Risk-constrained Generation Asset Scheduling for Price-takers in the Electricity Markets

Jianhui Wang
Division of Information and Sciences, Argonne National Laboratory, USA
jianhui.wang@anl.gov

Abstract

A risk-constrained generation asset scheduling model for generation companies (GENCOs) in the electricity markets is proposed in this paper. The model embodies the arbitrage opportunities for GENCOs through an optimization procedure. The risk exposure of GENCOs is managed by explicitly adding the downside risk constraints into the optimization problem. To avoid the inaccuracy of downside risk, the variance of expected profit is calculated to measure the fluctuation of GENCO's profit. The sensitivity of GENCOs' profit to risk is also calculated in the form of Sharpe ratio. The downside risk constraint will keep tightening iteratively until the risk exposure tolerance is satisfied. Consequently the profit and risk will be balanced automatically.

1. Introduction

In competitive electricity markets, GENCOs submit their bids into the energy and ancillary services markets one day before the real time market. The multi-products by units such as energy and ancillary service give the GENCOs opportunities to arbitrage among the various commodities. The existence of fuel market further provides GENCOs with incentives to optimize their assets across different markets.

The classical definition of arbitrage is the transactions utilizing the price discrepancies to make profit without risk. The activity of arbitrage is actually realized by a simultaneous purchase and sale of the same or equivalent commodity with net zero investment and without any risk [1]. But in electricity markets, it is impossible for the GENCOs to realize simultaneous arbitrage during the real time generation because the arbitrage opportunities are constrained by physical unit constraints such as ramp rate, capacities, etc. So it is not practical for them to arbitrage even if there are price discrepancies in the real-time markets as in the normal commodity markets. But for the day-ahead market, the price discrepancies across various markets encourage the GENCOs to maximize their profit by forecasting the future market prices and optimizing their assets.

There are several forms of arbitrages in the deregulated environment. Transactions between energy and ancillary service, between bilateral contracts and the energy market, between gas, power, and emission allowance, between steam and power offer the generation companies more flexible options to pursue larger profit. The concept of generation arbitrage is discussed in [1]. An optimal arbitrage strategy is proposed in [2] and a generation dispatch strategy for price-takers in electricity markets is discussed in [3]. A comparison of solutions to the price-based unit commitment problem is made in [4]. But the previous literature either ignores the risks involved in arbitrages or neglects the multi-arbitrage opportunities.

In this paper, a risk-constrained generation asset management model for GENCOs is proposed. We assume GENCOs always want to pursue the largest profit through arbitrage while forecasting the prices in the generation asset-related markets. For simplicity, we also assume the units of studied GENCOs aggregate in one zone, which results in a uniform locational market clearing price. It should be noted that this model can be extended to GENCOs owning distributed units in different zones with different market clearing prices without invalidity. Based on the forecasted market prices and relevant volatilities, GENCOs can form their price-based self-generation problem as their master optimization problem. The decision variables will be the unit commitment and generation dispatch. The concept of downside risk is used to embody the GENCO's risk preference by adding a shrinking risk constraint into the master problem. To avoid the inaccuracy of downside risk, the variance of expected profit is calculated as the risk tolerance level for GENCOs to describe how fluctuating GENCOs' profit would be even if they bear the downside loss in profit. This iterative optimization will keep proceeding until the variance is lower than GENCO's tolerance. This optimal solution will satisfy GENCOs' risk preference and maximize their profit together. The main mix-integer optimization problem can be solved by current available commercial solvers. The details of the mix-integer problem are discussed in [4].

This paper is organized as follows: Section 2 presents the problem formulation. Section 3 discusses risk management for GENCOs. Section 4 shows a case study. Section 5 concludes the paper.

2. Problem formulation

In this section, various arbitrage opportunities are modeled, which include the arbitrages between fuel and power, between ancillary service and energy, and between bilateral contracts and energy market. All the arbitrage activities are coupled with prevailing physical unit constraints.

As a price-taker in the competitive market, GENCOs have no capability to control the market clearing price. So GENCOs need to forecast the future market prices to optimally schedule their generation asset. Many forecasting techniques such as time-series and artificial neural network [1] have been applied in this area. Here it is assumed that GENCOs' generation can always be accepted by the ISO in the way of choosing proper bidding strategies based on certain price forecasting techniques as the price takers [3].

- Arbitrage between fuel and power

In practice, GENCOs can choose to sell their fuel in storage into the fuel market instead of generate power when the fuel price is high. On the other hand, if the fuel price is low, the GENCOs would buy the fuel from the market to generate more power in the energy market.

As shown in Figure 1, the price curve for transacting the FT type of fuel is generalized to be non-convex [2].

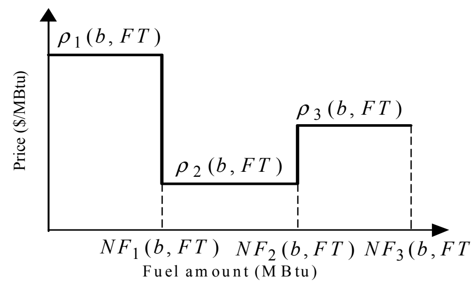

Figure 1 Nonconvex price curve for the FT type fuel

The cost of purchasing the FT type fuel is:

$$F_b(FT) = \sum_{m=1}^{NSB(FT)} [\rho_{f,m}(b,FT) * x_m(b,FT)] \qquad (1)$$

The payoff for selling the FT type fuel is:

$$F_s(FT) = \sum_{m=1}^{NSS(FT)} [\rho_{f,m}(s,FT) * x_m(s,FT)] \qquad (2)$$

$$q_{s,FT} = \sum_{m=1}^{NSS(FT)} x_m(s,FT)$$
$$q_{b,FT} = \sum_{m=1}^{NSB(FT)} x_m(b,FT) \qquad (3)$$

The detailed modeling can be found in [2].

$$Revenue_{fuel} = \sum_{FT=1}^{NFT} (F_s(FT) - F_b(FT)) \qquad (4)$$

- Arbitrage between the ancillary service and energy

Reserves are generally compensated for the capacity price for providing reserve capacity and the spot market energy price once called to generate energy in the real-time. Reserves can be further divided into spinning reserves and non-spinning reserves in terms of response time.

A general case of revenue for supplying energy and ancillary services in the spot market is modeled as follows, in which reserves are assumed to be called in the real time market:

$$Revenue_{reserves} = \sum_{t=1}^{T} (\rho_r^{est}(t) TR(t) + \rho_n^{est}(t) TN(t))$$
(5)

where

$$TR(t) = \sum_{i=1}^{N} R(i,t)$$
$$TN(t) = \sum_{i=1}^{N} [N_{on}(i,t) + N_{off}(i,t)] \qquad \forall t \qquad (6)$$

- Arbitrage between the bilateral contracts and the spot market

An arbitrage opportunity also exists in buying electricity from market to fulfill the bilateral contracts or generate electricity themselves to supply the load. A GENCO can sign contracts with QF (qualify facilities) or load [2].

$$Revenue_{bilateral} = \sum_{L} p_{bilateral}(l) q_{bilateral}(l) \quad (7)$$

where

$$\sum_{i=1}^{N} q(i,t) + \sum_{k \in K} QF_0(k,t) - TP(t) = \sum_{l \in L} q_{bilateral}(l,t) \quad \forall t \quad (8)$$

where positive $TP(t)$ is the generation offered to the market and negative $TP(t)$ is the purchased generation from the market.

- Regular energy sale revenue

Besides the described arbitrage opportunities above, GENCOs can regularly gain profit from their energy sale in the energy market.

$$Revenue = \sum_{t=1}^{T} (p^{est}(t) * TP(t)) \quad (9)$$

- Objective function for the GENCOs

Figure2 depicts the multi-decision problem for GENCOs in their day-ahead scheduling. They can choose to arbitrage in one certain market or choose to arbitrage for all possibilities while the units' physical constraints couple the entire problem.

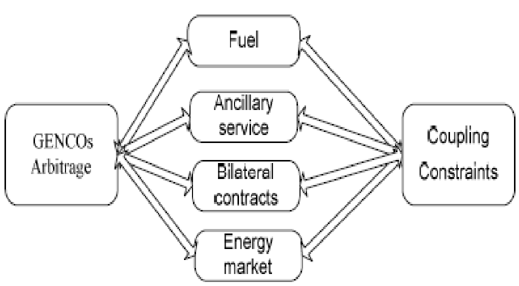

Figure 2 Arbitrage process for GENCOs.

The overall objective considering all the arbitrage activities is formed (10). The total revenue is the summation for various arbitrages. The total cost includes the generation cost and the cost for buying electricity from the market or from the QF if there is bilateral contract arbitrage:

$$Maximize \ \ Profit = \left[\begin{array}{l} Revenue_{fuel} + Revenue_{reserves} \\ + Revenue_{bilateral} + Revenue \\ - \sum_{FT}^{NFT} \sum_{i=1}^{N} \sum_{t=1}^{T} p_{fuel,FT} * C_{i,FT}(q(i,t)) \\ - \sum_{k=1}^{K} \sum_{t=1}^{T} QF_0(k,t) CP(k,t) \end{array} \right] \quad (10)$$

s.t.:

system fuel storage constraint **:**

$$q_{b,FT} - q_{s,FT} + \sum_{i=1}^{N} \sum_{t=1}^{T} C_{i,FT}(q(i,t)) \le S_{FT}$$

unit capacity constraints
unit ramping rate constraints
unit Min/Max on/off time constraints

3. Variance and downside risk

Due to the inaccuracy of price forecasting, there is always risk involved in the arbitrage activities. There are several measures available to describe the risk such as Value at Risk (VaR), Mean-variance analysis, Conditional Value at Risk (CVaR) etc [1, 6, 9]. To explicitly express the GENCO's risk tolerance in the optimization model, the concept of downside risk in [5] is used. An application of the downside risk concept in the supply chain design can be also found in [6]. The downside risk is described as the following:

$$RISK = \begin{cases} Profit^{*} - Profit & if \ \ Profit \le Profit^{*} \\ 0 & if \ \ Profit > Profit^{*} \end{cases} \quad (11)$$

$Profit^{*}$ is the target profit for GENCOs. The downside risk measures the risk that the GENCO cannot meet its target profit goal. If the profit is higher than its target profit, the downside risk is zero. Otherwise, the risk is quantified by the amount of profit that cannot be satisfied.

By explicitly including the downside risk constraint, the GENCO's risk preference is demonstrated in the optimization model. First the profit without risk consideration, $Profit_0$ can be calculated by running the arbitrage model with the forecasted market prices and then the downside risk, $RISK$,can be set, which is calculated as $RISK = Profit_0 - Profit^{*}$ .So the downside risk constraint can be added into the arbitrage model as $Profit - Profit^{*} \le 0.95 * RISK$

at the first iteration with 0.95 as the tightening step.

In practice, GENCOs always want to purse stable profit by controlling the variance of expected profit within certain range. They often have the motive to understand not only how much they can bear to lose but also how fluctuating their profit would be even if they have expected loss. Because the downside risk does not provide the volatility estimation, variance of profit is calculated. It will be shown in the next sections that the tightened downside risk may not guarantee the smaller variance of expected profit, which means lower profits may have even greater risk in terms of variance. High variances of profit will lead to high volatilities of expected profit even though the profit has been restricted by the downside risk constraint. In this sense the downside risk is not enough to measure the risk exposure for utilities.

Because optimizing generation assets such as limited fund, generation units, fuel storage requires forecasting all the prices in these markets, which could become far from accurate, the arbitrage activity depends pretty much on GENCOs' price forecasting accuracy. In the case of inaccurate forecasting, the utilities would rather have simultaneous arbitrage transactions in the spot market than assume the great risk in forecasting activities. This preference can be expressed directly by the risk tolerance in this proposed model. A convergence condition for satisfying GENCO's risk preference as the risk tolerance coefficient β [7] can be set. The β represents the balance between the variance risk and the downside risk. Smaller value of β will be chosen by a conservative GENCO while aggressive GENCOs will increase β values [7]. The choice of β also reflects the GENCOs' confidence for the accuracies of their forecasting techniques. The β at iteration *iter* is calculated as

$$\beta_{iter} = Variance_{iter} / Variance_0 \qquad (12)$$

$Variance_{iter}$ is the variance of profit at this iteration.

Since the energy price in the bilateral contract was fixed prior to arbitrage, the risk in the arbitrage between the bilateral contract and the spot market solely results from the energy price risk. In addition because it is assumed in this paper that the compensation of reserve is based on the energy price and fixed capacity price like some US markets, the associated risk is attributed to the energy price too. So, the actual variance of above risk can be calculated [8]:

$$V^{est} = \frac{1}{N_d}\sum_{\omega=1}^{N_d}(\rho_\omega^{actual} - \rho_\omega^{forecast})(\rho_\omega^{actual} - \rho_\omega^{forecast})^T \qquad (13)$$

Here the V^{est} is the $T \times T$ covariance matrix of energy market price. ρ_ω^{actual} is the actual market prices. $\rho_\omega^{forecast}$ is the forecsted market price. N_d is the number of days for which actual and forecasted prices are available. T is the number of study periods in a day.

To better capture the unique characteristics of electricity prices such as seasonality and volatility, the above equation can be modified with an exponentially weighted moving-average equation as [9]:

$$V^{est} = (1-\alpha)\sum_{\omega=0}^{N_d-1}\alpha^\omega(\rho_{N_d-\omega}^{actual} - \rho_{N_d-\omega}^{forecast})(\rho_{N_d-\omega}^{actual} - \rho_{N_d-\omega}^{forecast})^T \qquad (14)$$

Where α is the exponentially decaying weighting factor and N_d should be bigger than or equal to 24 to ensure the covariance matrix is positive definite.

The total variance is

$$Variance = \left(\begin{array}{l} \sum_{t_1=1}^{T}\sum_{t_2=1}^{T} V^{est}{}_{t_1 t_2} * (TP(t_1) * TP(t_2) \\ + TR(t_1) * TR(t_2) + TN(t_1) * TN(t_2)) \\ + \sum_{FT} V_{fuel,FT} * (\sum_{m=1}^{M} x_{m,FT})^2 \end{array} \right) \qquad (15)$$

Where V_{fuel} is the covariance coefficient of fuel price and it is assumed that fuel price and energy price are uncorrelated and fuel transactions are on a daily basis.

The optimization problem with risk preference consideration is solved by iteratively optimizing the arbitrage model and calculating the total variance until the risk tolerance β_{iter} is lower than the GENCO's preference β_0.

- Step one

Run the arbitrage model without any risk consideration and obtain the *Profit*$_0$ with the forecasted market prices. Then the variance of the profit without risk consideration can be computed as $Variance_0$.

- Step two

According to the results in the step one, GENCO sets its target profit, $Profit^*$,and calculates the downside risk as $RISK = Profit_0 - Profit^*$.

- Step three

The risk constraint is added to the arbitrage model taking the form of

$$Profit - Profit^* \leq 0.95*RISK$$

By optimizing the main problem with the new risk constraint, the variance for the second iteration can be found and β_{iter} as (12) can be calculated. If it is higher than the default tolerance level, we tighten the risk constraint as

$$Profit - Profit^* \leq 0.95*0.95*RISK$$

Then this new constraint will be returned to the arbitrage model and optimize again. The entire iteration will continue until the risk tolerance level is satisfied. The obtained solution will balance the profit requirement of GENCOs and the risk tolerance automatically.

4. Case study

A 54 thermal, 12 combined-cycle，7 hydro and 3 pump-storage units system [2] is taken as the study case. It is assumed the purchase/sale prices are the same for fuel in Table 1. The price for the GENCO's gas in storage is $1/MBtu. The weighted moving-average factor α is assumed to be 0.98. Also, the energy and ancillary services markets are assumed to be cleared hourly while fuel markets are cleared daily in this study. The storage of coal, oil, and gas by the GENCO are 1.8e+6MBtu, 5e+5MBtu, 3.3e+5MBtu, respectively. The case studies are executed on a Pentium-4 3.2GHz personal computer with 1G RAM memory. The commonly available optimizer CPLEX is applied to solve the mixed-integer problem.

Table 1
Market Price Curve for trading Gas

Segment #	From (MBtu)	To (MBtu)	Price ($/MBtu)
1	0	4000	1.20
2	4000	50000	1.10
3	50000	500000	1.15

A. Scheduling without risk consideration

In the first case, GENCOs do not consider the risk in the arbitrage model. The generation asset schedule is shown in Table 2.

Table 2
Generation asset allocation without risk consideration

Hour	Generation	Spinning	Non-spinning
1	808	654.167	0
2	735	594	0
3	927.5	540	0
4	1017.5	540	0
5	1075	550	0
6	1507.83	728.333	0
7	1827.5	728.333	0
8	3186.63	884.167	330
9	5189.17	1124.17	330
10	6464.01	1124.17	330
11	6416.1	1124.17	330
12	6000.03	1124.17	330
13	5600.19	1124.17	330
14	5440.09	1124.17	330
15	6210.35	1124.17	330
16	6340.31	1124.17	330
17	5923.48	1124.17	330
18	6288.24	1124.17	330
19	6718.51	1124.17	330
20	6807.5	1124.17	330
21	5798.17	1117.5	330
22	3840.17	965.833	330
23	3419	807.833	330
24	1519.67	686.667	0

$Profit_0$ is $4,711,330 in this case. And the variance of this profit can be computed as $Variance_0 = 8.3e+009$ according to the equation (15).

B. Risk constrained scheduling

In case B, the risk-constrained model is employed for GENCOs. Based on the asset allocation results in case A, the GENCO can assume its target profit, $Profit^*$, to be $4,000,000, and its risk tolerance coefficient β_0 to be 0.7.So the downside risk for the GENCO can be calculated as $RISK = Profit_0 - Profit^*$ .The first risk constraint added into the master arbitrage optimization model would be

$Profit - 4000000 \leq 0.95*RISK$. This risk constraint will keep tightening iteratively until the β_{iter} is lower than β_0 by calculating variances for each iteration. The profits for each iteration are shown in Figure 3 and the variance changes are shown in Figure 4.

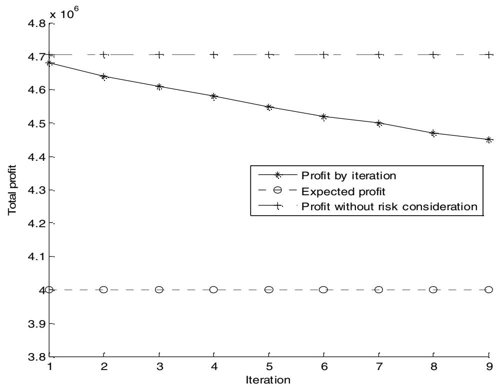

Figure 3 Profits for each iteration

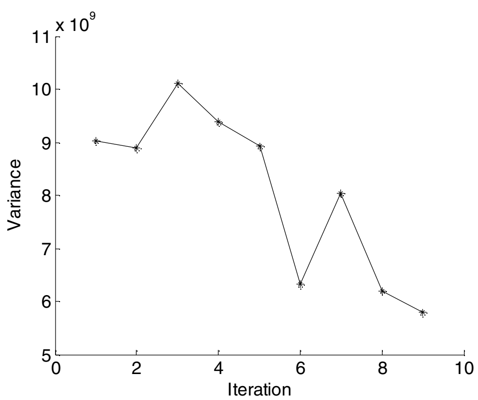

Figure 4 Variances for each iteration

The figures show that the maximum profit with the target profit and assumed risk tolerance can be reached at the ninth iteration. The optimization ends up with finding a maximum profit which is higher than the GENCO's target profit but lower than the profit without risk consideration. Once the risk toleration condition $Variance / Variance_0 = 0.7$ is satisfied, the optimization will end representing the current risk is below the fluctuation level that GENCO would like to bear.

It also can be seen that the variance profile has a little fluctuation at the beginning instead of monotonously decreasing. This is because with the tightening of the risk constraint, some units' generation may fall into the time slots where the covariance coefficients are bigger and more fuel is being sold to the market. But finally the computation will converge as shown in the figure.

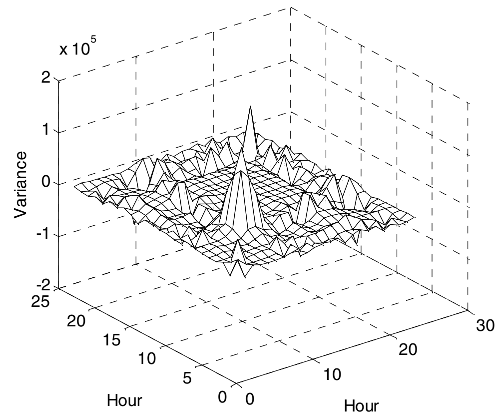

Figure5 Difference of variances between case A and iteration 4 in case B

In Figure 5, the differences of variance between the case A and iteration 4 in case B are shown. We can see the variances of profit in iteration 4 are mostly larger than case A where risk is not taken into account. But the profit in iteration 4 is about \$4,580,000 which is much lower than the profit of \$4,704,910 in case A. This means lower profit does not lead to lower variance even though the downside risk constraint is tightened. The variance change for all the iterations is demonstrated in Figure6.

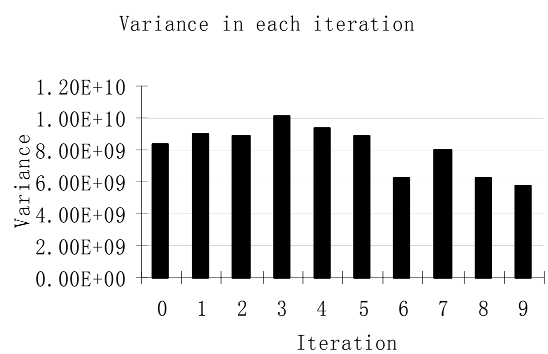

Figure6 Change of variances in all the iterations

In Figure 6, it can be seen that the variances in the first five iterations are even higher than the case without risk consideration, which means a bigger volatility of profit is expected. So it has shown that the downside risk is not able to demonstrate the fluctuation of expected profit even though the GENCOs have decided to decrease its profit. In other words, the profit could be more fluctuating than the case without risk consideration. However, as we can see in Figure 6, the variance will go below the risk tolerance level eventually with the tightening of the downside risk constraint.

The final arbitrage result is presented in the Table 3:

Table 3
Generation asset allocation with risk consideration

Hour	Generation	Reserve	Non-spinning
1	322	343.4	70.4
2	237.5	90	86.3
3	280.75	65.5	2.2
4	280	121.25	5.83333
5	351.75	258.75	19.8
6	503.833	389.333	99.3
7	606.333	493.467	56.4333
8	1190.83	635	221.967
9	3613	729.167	468.1
10	5416.5	801.167	388.833
11	5790.5	848.667	485.733
12	6000.03	863.333	530.9
13	5597.33	752.5	637.657
14	5440.09	870.833	451.2
15	6197.5	938.333	412.5
16	6337.46	961.667	417.267
17	5923.48	866.667	579.167
18	6275.39	755	646.433
19	6718.51	500	760.833
20	6772.17	1145.83	226.4
21	6751.73	860	450.767
22	5637.59	941.2	305.167
23	5074.27	1059.17	127.933
24	3476.92	620	282.833

The comparison of generation dispatch in Case A and Case B is shown in Figure 7, in which different schedules can be observed due to the risk consideration.

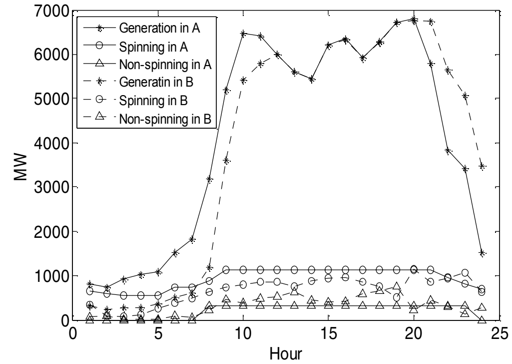

Figure7 Arbitrage results in Case A and Case B

The final total profit satisfying the risk tolerance preference is $4,450,690, which is higher than the target profit but lower than the profit without risk consideration. And the computational time is about 600s, which shows the efficiency of the modeling.

Motivated by the broad application of Sharpe ratio in finance, the Sharpe ratios associated with GENCOs' generation asset management are calculated. The Sharpe ratio is defined as the profit per unit of risk to measure the proportion of reward to variability [11]:

$$\textit{Sharpe ratio} = \frac{\text{Profit}}{\text{Standard deviation}}$$

So Sharpe ratios for generation asset management are computed as Figure 8, in which the Sharpe ratios change through iterations showing various risk levels. When the risk tolerance is satisfied, the Sharpe ratio reaches the highest point close to 60 where GENCOs can get the maximum profit per unit of risk.

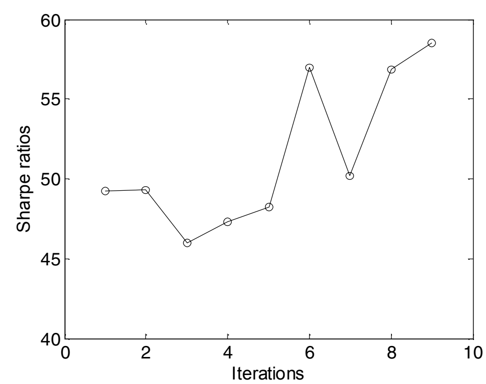

Figure8 Sharpe ratios through iterations

C. Discussion on hedging strategies

Due to the multi-arbitrage opportunities for GENCOs, a multi-hedging strategy can be developed accordingly to help the utilities decrease their risk exposure. Ancillary service, energy, fuel and so on render the GENCOs in a situation that is similar to the multi-product companies in other fields. A similar multi-product hedging strategy can be applied to hedge the risk faced by the electricity companies.

For example, GENCOs can utilize the financial contracts [12] in the respective transaction markets or form a comprehensive hedging strategy across different markets, which will finally lead to the adjustment of risk preference of the utilities.

It can be imagined that it is impossible for GENCOs to be engaged in all kinds of arbitrage activities assuming the increasing huge risk. Bidding for generation in the energy market is always the main source of revenue for GENCOs, which is stated in any power market design. So GENCOs usually face single or several limited arbitrage decisions, which is easier to develop the hedging strategies compared to the multi-hedging strategy. It should be noted that the existence of spot market helps GENCOs hedge the arbitrage risk to some extent. The mismatch between the forecasted and the actual prices can be balanced partly by rebidding into the spot market, in which arbitrages can take place simultaneously without risk.

5. Conclusion

The risk-constrained generation asset arbitrage model proposed in this paper can effectively model the practical generation asset allocation decisions for GENCOs. The risk consideration is explicitly expressed in the optimization model with a downside risk constraint. Also by calculating the variance of the expected profit, the fluctuation of the expected profit can be described. The iterative process will search the optimal solution that reaches a tradeoff between the pursuable profit and the involved risks.

Acknowledgement

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Nomenclature

Variables:

$C_{i,FT}(,)$ Fuel FT consumption of unit i

$F_{b/s}(FT)$ Cost/payoff for purchasing/selling the fuel type FT

$I(i,t)$ On/Off status of unit i at time t

N Number of units

$N_{off}(,)$ Non-spinning reserve of units when off

$N_{on}(,)$ Non-spinning reserve of units when on

$Profit_0$ GENCO's expected profit with the forecasted market prices

$Profit^*$ GENCO's target profit

$q(i,t)$ Generation for unit i at time t

$q_{s,FT}$ Quantity of fuel FT to sell

$q_{b,FT}$ Quantity of fuel FT to buy
$R(i,t)$ Spinning reserve for unit i at time t
$TP(), TR(), TN()$ Total generation, spinning, and non-spinning reserves
$x_m(,)$ Traded fuel for segment m in the price curve
V $T \times T$ covariance matrix of energy market price
V_{fuel} Covariance coefficient of fuel prices

Constants:

α Exponentially decaying weighting factor
β Risk preference of a GENCO
b Buy
i Denote a unit
k Denote a QF contract
l Denote a load contract
s Sell
t Hour index
$actual$ Superscript representing actual values
$CP(,)$ Contracted price with QF/load
est Superscript representing estimated values
FT Fuel type
$forecast$ Superscript representing forecasted values
N Number of units
N_d Number of days for which actual and forecasted prices are available
NFT Number of fuel types
$NSB()$ Number of segments in the purchase price curve for fuel
$NSS()$ Number of segments in the selling price curve for fuel
$QF_0(,)$ Contracted generation with QF
S_{FT} Fuel storage limit of fuel FT
T Number of study periods in a day
$p^{est}(t)$ Forecasted energy price at time t
$\rho_f^{est}(t)$ Forecasted fuel price at time t
$\rho_r^{est}(t)$ Forecasted spinning reserve price at time t
$\rho_n^{est}(t)$ Forecasted non-spinning reserve price at time t
$p_{fuel,FT}$ Fuel FT price for fuel in storage
$p_{bilateral}(t)$ Contracted energy price at time t
$q_{bilateral}(t)$ Contracted MW at time t
$RISK$ Denote the downside risk