Compromising Price and Security in the Short-Term Planning of Modern Power Systems

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Abstract— **One of the most challenging problems for operator in power system, in both regulated and deregulated environment is security in operation. With using regulated structure, separating various sectors to generation, transmission, and distribution, system operators are seeking for more benefit. Each entity has offered its desired prices to the power market. Independent system operator who is responsible for maintaining security interacts directly with market operator. Considering modern power and competitive system in which demands including price parameter are issued by consumer, the compromising between security and price should be considered. This article tends to accomplish this approach.**

Keywords— Competitive Market, Social Welfare, Bender Decomposition, Prevention and Modification Approach

I. INTRODUCTION

One of the most eminent cases in short-term planning is unit commitment in which the number of units and their product rate per hour are determined by an optimization program. The way of determination of units in the system and the rate of their productions are estimated by utilizing of mixed integer programs that binary variables "0" and "1" stand for units in a system and continuous variable is representative of product level in units that must confirm the productivity constraints and security.

Solving methods for unit commitment so far offered, can be divided in to three general species, including classical, heuristic, and compound. In more recent years, using heuristic methods on unit commitment such as Genetic algorithm, Simulated Annealing, Expert system, and Fuzzy systems have been considerably increased. As a problem increasingly grows more complex, along with regarding Security Constrained Unit Commitment (SCUC), the use of decomposition methods, particularly the method of Bender decomposition is more beneficial [3-4], and acquired results formulated in Bender form, give more appropriate responses [5].

The recent developments in restructured electric power systems provide an opportunity for electricity market participants, such as GENCOs, TRANSCOs, and DISCOs, to exercise least-cost or profit-based operations. However, the system security is still the most important aspect of the power system operation, which cannot be overlooked in the Standard Market Design (SMD) [1].

In this environment, the GENCOs propose their bidding to maximizing their revenue and in the other side of the power market; DISCOs are trying to supply their demands by minimum cost and the ISO is supervising market clearing using the SCUC software and finally, the rate and winning amounts of each participant would be announced. Indeed, GENCOs and DISCOs compete in order to contribute in power market. Generation scheduling in a power system considers network security constraints and system's reliability indices. Hence, economic operation of the network is in the second preference.

The traditional SCUC-SCOPF solution is an open-loop two-stage process. If SCOPF is unable to get a feasible solution based on the unit commitment at the first stage, additional security measures will have to be called upon. For instance, the system operator may be allowed to use heuristic methods to adjust unit commitment when SCOPF cannot obtain a satisfactory solution. However, such heuristic strategies will depend on the operator's experience and may not represent the least-cost solution. In this paper, a closed-loop approach is presented for solving contingency dispatch based on SCUC.

The proposed model is a closed-loop and iterative two-stage process which consists of a modified UC and SCOPF modules. Because of considering the elasticity for load in this model, the SCOPF is not confronting with a constant load as a constraint for each hour. Indeed, considering the elastic load causes the SCOPF process can obtain feasible solution for each contingency. In short, the load shedding (LS) process, like UC and SCOPF, is a matter of economic subject. In this model, DISCOs can offer their load curtailment cost to contribute in SCOPF problem too.

Solving methods of unit commitment can be divided into three species: classical ones, which are suboptimal algorithms based on priority list and equal incremental operating cost [2]; optimization ones, such as Lagrangian Relaxation (LR) [3]

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dynamic programming [4]; intelligent searching ones, which use various intelligent techniques [5]. The first sort can solve the problem quickly, but only give suboptimal results, and from the point of view of optimization theory, they aren't precise. The second sort of algorithms is based on rigorous mathematical model, but there is dimension disaster in dynamic programming, and modeling conditions are very critical in such algorithms. In this paper, a linearalizing approach is implemented to prevent dynamic programming disadvantages. The third sort of algorithm requires mathematically a less complex model but is more time consuming.

The method is used in this paper based on Benders dual decomposition theory. In this method coupling constraints involving all units are considered in the primal solution stage, local unit constraints are considered separately for each unit in the dual optimization stage, the solution settles down through iteration between the two stages. Since problem is non-convex, there will be duality gap between the primal values and the dual values, that is to say, the optimality of the result is conditional on the character of the problem. If the number of units to be committed is larger, the optimality is satisfactory [6].

II. UNIT COMMITMENT FORMULATION IN COMPETITIVE POWER MARKET

The statement of unit commitment formulation in competitive power market is mathematically different from conventional one. In fact, the presence of mathematical model of social-welfare in competitive market plays a significant role. Moreover, the style and type of confronting with this problem is distinctive from other economical systems i.e.; the form of supply and demand function and also the way of their expression are comparatively different. It means that with increasing prices, the rate of demand will decreasingly reduce. In the case of supply function, increase in production leads to cost rising [6].

In this situation, objective function maximizes social welfare which is illustrated in Fig. 1 by maximizing the gray area. To extend the surface in objective function, in this model, maximum supply load term is also added to other economical system models to achieve the supplied load ratio from point A to B.

For unit commitment modeling in a competitive power market, hourly aggregated supply and demand functions should be crossed to achieve settlement point of the market.

In deregulated power systems, a social welfare-based objective function should be applied. Equ.1 shows this objective function. Since Maximization of social welfare is the objective of optimization, a model like economical models is used. In order to finding settlement point of market, bid function of suppliers should be sorted in an ascending manner first. Fig. 1 shows one of these files.

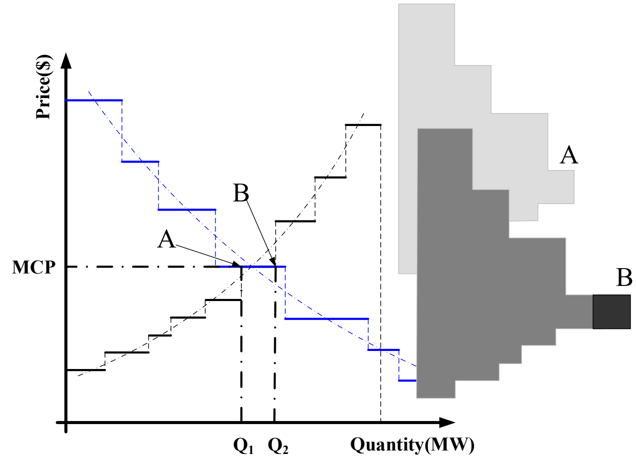

Fig.1. Market clearing in restructured power system subject to maximizing social welfare

$$MAX \; [(Bid * Demand - Offer * Supply) + Demand] \qquad (1)$$

From the prospect of imaging, achieving the settling point of the market will occur if the area between the supply curve and the demand curve becomes maximal. Fig. 1 shows it clearly. In formulation of this model, there is another term which is added to the objective function and provides the maximization of supplied load. So the amount of load is considered in the objective function. Consideration of the two first elements will lead to point “A” as market settling point and consideration of the third one will change it to point “B”.

In this part the UC problem is formulated based on social welfare maximization approach. The objective function of social-welfare based UC model is introduced in (2) and other constraints of UC problem in restructured power system are follows.

The cost function was described by a quadratic or linear piecewise function. The hourly UC constraints listed below include the system power balance (3), system spinning and operating reserve requirements (4), (5), net generation and demand (6), (7), unit generation and reserve limits (8) ramping up/down limits (9), (10). Additional system-wide constraints such as fuel constraints and emission limits are excluded in this formulation for representing the market interdependencies only.

$$MAX \begin{bmatrix} \sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{k=1}^{NK}\sum_{t=1}^{NT}[C_d(i,j,k,t)P_d(i,j,k,t)-C_g(i,j,k,t)P_g(i,j,k,t)] \\ +\sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{t=1}^{NT}P_D(i,j,t)-\sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{t=1}^{NT}SU(i,j,t)-\sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{t=1}^{NT}SD(i,j,t) \end{bmatrix} \qquad (2)$$

$S.T.:$

$$\sum_{i=1}^{NB}\sum_{j=1}^{NU}P_S(i,j,t)*I(i,j,t)=\sum_{i=1}^{NB}\sum_{j=1}^{NU}P_D(i,j,t)*J(i,j,t)+P_{L,t}$$
$$(t=1,\ldots,NT) \qquad (3)$$

$$\sum_{i=1}^{NB}\sum_{j=1}^{NU} R_S(i,j,t)*I(i,j,t) \geq R_{S,t} \qquad (t=1,...,NT) \qquad (4)$$

$$\sum_{i=1}^{NB}\sum_{j=1}^{NU} R_O(i,j,t)*I(i,j,t) \geq R_{O,t} \qquad (t=1,...,NT) \qquad (5)$$

$$P_S(i,j,t) = \sum_{k=1}^{NK} P_g(i,j,k,t)$$
$$(i=1,...,NB),(j=1,...,NU),(k=1,...,NK),(t=1,...,NT) \qquad (6)$$

$$P_D(i,j,t) = \sum_{k=1}^{NK} P_d(i,j,k,t)$$
$$(i=1,...,NB),(j=1,...,NU),(k=1,...,NK),(t=1,...,NT) \qquad (7)$$

$$P_{i,j,\min} * I(i,j,t) \leq P_S(i,j,t) + R(i,j,t) \leq P_{i,j,\max} * I(i,j,t)$$
$$(i=1,...,NB),(j=1,...,NU),(k=1,...,NK),(t=1,...,NT) \qquad (8)$$

$$P_S(i,j,t) - P_S(i,j,t-1) \leq$$
$$[1-I(i,j,t)][1-I(i,j,t-1)]UR_{i,j} + [I(i,j,t)][1-I(i,j,t)]P_{i,j,\min}$$
$$(i=1,...,NB),(j=1,...,NU),(t=1,...,NT) \qquad (9)$$

$$P_S(i,j,t-1) - P_S(i,j,t) \leq$$
$$[1-I(i,j,t-1)][1-I(i,j,t)]DR_{i,j} + I(i,j,t-1)[1-I(i,j,t)]P_{i,j,\min}$$
$$(i=1,...,NB),(j=1,...,NU),(t=1,...,NT) \qquad (10)$$

III. THE STATEMENT OF SOCIAL WELFARE IN A COMPETITIVE MARKET

To accomplish social welfare, each unit offers hourly price in the form of figure 1 to ISO. From the supply side's viewpoint, this offer is based on special assessment of market condition, uncertainty, competition condition, and so on.

On the other side, consumers propose their bids based on a desired function, along with considering economic issues and energy management. Acceptance done by each section in power market implied every section's satisfaction [7].

The objective function has been defined as follows:

$$MAX \left[\begin{array}{l} \sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{k=1}^{NK}\sum_{t=1}^{NT} [C_d(i,j,k,t)P_d(i,j,k,t) \\ \qquad -C_g(i,j,k,t)P_g(i,j,k,t)] + \\ \sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{t=1}^{NT} P_D(i,j,t) - \sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{t=1}^{NT} SU(i,j,t) \\ -\sum_{i=1}^{NB}\sum_{j=1}^{NU}\sum_{t=1}^{NT} SD(i,j,t) \end{array} \right] \qquad (11)$$

Where NT and NK indicate the number of hours and the number of steps respectively, with ten steps in Iran energy market. Moreover, NU indicates the number of the generation units in a power system that can offer independent suggestions, and NB is representative for the number of buses in system. In the intended objective function stated based on social welfare optimization, Cd and Cg are respectively, consumer bid steps and supply offer steps; Pd and Pg show the demand and generation that in this respect their multiplication and accumulated hours are taken in to account. The subtracted amount from objective function is due to the cost of units Startup and Shut down cost that must be considered; another term is accumulated Pg that should be optimized in following manner.

In the competitive power market same as conventional one; there is a balance constraint between production and consumption. Despite that, in the competitive market, demand is not fixed and fluctuates comparatively to the price this constraint is defined as follows:

PD(i,j,t) and *PS(i,j,t)* represent the won product level of every player in k step. *J(i,j,t)* and *I(i,j,t)* are binary variables that state market accepted steps against production and consumption offers. In competitive power market like uncompetitive one, the ramp rate of generation units and certain operation appropriate with hourly load rate are considered. Moreover, allowed limitation constraint in unit load production, the constraint of increase and decrease in production, and also the constraint relevant to minimum time off and on in units are the same in both competitive and uncompetitive market. Since these are technical constraints that don't differ in competitive market problem modeling.

IV. OPTIMAL POWER FLOW PROBLEM CONSIDERING SECURITY CONSTRAINTS

One of the most important issues for operators in operation in both regulated environment and modern power systems is security in steady state and meeting likely contingencies. According to energy system operator, economical operation is ranked in the second order in comparison with security one. The operation conditions of power system in confronting with probable contingencies have significant effect on state of power system in the interconnected power. The power that may be continuous and in a very short time interval, but it leads to a thorough blackout in power system; and hence, several political, social, and economical problems have been brought up.

This is important to note that in occurrence a contingency, if planned condition related to fixed state in optimal generation level can not reach to new stable equilibrium, the security system would be dramatically threatened. To solve the problem, the optimal power flow, considering security constraints (SCOPF) including probable contingencies, is used. So, (SCOPF) program with such an approach will remove in some extent the problems and will challenge existed regulated OPF.

The first step, in security constrained optimal power flow program is to calculate the unit hourly dispatch. This program dispatches energy economically in respect to likely contingencies by means of utilizing pre and post contingency criteria. In the economic dispatch program, minimization of operation cost, or in this paper approach, social welfare maximization for steady-state and any contingencies are considered. In proposed model constraints of the modified unit commitment facing with existing conditions are considered.

In operating of modern power system, a set of preventive operations must be selected for likely contingency management to compromise between safe and economic operation in power system. Since in the economic dispatch program considering preventive conditions is rather conservative, and it increases the total operation cost of the system. Accordingly, two various situations have been considered:

1) For likely contingencies that have the feasibility of system control that may benefit of modifying operations.

2) Likely contingencies with no feasibility of system control may use preventive operation while considering economical operation and system security either.

V. IMPROVEMENT OF MODIFIED APPROACH IN SCOPF

The traditional SCOPF program views the relevant problems very strictly; thus, operation costs of a system have been increased. One of the most significant objectives in modern power systems is to minimize operation cost and to increase consumer's welfare. So, the extra cost opposed on a system must be as much as possible minimized, and the security system must be kept as acceptable as possible level simultaneously.

The aim of representing an improved modifying corrective approach is development of operation allowed area comparatively with traditional state; then this state involves the maximum use of controlling equipment.

The energy system, in meeting likely contingencies if an appropriate control operation is not used, may encounter with voltage collapse or extra continuous energy arranged in transmission lines, consequently, their outage by protective system that ultimately leads to a thorough black out in the hole system. Therefore, some constraints for preventing the emergence of such unpleasant situations in energy system are considered. The offered approach has been stated in the following manner.

The proposed approach utilizes Banders decomposition algorithm to solve the main problem of OPF; also, it, in sub-problem issue, examines the ratio of system controllability against k-th event and system security against voltage collapse as well as frequent over loading. This objective function is as follow:

$$\begin{aligned} &Min \quad f_0(x_0,u_0) \\ &subject\ to: \\ &\qquad g_0(x_0,u_0)=0 \\ &\qquad h_0(x_0,u_0)\le h^{\max} \end{aligned} \tag{12}$$

Where:

f_0 : Cost function of control operation and system operation

x_0 : The vector of state variables in energy system

u_0 : The vector of control variables in energy system

p_k : The amount of energy system loading in k likely contingency

$\Delta_k^{\max}$: Maximum permitted change in control parameters in k-th likely contingency

And the controllability sub-problem is stated in following manner:

$$\begin{aligned} &Min \quad \sum_{m\in M} \varepsilon_m \\ &subject\ to: \\ &\qquad g_m(x_m,u_m)=0 \qquad m=1,2,...c \\ &\qquad h_m(x_m,u_m)\le h^{\max} \qquad m=1,2,...c \\ &\qquad \left|u_m-u_0^*\right|-\varepsilon_m\le \Delta_k^{\max} \qquad m=1,2,...c \end{aligned} \tag{13}$$

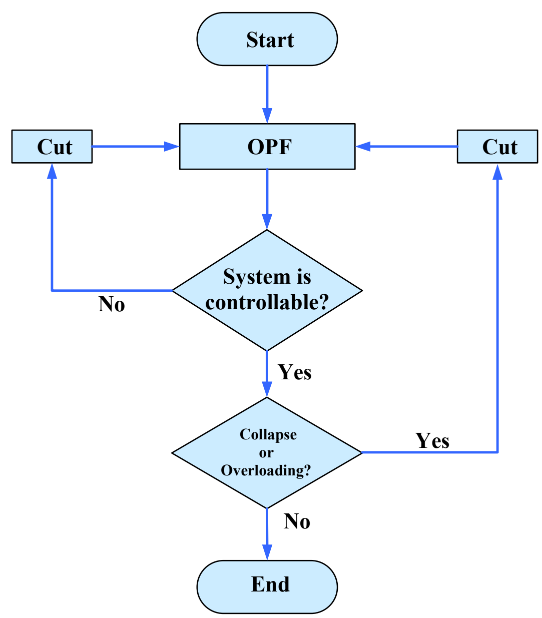

Fig. 2. Benders Decomposition Flowchart

In this objective function, minimizing of total slack control variables that may also be total weighted is considered. In this area, if the amount equals to zero, it means that that the available modified control is capable of retrieving system from likely contingency to normal conditions.

The other sub-problem is concerned with examining voltage collapse and cascaded overloading caused by line emersion immediately after contingency occurrence; this issue is expressed as follows:

$$\begin{aligned} & Min \quad \sum_{m \in M} \omega_m \\ & subject\ to: \\ & \quad g_m^0(x_m^0, u_0 + \omega_m) = 0 \qquad m = 1,2,...c \\ & \quad h_m^0(x_m^0, u_0 + \omega_m) \le p_k h^{\max} \quad m = 1,2,...c \end{aligned} \tag{14}$$

Where, ω_k is allowed amount of change in preventive control operation; the physical concept of this issue is stated below. This is assumed that when a contingency occurs, no controlling system performs; accordingly, one of the following situations may happen:

1. Some constraints are violated; however, it is not accompanied by voltage breakdown and cascaded overloading
2. Critical voltage fall made by under voltage protection system
3. Voltage collapse
4. Cascaded overloads that may lead to system lines outage caused by protection system.

VI. CASE STUDY (PEAK HOUR SURVEY)

To examine elaborately the proposed approach in this article, the researchers have studied (ICSOPF) at peak hour based on table (1). The intended system that is IEEE 6-bus RBTS referenced as [13] has been studied.

Optimal load dispatch program, bound with improved corrective approach (ICSCOPF) is represented and formulated in section 5. This case study has been represented to assess the offered approach and to compare its results with traditional

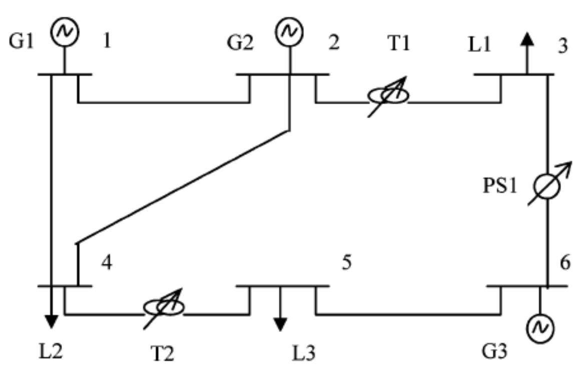

Fig. 3. IEEE 6-bus RBTS Single Line Diagram

SCOPF. This is assumed that the only controlling parameter is the change in unit production level. The limitation for allowed voltage for all buses is (0.9-1.1 p.u); this amount for line L1 is 200 MW and for the rest ones are 100 MW. For calculating the limitation of allowed change in existing controlling parameter, the ramp rate is used in production level, and required time is used in changing load re-dispatching. For example, if the ramp rate in production level is 0.5 and required time for modifying re-dispatching is 1 minute, the allowed limitation will be($\Delta = 0.5 \times 1 = 0.5$) which goes through three scenarios. The first scenario states situation that system is capable of passing critical situation. The second scenario refers to the condition that is accompanied by voltage collapse, and finally the third scenario has been considered to illustrate cascaded overload. Optimal power flow result, regardless of security constraints at peak hour is calculated as $ 3533.48.

Scenario 1: In this situation, there is probability of outage of each line; the limitation of allowed voltage is (0.9-1.1 p.u), and loading in turbulent conditions is 1.4 times as much as normal system allows. The required time for load re-dispatching is regarded 12 minutes that in facing with likely contingencies, the conditions are in a way that no constraints violate and possible response is achievable.

Scenario 2 (voltage collapse): In this scenario, for all lines, except line L3, there is the possibility of outage in a system; allowed voltage limit in this scenario is (0.8-1.1 p.u), and loading in turbulent conditions is 2.0 times as much as normal system allows. The required time for load re-dispatching is 72 minutes (the time is considered to guarantee voltage collapse conditions). Outage of line L1, the condition is susceptible for voltage collapse that causes opposed cost on a system. Therefore, in this situation, in loop corresponding to examining collapse or cascaded overload in intended sub-problem, the required cut is produced, and it promotes the production level in unit (2) up to 45.31 MW and 40.47 MW by unit (3); hence it reduces the unit production rate which is, in turn, resulted in increasing operation cost. Although increasing in modifying process time in this state is economically more useful than traditional one, it increases the voltage collapse risk.

Scenario (3) Cascaded Overload: In this state, there is also the possibility of outage for each line; allowed voltage limitation is similarly (0.9-1.1 p.u), and loading in turbulent condition is 1.2 time as much as normal state in a system allows. The required time for load re-dispatching is considered 24 minutes. The outage of line L1 causes serious overloading on line L2; then the cascaded outage of the remaining lines would be protective due to protection system. In this case, production levels in units(2) and (3) are respectively 39.12 MW and 41.97 MW that in confronting such condition, the required cut produced and the production level of these units promoted up to 48.52 MW and 47.54 MW respectively, so this action prevents the overloading.

Fig. 4 illustrates the issue of both the offered approach results and traditional one result. It should be noted that horizontal and vertical axis indicates the production level in unit (2) and (3) respectively. With considering the clarity of ramp rate in a system, the remaining load, the cheapest unit, is provided by unit (1). In this figure, the production unit area determined by traditional (SCOPF) has relatively high production in units (2) and (3), so the operation cost of a system is higher than what is determined by other scenarios.

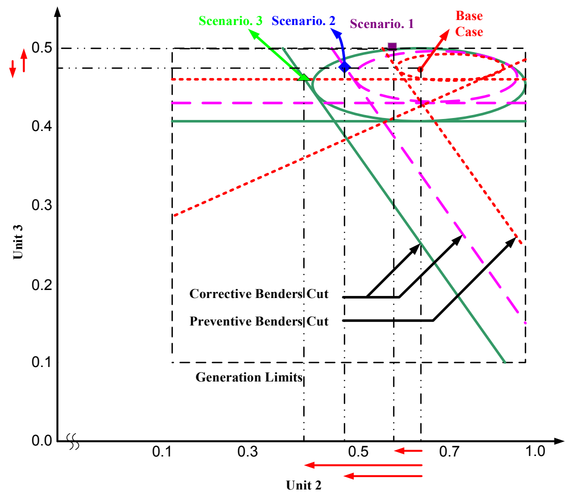

Fig. 4. produced cuts in corrective and preventive operation and various scenarios results

Operation points of a system in traditional and base case are highlighted by numbers and in various scenarios as well. In defined scenarios, with considering allowed conditions for modifying, there is the possibility of movement in unit production optimal level in the way that opposed cost on a system has been decreased, and security has been remained as acceptable as possible.

VII. CONCLUSION

This article aims at formulating and modeling the issue of dispatching power units in the competitive power markets. In modern power system, market players compete with each other, and independent operator in a system is responsible for maintaining the system security. Then, the operator should design and implement a mechanism in which maximum available control equipment is used to satisfy subscribers with receiving or delivering energy with the highest quality and certainty. In operation, based on the proposed approach, by compromising between security and cost issue, it is feasible to decrease cost while having the maximum ability in energy commitment.

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Table 1: Production Unit and Consumption Rate Information

Bus Number	c (MBtu/MW^{2}h)	b (MBtu/MWh)	a (MBtu)	Pgmax	Pgmin	Qgmax	Qgmin	Ramp Rate	PL	QL
1	0.0004	13.51	176.95	220	100	68	-32	80	-	-
2	0.001	32.63	129.97	100	10	59.5	-16	50	-	-
3	-	-	-	-	-	-	-	-	65	27.6
4	-	-	-	-	-	-	-	-	65	23.8
5	-	-	-	-	-	-	-	-	89.7	35.3
6	0.005	17.69	137.41	50	10	42.5	-16	20	-	-