열과 전기 제약을 고려한 최적화 CHP 운전

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OPTIMIZATION OF CHP OPERATION WITH HEAT AND ELECTRICITY CONSTRAINTS

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Abstract - This paper presents the optimization of CHP (Combined heat and power) plant under deregulated market. In this case, a boiler is added as different source for heat providing, that gives flexible and efficient operation for the plant. The purpose of optimization is to maximize the profit in period of 24 hours by making unit commitment decision, called "optimal policy". In this paper, Dynamic Programming method is introduced as the effective and efficient method. Finally, an example is solved to illustrate the optimal policy of such a CHP and boiler.

1. INTRODUCTION

Generally, the market is tending to change into the form of deregulated market in which the roll of customer varies extremely. Electric market is not an exception, under deregulated market, electricity is seemed as common commodity for selling or buying, that makes customer no longer being seem as user or consumer, they are able to buy generators, operating to provide for their own demand, buy electricity when being short or sell when being superfluous, to get the maximum profit. These are some characteristics of deregulated market that changes the optimization problem in power system and make it necessary to be considered.

Moreover, the efficiency of thermal plant provides electricity only is quite poor, around 30-40%. But when the waste heat is used, for example in CHP, the efficiency can be improved significantly, up to 80%. It is reasonable to build the thermal network to provide for consumer, and this is the case in some Europe Countries, notably Sweden, Denmark and Germany.

With all the motivation, this paper tries to point out the optimization of CHP and boiler's operation, working in deregulated market. Supposed that real-time price of electricity and heat in coming day are given from the spot market, the producer want to make the decision for their utilities to get the maximum profit over 24 hours. So, it makes difference from other optimization problem by dealing with both heat and electricity. For best understanding, this paper is organized as follows: Section II describes all the notations used in the paper. Section III presents the unit commitment formulation, its components and the constraints. Section IV recommends Dynamic Programming (DP) as the effective and efficient method. Section V illustrates an example of such CHP and boiler and expresses the result of optimization. Finally, the conclusions are summarized in Section VI.

2. NOTATIONS

For convenience, all the notations used in this paper are listed as following:

- k: index of stage (k= 0, 1··· 23).
- u_{k_chp}: zero-one control decision for CHP at stage k, (1=on and 0=off).
- x_{k_chp}: state variable indicating the length of time CHP has been on or off at stage k, [hour].
- u_{k_boiler}: zero-one control decision for boiler at stage k, (1=on and 0=off).
- x_{k_boier}: state variable indicating the length of time boiler has been on or off at stage k, [hour].
- t^{chp}_{up}, t^{chp}_{dn}: minimum-up, -down time of CHP, [hour].
- t^{boiler}_{up}, t^{boiler}_{dn}: minimum-up, -down time of the boiler, [hour].
- P^{chp}_{max}, P^{chp}_{min}: maximum, minimum of CHP's capacity, [kW].
- P^{boiler}_{max}, P^{boiler}_{min}: maximum, minimum of boiler's capacity, [hour].
- L_k^E, L_k^H: electricity, heat load at stage k, [kW].
- p_k^E, p_k^H: electricity, heat price at stage k, [$/kWh].
- $c_G^{chp}(P^{chp})$: cost for CHP to generate P^{chp}, [$/kWh].
- $c_G^{boiler}(P^{boiler})$: cost for boiler to generate P^{boiler}, [$/kWh].
- S^{chp}: start-up cost of CHP, [$/time].
- T^{chp}: shut-down cost of CHP, [$/time].
- S^{boiler}: start-up cost of boiler, [$/time].
- T^{boiler}: shut-down cost of boiler, [$/time].
- c_f^{chp}, c_f^{boiler}: fixed cost of CHP and boiler, [$/hour].
- I_S: insurance payment in the case of losing heat services, [$/kWh].
- R: percentage of heat load provided.

3. FORMULATION

We are considering the problem in which the producer owns a set of one CHP and one boiler, working in deregulated market. The solution is to determine the optimal policy or unit commitment decision at each hour to maximize the profit over period of 24 hours. All the necessary parameters are assumed given, such as parameters of CHP and boiler, load, electric and heat price in next 24 hours as well. In this case, there are some definition and assumption need to be clarified before formulating.

3.1 GENERATION COST

Generally, generation cost is the payment for producing including fuel, maintenance and losses cost. In this paper, we supposed that it is given as the quadratic function of power produced:

$$c_G^{chp}(P^{chp}) = a_1(P^{chp})^2 + b_1.P^{chp} + c_1$$
$$c_G^{boiler}(P^{boiler}) = a_2(P^{boiler})^2 + b_2.P^{boiler} + c_2 \quad (1)$$

3.2 START-UP AND SHUT-DOWN COST

Start-up and shut-down process have to follow a certain procedure under the safety constraints or physical constraints... it takes not only the cost, but also the time known as minimum-up time, t^{up}, and minimum-down time, t^{dn}.

$$C_k^{up/dn} = u_k.I(x_{k-1}<0).S + (1-u_k).I(x_{k-1}>0).T \quad (2)$$

3.3 INSURANCE PAYMENT

There exists a contract for insurance payment, which means that, in the case of shortage in heat providing, the producers are expected to reimburse to their customer with a predetermined quantity.

$$C_k^{Ins} = (1-R_k).L_{Hk}.I_S \quad (3)$$

3.4 ENERGY EXCHANGE

In this paper, for convenience, we assumed that price of selling or buying electricity are the same, and there is no limitation in power transmission, producer can buy as much as they want with the same price of selling. Therefore, the electricity imbalance is no longer concerned about; the only thing producer concern is to make the decision to maximize their benefit, that is the point in this paper.

3.5 REVENUE

With all assumption above, the revenue can be simply calculated as the product of power and price.

$$R_k = P_k^e.p_k^e + P_k^h.p_k^h \quad (4)$$

3.6 PROFIT

The profit is also simply calculated as the difference of the revenue to all the costs:

$$\Pi_k = u_k^* \{P_k^*.p_k - c_G(P_k) - I(x_{k-1}<0)S\}$$
$$- (1-u_k^*)\left(c_f + I(x_{k-1}>0).T\right) - (1-R).L_H.I_S \quad (5)$$

Where

$$x_k = \begin{bmatrix} x_k^{chp} \\ x_k^{boiler} \end{bmatrix} \quad u_k = \begin{bmatrix} u_k^{chp} \\ u_k^{boiler} \end{bmatrix} \quad p_k = \begin{bmatrix} p_k^E \\ p_k^H \end{bmatrix}$$

$$c_f = \begin{bmatrix} c_f^{chp} \\ c_f^{boiler} \end{bmatrix} \quad S = \begin{bmatrix} S^{chp} \\ S^{boiler} \end{bmatrix} \quad T = \begin{bmatrix} T^{chp} \\ T^{boiler} \end{bmatrix}$$

$$P_k = \begin{bmatrix} P_k^{E\text{-}chp} & 0 \\ P_k^{H\text{-}chp} & P_k^{H\text{-}boiler} \end{bmatrix} \quad c_G(P_k) = \begin{bmatrix} c_G^{chp}(P_k^{chp}) \\ c_G^{boiler}(P_k^{boiler}) \end{bmatrix}$$

$$I(x_k<0) = \begin{bmatrix} I(x_k^{chp}<0) & 0 \\ 0 & I(x_k^{boiler}<0) \end{bmatrix}$$

3.6 OPERATIONAL CONSTRAINTS

In operation, there are some constraints must to be satisfied, such as capacity constrains, minimum-up and down-time constrains...

3.6.1 MINIMUM-UP, MINIMUM-DOWN TIME CONSTRAINTS

$$u_k = \begin{cases} 1 & \text{if } 1 \le x_{k-1} < t^{up} \\ 0 & \text{if } -1 \ge x_{k-1} > t^{dn} \\ 0 \text{ or } 1 & \text{other case} \end{cases} \quad (6)$$

3.6.2 STATE TRANSITION CONSTRAINTS

$$x_{k+1} = \begin{cases} \max(1, x_k+1) & : \text{ if } u_{k+1} = 1 \\ \min(-1, x_k-1) & : \text{ if } u_{k+1} = 0 \end{cases} \quad (7)$$

3.6.3 CAPACITY CONSTRAINTS

$$\begin{cases} P_{min}^{chp} \le P_k^{chp} \le P_{max}^{chp} \\ P_{min}^{boiler} \le P_k^{boiler} \le P_{max}^{boiler} \end{cases} \quad (8)$$

3.7 PROBLEM FORMULATION

The problem is to maximize the profit of producer over the period of 24 hours. Obviously, the total profit is the sum of profit at each of 24 hour:

$$\max_{u_k} \left\{ \sum_{k=1}^{24} \Pi_k \right\} =$$
$$\max_{u_k} \sum_{k=1}^{24} \left\{ \begin{matrix} u_k^* \left(P_k^*.p_k - c_G(P_k) - I(x_{k-1}<0)S\right) - \\ (1-u_k^*)\left(c_f + I(x_{k-1}>0).T\right) - (1-R).L_H.I_S \end{matrix} \right\} \quad (9)$$

4. DYNAMIC PROGRAMMING METHOD

Dynamic programming algorithm can be expressed mathematically as:

$$J_{24}(x_{24}) = 0$$
$$J_k(x_k) = \max_{u_k \in (0,1)} \underset{P_k}{E}\{\Pi_k(x_k, u_k) + J_{k+1}(x_{k+1})\} \quad (11)$$

Where

$\underset{P_k}{E}\{\Pi_k(x_k, u_k) + J_{k+1}(x_{k+1})\}$ denotes the expected profit over last (24-k) hours.

$J_k(x_k)$ denotes the maximum profit when begin at stage k with system state x_k.

5. EXAMPLE

This is an example of CHP and boiler with the parameters is given in Table I, the real-time price provided by JPM in Figure II, and finally, the detail unit commitment decision, the power providing and profit at each hour are shown in Figure III. The total profit in 24 hours in this case, is 345.17 USD.

Table I: Parameter of CHP and Boiler.

Parameter	Value	Unit
N	24	hour
t^{chp}_{up}	4	hour
t^{chp}_{dn}	3	hour
t^{boiler}_{up}	2	hour
t^{boiler}_{dn}	2	hour
P^{chp}_{max}	1000	kW
P^{chp}_{min}	300	kW
P^{boiler}_{max}	400	kW
P^{boiler}_{min}	100	kW
S^{chp}	4	$/time
T^{chp}	4	$/time
S^{boile}	3	$/time
T^{boiler}	3	$/time
c_f^{chp}	2	$/hour
c_f^{boiler}	2	$/hour
Is	0.3	$/kWh

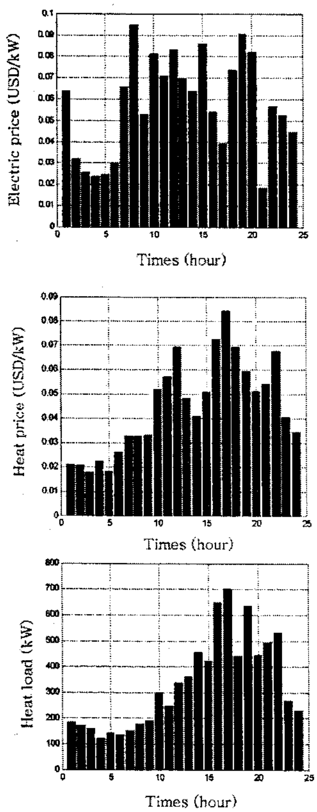
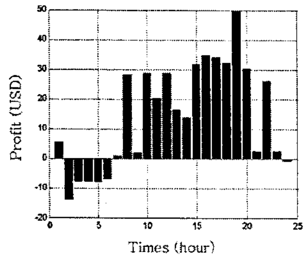


Figure II: Heat load and price of electricity and heat.



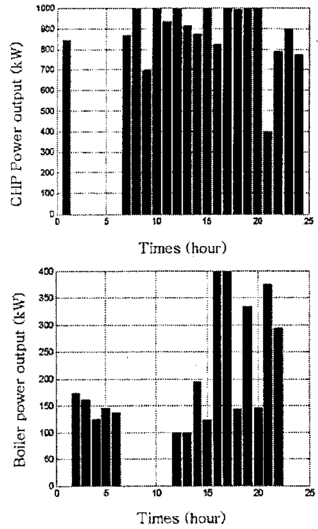


Figure III: Result of optimization.

6. CONCLUSION

This paper introduces the unit commitment problem for optimization the operation of CHP and boiler in deregulated market. The unit decisions are made to maximize the profit over period of 24 hours with some constraints must be remained, such as capacity constraint, minimum-up and -down time constraint... The contract for insurance payment in case of lack of heat providing is also concerned. Finally, an example is used to illustrate the optimal policy and the result is shown in the case of CHP and boiler initially being on.

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REFERENCE

[1] Eric H. Allen and Marija D. Ilic, "Price-based Commitment Decision in the Electricity Market", 2006.
[2] Benjamin F. Hobbs, Michael H. Rothkopf, Richard P. O'Neill, Hung-po Chao, "The Next Generation of Electric Power Unit Commitment Models", 2001.
[3] Dimitri P. Bertsekas, "Dynamic Programming and Optimal Control" , 1995.
[4] Eric H. Allen and Marija D. Ilic, "Reserve Market for Power System Reliability", 2000.
[5] Eric H. Allen and Marija D. Ilic, "A Combined Equivalenced-Electric, Economic, and Market Representation of the Northeastern Power Coordinating Council U.S.Electric System", 2008.
[6] Lee N. Fred, "A Fuel-Constrained Unit Commitment Method", 1989.