Effects of Interruptible Load on Decision Making of a Distribution Company in Competitive Environments

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***Abstract*: The main goal of this paper is to present a new day-ahead energy acquisition model for a distribution company (Disco) in a competitive electricity market environment with interruptible load (IL). The work formulates the Disco energy acquisition model as a bilevel optimization problem with some real considerations, and then studies and designs a genetic algorithm (GA) of this optimization problem too. In order to achieve this goal, a novel two-step procedure is proposed. At the first step, a real model for an industrial interruptible load is introduced, and it is shown that Interruptible load model can affects on the problem modeling and solving. At the second step, Disco energy acquisition program is formulated and solved with this real model. As a result, this paper shows energy acquisition programming model with ILs, and considering real assumptions. The introduced method shows a good performance of problem modeling and solving algorithm both in terms of solution quality and computational results. A case study is carried out considering a test system with some assumptions. Results show the general applicability of the proposed model, with potential cost saving for the Disco.**

***Keywords*: Distribution company, Interruptible load, Electricity market, bilevel optimization**

1. INTRODUCTION

1.1 Motivation

In a deregulated electricity market environment, and unlike the traditional vertical utility structure, both economic and technical decisions are treated with the same level of importance and are usually handled simultaneously in the same time frame. Nevertheless, the restructuring process of the energy sector has stimulated the introduction of new agents and products, and the unbundling of traditional Disco into technical and commercial tasks. [1] Disco usually buys energy from the wholesale market to meet the requirement of its end customers. However, a Disco will have more choices to acquire energy if it possesses interruptible loads (ILs). ILs can be used by Disco to improve its market response capabilities, and accordingly change the passive position of it in the market. Real or physically based model and formulation for industrial loads (as IL) has considerable effects on solution quality and computational results of the problem.

1.2 Literature Review

So far, IL services have attracted significant attention from both academia and industry. The existing research broadly falls into two main categories. A major research problem of IL services is to design appropriate incentive rate structures for customers to participant voluntarily in to the IL programs. In [2] and [3], optimal incentive-rate structures are designed for IL contracts using mechanism-design theory. Another category of IL research focuses on evaluating the influences of IL services on the whole market. Impact of IL on the price volatility is proposed in [4]. In [5] it is constrained that IL can provide price spikes and not any proposed for IL. IL contracts have been widely practiced in many countries through their reserve markets. According to North America Electricity Reliability Council (NERC), interruptible load management (ILM) is recognized as one of the contingency reserve services [6]. A Disco energy acquisition market model with DGs and ILs is presented in [7] under a market structure based on pool and bilateral contracts. The energy acquisition model in [7] is a static single period model. In [8] a multiperiod energy acquisition model for a distribution company with DG and IL is introduced. However, the energy acquisition model in [8] is assumes some unreal assumptions such as quadratic form of cost functions (both of DGs and ILs), considering only one type of ILs, considering only one type IL contract (fixed for all IL types), that doesn't consider impact of real situations, avoiding constraints that link successive hours, etc.

This paper develops a multiperiod energy acquisition model for a Disco with multiple options including:

- Interruptible load with low price compensation before supply unavailability, that is independent of power supply unavailability.
- Interruptible load with high price compensation after supply unavailability that is performed only after actual power supply unavailability.
- Real interruptible load model.
- And, Wholesale market purchase.

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1.3 Approach and Contributions

The main aim of this paper is to model interruptible load in the electricity market with real considerations, and developing a multiperiod energy acquisition model for Disco. The focus is to study the roles of ILs in demand side response. Disco with ILs can use this model to increase their flexibilities in energy acquisition, improve the demand side responses, and maximize their benefits. Distribution company acquisition market can be formulated for each time period as a mathematical optimization problem and the resulting problem can be solved using proposed Genetic algorithm bilevel optimization (GABLO). An 8-bus system is employed to illustrate the proposed method and algorithm. The obtained results show by considering real model for IL, traditional approaches do not lead to good results.

1.4 Paper Organization

This paper is organized as follow: market structure is introduced in section 2, Modeling of the IL with real considerations is presented in section 3, Disco Energy acquisition model is described in section 4. Sections 5 and 6 contain solution to the acquisition of Disco and simulation results of test system respectively. Finally, paper summarized and concluded in section 7.

2 STRUCTURE OF ELECTRICITY MARKET

The general structure of the day-ahead market considered in this work is shown in Fig. 1. In this structure Gencos sell energy to the market by bidding into the market.

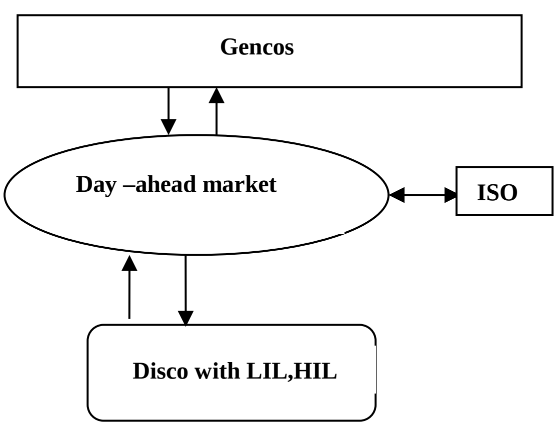

Fig. 1 General market structure

The information Gencos submit to the ISO includes:

- Lower and upper generation limits.
- Bidding price.
- Ramping up/down limits.

Disco buys energy either financial bilateral contracts or in the pool. If necessary, Disco may interrupt low price interruptible loads (LIL) and finally in emergencies, Disco can interrupt high price interruptible loads (HIL).

The information Disco submits to the ISO includes:

- Maximum demand for each hour and at each bus.
- Lower and upper limits of LILs.
- Cost information (or curves) for LILs.

The day-ahead market serves as a platform for Gencos and Disco to sell and buy energy. The objective of Disco is to maximize its profit by determining the amount of ILs and the quantity of the energy purchased from the day-ahead market.

3 MODELING OF THE INDUSTRIAL LOAD AS IL

Since the industrial sector accounts for a significant proportion of the total electricity consumption, and the average electricity consumption per consumer is high, industrial load management (ILM) is an important option for utilities to manage their peak deficit. Industrial loads can be classified into a) controllable loads, that can be subjected to any type of load management actions. b) fixed time loads, that occur at specified time periods and cannot be controlled or subjected to LM actions (e.g., lighting load). Controllable loads can be grouped into process independent loads, process interlocked loads, storage constraint loads and sequential loads. In this section, it is supposed that Cement factory as an IL can participate in power market. Cement production process generally, as shown in Fig.2. Includes 3 main parts:

1. Before the furnace: Grinding, Crushing, Raw mill, homogenizing silos and pre blending bin.
2. Baking system: Furnace and Cooler, Pre heaters.
3. Final system: Rotary Klin, cement silos and dispatching.

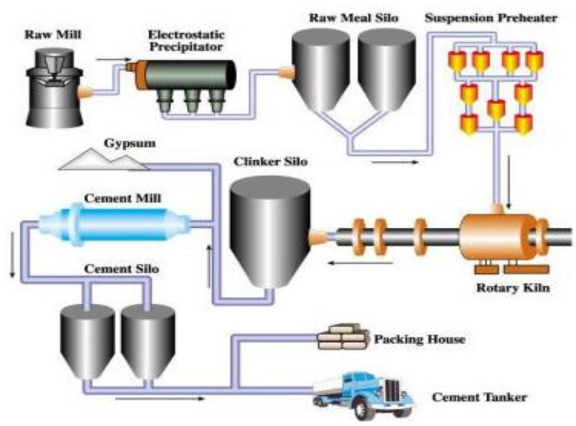

Fig.2 Cement production process

First, Raw materials arrive in part 1 and in this part, convert to a compound powder, in part 2, this compound powder converts to clinker that is bullet form. in part 3, this clinkers convert to final cement and prepare for transporting. Fig.3. shows percent of electrical energy consumption in each of 3 parts. Cement manufacturer can install 2 silos, one for raw materials and another for clinkers and then 3 main parts can be utilized separately. The plant (That is considered in section 6) has a production about 2000t of cements in 3 shifts per day (about 83.3 t/hour), the first 2 shift's load factor is 83% and it is 63% in 3th shift. The storage capacity is expressed as a percentage of the capacity required for one-day operation of the plant at full load.

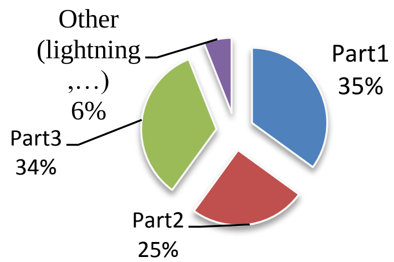

Fig.3 Electrical energy consumption in cement factory

Equipment is grouped into 5 groups based on their controllability. Table 1 shows the plant equipment ratings and details. The plant has an office and lighting load of 74kWh for 2 shifts and 98 kWh for 3 shifts operation in a day. Here formulation is based on discrete time representation of the entire time horizon of interest (here, one day). [9] Events such as start or end of processes are only allowed at the interval boundaries.

$$\sum_{i=1}^{N_I} t_i = 24 \tag{1}$$

The decision variable, shows that a subprocess (Sp) is active in an interval or not.

$$I_{mi} = \begin{cases} 0 & the subprocess m isn't active on the interval i \\ 1 & the subprocess m is active on the interval i \end{cases} \tag{2}$$

Here, we have 4 intervals and 11 subprocesses. t is required to have a specified minimum output (Q) of the final product in the time horizon. Then

$$\sum_{i=1}^{4}\sum_{m=1}^{11}(Pmi * tmi * Imi) \geq Q \tag{3}$$

Process loads with storage space with maximum capacity limitations can be modeled as follows

$$\sum_{i=1}^{T}\left[\sum_{m=1}^{11} P_{mi} * t_{mi} * I_{mi} - \sum_{r=1}^{11} q_{ri} * t_{ri} * I_{ri}\right] \leq Sm \tag{4}$$
$$for\ T = 1\ to\ 4$$

Peak demand limit is an important factor to be considered in load scheduling since many industries are subjected to maximum demand restrictions.

For interval i

$$\sum_{m=1}^{11}\left(\frac{EP_{mi}}{pf_{mi}}\right) * I_{mi} \leq KVA_{mi} \tag{5}$$

Table 1 Plant equipment for LM actions

Description	Production capacity t/hr	Rated KWh/t	Capacity utilization (u)	Efficiency (E)
Sp_1, Sp_2	200	2.4	0.95	0.9
Sp_3	175	28	0.9	0.85
Sp_4, Sp_5, Sp_6	170	14.6	0.9	0.9
Sp_7, Sp_8	165	23.4	0.85	0.75
Sp_9, Sp_{10}	150	43.5	0.9	0.9
Sp_{11}	120	1.1	0.98	0.95

The electrical power input in kW to any machine at any interval i:

$$EP_{mi} = \{(R_m * UF_{mi})/E_{mi}\} * I_{mi} \tag{6}$$

The objective function is the minimization of the electricity cost.

$$min \sum_{i=1}^{4}\sum_{m=1}^{11}[(EP_{mi} * t_{mi} * I_{mi} * C_i) + \{C_{ai} * I_{ai}\} * t_i] \tag{7}$$

$$Ia = \begin{cases} 1 & LM\ action\ correspondng\ to\ C_{ai}\ is\ taking\ place \\ 0 & otherwise \end{cases} \tag{8}$$

The decision variable I_a will be 1 or 0 indicating which machines should be on or off in the corresponding interval. Solving of this optimization problem shows that Cement manufacturer (That is considered in section 6) can participate in IL programs as shown in Fig. 4, t_1 is start time of ILM program.

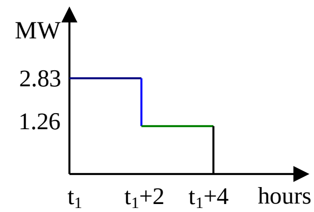

Fig.4 Cement factory (as IL) cost function

4 ACQUISITION MARKET MODELLING

A bilevel optimization formulation is developed wherein the upper sub problem maximizes the Disco's revenue, while the lower sub problem addresses the independent system operator's (ISO's) market clearing by minimizing generation costs and compensation costs for ILs.

4.1 Market Clearing Model

It is assumed that the Independent System Operator (ISO) clear the market using a security-constraint economic dispatch model to minimize the generation costs and compensation costs for LILs, subject to the bids and line flow constraints and LIL constraints too:

$$min \quad [\sum_{i\in GS,k\in TS} C_{G,ik}(p_{G,ik}) + \sum_{i\in SLI,k\in TS} CLIL_{i,k} \tag{9}$$

We assume that a Genco 's bid function is given as

$$\rho_{G,ik}(p_{G,ik}) = 2\alpha_{ik} p_{Gik} + \beta_{ik} \quad i \in GS, k \in TS \tag{10}$$

Accordingly, generation cost function assumed as

$$C_{G,ik}(p_{G,ik}) = (\alpha_{ik} p_{Gik}{}^2 + \beta_{ik} p_{Gik} + \gamma_{ik})u_{ik} \tag{11a}$$

$$u_{ik} = \begin{cases} 0 & unit\ has\ no\ generation \\ 1 & unit\ generates \end{cases} \tag{11b}$$

$$i \in GS, k \in TS$$

Generation capacity constraint is:

$$p_{G,ik}{}^{min} \leq p_{G,ik} \leq p_{G,ik}{}^{max} \quad i \in GS, k \in TS \tag{12}$$

Transmission line flow constraint is:

$$-p_{ij,k}^{\min} \le p_{ij,k} \le p_{ij,k}^{\max} \quad i,j \in BS, k \in TS \tag{13}$$

Ramping Up and Ramping Down constraints are:

$$p_{G,ik} - p_{G,i(k-1)} \le Ru_{G,ik} \quad i \in GS, k \in TS \tag{14}$$

$$p_{G,i(k-1)} - p_{G,ik} \le Rd_{G,ik} \quad i \in GS, k \in TS \tag{15}$$

The Gencos' bidding curves are reached using game theory [10] and neural network method [11], which are based on the predicted load or LMP published on the ISO website. Load balance constraint is:

$$p_{G,ik} - (p_{D,ik}^{\max} - p_{ILL,ik} - p_{ILH,ik}) + \sum_{j=1}^{B(i)} p_{ij,k} = 0$$

$$j \in B(i), i \in B, k \in TS \tag{16}$$

Based on DC power flow equation, the summation of branch voltages for any independent loop should be zero:

$$\sum_{i,j \in BSl, k \in TS} p_{ij,t} x_{ij} = 0 \quad i,j \in BSl, t \in TS \tag{17}$$

The ramping constraints (14) and (15) makes the ISO market clearing model a linked mutiperiod optimization problem and the unit commitment constraint links successive hours.

LIL bids are evaluated along with generation supply bids in day-ahead market. However, to the best of the authors knowledge, no research has been conducted to integrate LIL and HIL methods till now. Because HIL incurs no fees when there are no faults and interruption actions, it is more economical to deal with the capacity faults with small probability and high risk, the compensation risk of HIL is relatively high for capacity faults with higher probability. Obviously, to cope with all kinds of possible capacity faults, both methods are important because they are mutually complementary to each other. The decision variables in this model include $p_{G,ik}$, $p_{ij,k}$ and $p_{LIL,ik}$

4.2 Disco Energy Acquisition Model

The operational aspects of a Disco are considered over a 24-hour demand cycle. The distribution substation transformer represents the main point of connection of the Disco with the bulk power system. High price interruptible load decisions are included at this stage. In this model, the first energy provision component is the power purchased from the grid which is the power imported via the substation and is priced at electricity market price on an hourly basis. We assume that a Disco does not bid its HILs into the day-ahead market but serves its HILs according to estimated LMPs and in faulty situations and, if the load of a Disco (LIL) is interrupted, the Disco will be paid according to LMP and load reduction. Disco returns all the compensation collected from the interruption of load (LIL) to the interrupted end customer and does not benefit from the LIL compensation. A Disco's profit only comes from the difference between the revenue it collects from customers and the cost it pays for the same amount of energy.

Disco profit is:

$$R = \sum_{i \in BD, k \in TS} (\lambda_k (P_{D,ik}^{\max} - P_{LIL,ik} - P_{HIL,ik})) \tag{18}$$

$$- \sum_{i \in BD, k \in TS} \left[\rho_{Dik} . (P_{D,ik}^{\max} - P_{LIL,ik} - P_{HIL,ik}) \right]$$

$$- \sum_{i \in BD, k \in TS} (C_{HIL\,ik})$$

Disco intends to maximize its own profit subject to IL constraints:

$$\max \ R \tag{19a}$$

$$s.t.$$

$$P_{HIL,ik}^{\min} \le P_{HIL,ik} \le P_{HIL,ik}^{\max} \tag{19b}$$

$$and\ constrains\ (12)-(15)$$

The decision variable in this model is $P_{HIL,ik}$

5. SOLOUTION TO THE ACQUISITION OF DISCO

The Disco energy acquisition model (9)–(19) is a bilevel optimization problem, where the upper level represents the decision maker Disco, while the lower level is for the ISO's market clearing. genetic algorithm bilevel optimization (GABLO) is used to solve this model. For the convenience of description, we first introduce the basic idea of GABLO, and then derive the solution approach.

5.1 Bilevel Optimization

Bilevel problem (BP) is one of the basic types of optimization systems in that for the objective function of the upper-level problem is decided by the solution function of the lower-level problem which, generally speaking, is neither linear nor differentiable. Although the objective function and the constraints of the upper sub problem and lower sub problems include linear constraints, the BP is neither continuous everywhere nor convex. When constraints or cost functions are quadratic, the problem can be solved by a large number of mathematical approaches [12], that can be classified into local and global searches, such as gradients descent, Newton's method, conjugate-gradient method, Lagrange multiplier method etc. When constraints or cost functions are linear or discrete or special forms, as shown in Fig.4. convergence or unconvergence and convergence speed reduction can be occurred. 4 possible behaviors of the search trajectory are:

5.a. The trajectory converges without oscillations (when cost functions are quadratic, case 2A in section VI-B);

5.b. The trajectory gradually reduces its oscillations and eventually converges. (When some cost functions are linear, case 2B in section VI-B);

5.c. The trajectory oscillates within some range but never converges. (When cost functions are discrete form, case 2C in section VI-B with cement factory) ;

5.d. The magnitude of oscillations increases, and the trajectory eventually diverges. (When cost functions are discrete form, case 2C in section VI-B without cement factory) ;

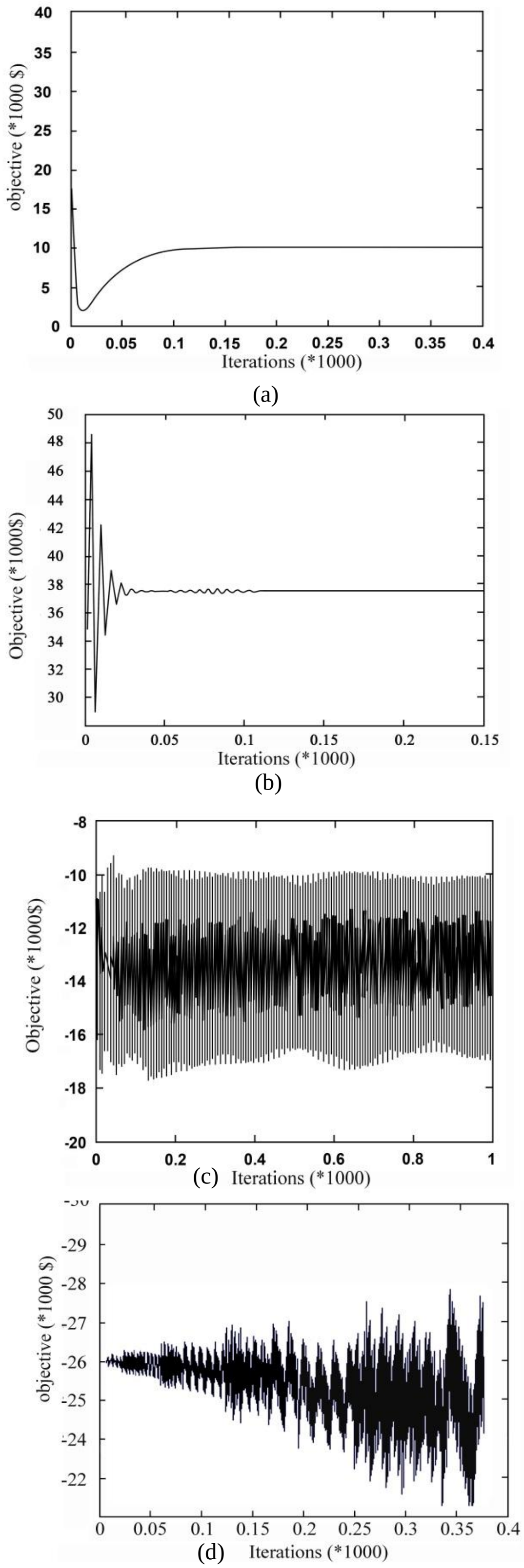

Fig.5 Four possible behaviors of the search trajectory

Obviously, the first two cases are desirable, and the other two are not. This work studies and completes GA of BP that avoids the use of penalty function to deal with the constraints, by changing the randomly generated initial population into an initial population satisfying the constraints in order to improve the ability of the GA to deal with the constraints.[13]

5.2 Using Genetic Algorithm Bilevel Optimization (GABLO)

The solution strategy that named 'genetic algorithm bilevel optimisation (GABLO)' shown in Fig. 6.

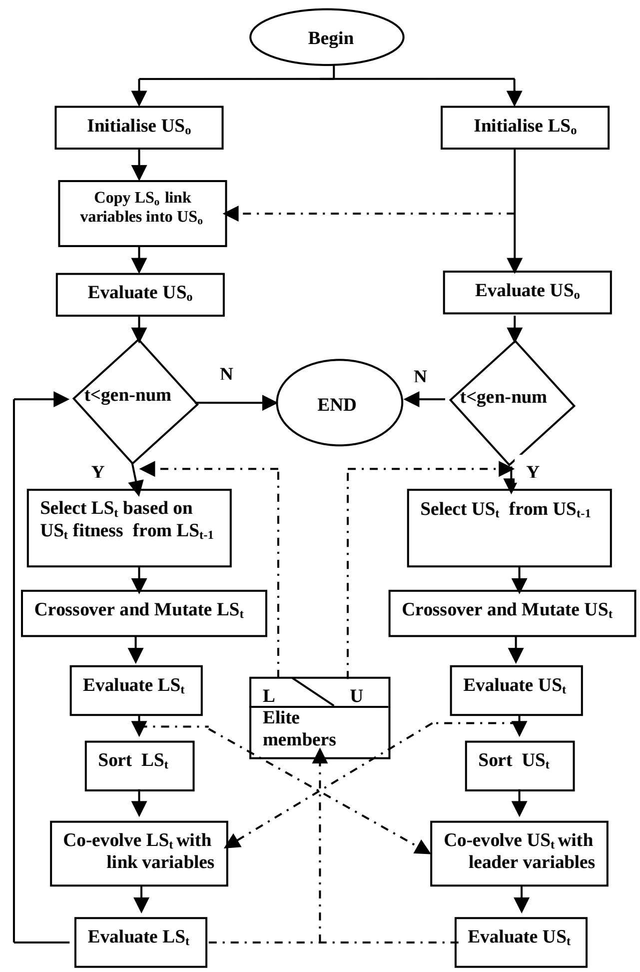

Fig.6 GABLO flowchart

The basic idea solving BP by GA is: firstly, choose the initial population satisfying the constraints, then the lower-level decision maker makes the corresponding optimal reaction and evaluate the individuals according to the fitness function constructed by the feasible degree, until the optimal solution is searched by the genetic operation over and over. After the initialisation of the Upper subproblem population (US), the members represented are copied from the lower subproblem (LS) into the population. Selection, crossover and mutation operations are similar to conventional simple GA technique. The sort operator is designed to give a larger selective preference to the fitter members of the population when the coevolutionary operator is invoked. It sorts the population in descending order of fitness with the fittest member towards the front end of the population and the less fitter members towards the back end of the population. An external elite population is maintained to identify the elite members of both populations after the coevolutionary operator for every generation. Members in the elite population are replaced with the best members from current generation if best members are fitter than the elites.

5.3 Distribution Company Energy Acquisition Model As A GABLO

In this section, Disco energy acquisition model will be formulated as a bilevel optimization problem, the upper subproblem represents Disco's profit problem, and the lower subproblem shows the ISO's market clearing model. The final equilibrium point is the point on that Disco's profit maximized. Lower subproblem (LS problem):

$$min\left[\left(\sum_{i=1}^{Ng}\sum_{k=1}^{24}(\alpha_{ik}\,p_{Gik}{}^{2}+\beta_{ik}\,p_{Gik}+\gamma_{ik})u_{ik}\right)\right. \quad (20a)$$

$$\left.+\left(\sum_{i=1}^{N_{LIL}}\sum_{k=1}^{24}CLIL_{i,k}\right)\right]$$

$$\text{s.t. } p_{G,ik}{}^{\min} \le p_{G,ik} \le p_{G,ik}{}^{\max} \quad (20b)$$

$$-\,p_{ij,k}{}^{\min} \le p_{ij,k} \le p_{ij,k}{}^{\max} \quad (20c)$$

$$p_{G,ik} - p_{G,i(k-1)} \le Ru_{G,ik} \quad (20d)$$

$$p_{G,i(k-1)} - p_{G,ik} \le Rd_{G,ik} \quad (20e)$$

$$\sum_{i=1}^{B}\sum_{j=1}^{B} p_{ij}x_{ij} = 0 \quad (20f)$$

$$P_{LIL,ik}{}^{\min} \le P_{LIL,ik} \le P_{LIL,ik}{}^{\max} \quad (20g)$$

The decision variables in this model include $p_{G,ik}$ and $p_{ij,k}$

Upper subproblem (US problem) :

$$max\left[\left(\sum_{i=1}^{N_D}\sum_{k=1}^{24}(\lambda_k(P_{D,ik}{}^{\max} - P_{LIL,ik} - P_{HIL,ik})\right)\right.$$

$$-\left(\sum_{i=1}^{N_D}\sum_{k=1}^{24}\left[\rho_{Dik}.(P_{D,ik}{}^{\max} - P_{LIL,ik} - P_{HIL,ik})\right]\right) \quad (21)$$

$$\left.-\sum_{i=1}^{N_D}\sum_{k=1}^{24}(C_{HILik})\right]$$

$$s.t.$$

$$P_{HIL,ik}{}^{\min} \le P_{HIL,ik} \le P_{HIL,ik}{}^{\max} \quad (21a)$$

$$and\ constrains(25a)-(25f)$$

(22b)

6. APPLICATION TO A REAL NETWORK

An eight-bus system is used to illustrate the proposed model and solution algorithm.

6.1 System Description

The Disco, named MEDC (Mashhad Electric Distribution Company), is fed by 4 step-down substations from the central interconnected system. MEDC serves nearly 1 million people in the city of mashhad (second big city of Iran). A scheme showing the main features of MEDC and central interconnected system is presented in Fig.7. This system includes 3 Gencos, 6 interruptible loads. In MEDC region, Mashhad cement factory is one of high consumption loads that can participate in IL programs as HIL.

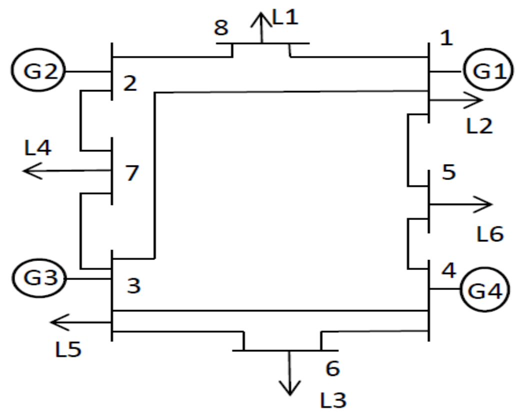

Fig. 7 Real case study

Detailed information on MEDC, IL types, Gencos, and transmition lines are shown in Tables 2-4, which are assumed to be the same for all hours. The demand profile for 24 trading periods is shown in Fig. 8.

Table 2 Gencos Data

Genco	P_{min} (MW)	P_{max} (MW)	α ($/((MW)^{2}h)	β ($/MWh)	γ ($/h)
G1 (Toos)	0	600	0.09	54.76	685
G2 (Shariati)	0	160	0.13	65.57	712
G3 (Mashhad)	0	160	0.21	76.53	840
G4 (Ferdowsi)	0	450	0.07	46.94	650

Table 3 Transmition Lines Data

Line	*From bus*	*To bus*	*X (p.u.)*	*Power limit (MW)*
1	1	3	0.090	34
2	1	5	0.020	120
3	1	8	0.025	40
4	2	7	0.025	20
5	2	8	0.020	32
6	3	4	0.055	12
7	3	6	0.025	120
8	3	7	0.012	16
9	4	5	0.020	23
10	4	6	0.023	32

Table 4 Interruptible load programs in test system

Name	IL type	Minimum Curtailment	Maximum Curtailment	$\kappa 1$ or $\tau 1$	$\kappa 2$ or $\tau 2$	$\kappa 3$ or $\tau 3$	Value Coefficient (ν_i)	Bus
Ghods agriculture industries	HIL	2.5 MW	12 MW up to 4 hours	0.01	12	0.021	0.93	8
Part lastic factory	LIL	1.75 MW	11.2 MW	0	530	0	0.67	5
Fan Generator	LIL	0.5 MW	10 MW	0	350	0	0.91	6
Jahade Nasr	LIL	2.3 MW	14.6 MW	0	240	0	0.74	1
Pegah factory	LIL	1 MW	11.3 MW	0	350	0	0.87	5
Mashad Cement factory	HIL	1.26 MW	2.83 MW	As Fig. 4.				7

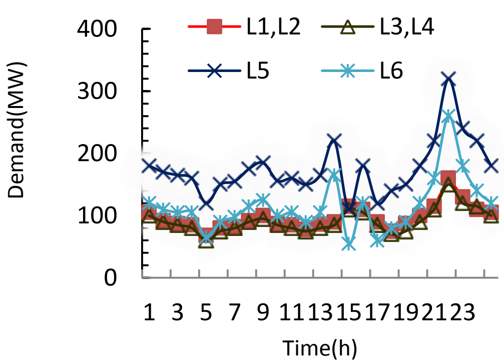

Fig.8 MEDC demand profile

Table 5 Resuls

Case	*2A*	*2B*	*2C*
LIL (MW)	0	32.5	21.2
HIL (MW)	0	0	14.83
DAM (MW)	1185.2	1152.7	1149.17
Total (MW)	1185.2	1185.2	1185.2
Profit ($)	-17217.41	13563.57	21738.64
Cost for Gencos ($/h)	100165.73	974761.27	81235.52
LMP at Bus1 ($/MWh)	25.34	24.39	21.86
LMP at Bus2 ($/MWh)	162.84	92.57	74.61
LMP at Bus3 ($/MWh)	135.42	96.64	82.14
LMP at Bus4 ($/MWh)	32.87	26.31	24.12
LMP at Bus5 ($/MWh)	23.64	22.57	22.01
LMP at Bus6 ($/MWh)	27.46	23.82	20.57
LMP at Bus7 ($/MWh)	125.37	87.23	67.24
LMP at Bus8 ($/MWh)	28.97	29.34	27.21

6.2 COMMENTS

MEDC 8-bus system shown in Fig.7 is used to illustrate proposed model and solution algorithm. In this work it is assumed that:

- price that Disco charges its customers for energy is

$$\lambda = \begin{cases} 50\,\$/MWh \;\; at \;\;\; 6:00-19:00 \\ 70\,\$/MWh \;\; at \;\;\; 19:00-23:00 \\ 30\,\$/MWh \;\; at \;\;\; 23:00-6:00 \end{cases}$$

- All generator's ramping-up and ramping-down rates are $Ru_G = Rd_G = 20$ MW/h (for G2, G3)
  And $Ru_G = Rd_G = 50$ MW/h (for G1, G4)
- Cost functions for some ILs are quadratic or linear:

$$C_{ILL} = \kappa 1 \,.P^2{}_{ILL} + \kappa 2 \,.\nu.P_{\;ILL} + \kappa 3 \quad (23)$$

$$C_{ILH} = \tau 1 \,.P^2{}_{ILH} + \tau 2 \,.\nu.P_{\;ILH} + \tau 3 \quad (24)$$

The strategy of Disco depends on the demand and LMPs of day ahead market. From Fig.8, we can see that demand increases slowly for the hours before 18:00 and after 23:00, therefore the impact of ramping-up and ramping-down limits on LMPs can be ignored and the optimal solutions for those hours don't depend on other hours.

Case 1: considering three continuous periods18:00–19:00–20:00. In this case, ramping limits for some generators are active and flow limits for some lines also are active. Three periods are linked with each other.

1) G3 is an expensive unit compared with G1,G2,G4. Its generation will be as small as possible if ramp limits are not considered. When there is another 1 MW of load increment at Bus 3 in the system, G3's generation increases by more than 1 MW while the generations of other cheap units decrease due to transmission congestion, which leads to high LMPs.

2) However, generation of G3 increases at 18:00 once ramp limits are enforced. When the same 1 MW load increment occurs at Bus 1, G3's generation does not change

at all. Thus, LMPs are lower although ramping limits are active. This also indicates that the decrease of cheaper power or the increase of more expensive power can cause less congestion to a certain extent. Because the LMPs at 18:00 are lower, The Disco would like to purchase more energy from the day ahead market, thus their LIL programs are less than those when no ramping limits are enforced. Ramping limits have smaller impact on the LMPs at 19:00. With the increase of demand and due to ramping-up limits, the LMPs at 20:00 are much higher, so more LILs are utilized in order to maximize Disco's profits. The same analysis can be made to the trading periods 21:00–22:00–23:00, where ramping-down limits are active.

Case 2: this case is to analyze the roles of LIL and HIL when congestion occurs in the system. Ramping limits are not considered in this case. Demands in the system are at their peak with L1,L2=165MW, L3,L4=150MW, L5 =310MW, L6=245MW. Three subcases are considered

2A. Disco has no LIL and HIL;

2B. Disco has LIL but no HIL;

2C. Disco has both HIL and LIL.

The comparisons of Disco's optimal strategiy, Disco's profit, LMPs, cost for Gencos, and IL's costs are shown in Table 5. From Table 5, the following observations can be made.

1) In Case 2A, congestion leads to much high LMPs. Disco's profit is negative since it has no LIL and HIL and can only purchase energy from the day-ahead market with high prices.

2) In Case 2B, Disco would prefer to use LIL when market prices are high. The net demand decreases and LMPs decrease significantly compared to those in Case 2A. It's profit increase accordingly. This means that congestion offers potential incentive to Disco to develop using of LILs.

3) Besides LIL, HIL is a useful resource to mitigate congestion, as shown in Case 2C. When Disco's demand is interrupted, LMPs are lower than those in Case 2A. This means that Disco will be encouraged to sign flexible HIL contracts with the end customers. It should be pointed out that the cost of HIL is usually higher than the cost of LIL. So in general, LIL is more suitable to be used in emergency states. where there are HILs and LILs in the system, the proposed model can help Disco make its energy purchase plan to maximize its profit.

4) When LIL and HIL participate in the competition of day-ahead market (Cases 2B-2C), the ISO pays less money to Gencos, which can restrict Gencos' capabilities of earning more profits by means of capacity withholding and strategic bidding.

7. Conclusion

In this paper, a novel day-ahead energy acquisition programming model for a distribution company was proposed. One of the most important concepts that introduced was considering real assumption for interruptible load modeling. The proposed concept can be employed to gain good understanding of interruptible load modelling. Therefore, it can be useful in studies of the energy acquisition programming for distribution companies. The results that achieved can assistant the market operator and distribution companies to make the best decisions. In this paper it is shown that a Disco can obtain the best mix of energy acquisition from the Gencos and Interruptible loads. Results show increasing in Disco's profit and decreasing in ISO payments to Gencos (decreasing the generation cost). Moreover, the proposed concept could be used with distributed generation units (DG's), in the further researches.

Appendix

The nomenclature is as follows.

K	Index for hours.
i,j	Index for buses.
α,β,γ	Generation bid coefficients.
P_G	Generation awarded to a Genco .
P_G^{min}	Lower limit on bid quantity submitted by a Genco .
P_G^{max}	Upper limit on bid quantity submitted by a Genco .
R_{uG}	Ramping up limit submitted by a Genco.
R_{dG}	Ramping down limit submitted by a Genco.
U	Unit commitement variable.
$P_{i,j}$	Line flow of line i-j.
$P_{i,j}^{min}$	Lower flow limit on line flow of line i-j.
$P_{i,j}^{max}$	Upper flow limit on line flow of line i-j.
$X_{i,j}$	Reactance of line i-j.
N_g	Set of Genco buses.
$P_D^{max`}$	Maximum demand of Disco.
B	Set of all buses.
$B(i)$	Set of buses connected to bus i.
l	Set of independent loops.
BS	Set of all branches.
BSl	Set of branches in independent loop l.
BD	Set of Disco buses.
BLI	Set of LIL buses.
BHI	Set of HIL buses.
GS	Set of Gencos.
TS	Set of hours.
ρ_G	LMP paid to a Genco.

ρ_D Electricity market price (LMP paid by Disco).

P_D Net demand of Disco.

P_{LIL} LIL granted to Disco.

P_{LIL}^{min} Lower limit of LIL.

P_{LIL}^{max} Upper limit of LIL.

ν Value Coefficient of LIL.

$\kappa_1, \kappa_2, \kappa_3$ LIL cost coefficient.

P_{HIL} HIL curtailed by Disco.

P_{HIL}^{min} Lower limit of HIL.

P_{HIL}^{max} Upper limit of HIL.

τ_1, τ_2, τ_3 HIL cost coefficient.

λ Disco's retail energy rate.

N_I Set of time intervals.

t Time interval.

I Subprocess binary decision variable

P_{mi} Production rate of machine m in the interval i.

q_{mi} Output of machine m in the interval i

E_{mi} efficiency of the machine or device.

UF_{mi} utilization factor of the device.

KVA_{mi} maximum demand limit.

EP_{mi} electrical power input in kW.

R_{mi} rated capacity of the machine/device in kW.

pf_{mi} power factor of the machine for the interval.

S Storage at the end of a subprocess.

C_i cost of energy for the interval i.

C_{ai} additional cost of LM actions for the interval i.

REFERENCES

[1] P. M. Sotkiewicz and J. M. Vignolo, "Nodal pricing for distribution networks: efficient pricing for efficiency enhancing DG," *IEEE Transactions on Power Systems*, Vol. 21, May 2006, pp. 1013-1014.

[2] L. A. Tuan and K. Bhattacharya, "Competitive framework for procurement of interruptible load services," *IEEE Transactions on Power Systems*, vol. 18, May 2003, pp. 889-897.

[3] M. Yousefi Ramandi, K. Afshar, and N. Bigdeli,"Unit commitment considering position of interruptible load in energy and reserve simultaneous market", *International Journal on Technical and Physical Problems of Engineering*, June 2014, vol. 2, pp. 1–10.

[4] Omid Ziaee, Ashkan Rahimi-Kian and Mohsen Parsa-Moghadam, "An Optimal Pricing Policy for Interruptible Load Contracts in Power Markets: A Case Study for Iran ", *Energy and Power*: 2011; 1(1)

[5] D. Lawrence and B. Neenan, "The status of demand response in New York" , *IEEE Power Eng. Soc. General Meeting proc.*, 2009, vol. 4, pp. 2270–2274.

[6] NERC Operating Policy-IO on Interconnected Operations Services, Draft-3.1, February 2010.

[7] Haghighat H. and Kennedy S.W., "A Bilevel Approach to Operational Decision Making of a Distribution Company in Competitive Environments" *IEEE Trans. Power Syst*., vol. 20, pp. 1797–1807, Nov. 2012.

[8] Haiying Li., Yuzeng Li and Zuyi Li, "A multi period energy acquisition model for distribution company with distribution generation and interruptible load" *IEEE Trans Power Syst.*, vol. 22, pp. 588–596, Nov. 2007.

[9] S. Ashok and Rangan Banerjee,"An Optimization Mode for Industrial Load Management", IEEE Trans Power Syst., vol. 16, pp. 879–883, Nov. 2001.

[10] Fahrioglu, M. and Alvarado F.L, "Using utility information to calibrate customer demand management behavior models", *IEEE Trans*., 2001, PWRS-16, (2), pp. 317–322

[11] B. Hobbs, C. Metzler and J. Pang, "Strategic gaming analysis for electric power systems: An MPEC approach" *IEEE Trans. Power Syst.*, vol. 15, no. 2, pp. 638–645, May 2000.

[12] Jahan, M.S. and Amjady, N., "Solution of large-scale security constrained optimal power flow by a new bi-level optimisation approach based on enhanced gravitational search algorithm," *Generation, Transmission & Distribution, IET*, Vol.:7 pp. 1481 – 1491, December 2013 .

[13] Yin, Y., "Genetic Algorithm based approach for bilevel programming models", *Journal of Transportation Engineering*, 2000. **126**(2): p. 115-120.

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