.63kW$, the $P_{set}=40kW$, and the threshold value was 20kW. At 17:19:34, reseted $P_{set}$ to 60kW, CCPS needed to reduce $P_{MT}$ to 38kW, so $P_{MT}$ instruction was changed to 160kW, and assigned it to two MTs on average. At 17:20:24, a single MT was enough to provide 160kW $P_{MT}$ by increasing $P_{MT}$ itself and another MT was turned off. It leaded to decrease the $P_{MT}$ and increase the $P_{Grid}$. When $P_{MT}$ increased to 160kW, $P_{Grid}$ was about 60kW and became stable again.

From the experimental results, it can be shown that $P_{Grid}$ and $P_{MT}$ can trace EL changes according to the requirements of this mode.

**CONCLUSIONS**

Based on the deep research of the operating characteristics of MT and LBDEAR, this paper has presented four EMS strategies including OC Mode and OP Mode etc. Some control experiments were implemented for the proposed strategies and the conclusions are as follows:

1. The control system can adjust the $P_{MT}$ well in accordance with the established strategy by tracing the real-time changes of EL and $Q_r$. Then, the status of the CCPS will be optimized and the expected control objective can be achieved.

2. The operating characteristics of the main devices in CCPS were tested and the mathematical model of the system was revised, which can reduce the optimization deviation.

3. The experiments show that MT has good dynamic response ability to quickly trace the control instructions. However, $Q_{ac}$ with long time delay is a slow dynamic system, and this characteristic should be paid more attention in the optimal control procedure.

4. In DE Mode, extra heat is drained away when the cooling power of CCPS can fulfill $Q_r$, so the whole system is with lower PER as well as poor economy. However, PER is higher in DC Mode. Besides fulfilling EL and $Q_r$, OC Mode and OP Mode can achieve the maximum income and PER respectively.

Due to condition limit, only 2 MTs were adopted in this experiment, and all experiments were carried out in September. besides the power of EAC did not include in the cooling load during experiment time. In the future, 3 MTs and EAC will be included and the experiments will be implemented during the whole year.

**REFERENCES**


