International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID:0234

CHANCE-CONSTRAINED OPERATION STRATEGY FOR CCHP MICROGRID

Wei Shangshang, Li Yiguo*, Zhang Junli, Wu Xiao

School of Energy and Environment, Southeast University, Nanjing 210096, China (* Corresponding Author)

ABSTRACT
Operation strategy is critical to the economic performance of combining cooling, heat and power (CCHP) microgrid. This work took different costs of operation, maintenance, startup and shut down, storage aging, and different nonlinear characteristics of tariff electricity, storage loss and COP, etc. into consideration. To tackle the uncertainties of renewable energy and load demands, a chance-constrained operation strategy was established. PSO algorithm was applied to solve the problem. Simulation results show that uncertainty of CCHP deteriorates system economic performance compared with deterministic economic operation strategy. And following electrical load and following thermal load are inefficient for economic operation of CCHP microgrid.

Keywords: CCHP microgrid, operation strategy, economic performance, chance-constrained

NONMENCLATURE

Abbreviations

AC	Absorption chiller
CCHP	Combining cooling heat and power
CCO	Chance-constrained operation
CL	Cooling load demand
DO	Deterministic operation
EC	Electrical chiller
EL	Electricity load demand
FEL	Following electrical load
FTL	Following thermal load
GB	Gas boiler
GT	Gas turbine
HL	Heat load demand
PLR	Part load ratio
PV	Photovoltaic power
SC	Solar thermal collector
SR	Spinning reserve
WT	Wind turbine

1. INTRODUCTION

In the principle of energy cascade utilization, CCHP possesses notable advantages of efficiency, environment friendly, safety, etc[1], and captures more and more attention. The typical operation strategies of CCHP are FEL and FTL. Base on the concepts, there are several retrofit operation strategies, FLB[2], FTL-ECR[3], MD[4], etc. However, the influences of operation and maintenance cost, start up and shut down cost, battery aging cost, and nonlinear character of tariff electricity, storage loss, etc. on the system performance are rarely all taken into consideration.

In addition, the installation of distributed generator has turned the traditional CCHP into CCHP microgrid[5]. Due to the complexity of CCHP microgrid, optimal operation is a necessity to coordinate different devices economically. There are several papers with regard to economic operation strategy of CCHP microgrid[6, 7].However, the stochasticity of renewable energy and the uncertainty of load demands are simplified to a deterministic problem, whereas they are taken into account using the chance-constrained method in this work.

2. MODEL OF CCHP MICROGRID

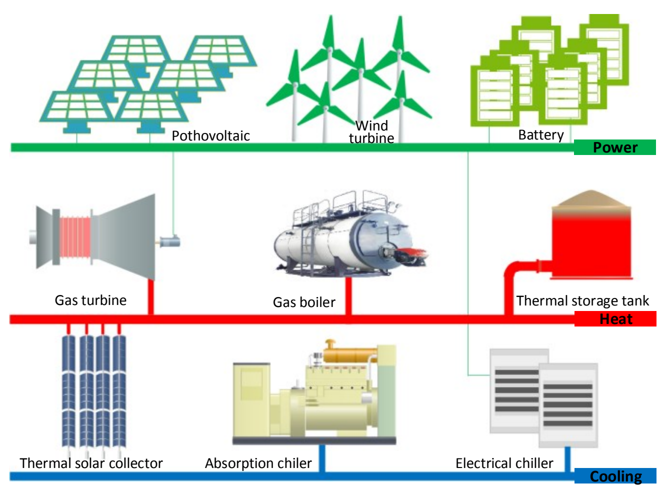

Fig 1. CCHP microgrid system

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).
Copyright © 2019 ICAE

The CCHP microgrid proposed here is shown in Fig. 1. Model and parameters of WT, PV, and SC can be find in Ref. [3]. Operational characteristics of GT are related to PLR. The electricity efficiency of GT is calculated by Eq. (1), where, η_{GT}^{rate} is rated power efficiency.

$$\eta_{GT} = \sum_{i=0}^{3} \alpha_{GT,i} PLR^i \eta_{GT}^{rate} \tag{1}$$

The thermal energy to the electricity ratio, r_{GT}, of gas turbine is expressed as Eq. (2), and parameters can be found in Ref. [8].

$$r_{GT} = \frac{H_{GT}}{P_{GT}} = \frac{r_{GT}^{rate}}{\eta_{GT}} \tag{2}$$

The power of gas turbine should satisfy the following physical constraints:

$$\begin{cases} P_{GT}^{\min} \le P_{GT}^{i} \le P_{GT}^{\max} \\ \Delta P_{GT}^{\min} \le P_{GT}^{i} - P_{GT}^{i-1} \le \Delta P_{GT}^{\max} \end{cases} \tag{3}$$

The AC utilizes heat to produce cooling energy. The coefficient of performance, COP, depends on its part load ratio, PLR_{AC}. Based on the COP, the cooling power can be derived as follows:

$$C_{AC} = H_{AC} COP_{AC} = H_{AC} \sum_{k=0}^{2} c_{AC,i} PLR_{AC}^{k} \tag{4}$$

where H_{AC} is the heat supplied to absorption chiller. And $c_{AC,0}$, $c_{AC,1}$, $c_{AC,2}$ are 0.1703, 0.6040, 0.5845, respectively[3]. The following constraints of absorption chiller should be satisfied as:

$$\begin{cases} C_{AC}^{\min} \le C_{AC}^{i} \le C_{AC}^{\max} \\ C_{AC}^{i} - C_{AC}^{i-1} \le \Delta C_{AC}^{I} \\ C_{AC}^{i-1} - C_{AC}^{i} \le \Delta C_{AC}^{D} \end{cases} \tag{5}$$

Power of EC can be calculated by Eq. (6) with a constant COP_{EC} equal to 4.

$$C_{EC} = P_{EC} COP_{EC} \tag{6}$$

Energy stored in battery can be calculated by:

$$S_{BA}^{t} = S_{BA}^{t-1}\left(1-\mu_{BA}\right) + \left(\eta_{BA,ch} P_{BA,ch} - P_{BA,dch}/\eta_{BA,dch}\right)\Delta t \tag{7}$$

where the $P_{BA,ch}$, $\eta_{BA,ch}$ are charge power and charge efficiency, and $P_{BA,dch}$, $\eta_{BA,dch}$ are discharge power and discharge efficiency. μ_{BA} is energy loss rate. Δt is the sampling time, which is simplified as 1 hour. The amount of energy, S_{BA}, stored in battery should be limited to its capacity available, as well as the charge/discharge rate in each time interval. Note that thermal tank and battery storage have similar forms.

$$\begin{cases} S_{BA}^{\min} \le S_{BA}^{t} \le S_{BA}^{\max} \\ P_{BA,ch}^{\min} \le P_{BA,ch} \le P_{BA,ch}^{\max} \\ P_{BA,dch}^{\min} \le P_{BA,dch} \le P_{BA,dch}^{\max} \end{cases} \tag{8}$$

During the operation, the CCHP should satisfy the energy balances of cooling, heat and power, which are expressed as:

$$P_{GD} + P_{PV} + P_{WT} + P_{GT} = P_{EC} + P_{BA} + P_{PL} \tag{9}$$

$$H_{GB} + H_{SC} + H_{GT} = H_{AC} + H_{TA} + H_{HL} \tag{10}$$

$$C_{AC} + C_{EC} = C_{CL} \tag{11}$$

3. CHANCE-CONSTRAINED OPTIMIZATION MODEL

3.1 Chance-constrained optimization

The uncertainty is the inherent characteristic of renewable energy, and the subjectivity of user makes load demands have a certain degree of volatility. Therefore, renewable energy output and load demands are expressed as follow:

$$P_{re} = P_{gv} + \xi_{er} \tag{12}$$

where P_{re} represents real value, P_{gv} is given value, and ξ_{er} is uncertainty. CCO is simplified to a DO problem when ξ_{er} is ignored.

In order to deal with the uncertainty, SR is employed. For the CCHP microgrid system, GT is the reserve device for electricity to compensate the uncertainties of the WT, PV, and the EL. GB is for heating reserve to compensate the uncertainty of SC and the HL. Note that uncertainty of CL is shared by EC and AC based on the electrical cooling ratio, α_{ECR} . Thus, chance-constrained formulations with certain confidence level, β , of cooling, heat and power are as follows:

$$\Pr\left\{SR_C > \xi_{CL}\right\} \ge \beta_C \tag{13}$$

$$\Pr\left\{SR_H + \left(1-\alpha_{ECR}\right)SR_C > \xi_{SC} + \xi_{HL}\right\} \ge \beta_H \tag{14}$$

$$\Pr\left\{SR_E + \alpha_{ECR} SR_C > \xi_{PV} + \xi_{WT} + \xi_{EL}\right\} \ge \beta_E \tag{15}$$

To simplify the chance-constrained formulation and convert them into a determinist problem, the uncertainties of renewable energy and load demands are assumed to be normal distribution, N (0, σ). Then the chance-constrained formulations can be converted to deterministic inequality form, where ϕ is the cumulative distribution function.

$$F_1 = SR_C - \phi^{-1}\left(\beta_C\right) \ge 0 \tag{16}$$

$$F_2 = SR_H + \left(1-\alpha_{ECR}\right) SR_C / COP_{AC} - \phi^{-1}\left(\beta_H\right) \ge 0 \tag{17}$$

$$F_3 = SR_E + \alpha_{ECR} SR_C / COP_{EC} - \phi^{-1}\left(\beta_E\right) \ge 0 \tag{18}$$

with the following constraints:

$$F_4 = C_{EC}^{\max} - \left(\alpha_{ECR} SR_C + C_{EC}\right) > 0 \tag{19}$$

$$F_5 = C_{AC}^{\max} - \left(1-\alpha_{ECR}\right) SR_C - C_{AC} > 0 \tag{20}$$

$$F_6 = H_{GB}^{\max} - SR_H - \left(1-\alpha_{ECR}\right) SR_C / COP_{AC} > 0 \tag{21}$$

$$F_7 = E_{GT}^{\max} - \left(SR_E + \alpha_{ECR} SR_C / COP_{EC} + P_{GT}\right) > 0 \tag{22}$$

Copyright © 2019 ICAE

3.2 Objective function

The objective function is the summary of different costs as shown in Eq. (23). The last term is the penalty of inequality constraints.

$$\begin{aligned} \min \quad & \sum_{j=1}^{24} \begin{pmatrix} CO_{GT} + CO_{G} + CO_{EC} + CO_{AC} + CO_{BA} + CO_{TA} + CO_{SR} \\ -\sum_{i=1}^{7} \omega_i \min(0, F_i) \end{pmatrix} \quad (23) \\ s.t. \quad & (9)(10)(11) \end{aligned}$$

Cost of gas turbine is expressed as Eq. (24). Advantages of such form are that device status can be easily obtained according to the particle value without introducing extra status variable.

$$CO_{GT} = \begin{cases} R_{gas}\dfrac{P_{GT}^{i}}{\eta_{GT}} + K_{GT}P_{GT}^{i} + ST_{GT} & P_{GT}^{i-1} > 0, P_{GT}^{i} = 0 \\ SD_{GT} & P_{GT}^{i-1} = 0, P_{GT}^{i} > 0 \\ 0 & P_{GT}^{i-1} = 0, P_{GT}^{i} = 0 \\ R_{gas}\dfrac{P_{GT}^{i}}{\eta_{GT}} + K_{GT}P_{GT}^{i} & else \end{cases} \quad (24)$$

The cost of absorption chiller is calculated as Eq. (25). Note that EC has similar form.

$$CO_{AC} = \begin{cases} K_{AC}P_{AC}^{i} + ST_{AC} & P_{AC}^{i-1} > 0, P_{AC}^{i} = 0 \\ SD_{AC} & P_{AC}^{i-1} = 0, P_{AC}^{i} > 0 \\ K_{AC}P_{AC}^{i} & else \end{cases} \quad (25)$$

Costs of energy storage device consist of maintenance and aging cost.

$$CO_{BA} = \begin{cases} K_{BA}P_{BA}^{i} + \dfrac{IV_{BA}P_{BA}^{i}\eta_{BA,ch}}{2N} & P_{BA}^{i} < 0 \\ K_{BA}P_{BA}^{i} + \dfrac{IV_{BA}P_{BA}^{i}\eta_{BA,dch}}{2N} & else \end{cases} \quad (26)$$

The purchasing gas cost and electricity cost are calculated as:

$$CO_{G} = R_{gas}H_{GB} + R_{el}P_{GD} \quad (27)$$

The reserve cost should be added when uncertainties are considered.

$$CO_{SR} = R_{SR,H}P_{SR,H} + R_{SR,E}P_{SR,E} \quad (28)$$

3.3 Solution procedures

Since the renewable energy is uncontrollable, and considering the equality equations in Eqs. (9-11), the decision variables here are chosen as P_{GT}, P_{EC}, P_{BA}, and P_{TA}. And the following procedures of PSO algorithm should be checked in each time interval.

1) Calculating the power of renewable energy according to Ref. [3].
2) According to Eq. (3), if gas turbine output power violates the constraints, then it is assumed to be equal to the boundary value. Next calculating the electricity efficiency and thermal to electricity ratio according to Eqs. (1-2), respectively.
3) Calculating the absorption chiller power according to Eq. (4). If it violates the constraints in Eq. (5), then modifying the electrical chiller power, P_{EC}, to keep the absorption chiller power at boundary value.
4) Checking the state of battery according to Eq. (7). If the amount of energy or charge/discharge rate violate the constraints in Eq. (8), it will be modified to equal to boundary limitation. The same procedures to thermal storage tank.
5) According to steps 1-4, calculating the P_{BA}, P_{GT}, P_{EC}, H_{TA}, H_{GT}, H_{AC}. Then deriving from the equality Eq. (9) and Eq. (10), the electricity from grid and purchasing natural gas of gas boiler are obtained.
6) Calculating different cost terms based on device status according to Eqs. (24-28), and summing them to the objective function.

4. SIMULATION RESULTS

The cooling, heat and power demands profile are plotted in Figs 2-4. Power of PV, WT and SC are shown in Figs 3-4. And parameters can be found in Tables 1, 2 and Table 3.

Table 1. Technical parameters of devices [6, 7]

parameters	Value ($/kWh)	parameters	Value ($)	parameters	Value (kW)	parameters	Value (kW)
K_{GT}	0.005	ST_{GT}	1.17	$P_{GT}^{\max}$	200	ΔP_{GT}^{I}	180
K_{AC}	0.0024	ST_{AC}	3	$P_{GT}^{\min}$	20	ΔP_{GT}^{D}	150
K_{EC}	0.0016	ST_{EC}	1.0	$C_{AC}^{\max}$	400	ΔC_{AC}^{I}	300
K_{BA}	0.00106	SD_{GT}	1.17	$C_{AC}^{\min}$	80	ΔC_{AC}^{D}	200
K_{TA}	0.0031	SD_{AC}	3	$S_{BA}^{\max}$	400	$P_{BA,ch}^{\max}$	-200
K_{BO}	0.0027	SD_{EC}	0.5	$S_{BA}^{\min}$	10	$P_{BA,dch}^{\max}$	200
$R_{SR,H}$	0.045	IV_{BA}	400	$S_{TA}^{\max}$	1200	$P_{TA,ch}^{\max}$	-800
$R_{SR,E}$	0.02	IV_{TA}	100	$S_{TA}^{\min}$	60	$P_{TA,dch}^{\max}$	800
R_{gas}	0.045						

Table 2. Technical parameters of devices

parameters	Value	parameters	Value	parameters	Value	parameters	Value
μ_{TA}	0.02	N_{BA}	9800	$\eta_{BA,ch}$	0.95	σ_{E}	12
μ_{BA}	0.01	N_{BA}	3000	$\eta_{BA,dch}$	0.95	σ_{H}	9
β_{E}	0.90	β_{C}	12	$\eta_{TA,ch}$	0.9	σ_{C}	6
β_{H}	0.85			$\eta_{TA,dch}$	0.9		

Table 3. Electricity tariff

Time interval	[1,6],[23,24]	[7,11],[18,22]	[12,17]
R_{el} ($/kWh)	0.10	0.169	0.112

Simulation results of CCO are shown in Figs 2-4. It can be seen that at the first 6 hours, heat is supplied by gas boiler. Because of sufficient wind power, no electricity is purchased, and cooling is supplied by electrical chiller. At the first peak demands, gas turbine starts up to supplement both power and heat, the minor surplus heat and power are stored in battery and thermal

Copyright © 2019 ICAE

tank accordingly. With the increase of solar irradiation, power from both photovoltaic and solar collector increases, resulting in charge of storage devices. At this time, absorption chiller and electrical chiller work together to supply cooling demand. Gas turbine starts again at the second peak demands time, meanwhile, storage device discharges energy. Shortage of energy is replenished from grid and gas boiler when necessary.

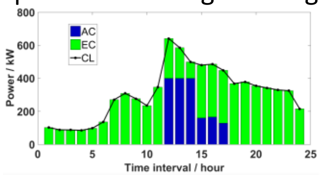

Fig 2. Results of CCO for cooling

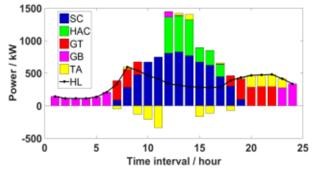

Fig 3. Results of CCO for heat

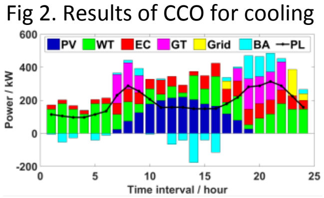

Fig 4. Results of CCO for power

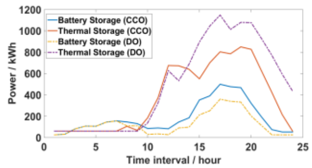

Fig 5. Results of energy storage device

Table 4 shows the comparison of total operation cost between DO and CCO. It can be found that uncertainty deteriorates system economic performance because more reserve devices are needed to deal with the uncertainty. Uncertainty type also has influence on the operation cost, resulting from different types of reserve device. Moreover, device status of the operation results is also affected by the uncertainty as plotted in Fig. 5. Therefore, change of operation cost is due to the reserve cost and the adjustment of device status.

Table 4. Operation cost of DO and CCO

Performance	Deter-minist	power uncertainty	heat and power uncertainty	cooling, heat and power uncertainty
Operation cost	374	391	404	420

Table 5 shows the total operation cost of FEL and FTL with different α_{ECR}. It suggests that with increase of α_{ECR}, both operation costs of FEL and FTL decrease. However, the cost is still higher than that of DO, suggesting FEL and FTL have limitations to economic operation of CCHP microgrid.

Table 5. Operation cost of FEL and FTL

α_{ECR}	FEL	FTL
0	704	754
0.5	468	565
1	439	523

5. CONCLUSIONS

This paper established a chance-constrained operation strategy for CCHP microgrid considering different costs and nonlinear characteristics of devices. Then the PSO algorithm was applied to solve the model. The simulation results suggest that uncertainty of CCHP will affect device status, and deteriorate system economic performance compared with deterministic operation. Hence uncertainty of system should not be ignored. Besides, FEL and FTL strategies are inefficient for economic operation of CCHP microgrid

ACKNOWLEDGEMENT

This work is supported by the National Key R&D Program of China under Grant 2018YFB1502900.

REFERENCE

[1] Yan BF, Xue S, Li YF, Duan JH, Zeng M. Gas-fired combined cooling, heating and power (CCHP) in Beijing: A techno-economic analysis. Renew Sust Energ Rev, 2016; 63: 118-131.

[2] Wang JJ, Zhai ZQ, Jing YY, Zhang CF. Influence analysis of building types and climate zones on energetic, economic and environmental performances of BCHP systems. Applied Energy, 2011;88:3097-3112.

[3] Yang G, Zhai XQ. Optimization and performance analysis of solar hybrid CCHP systems under different operation strategies. Applied Thermal Engineering, 2018;133: 327-340.

[4] Zheng CY, Wu JY, Zhai XQ. A novel operation strategy for CCHP systems based on minimum distance. Applied Energy, 2014;128:325-335.

[5] Gu W, Wu Z, Bo R, Liu W, Zhou G, Chen W, Wu Z. Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review. International Journal of Electrical Power & Energy Systems, 2014;54:26-37.

[6] Gu W, Wang ZH, Wu Z, Luo Z, Tang YY, Wang J. An Online Optimal Dispatch Schedule for CCHP Microgrids Based on Model Predictive Control. IEEE Trans. Smart Grid, 2017;8:2332-2342.

[7] Tian Z, Niu JD, Lu YK, He SM, Tian X. The improvement of a simulation model for a distributed CCHP system and its influence on optimal operation cost and strategy. Applied Energy, 2016;165:430-444.

[8] Tichi SG, Ardehali MM, Nazari ME. Examination of energy price policies in Iran for optimal configuration of CHP and CCHP systems based on particle swarm optimization algorithm. Energ Policy, 2010;38:6240-6250.

Copyright © 2019 ICAE