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

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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 Purchase 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);
$Q_{ac\text{-}max}$ Cooling capacity of MTs with full power output (kW);
LHV Lower heating value (MJ/m^3);
V_{COP} Refrigeration coefficient of EAC;
V_{fuel} the amount of flux natural gas in unit time (Nm^3/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

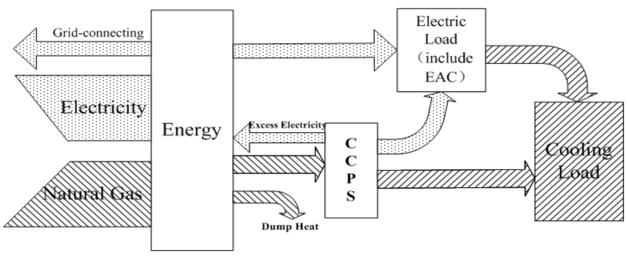


Figure 1 Energy supply system

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. The details of

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,

$$C_t=Min(C_f+C_e)=Min(p_f V_{fuel}+k_e P_{Grid})t \qquad (1)$$

if $P_{Grid}>0$, $k_e=p_e$; else $P_{Grid}<0$, $k_e=p_{MT}$.
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 ΔT time, the power of MT is adjusted.

OP Mode

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

$$C_t = \mathrm{Max(PER)} = \mathrm{Max}((P_{MT}+Q_{ac})/Q_{fuel}) \qquad (2)$$

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,

$$Q_{ac}=Q_r-Q_{air} \qquad (3)$$

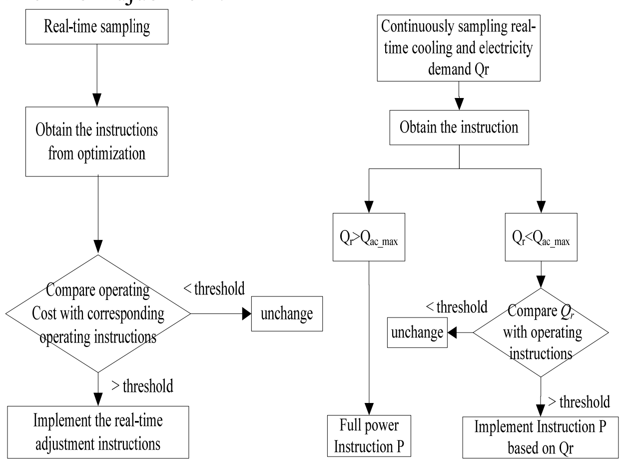
The control schedule is shown in Fig.2(b). It also uses delay control method. If the $Q_r>Q_{ac\text{-}max}$ is true for ΔT, MT will be set to full power status and LBDEAR will generate the greatest cooling capacity; Otherwise, only when the Q_r difference between last instructions and operating instructions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

$$\left| P_{Grid}-P_{set} \right| < \mathrm{YD} \qquad (4)$$

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 be not adjusted during the period of T after last adjustment.



(a) OC Mode (b) DE Mode

Figure 2 The logical diagram of operation modes

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,

$$Q_{ac}=18.919P_{MT}+246.22 \qquad (5)$$

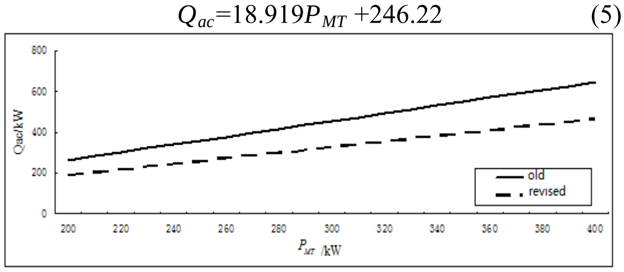


Figure 3 the relationship between P_{MT} and Q_{ac}

To improve the accuracy of the model, based on more pracatical 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=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 P_{MT} 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 P_{MT} instructions and P_{MT} was increasing with the continuous growth in Q_r.

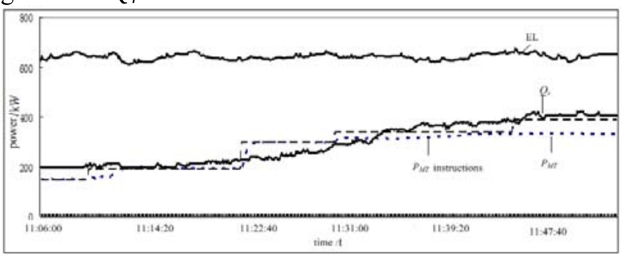


Figure 4 the results of OC Mode

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 $P_{MT.}$ If the CL is only supplied by EAC (without CCPS), the cost is expressed as $C_t=(k_eP_{Grid}+Q_{ac}/V_{COP})t$. 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.

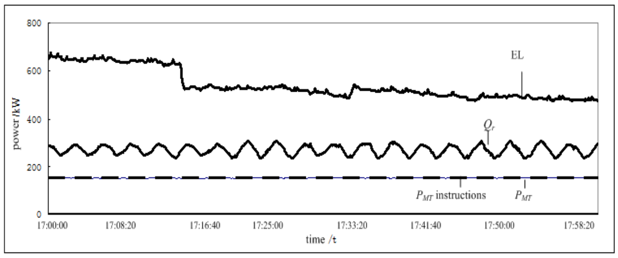


Figure 5 the results of OP Mode

Table 1 Experimental Results of OC Mode (12：00~13：00)

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

Table 2 Experimental Results of OP Mode (17：00~18：00)

Time	Q_r (kW)	P_{Grid} (kW)	Actual P_{MT} (kW)	Theoretical P_{MT} (kW)	Actual PER (%)	Theoretical PER (%)
17：00	288.96	498.32	153.57	152	83.3	83.0
17：15	293.05	362.79	155.87	152	84.5	83.8
17：30	257.36	356.52	153.06	152	77.1	76.9
17：45	258.54	343.42	148.93	152	76.5	77.1
17：00	293.36	328.95	151.21	152	83.7	83.9

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.

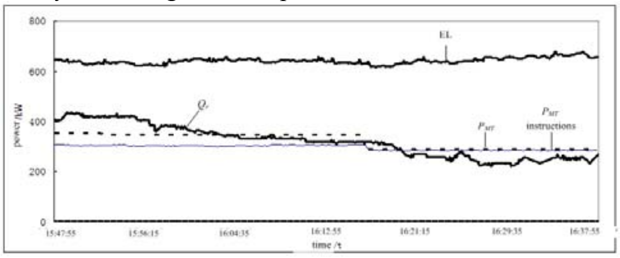


Figure 6 the results of DC Mode

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 200kW, 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} iteself and another MT was turned off. It leaded to decrease the P_{MT} and increase the P_{Grid}. When P_{MT} increased to160kW, P_{Grid} was about 60kW and became stable again.

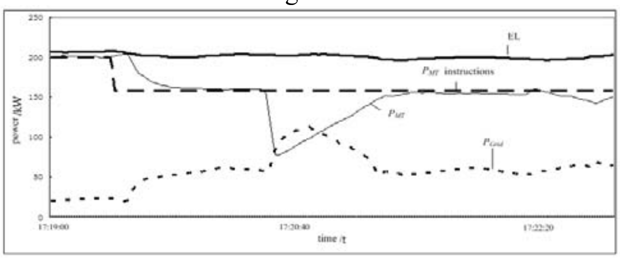


Figure 7 the results of DE Mode

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.

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