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Back-Pressure Cogeneration Economic Dispatch For Physical Bilateral Contract Using Genetic Algorithms

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***Abstract* - A method based on genetic algorithms (GA) is proposed for economic dispatch among multi-plant (cogeneration systems) with multi-generators, which transmit MW to designated buyers (load buses) via physical bilateral contracts. The operation constraints in the cogeneration systems were considered. Virtual Lagrange multipliers were proposed for enhancing the convergence speed to optimality. GA parameters were also investigated for the convergence performance. The IEEE 30- and 118-bus systems were used as test systems to illustrate the applicability of the proposed method.**

Key words: **Cogeneration, Genetic algorithms, Bilateral contract**

I. INTRODUCTION

THE power industry is evolving into a new era of deregulation due to restructure of the power markets in many countries. In the deregulated environment, biddings and bilateral contracts are two main transaction modes. The bilateral contract can be categorized into physical contracts and financial contracts: The physical bilateral contracts involve two entities/parties (buyer and seller) with realistic energy/capacity transactions. The bilateral physical contract involves MW wheeling which has been defined as “the use of a utility’s transmission facilities to transmit power for other buyers and sellers” [1]. In a deregulated market, the transmission system owner could be considered as the third party to provide wheeling for buyers (distribution companies or loads) and sellers (generation companies or independent power producers). Bilateral financial contracts, on the other hand, serve as a hedge due to volatile market prices for market participants. This paper addresses the physical bilateral contracts.

Physical bilateral contracts are currently essential in deregulated power markets. This is due to the dramatic growth of independent power producers (IPPs) and non-utility generations (NUGs). In the past, research focused on the wheeling cost calculation [2-6] and the evaluation of transmission network capacity use [6]. The embedded cost (postage stamp method and contract path method) [2,3,4], marginal cost [2,4,5], incremental cost [2,4], and MW-mile cost [2,4,6] were discussed.

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The cogeneration system is one of the NUGs. The cogeneration system plays an increasingly important role in the power industry. Cogeneration systems in factories can provide not only electric power but also heat to the factories themselves for processing. They also help reduce the spinning reserve required in the power system. If the electric power generated from the cogeneration system is much more than the consumption in the local factory, the additional electric power can be transmitted via wheeling to buyers at other buses.

The problem of economic dispatch (ED) for cogeneration systems was addressed in previous papers [7]-[15]. A two-layer algorithm using Lagrangian relaxation was developed to iteratively determine the heat/power amounts by Guo et al. [7]. Genetic algorithms (GA) were applied to solve the scheduling problem for daily operation of a cogeneration system by Lai et al. [8]. Rooijers, etc. proposed a Newton-based method to solve the Lagrange multipliers for obtaining a static economic dispatch solution [9]. Achayuthakan used GA to solve the ED problem including combined cycle and cogeneration plants by taking all physical quantities as chromosomes [10]. Chen investigated the ED for a back-pressure cogeneration system under time-of-use rates using Newton method [11]. Ashok presented optimal operating strategies using the Newton method for different equipment combinations for a typical industrial configuration under different electricity tariff rates for industrial cogeneration schemes [12]. The results show that industrial cogeneration has a significant potential in reducing peak coincident demand. Tsay and Lin proposed an interactive best-compromise approach, based on evolutionary programming, to solve the economical operation of cogeneration systems under emission constraints [13]. The steam and fuel mix was found by considering the time-of-use dispatch between cogeneration systems and utility companies. Gonzalez presented an algorithm taking sequential quadratic programming (SQP) algorithms to solve the nonlinear cogeneration ED problems. Lagrangian relaxation technique was used before the optimal schedule of the cogeneration system [14]. Finally, a paper used GAs to develop an optimal operation strategy for the cogeneration power plant to improve its competitiveness in the power market [15] by Huang, et. al. However, these papers [7]-[15] did not involve the wheeling problem for the bilateral physical contract.

On the other hand, GAs can be used for obtaining an optimal solution while dealing with the inequality constraints efficiently [16]. Moreover, GA can easily deal with non-differentiable functions. Genetic Algorithms have been used in many applications for power engineering, e.g., [17]~[22]. GA was used to solve an interactive multi-objective passive filter planning problem in the distribution systems [17]. In [18], transformer capacities in an industrial factory with intermittent loads were determined by binary-encoded GA. In [19], the network configuration considering multi-objective (voltage drop and loss) in the distribution system is determined by integer-encoded GA. Other applications of GA are direct load control [20], reactive power compensation [21], and network reconfiguration [22]. These papers show that GA has the strong capability to solve the optimization problem with proper treatments of encoding and inequality constraints.

This paper addresses an ED problem involving electric power wheeling from multiple cogeneration systems at different buses to designated buyers at discriminated buses. Assume that the multiple cogeneration systems belong to an owner. Hence, optimal operations for different cogeneration plants at different buses should be simultaneously achieved for transmitting MW power to designated buyers at discriminated buses. Suppose that the cogeneration systems are the back-pressure type [11]. In this paper, GAs will be also used to solve the optimal operation problem for the cogeneration systems considering bilateral contracts. GA parameters, e.g., penalty weight, crossover rate, mutation rate, and population size, etc., were also investigated for the convergence performance.

In the following sections, the model for the back-pressure cogeneration system is provided first. Then the problem formulation was given in Sec. III. The outline of GA and varying weighting coefficients of penalty functions for GA were discussed in Sec. IV. Simulation results based on the IEEE 30- and 118-bus system data were shown in Sec. V.

II. MODELS FOR BACK-PRESSURE COGENERATION

A. Back-pressure Cogeneration System

As shown in Fig. 1, the back-pressure cogeneration system is composed of several boilers and turbine-generator sets. The high pressure steam from boilers is divided into 3 parts: the first part is piped into the turbines for generating electricity; the second part is used directly for processing; the remaining part is sent to the medium pressure steam common header via valves. The steam out of the turbines is piped to the medium-pressure steam common header.

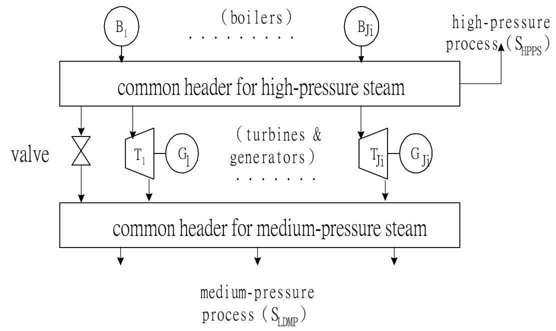

Figure 1 A Single Back-pressure Cogeneration System

B. Boiler/Generator Enthalpy Functions

Suppose there are I cogeneration systems at different I buses, i=1, …, I. These separated cogeneration systems were owned by a company. For the i-th cogeneration system, there are J_i boilers. According to [11], the enthalpy function for the high-pressure boiler is given as follows:

$$H_{bij} = b_{ij3} \times M_{ij}^{3} + b_{ij2} \times M_{ij}^{2} + b_{ij1} \times M_{ij} + b_{ij0} \qquad (1)$$

where

H_{bij} : enthalpy of fuel (MBTU/h) into the j-th high pressure boiler for M_{ij}(T/h) steam output, $i=1,2,3,\ldots I$, $j=1,2,\ldots,J_i$

M_{ij} : generated high-pressure steam (T/h) from the j-th boiler at bus i

b_{ijk} : coefficients of the boiler enthalpy function for the j-th boiler at bus i, $k=0,1,2,3$

On the other hand, the enthalpy function for the turbine-generator set is as follows:

$$H_{gij} = t_{ij3} \times PG_{ij}^{3} + t_{ij2} \times PG_{ij}^{2} + t_{ij1} \times PG_{ij} + t_{ij0} \qquad (2)$$

where

H_{gij} : enthalpy (MBTU/h) consumed by the j-th turbine to produce PG_{ij} MW at bus i, $i=1,2,3,\ldots I$, $j=1,2,\ldots,J_i$

PG_{ij} : power generation (MW)by the j-th turbine generator at bus i

t_{ijk} : coefficients of the enthalpy function for the j-th turbine-generator at bus i, $k=0,1,2,3$

III. PROBLEM FORMULATION

A. Assumptions

The economic operation analysis for multiple separated cogeneration systems at different buses to transmit MW to designated buyers via bilateral contracts can be formulated as an optimization problem. For simplification, there are 4 assumptions for this problem:

(1) A single company owns the cogeneration systems at

different buses.
(2) The cogeneration systems are the back-pressure type.
(3) The system has adequate available transfer capability (ATC) for accommodating the bilateral contract transactions.
(4) The dispatcher in the cogeneration systems is not responsible for the system security and stability but tends to avoid transmission congestion causing by the bilateral contracts.

Several comments will be raised for the above assumptions:

(1) The cogeneration operators dispatch their multiple cogenerations at different plants (a portfolio of cogenerations) to satisfy the static contracted amounts in each period. The dynamic time frame is not considered in this paper.
(2) The cogeneration dispatchers who use the proposed method to dispatch their own cogenerations. The cost functions of the utility generators as well as other IPPs/NUGs are not required to the cogeneration dispatchers.
(3) In broad terms, the ATC can be defined as "a measure of how much additional electricity in MW could be transferred from the seller to the buyer of a path." The seller and buyer can be any group of power injections; moreover, the term "additional" means that no overload will occur in the normal/contingent system when the transfer is increased.

B. Objective Function

The objective function includes the fuel (enthalpy) cost and the wheeling cost for the third entity as follows:

$$Min \quad CT = \sum_{i=1}^{I} UCS_i \sum_{j=1}^{J_i} H_{bij} + \sum_{i=1}^{I} WCT \times PG_i \tag{3}$$

where

i : bus index, $i=1,2,\ldots,I$.
j : cogenerator index; $j=1,2,\ldots,J_i$
CT : total cost ($)
UCS_i : fuel price ($/MBTU) for generating the high-pressure steam at bus i
WCT : wheeling price ($/MWh) paid for the third entity
PG_i : total MW generation at bus i

The first term in Eq. (3) is the fuel cost for all cogeneration systems, each of which includes multiple cogenerators. The second term in Eq. (3) is the wheeling cost, which is calculated by the postage-stamp method. It also can be achieved by the other method (e.g., incremental cost, MW-mile cost, or marginal cost method) without changing the main issue in this paper.

C. Steam Balance Constraints

There are high-pressure and medium-pressure balance constraints in a cogeneration system as follows:

$$\sum_{j=1}^{J_i} M_{ij} - S_{HPPS,i} - \sum_{j=1}^{J_i} \frac{1}{w_i} \times H_{gij} - \frac{S_{v,i}}{(1+R_i)} = 0 \quad , i=1,2,\ldots,I \tag{4}$$

$$\sum_{j=1}^{J_i} \frac{1}{w_i} \times H_{gij} + S_{v,i} - S_{LDMP,i} = 0 \quad , i=1,2\ldots,I \tag{5}$$

where

$S_{HPPS,\,i}$: high-pressure process steam (T/h) required at bus i
w_i : consumed enthalpy (MBTU/T) corresponding to the electricity production between a turbine inlet and outlet steams
$S_{v,i}$: medium-pressure steam flow (T/h) passing through the pressure-regulating valves at bus i
R_i : the spurting-water rate for the pressure-regulating valves at bus i
$S_{LDMP,i}$: medium-pressure steam demand (T/h) at bus i

D. Power Balance Constraints

In additional to the total internal load in individual cogeneration systems, the total MW generation from I cogeneration systems should satisfy the buyers' total load as follows:

$$\sum_{i=1}^{I} \left(\sum_{j=1}^{J_i} PG_{ij} - P_{LD,i} \right) = P_W \tag{6}$$

where

$P_{LD,i}$: internal load (MW) at bus i
P_w : buyers' total load (MW) at different buses
PG_{ij} : MW generation for the j-th generator at bus i

E. Operation Limit Constraints

The steam, MW and steam flow via pressure-regulating valve should meet the operation constraints for the cogeneration system:

$$M_{ij}^{Min} \le M_{ij} \le M_{ij}^{Max} \tag{7}$$

$$PG_{ij}^{Min} \le PG_{ij} \le PG_{ij}^{Max} \tag{8}$$

$$S_{v,i}^{Min} \le S_{v,i} \le S_{v,i}^{Max} \tag{9}$$

where

M_{ij}^{Max} (M_{ij}^{Min}) : maximum (minimum) steam limit for the j-th boiler at bus i
PG_{ij}^{Max} (PG_{ij}^{Min}) : maximum (minimum) MW generation limit for the j-th generator at bus i
$S_{v,i}^{Max}$ ($S_{v,i}^{Min}$) : maximum (minimum) steam limit for the steam flow through the pressure-regulating valves at bus i

The optimal MW dispatch in all cogeneration systems should not violate the line flow constraints in the network:

$$\left|P_{line,\ell}\right| \le P_{line,\ell}^{Max} \tag{10}$$

and

$$P_{line,\ell} = P_{line,\ell}{}^{0} + a_{\ell i} \times \Delta PG_i \tag{11}$$

where

$P_{line,\ell}^{Max}$: the upper line flow limit for the ℓ-th transmission line

$P_{line,\ell}$ ($P_{line,\ell}{}^{0}$): (initial) line flow at the ℓ-th transmission line

Generation Shift Factor is defined as follows:

$$a_{\ell i} = \frac{\Delta P_{\ell ine,\ell}}{\Delta PG_i} \tag{12}$$

where

i : bus index; $i=1,2,\ldots,I,I+1,\ldots,\hat{I}$. Suppose that the cogeneration systems are located at buses $i=1,2,\ldots,I$. Buses I+1 through $\hat{I}$ are buses for the utility.

ℓ : transmission index; $\ell=1, 2, \ldots, L$

IV. PROPOSED METHOD

A. Background of Genetic Algorithms (GA)

GA is used in this paper because GA can theoretically approach the global optimum and has the capability of handling the inequality constraints [16] efficiently. More specifically, GA is summarized as follows:

(i) If the “independent variables” are considered as “genes” in a chromosome, all independent variables will within the limits during the iterations. The binary bits are used for the gene variable representation. The length (32, 16 or 8 bits) of the gene depends on the precision required. All genes (independent variables) including binary bits are cascaded to be a chromosome (individual or string). In this paper, the variables M_{ij} and PG_{ij} are the independent variables which will be encoded into binary bits.

(ii) A new evaluation (objective) function will be given for evaluating the performance (fitness) of the strings. In this paper, the Lagrangian with the original objective function in Eq. (3) plus the penalty functions (which will be defined below) was defined as the evaluation function.

(iii) The GA is further achieved by 3 genetic operations: crossover, mutation and reproduction. A set of population with many chromosomes is considered for these three genetic operations:

Crossover: two crossover points are considered. These points are selected for separating the string into three segments. The second segments on any two identified chromosomes are switched. The crossover rate is 0.9 in this paper.

Mutation: The mutation rate is set to the value of 0.0001 in this paper for avoiding a local optimum.

Reproduction: Elitist strategy is employed to select a portion of the strings with better evaluation function values. The roulette wheel approach [16] is also used for selecting the rest of the strings to make sure that the number of a new generation is the same as that of the initial population. Only the selected chromosomes with better evaluation function values are allowed to crossover/mutate for further evolution.

Detailed information related to GA can be referred to [16].

B. Penalty Functions

There are several approaches for the determination of independent variables. The straightforward approach is to consider all PG_{ij} and M_{ij} as the independent variables. The advantage for this treatment is that the feasibility is not required to be verified. The chromosomes (individuals) generated from the reproduction, crossover and mutation will be within their limits. Hence, all independent variables will be automatically within the constraints in GA; however, the equality constraints and the state variables (e.g., $S_{v,i}$) may violate the constraints during evolution (generations).

The penalty functions are efficient in dealing with infeasibility and can be considered in GA to enforce the corresponding violated constraints from the infeasible region into the feasible region. These penalty functions are augmented to the original fitness (objective function) to help guide the next generation into the feasible region after detecting the existence of the infeasibility. This paper addresses the approach of different initial weighting coefficients for different constraints and how to use varying weighting coefficients.

The penalty functions for the steam balance constraints, Eqs. (4) and (5), and the power balance constraint, Eq. (6), are as follows:

$$Penalty = \left(\alpha_e \times 2^{\left(N_2/N_1\right)}\right) \times \left(violation\ \ amount\right)^2 \tag{13}$$

where α_e and N_1 are constants and N_2 is an iteration counter. The penalty weighting coefficient is $\alpha_e \times 2^{\left(N_2/N_1\right)}$, where α_e is the constant part and $2^{\left(N_2/N_1\right)}$ is the varying part. The value of α_e for Eqs. (4) and (5) should be larger than that of Eq. (6) because the numerical order for the steam (e.g., 100~200) is larger than that for the power (e.g., 5~10). On the other hand, the iterative solutions are expected to approach optimality first and then feasibility from the viewpoint of optimization theory. Hence, a larger solution space including the infeasible region is preferred initially for searching to avoid a local optimum and ensure a global optimum. This can be achieved by controlling the varying part $2^{\left(N_2/N_1\right)}$. Initially, N_2 is smaller than N_1 and the penalty weighting is inefficient. Under this condition, only the original objective function in Eq. (3) is addressed in the evaluation function. When N_2 is equal to N_1, the penalty functions start to be addressed in the evaluation function.

C. Lagrangian and Lagrange Multipliers

This paper adopts the Lagrangian as the new evaluation function. Equation (14) is the Lagrangian without the penalty functions for simplification:

$$\begin{aligned} L = &\sum_{i=1}^{I} UCS_i \sum_{j=1}^{J_i} H_{bij} + \sum_{i=1}^{I} WCT \times PG_i - \\ &\lambda_1 \left[\sum_{i=1}^{I} \left(\sum_{j=1}^{J_i} PG_{ij} - P_{LD,i} \right) - P_w \right] - \\ &\sum_{i=1}^{I} \lambda_{2i} \left[\sum_{j=1}^{J_i} M_{ij} - S_{HPPS,i} - \sum_{j=1}^{J} \frac{1}{w_i} \times H_{gij} - \frac{S_{v,i}}{(1+R_i)} \right] - \\ &\sum_{i=1}^{I} \lambda_{3i} \left[\sum_{j=1}^{J_i} \frac{1}{w_i} \times H_{gij} + S_{v,i} - S_{LDMP,i} \right] \end{aligned} \quad (14)$$

where λ_1, λ_{2i}, and λ_{3i} are Lagrange multipliers. If optimum is attained, $S_{v,i} = S_{LDMP,i} - \sum_{j=1}^{J_i} \frac{1}{w_i} \times H_{gij}$ from Eq. (5). Therefore, Eq. (14) can be simplified to be Eq. (15):

$$\begin{aligned} L = &\sum_{i=1}^{I} UCS_i \sum_{j=1}^{J_i} H_{bij} + \sum_{i=1}^{I} WCT \times PG_i - \\ &\lambda_1 \left[\sum_{i=1}^{I} \left(\sum_{j=1}^{J_i} PG_{ij} - P_{LD,i} \right) - P_w \right] - \\ &\sum_{i=1}^{I} \lambda_{2i} \left[\sum_{j=1}^{J_i} M_{ij} - S_{HPPS,i} - \left(\frac{R_i}{1+R_i} \right) \left(\sum_{j=1}^{J_i} \frac{1}{w_i} \times H_{gij} \right) - \frac{S_{LDMP,i}}{(1+R_i)} \right] \end{aligned} \quad (15)$$

The first derivatives of Eq. (15) with respect to PG_{ij} and M_{ij} should be zero in order to attain the optimum. Hence one can find that

$$\lambda_{2i} = UCS_i \left(2 b_{ij2} M_{ij} + b_{ij1} \right) \quad (16)$$

$$\lambda_1 = WCT + \lambda_{2i} \left(\frac{R_i}{1+R_i} \right) \left[\frac{1}{w_i} \left(2 t_{ij2} PG_{ij} + t_{ij1} \right) \right] \quad (17)$$

$$, i = 1,2,...,I \text{, } j = 1,2,...,J_i$$

In this paper, a negative Lagrangian was defined as the new fitness function in the GA. The proposed method searches for the values of M_{ij} and PG_{ij} for maximizing the fitness function.

D. Virtual Lagrange Multipliers

Theoretically, if optimal M_{ij} and PG_{ij} are within the constraints, Eqs. (7) and (8), each turbine steam M_{ij} at bus i should have the same incremental cost λ_{2i} and each generation PG_{ij} in the system should have identical incremental cost λ_1. Once one of the M_{ij} (PG_{ij}) is bounded to its limits, λ_{2i} (λ_1) will not be equal for the turbine steam (generator) i. In other words, Eqs. (16) and (17) are valid for only optimal M_{ij} and PG_{ij} within the constraints.

Based on the above discussion, a virtual λ_1^* is defined as a virtual multiplier and given in the following: For a given PG_{ij} from GA, λ_1 is obtained from Eq. (17). Because all λ_1's resulting from all PG_{ij}, $i=1,2,3,\ldots I$, $j=1,2,\ldots,J_i$, won't be identical, the virtual λ_1^* is given by the average of all λ_1's. For the same reason, a virtual λ_{2i}^* is obtained. Once the virtual λ_1^* and λ_{2i}^* are obtained, the state variables λ_1 and λ_{2i} are penalized to be λ_1^* and λ_{2i}^*, respectively, for the next iterations. However, it is unnecessary for λ_1 and λ_{2i} to converge to λ_1^* and λ_{2i}^*, respectively. This treatment will help increase convergence speed.

V. SIMULATION RESULTS

In this paper, the IEEE 30- and 118-bus systems were used as examples to show the applicability of the proposed method. In each IEEE system, suppose that there are 2 cogeneration systems at 2 different buses. Each cogeneration system has 5 cogenerators/boilers and has the same set of enthalpy functions. Tables 1~4 illustrate the cogeneration system data. The string length of each gene variable, population size, crossover rate and mutation rate are 32 bit, 200, 0.9 and 0.0001, respectively.

TABLE 1 COEFFICIENTS OF ENTHALPY FUNCTIONS FOR BOILERS

Coeff. / Boiler	b_{ij3}	b_{ij2}	b_{ij1}	b_{ij0}
Unit 1	2.13E-05	-0.0066	3.441	-20.08
Unit 2	-9.64E-04	0.2533	-17.60	516.8
Unit 3	7.56E-04	-0.2334	25.33	-706.0
Unit 4	-3.13E-05	0.0094	1.665	26.77
Unit 5	6.08E-06	-0.0028	2.731	-14.18

TABLE 2 COEFFICIENTS OF ENTHALPY FUNCTIONS FOR TURBINES

Coeff. / Turbine	t_{ij3}	t_{ij2}	t_{ij1}	t_{ij0}
Unit 1	0.0231	-0.461	7.300	-0.0743
Unit 2	0.03272	-0.5064	5.959	-0.0143
Unit 3	0.11645	-1.5486	9.319	-0.0076
Unit 4	0.04925	-0.7323	6.961	-0.0079
Unit 5	0.02324	-0.3778	5.539	-0.0115

TABLE 3 OPERATION LIMITS FOR STEAMS

Limits / Boiler	Lower Limit (MBTU)	Upper Limit (MBTU)
Unit 1	68	237.5
Unit 2	52	120
Unit 3	60	237.5
Unit 4	52	200
Unit 5	127	250

TABLE 4 OPERATION LIMITS FOR MW GENERATION

Limits / Generators	Lower Limit (MW)	Upper Limit (MW)
Unit 1	4.1	15
Unit 2	4.9	15
Unit 3	4.4	15
Unit 4	4.6	15
Unit 5	4.9	15

A. IEEE 30-bus System

Figure 2 shows the one-line diagram for the IEEE 30-bus system. In the IEEE 30-bus system, the cogeneration plants are assumed at buses 8 and 11 while the buyers are at buses 21 (13.5 MW) and 30 (7.5 MW). The coefficients of the enthalpy functions and the operation limits for these 2 cogeneration systems are identical, as shown in Tables 1~4. The wheeling rate is 0.092 $/kWh. Other cogeneration system information is provided in Table 5. Table 6 shows the optimal solution obtained by two methods: without (approach 1) and with (approach 2) penalizing Lagrange multipliers. The symbols M_i and P_i denote the steam and generation at the i-th boiler and generator, respectively. It can be found that approach 2 took more CPU time/iterations but obtained more optimal solution.

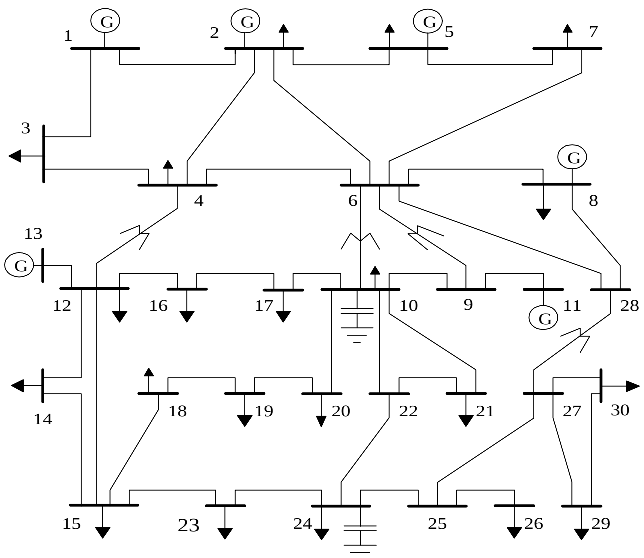

Figure 2 One-line Diagram for the IEEE 30-bus System.

TABLE 5 TWO COGENERATION SYSTEMS AT BUSES 8 AND 11FOR IEEE 30-BUS SYSTEM

	Plant #1	Plant #2
Unit Number	5	5
Location	Bus 8	Bus 11
UCS_i ($/ MBTU)	157.12	157.12
$S_{HPPS,i}$ (MBTU)	113	113
$S_{LDMP,i}$ (MBTU)	635	656
Internal Loads(MW)	25	25
$S_{v,i}^{Min}$ (MBTU)	0	0
$S_{v,i}^{Max}$(MBTU)	200	200
w_i (MBTU/T)	0.315395	0.315395
R_i	11.54%	11.54%

B. IEEE 118-bus System

Suppose that 2 cogeneration systems are located at buses 8 and 10. The coefficients of the enthalpy functions and the operation limits for these 2 cogeneration systems are identical as shown in Tables 1~4. Other operation data for these 2 cogeneration systems are illustrated in Table 7. The buyers at buses 28, 58 and 86 consume 17, 12 and 21 MW, respectively.

Table 8 illustrates the solutions for Approaches 1 and 2. Approach 2 took more CPU time and more iterations but obtained more optimal solution.

TABLE 6 SOLUTIONS WITH/WITHOUT PENALIZING LAMBDAS FOR IEEE 30 BUS SYSTEM

	Approach 1		**Approach 2**	
	Plant #1	Plant #2	Plant #1	Plant #2
M_1	140.07	109.93	111.9	103.98
M_2	63.72	64.1	57.07	64.12
M_3	124.3	132.47	124.5	131.29
M_4	152.39	200	199.86	199.98
M_5	249.91	247.68	242.53	250
Total steam (MBTU)	730.39	754.18	735.86	749.37
Valve steam (MBTU)	170.16	143.16	117.16	189.70
P_1	4.697	4.345	5.19	6.421
P_2	6.047	9.445	10.267	7.172
P_3	7.142	6.497	6.679	5.711
P_4	8.104	6.549	8.0	8.467
P_5	7.719	10.449	7.37	5.723
Total MW	33.709	37.285	37.506	33.494
CPU time	5 min 32 sec		11 min 55 sec	
iterations	916		2256	
Cost ($/h)	590094.13		584621.2	

TABLE 7 TWO COGENERATION SYSTEMS AT BUSES 8 AND 10 FOR IEEE 118-BUS SYSTEM

	Plant #1	Plant #2
Unit Number	5	5
Location	Bus 8	Bus 10
UCS_i ($/ MBTU)	157.12	157.12
$S_{HPPS,i}$ (MBTU)	125	113
$S_{LDMP,i}$ (MBTU)	535	656
Internal Loads(MW)	10	15
$S_{v,i}^{Min}$ (MBTU)	0	0
$S_{v,i}^{Max}$(MBTU)	200	200
w_i (MBTU/T)	0.315395	0.315395
R_i	11.54%	11.54%

TABLE 8 SOLUTIONS WITH/WITHOUT PENALIZING LAMBDAS FOR IEEE 118-BUS SYSTEM

Unit	Approach 1		Approach 2	
	Plant #1	Plant #2	Plant #1	Plant #2
M_1	151.61	140.87	107.72	108.95
M_2	64.87	71.16	64.63	62.87
M_3	126.88	129.21	129.41	130.97
M_4	69.91	200	199.98	200
M_5	246.69	211.27	157.63	250
Total Steam (MBTU)	659.96	752.51	659.37	752.79
Valve Steam (MBTU)	0.4	159.47	6.03	156.6
P_1	7.666	5.026	5.86	6.413
P_2	6.778	7.352	7.397	8.034
P_3	6.572	7.329	6.94	5.649
P_4	7.146	6.535	8.204	7.147
P_5	10.684	9.902	10.17	9.176
Total MW	38.846	36.144	38.571	36.419
CPU time	6 min 26 sec		6 min 47 sec	
iterations	1090		1677	
Cost ($/h)	598501.3		592431.3	

C. Investigation of GA Parameters

Tables 9-14 show the convergence performance for the IEEE 30-bus system, considering different GA parameters, including penalty weight, N_2/N_1, encoding bit number, population size, crossover rate, and mutation rate. For testing a GA parameter, the other parameters are set to the same values. The description related to other parameters for testing will be ignored due to the space of the paper.

From the Tables 9-14, it can be summarized as follows:

(1) The penalty weight for the steam should be greater than that for the real power.

(2) A proper N_2/N_1 ratio will help improve convergence.

(3) A proper bit length will improve convergence; a small number may cause divergence or slow convergence due to precision while a large number will result in more CPU time.

(4) The population size, crossover rate and mutation rate should be coordinated one another to attain an optimal solution.

TABLE 9 DIFFERENT PENALTY WEIGHTS FOR CONVERGENCE PERFORMANCE

Penalty Weight	α_e=1 for both MW and MBTU	α_e=1 for MW，α_e=10 for MBTU
CPU time	7 min 05 sec	4 min 0 sec
Iterations	1681	1026

TABLE 10 DIFFERENT N_2/N_1 FOR CONVERGENCE PERFORMANCE

N_2/N_1	10	50	70
CPU time	15 min 0 sec	2 min 15 sec	2 min 43 sec
Iterations	3653	534	658

TABLE 11 DIFFERENT BIT LENGTHS FOR CONVERGENCE PERFORMANCE

Bits	8	16	32
CPU time	15 min 0 sec	5 min 11 sec	5 min 37 sec
Iterations	3760	1271	1316

TABLE 12 DIFFERENT POPULATION SIZES FOR CONVERGENCE PERFORMANCE

Populations	50	200	500
CPU time	3 min 44 sec	3 min 35 sec	10 min 16 sec
Iterations	1836	932	1370

Table 13 Different Crossover Rate for Convergence Performance

Crossover rate	0.3	0.6	0.9
CPU time	2 min 33 sec	8 min 35 sec	4 min 48 sec
Iterations	470	1974	1236

TABLE 14 DIFFERENT MUTATION RATE FOR CONVERGENCE PERFORMANCE

Mutation rate	0.5	0.01	0.0001
CPU time	11 min 24 sec	6 min 50 sec	2 min 54 sec
Iterations	3002	1780	741

VI. CONCLUSIONS

A new approach based on GA was proposed for the economic dispatch involving multiple cogeneration plants and multiple buyers. The dispatchers in the cogeneration company tend to dispatch MW from all generators in different cogeneration systems at discriminated buses to their buyers through the physical bilateral contracts.

The steam and MW generation were encoded and the feasibility in GA was ensured. Two virtual Lagrange multipliers were proposed for enforcing the steam and MW balance equations to optimality. Different GA parameters were also studied. The simulation results for the IEEE 30- and 118-bus systems show the applicability of the proposed method.

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