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Joint Operation of Several Types of Power Plants to Increasing Net Profit in Deregulated Power Market

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Abstract: This study proposes joint operation of power plant and electric energy storage plant in order to maximizing overall profit in a restructured electricity market. The goal is investigating the coupling efficiency on profit increment considering various intensities of power plant's fuel constraint. In order to reach this goal, the amount of overall profits of fuel-constrained power plant, battery plant and their coupling are first calculated in a specific time interval. Then, the coupling efficiency is determined using incremental profit rate. Having an appropriate strategy to calculate this parameter is essential. Hence, a comprehensive approach to self-schedule of individual and coupled plants is developed. This comprehensive self-scheduling approach is therefore formulated and solved as a Mixed Integer Non-linear Programming (MINLP) problem. Numerical results for a case study are discussed.

Key words: Battery plant, day-ahead market, power plant, self-scheduling problem

INTRODUCTION

The deregulation of the electric-power industry has created energy markets in which power producers compete with each other to sell the amount of power that maximizes their profit. Power producers participate in the power pool trading aim to maximize their profit in Day-Ahead (DA) energy and spinning reserve markets. Each power producer must submit his production bids in the energy and the spinning reserve markets, based on the forecasted Market Clearing-prices (MCPs) and other considerations such as fuel constraint. Hence, developing an appropriate strategy for Self-Scheduling of a price-taker power producer is very crucial to maximize its potential profit (Shahidehpour *et al.*, 2002). In the technical literature, there are several contributions dealing with the self-scheduling problem of individual power producers such as thermal power plants, hydro power plants and electric energy storage plants (Conejo *et al*., 2002; Arroyo and Conejo, 2002; Arroyo, 2000; Fleten *et al*., 2008; Lu *et al.*, 2004; Deb, 2000).

Electric Energy Storage is the capability of storing electricity or energy to produce electricity and releasing it for using during other periods when energy delivering is more beneficial (Walwalker *et al*., 2007). In a vertically integrated system, electric energy storage plant is used to reduce the fuel cost of power plants through discharging in peak load and then charging at light-load periods. Under a cost-based dispatch, it is not unusual for an electric energy storage plant to be always in either the discharging (selling) or the charging (purchasing) mode. In a competitive electricity market, power producers can use electric energy storage plants to coordinate with their thermal power plants to increase their overall profit.

In this study, the coupling impact of fuel-constrained power plant and energy storage plant on the overall profit increment is addressed. In addition, the coupling efficiency is analyzed considering various intensities of power plant's fuel constraint. In order to achieve these goals, it is essential to have an appropriate strategy for self-scheduling of coupled plant. Hence, a comprehensive approach to self-schedule of coupled plant is developed in this paper. The coupling concept of power plant and energy storage plant is shown in Fig. 1.

As it can be seen in Fig. 1, the fuel-constrained power plant can transfer energy to the electric energy storage as well as participating in the energy and the spinning reserve markets. Consequently, electric energy storage plant can be charged through fuel-constrained power plant as well as energy purchasing from energy market. The electric energy storage plant can participate in the energy and the spinning reserve markets when it operates in its selling mode. In purchasing mode, the electric energy storage plant purchases electricity but it can be committed for spinning reserve, because it can readily reduce its purchasing power and consequently reduce the overall system load. The electric energy storage plant can only be

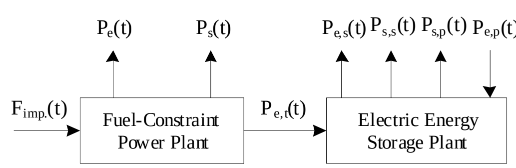

Fig. 1: The coupling concept of power plant and energy storage plant

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participated in the spinning reserve market when it is in its off-line mode.

In this study, NaS battery (Natrium Sulfur battery) is considered as an emerging electric energy storage technology, because of its enough technological maturation and less environmental impacts.

The fuel constraint modeling: Basically, the power plant fuel constraint could be modeled by two appropriate cases. In the first case, the quantity of fuel reservoir is assumed to be fixed. Hence, the fuel constraint is modeled considering lower and upper limits for the amount of fuel that could be consumed in each hour. This case has been used in (Yamin and Shahidehpour, 2004).

In the second case, a limited additional fuel is deployed for each hour as well as the fixed fuel reservoir quantity. In other words, in addition to the fuel that is stored in the beginning of concerned time interval, a limited amount of fuel could be imported to the reservoir in each hour. This case is more difficult and more comprehensive to model the fuel constraint than the first case. In this paper, the second case is modeled.

NAS battery:

Principles and features: Principles of NaS battery system were first introduced by Ford Motor Company, USA, in 1966. Since then, active researches have been conducted for the development and application of these batteries (Ohtaka and Iwamoto, 2002; Ohtaka *et al*.,2004). The NaS battery has fused sodium as the cathode-active material, and has fused sulfur and sodium polysulfide as the anode-ative material. Moreover, beta alumina is used as a solid electrolyte, which conducts sodium ions selectively.

Characteristics of operation control: For the AC-DC converter device of the NaS battery system, a separately-excited inverter and self-excited inverter (current type and voltage type) have been used. Especially, the voltage type of the self-excited inverter can simultaneously adjust active and reactive powers at high speed, and charge and discharge of leading or lagging currents by reversing the firing angle. Thus, they can contribute to the system operation considerably (Ohtaka and Iwamoto, 2002; Ohtaka *et al*., 2004).

NaS pulse limit: NaS battery can independently control the active and reactive power outputs through the AC-DC converter device. Such a system can instantaneously discharge the power from one to five times as much as the rated capacity, if the capacity of the AC-DC converter device is sufficient. However, NaS battery has an output limit based on the internal temperature, where the feasible discharging times are specified according to this limit which is called NaS pulse limit. Figure 2 shows NaS pulse limit versus the different discharging duration. For instance, the NaS battery plant can discharge 7 h as much as the rated output, 3 h for 1.5 times as much as the rated output, 1 h for 2.6 times and 15 min for 4 times, respectively (Grossmann *et al*., 2003). It is obvious that increment of the NaS pulse factor leads to increase in power loss.

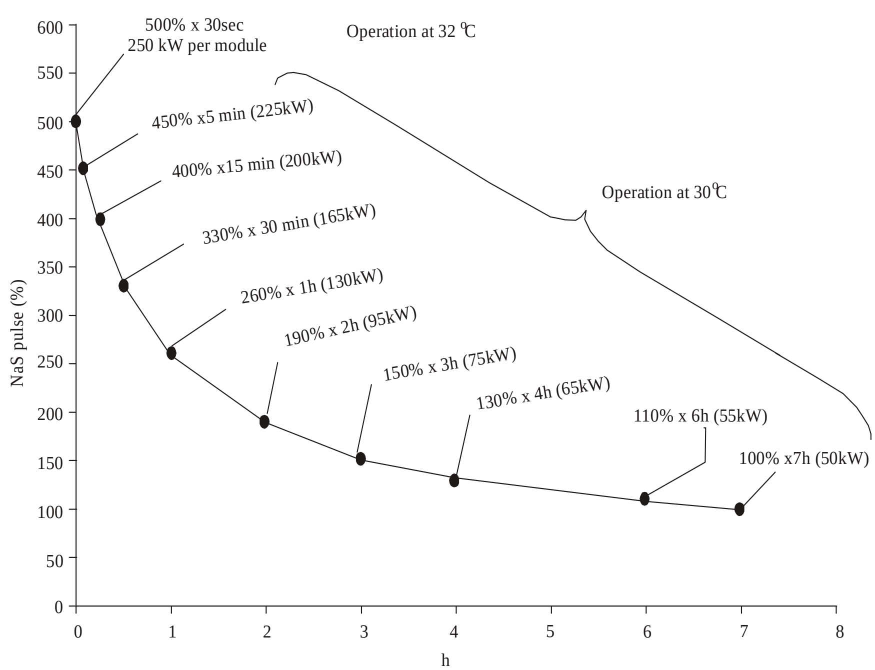

Fig. 2: NaS puls trend versus the different discharge duration

Self-scheduling problem formulation: In order to analyze the efficiency of proposed coupling fuel-constrained plant and NaS battery plant, a comprehensive approach to self-schedule of coupled plant must be developed which is introduced in this section. It should be noted that a horizon of one day is too short to consider the optimal utilization of coupled plant, while a horizon of one month is too long to forecast the prices (Lu *et al*., 2004), hence the approach developed in this paper optimizes the coupled plant on a weekly basis with hourly prices. The analysis will be performed considering the energy and the spinning reserve markets, simultaneously. By assuming the incomes, payments and O&M costs of coupled plant, the objective function of self-scheduling problem over a week can be represented by (1)-(32):

Maximize:

$$\begin{aligned}&\sum_{t=1}^{T}[P_e(t)+P_{e,s}(t)]\lambda_e(t)-\sum_{t=1}^{T}P_{e,p}(t).\lambda_e(t)+\\&\sum_{t=1}^{T}[P_s(t)+P_{s,s}(t)+P_{s,p}(t)]\lambda_s(t)+\\&P_{del}.\sum_{t=1}^{T}[P_s(t)+P_{s,s}(t)+P_{s,p}(t)]\lambda_{spot}(t)\\&-\sum_{t=1}^{T}\left[\lambda_{fixed}+\lambda_{s,up}.y(t)+\lambda_{s,down}.Z(t)\right]\\&-\sum_{t=1}^{T}\lambda_{fuel}(t).F_{imp}(t)\\&-\sum_{t=1}^{T}\left\{A_1+A_2.(P_{e,s}(t)+P_{e,p}(t)+P_{del}.[P_{s,s}(t)-P_{s,p}(t)]\right\}\end{aligned} \quad (1)$$

s.t.

$$\begin{aligned}F_{con}.(t)=u(t).(a_f+b_f.P_{\exp}.(t)\\+c_f.p^2_{\exp}.(t)+y(t).F_{s,up})\end{aligned} \quad (2)$$

$$P_{\exp.}(t)=P_e(t)+P_{e,t}(t)+P_{del.}.P_s(t) \quad (3)$$

$$u(t).P_{\min}\le P_e(t)+P_{e,t}(t)\le u(t).P_{\max} \quad (4)$$

$$0\le P_s(t)\le u(t).P_{s,\max} \quad (5)$$

$$P_e(t)+P_{e,t}(t)+P_s(t)\le u(t).P_{\max} \quad (6)$$

$$u(t).[1-u(t-1)].[P_e(t)+p_{e,t}(t)+P_s(t)]\le SU \quad (7)$$

$$u(t-1).[1-u(t))].[P_e(t-1)+P_{e,t}(t-1)+P_s(t-1)]\le SD \quad (8)$$

$$\begin{aligned}&u(t).u(t-1).[P_e(t)+P_{e,t}(t)+P_s(t)\\&-P_e(t-1)-P_{e,t}(t-1)]\le RU\end{aligned} \quad (9)$$

$$\begin{aligned}&u(t).u(t-1).[P_e(t-1)+P_{e,t}(t-1)\\&+P_s(t-1)-P_e(t)-P_{e,t}(t)]\le RD\end{aligned} \quad (10)$$

$$u(t)-u(t-1)=y(t)-z(t) \quad (11)$$

$$y(t)+\sum_{i=1}^{MU-1}Z(t+i)\le 1 \quad (12)$$

$$y(t)+z(t)\le 1 \quad (13)$$

$$Z(t)+\sum_{i=1}^{MD-1}y(y+i)\le 1 \quad (14)$$

$$F_{res.}(t)=F_{res.}(t-1)+F_{imp.}(t)-F_{con}(t) \quad (15)$$

$$F_{imp,min}<F_{imp}.(t)<F_{imp,max} \quad (16)$$

$$F_{res.}(t)<F_{res,max} \quad (17)$$

$$E_{res.}(t)=\frac{-b_f+\sqrt{b^2-4c_f[a_f-F_{res.}(t)]}}{2c_f} \quad (18)$$

$$u_s(t)<N_{pulse}(t)<2.6.u_s(t) \quad (19)$$

$$0<P_{e,s}(t)<N_{pulse}(t).\ P_{N,max} \quad (20)$$

$$0<P_{e,p}(t)+P_{e,t}(t)<u_p(t).\ P_{N,max} \quad (21)$$

$$0<P_{s,s}(t)<N_{pulse}(t).P_{N,max} \quad (22)$$

$$0<P_{s,p}(t)<u_p(t).\ P_{e,p}(t) \quad (23)$$

$$P_{e,s}(t)+P_{s,s}(t)<N_{pulse}(t).\ P_{N,max} \quad (24)$$

$$P_{N,exp}(t)=P_{e,s}(t)+P_{del}.\ P_{s,s}(t) \quad (25)$$

$$\begin{aligned}d(t)=-3.4497.N^3_{pulse}(t)+21.5962.\\N^2_{pulse}(t)-45.7961.N_{pulse}(t)+34.7117\end{aligned} \quad (26)$$

$$P_{loss}(t)=\frac{7-(N_{pulse}(t)\times d(t))}{d(t)}u_s(t) \quad (27)$$

$$u_s(t)+u_p(t)\le 1 \quad (28)$$

$$\begin{aligned}E(t)=E(t-1)-P_{exp,N}(t)[1+P_{loss}(t)]+\eta\\[P_{del.}P_{s,p}(t)+P_{e,p}(t)+P_{e,t}(t)]\end{aligned} \quad (29)$$

$$E(t)\le E_{max} \quad (30)$$

$$E_{res,end} + E_{end} = \tau.(E_{res,0} + E_0) \quad (31)$$

$$E_{res}(t) + N_{pulse}(t+1).\ E(t) > P_s(t+1) + P_{s,s}(t+1) \quad (32)$$

The first and second terms of (1) represent the revenue and cost of coupled plant resulted from selling and purchasing in energy market, respectively. The revenue of coupled plant due to participation in the spinning reserve market is represented by third term. In addition, the coupled plant owner expects to receive extra income when plant is called to generate in the spinning reserve market. This expected income is shown by fourth term. The fifth term shows the fixed, start-up and shut-down costs of power plant. The sixth term represents the cost of hourly imported fuel to the reservoir of power plant. The O&M costs of NaS battery plant are considered by the seventh term including fixed and variable costs.

It should be noted that (2)-(18) are incorporated with power plant characteristics. Equations (19)-(30) represent the characteristics of NaS battery plant. Also, (31)-(32) are related with coupled plant.

In (2), the amount of fuel expected to be consumed in each hour during the concerned time interval is calculated. The amount of hourly expected power which must be generated by power plant in each hour to response in the energy and the spinning reserve markets and to charge of NaS battery plant is represented by (3). The lower and upper limits of energy and spinning reserve could be produced by power plant are represented by (4)-(6). Eq. (7)-(10) show the constraints of the power plant concern to the start-up ramp limit, the shut-down ramp limit, the ramp-up rate limit and the ramp-down rate limit, respectively. Also, the minimum up time and the minimum down time constraints are applied by (11)-(14). The hourly fuel amount of power plant in the reservoir is calculated by (15). Equation (16) depicts the limits of fuel quantity which can be imported to the reservoir during an hour. The constraint of fuel reservoir capacity is represented by (17). Equation (18) shows the amount of power which can be generated by available reserved fuel.

For participation of NaS battery plant in the hour-based DA market, it is essential that the plant be able to trade at least for one hour, hence according to the Fig. 2, the NaS pulse factor must be less than 2.6. This constraint is applied by (19). In (20)-(21), energy discharging and charging limits of NaS battery in its selling and purchasing modes are shown, respectively. Also, limits of spinning reserve amount that NaS battery can bid in the spinning reserve market in its selling and purchasing modes are represented in (22)-(23), respectively. Equation (24) depicts the limit of energy could be supplied by NaS battery plant in the energy and the spinning reserve markets in its selling mode. Equation (25) calculates the expected power to response in the energy and the spinning reserve markets when NaS battery plant operates in its selling mode. In (26), the NaS pulse trend shown in Fig. 2 is fitted by using a third order polynomial. Also, the power loss versus the different NaS pulse factors is calculated by (27). To eliminate conflict between selling and purchasing modes of NaS battery plant in a specific hour, (28) is considered. Also, (29)-(30) are related to the amount of energy stored in the NaS battery plant. The

The spinning reserve must be ready to deliver in ten minutes; hence according to the considered ramp-up rate limit of power plant, the maximum spinning reserve of power plant is determined as 30 MW. The probability of calling plants for generating energy in the spinning reserve market (Pdel.) is assumed to be 3% (Bury, 1999), Also, the hourly fuel price (λfuel) and adjusting constant (τ) are assumed as 2$/MBtu and 1, respectively.

The following random-based method shown by (33) is used to forecast the hourly spot price. The hours between 9 and 18 are contemplated as the peak period. In amount of energy stored in each hour is calculated by (29). In (30), the limit of energy amount stored in NaS battery plant is presented.

The lower limit of hourly energy stored in power plant and NaS battery plant must be adjusted so that the coupled plant can response to the worst condition from the viewpoint of energy stored level. The worst condition may occur when coupled plant is called to generate in spinning reserve market. To consider this condition, (31) is applied. In addition, in order to reserve enough energy stored in coupled plant for the subsequent week, (32) is contemplated. The parameter τ adjusts the amount of energy that should be stored for the subsequent week. If lower prices for the next week are forecasted, the coupled The optimization problem in (1)-(32) is a Mixed Integer plant owner will choose a low value for τ. This parameter can be varied while energy stored constraints are satisfied.

Non-Linear Programming (MINLP) problem that can be solved by any commercial software. In this paper, it is solved using DICOPT under GAMS.

RESULTS AND DISCUSSION

In this section, the overall weekly profits of power plant, NaS battery plant and their coupling plant are first determined. These results are represented versus various intensities of fuel constraint of power plant and various capacities of NaS battery plant. Next, the amount of overall weekly profit of coupled plant is compared with total overall weekly profits of fuel-constrained power plant and NaS battery plant when they operate separately. In addition, effects of fuel constraint intensity and NaS battery's size on efficiency of coupling are discussed.

The time horizon is considered 168 hours. The assumed forecasted prices for the energy and the spinning

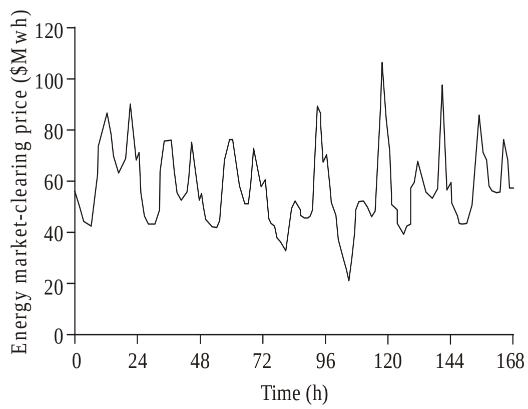

Fig. 3: Hourly forecasted energy market-clearing prices

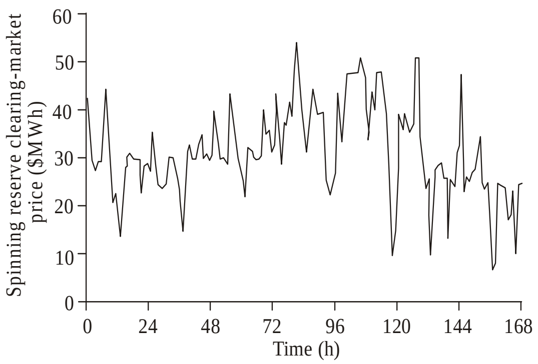

Fig. 4: Hourly forecasted spinning reserve market-clearing prices

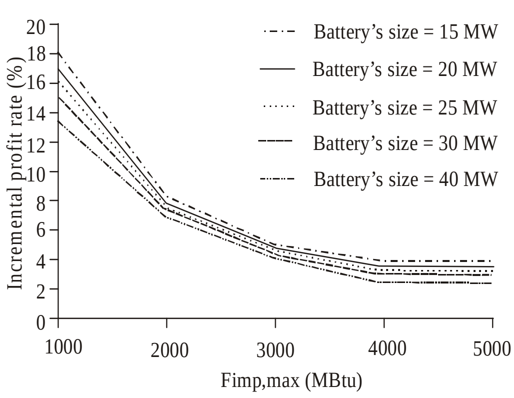

Fig. 5: Incremental profit rates versus various fuel constraints of power plant

reserve are shown in Fig. 3 and 4, respectively. Price data are adopted from electric energy market of Mainland, Spain (Kirby, 2007) with a few adjustments. Also, the relevant data about fuel-constraint power plant and NaS battery plant are presented in Table 1. order to present the spike price in the peak hours, a number of spikes are randomly generated using Frechet distribution.

Table 1: Fixed parameters

P_{min} (MW)	140	$F_{imp,min}$ (MBtu)	0
P_{max} (MW)	350	$F_{s,up}$	500
$P_{s,max}$ (MW)	30	a_f	176.06
SU (MW/h)	250	b_f	10.662
SD (MW/h)	250	c_f	0.0014
RU (MW/h)	180	λ_{fixed} ($)	700
RD (MW/h)	180	$\lambda_{s.up}$ ($/start-up)	80
MU (h)	3	$\lambda_{s.down}$	80
MD (h)	3	η (%)	90
$F_{res,max}$ (MBu)	400000	A1 ($/h)	179.8
F_0 (MBu)	200000	A2 ($/Mwh)	8.48

Table 2: Numerical results

		Overall weekly profit ($)			
$F_{imp,max}$ (MBu)	Battery's size (MW)	NaS battery plant	Fuel-constrained power plant	Coupled plant	Incremental profit rate (%)
1000	15	24723.043	652190.683	801773.688	18.445
	20	71686.068	652190.683	849515.812	17.356
	25	117899.922	652190.683	896866.936	16.462
	30	164334.018	652190.683	944386.729	15.659
	35	207823.868	652190.683	992996.805	15.462
	40	257020.245	652190.683	1038587.363	14.229
	45	300343.323	652190.683	1087234.11	14.141
2000	15	24723.043	1227930.895	1371432.858	9.4822
	20	71686.068	1227930.895	1417700.673	9.086
	25	117899.922	1227930.895	1464542.305	8.82
	30	164334.018	1227930.895	1511717.719	8.579
	35	207823.868	1227930.895	1559087.02	8.59
	40	257020.245	1227930.895	1606222.306	8.166
	45	300343.323	1227930.895	1652334.032	8.117
3000	15	24723.043	1656177.45	1792277.827	6.626
	20	71686.068	1656177.45	1837773.243	6.361
	25	117899.922	1656177.45	1882912.34	6.134
	30	164334.018	1656177.45	1928744.911	5.945
	35	207823.868	1656177.45	1974969.449	5.953
	40	257020.245	1656177.45	2020634.485	5.615
	45	300343.323	1656177.45	2066368.102	5.614
4000	15	24723.043	1873598.864	2003451.078	5.538
	20	71686.068	1873598.864	2046429.847	5.199
	25	117899.922	1873598.864	2089445.983	4.918
	30	164334.018	1873598.864	2132534.868	4.642
	35	207823.868	1873598.864	2175697.352	4.529
	40	257020.245	1873598.864	2219095.681	4.152
	45	300343.323	1873598.864	2262456.909	4.071
5000	15	24723.043	1873598.864	2003447.078	5.537
	20	71686.068	1873598.864	2046444.938	5.2
	25	117899.922	1873598.864	2089455.011	4.918
	30	164334.018	1873598.864	2132525.771	4.641
	35	207823.868	1873598.864	2175724.248	4.53
	40	257020.245	1873598.864	2219073.156	4.151
	45	300343.323	1873598.864	2262431.039	4.07

$$\lambda spot(t) = \begin{cases} (t-\gamma)\lambda_e(t) & 0 \le \gamma \le 0.25 \quad t \in [9,18] \\ (1+\mu)\lambda_e(t) & -0.1 \le \mu \le 0.1 \quad otherwise \end{cases} \tag{33}$$

Numerical results: The results of self-scheduling problem are presented in Table 2. In this table, the amount of overall weekly profit for NaS battery plant, fuel-constrained power plant and their coupling plant is also presented in terms of the various maximum amounts of imported fuel to the power plant's reservoir (Fimp,max) and the various capacities of NaS battery plant (PN,max). Also, the amount of incremental profit rate due to coupling is represented in this table. The amount of incremental profit rate is calculated using (34).

As it can be seen in Table 2 in serious fuel constraint of power plant, the economic merit of coupling appears more obviously. By releasing fuel constraint of power plant, incremental profit rate will decrease and consequently coupling will have a less economic merit. The trends of incremental profit rate decreasing due to releasing of fuel constraint for different capacities of NaS battery are depicted in Fig. 5.

Incremetal profit rate = (Coupled plant profit/NaS battery plant profit+power plant profit − 1)×100 (34)

Also, the numerical results show that utilization of batteries with higher capacities coupled to power plant leads to lower incremental profit rate for a specific fuel constraint. It should be noted that economic analysis of coupling justification and also sizing of battery plant needs more investigations. In order to reach these aims, investment cost of battery and its Internal Rate of Ratio (IRR) should be considered.

CONCLUSION

This study addresses economic analysis of fuel-constrained power plant and NaS battery plant coupling in a restructured electricity market. In order to reach this purpose, self-scheduling problems for fuel-constrained power plant, NaS battery plant and their coupling plant were performed separately. Numerical results show that coupling leads to increase in overall weekly profit which is more remarkable for serious fuel constraints. Economic analysis of coupling justification and also sizing of battery plant needs more investigations such as considering the investment cost of battery and its Internal Rate of Ratio (IRR) which will be included in the future works.

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