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IGDT Based Genco's Trading Decision Making in Multimarket Environment

Parul Mathuria

Department of Electrical Engineering,
Malaviya National Institute of Technology Jaipur,
Jaipur, India
parulvj14@gmail.com

Rohit Bhakar

Department of Electronic and Electrical Engineering,
Faculty of Engineering & Design, University of Bath,
Bath, UK
r.bhakar@bath.ac.uk

Abstract—Fossil fuel gencos are subject to influence of multiple uncertain but interactive energy and emission markets. It procures production resources from fuel and emission market and sells its generation through multiple contracts in electricity market. With increasing volatility and unpredictability in energy markets, a genco needs to make prudent decision to manage its trading in all involved markets, to guarantee minimum profit. Considering the existing market uncertainties and associated information gap, this paper proposes a robust decision making approach for gencos trading portfolio selection in all three involved markets, based on Information Gap Decision Theory (IGDT). Results from a realistic case study provides a range of decisions for a risk averse genco, appropriate to its nature, and based on the trade-off existing between robustness and targeted profit.

Index Terms—Electricity price uncertainty, emission price uncertainty, fuel price uncertainty, information gap decision theory, portfolio optimization.

I. INTRODUCTION

Fossil fuel generation companies are key supplier of electricity in power industry. They trade in markets with an objective of maximizing profit. They are involved in multiple market trading to procure resources for electricity production and sell generation outcomes [1]. They procure fuel and emission permits and sell electricity in their respective markets [2]. With growing volatility in energy markets, they are exposed to previously unknown levels of price volatility in purchase as well as sell side, while trading in such markets.

In such situations, gencos need to efficiently cope with risk of losing profitability. Gencos participate in various markets via several contractual instruments. They strategically trade in available options to obtain risk constrained maximum profit [3]. This allows power producers in identifying their optimal hedging strategies to limit their financial exposure towards risk, which is known as portfolio optimization [4]. Portfolio optimization is a core concern of electricity markets for decision making where multiple market uncertainties are involved [5]-[6]. The problem has been solved by tools like Markowitz mean-variance theory [5], [6], stochastic programming using Value at Risk (VaR), Conditional Value

at Risk (CVaR), *etc.* which require historical data based estimate/forecast of market prices.

Gencos are involved in fuel, emission and electricity markets. Their overall profit and associated risk is affected by trading decisions in each of the markets. Trading decision making for three involved markets in a single framework can make such trading portfolio selection problem efficient and effective [7]. Further, portfolio optimization involving multiple market uncertainties requires precise estimates of many input parameters for decision making. However, energy prices are affected by many unpredictable factors and their estimated prices may severely differ from actual ones. Gap between estimation and actual values leads to imprudent portfolio selection. IGDT quantifies this information gap for decision making and provides a strategy to satisfy performance requirements [8]. This theory has recently become an attractive option to solve a wide variety of market issues, *viz.* electricity purchase bidding, robust scheduling of large consumers [9]-[10]. However, its application for portfolio selection involving uncertainties of multiple markets is yet to be explored.

Considering the poor predictability of market prices and the interactive nature of involved markets [11], this paper models the system uncertainties in an IGDT framework, for an integrated portfolio selection of fuel, emission permits and electricity. The involved markets consider deterministic and uncertain contracts. Price uncertainties of emission, fuel, electricity markets (pool and congestion charges) and their correlations have been considered by variance-covariance matrix. Genco's profit uncertainty has been modeled using envelope bound info-gap uncertainty model. Based on a realistic case study, the considered approach offers a range of decisions which are robust against losses.

II. PROBLEM DESCRIPTION AND FORMULATION

Fossil fuel gencos require securing carbon permits for each unit they emit by burning carbon fuels in process of electricity generation [12]. They procure these emission permits and required fuel from their respective markets *via* contracts and spot trading. Gencos sell their generation in zonal pricing based electricity market *via* multiple bilateral contracts and spot trading. In zonal pricing scheme, prices of

all zones are uniform during normal operating conditions and price separation between different zones arises due to congestion. Bilateral contracts with consumers of a different zone may be subject to congestion and consequent charges, which are uncertain. Thus, a genco is subject to multiple uncertain trading options, at purchase side and sell side, *i.e.* spot market of fuel, emission permits and electricity and bilateral contacts with consumers of different zone.

The overall problem for genco is to maximize net profit attained from trading in all involved markets, by coordinating three portfolios of interrelated markets over specified period for the given information about prices for emission permits, fuel and electricity. For this medium-term planning (month to year), presumed generation satisfies fuel availability and emission cap constraints. Markets are assumed to be completely liquid. Generation cost based on quadratic heat rate is considered to best reflect operational cost.

A. Generation Cost

Cost of electricity generation is usually calculated based on the amount of fuel required to generate electricity. With the introduction of ETS in the European Union, emission costs are being considered as a component of generator's short-term marginal cost [13]. The fuel usage of the plant is generally expressed in terms of its heat rate.

$$\phi(p) = a p^2 + b p + c \quad (1)$$

where a , b and c are heat rate coefficients. Thus, amount of fuel required to generate P_i^G power, in MBtu is

$$Fuel_i = \phi(P_i^G) \quad (2)$$

Amount of emission permits required for certain generation is related to the quantum of fuel consumed and usually calculated in terms of CO₂ emissions based on emission factor e_f [13]. Each unit of emission permit gives the holder a right to emit 1 ton CO₂ emissions.

$$CO_{2i} = e_f \phi(P_i^G) \quad (3)$$

Gencos' requirement for fuel and emission permits can be met through certain contracts and purchase from spot market. Starting from year 2013, gencos have to purchase emission permits, as the prevailing free allocation mechanism has been replaced with auction [12]. Total fuel cost (FC) and emission cost (EC) for purchasing quantity of fuel and emission permits from contracts $Fuel_i^B$, CO_{2i}^B at prices $\lambda_i^{F,B}$, $\lambda_i^{E,B}$ and from spot trading $Fuel_i^S$, CO_{2i}^S at market clearing prices $\lambda_i^{F,S}$, $\lambda_i^{E,S}$ respectively, is

$$FC = t \sum_{i=1}^I Fuel_i^B \lambda_i^{F,B} + t \sum_{i=1}^I Fuel_i^S \lambda_i^{F,S} \quad (4)$$

$$EC = t \sum_{i=1}^I CO_{2i}^B \lambda_i^{E,B} + t \sum_{i=1}^I CO_{2i}^S \lambda_i^{E,S} \quad (5)$$

To hedge against uncertainties involved in emission and fuel spot prices, genco have to optimize emission and fuel portfolios.

B. Revenue from Sale

In considered zonal pricing based market, genco is assumed to be located at $l = 0$ area. It can trade in three types

of contracts: i) bilateral contract with consumer of same area ($l = 0$) ii) bilateral contract with consumers of other area ($l = 1 \sim n$) and iii) spot market contract. l is area index for $n+1$ zones. Considering a single spot market and only one bilateral contract with consumer of a certain zone, revenue from spot market R^S and bilateral contracts R^B is

$$R^S = t \sum_{i=1}^I P_i^S \lambda_{0,i}^S \quad (6)$$

$$R^B = t \sum_{l=0}^n \sum_{i=1}^I P_{l,i}^B \lambda_{l,i}^B \quad (7)$$

where effective payable bilateral prices $\lambda_{l,i}^B$ for area l at i^{th} trading interval are considered with congestion charges as

$$\lambda_{l,i}^B = \lambda_{l,i}^C - \gamma (\lambda_{l,i}^S - \lambda_{0,i}^S) \quad (8)$$

Here, $\lambda_{l,i}^S$ and $\lambda_{l,i}^C$ represents zonal prices and bilaterally agreed contract price of area l . Differences between two zonal prices (where generator and load are connected) are applicable congestion charges for underlying contract. Proportion of these charges to be paid by supplier or consumer depends upon congestion charge factor γ ($0 \leq \gamma \leq 1$) based on market rule. For intra-zonal trading, no congestion charges are applicable and genco receives contracted prices

$$\lambda_{0,i}^B = \lambda_{0,i}^C \quad \text{for } (l = 0) \quad (9)$$

For spot market trading, genco would receive prices of its own area as spot market price.

C. Total Profit

Total profit π_C of genco can be calculated as the difference of total revenue generated by selling electricity in different contracts (from (6)-(9)) and involved generation cost from (4) and (5), as

$$\pi = R^S + R^B - FC - EC \quad (10)$$

$$\Rightarrow \pi = t \sum_{i=1}^I \lambda_{0,i}^S P_i^S + t \sum_{l=0}^n \sum_{i=1}^I \lambda_{l,i}^B P_{l,i}^B - t \sum_{i=1}^I \left(Fuel_i^B \lambda_i^{F,B} + Fuel_i^S \lambda_i^{F,S} + CO_{2i}^B \lambda_i^{E,B} + CO_{2i}^S \lambda_i^{E,S} \right) \quad (11)$$

III. INFO-GAP DECISION MAKING

The profit function (11) contains trading decisions (quantities) of three involved markets, which are evaluated for desired risk constrained profit. The uncertainty encountered in profit is due to uncertainty existing in prices of different markets or contracts. Considering the severity of this uncertainty, problem discussed in Section II is formulated and solved using IGDT. It models size of gap between estimated and actual value of uncertain input parameters as uncertainty parameter α and evaluates decisions at its different values [8].

A. Decision Variables

Quantum of power traded in various uncertain trading options *i.e.* spot market P_i^S and inter-zonal bilateral electricity contract $P_{l,i}^B$ ($l \neq 0$) are sell side decision variables.

Purchase side decision variables are quantum of fuel and emission permits procured from their respective spot markets at each trading interval. All are considered as set

$$P = [P_i^S, P_{l,i}^B, Fuel_i^S, CO_{2i}^S] \quad (12)$$

B. Price Modelling

Spot prices of different involved markets and inter-zonal bilateral electricity contract prices are uncertain. These prices are represented based on their average value and variance, and are presumed to follow normal distribution, providing basic information required to make uncertainty assumptions.

$$\lambda_i^S \sim N(\tilde{\lambda}_{0,i}^S, \sigma_{\lambda_i^S}^2) \quad \forall i \quad (13)$$

$$\lambda_{l,i}^B \sim N(\tilde{\lambda}_{l,i}^B, \sigma_{\lambda_{l,i}^B}^2) \quad \forall i, (l=1 \sim n) \quad (14)$$

$$\lambda_i^F \sim N(\tilde{\lambda}_i^F, \sigma_{\lambda_i^F}^2) \quad \forall i \quad (15)$$

$$\lambda_i^E \sim N(\tilde{\lambda}_i^E, \sigma_{\lambda_i^E}^2) \quad \forall i \quad (16)$$

C. Uncertainty Model

IGDT models uncertainty in parameter of interest by minor assumptions on uncertainty structure [8]. To reflect uncertainty for the estimated profit $\tilde{\pi}$, it is assumed that $\tilde{\pi}$ differs from the true value π by some margin which may be very large. In IGDT, this margin is calculated based on α , which is allowed to be unbounded. An envelope bound info-gap model which models the uncertain deviations to an expandable envelope is considered to formulate uncertainty $U(\alpha, \pi)$ of profit π , and can be mathematically defined as

$$U(\alpha, \pi) = \left\{ \pi : |\pi - \tilde{\pi}| \leq \alpha \sigma_\pi \right\}, \quad \alpha \leq 0 \quad (17)$$

where σ_π is profit standard deviation. Since the prices of different market are assumed to follow normal distribution, profit would follow joint normal distribution considering probability point of view. This can be defined by an estimate $\tilde{\pi}$ (average) of profit and its variance σ_π^2 as

$$\pi(P, \lambda) \sim N(\tilde{\pi}, \sigma_\pi^2) \quad (18)$$

Estimated profit $\tilde{\pi}$ can be calculated from estimated prices as

$$\begin{aligned} \tilde{\pi} = & t \sum_{i=1}^I \tilde{\lambda}_{0,i}^S P_i^S + t \sum_{l=0}^n \sum_{i=1}^I \tilde{\lambda}_{l,i}^B P_{l,i}^B \\ & - t \sum_{i=1}^I \left(Fuel_i^B \lambda_i^{F,B} + Fuel_i^S \tilde{\lambda}_i^{F,S} \right. \\ & \left. + CO_{2i}^B \lambda_i^{F,B} + CO_{2i}^S \tilde{\lambda}_i^{F,S} \right) \end{aligned} \quad (19)$$

Separating deterministic and uncertain terms

$$\begin{aligned} \tilde{\pi} = & t \sum_{i=1}^I \tilde{\lambda}_{0,i}^S P_i^S + t \sum_{l=1}^n \sum_{i=1}^I \tilde{\lambda}_{l,i}^B P_{l,i}^B - t \sum_{i=1}^I \left(Fuel_i^S \tilde{\lambda}_i^{F,S} + CO_{2i}^S \tilde{\lambda}_i^{F,S} \right) \\ & + t \sum_{i=1}^I \left(\lambda_{0,i}^B P_{0,i}^B - Fuel_i^B \lambda_i^{F,B} - CO_{2i}^B \lambda_i^{F,B} \right) \end{aligned} \quad (20)$$

Based on variances and covariances between different uncertain trades of revenue and cost sides and considering them correlated, variance of profit function is calculated as (21). Formulation of each term in (21) is expressed in (22), considering variance-covariances between normally distributed uncertain prices.

$$\begin{aligned} \sigma_\pi^2 = & Var(R^S) + \sum_{l=1}^n Var(R_l^B) + Var(FC^S) + Var(EC^S) \\ & + 2 \sum_{l=1}^n \left\{ Cov(R^S, R_l^B) - Cov(R_l^B, FC^S) - Cov(R_l^B, EC^S) \right\} \\ & - 2Cov(R^S, FC^S) - 2Cov(R^S, EC^S) \\ & + \sum_{l=1}^n \sum_{m=1}^n 2Cov(R_l^B, R_m^B) \\ & + 2Cov(FC^S, EC^S) \\ & \left[\begin{aligned} & \left(P_i^S \right)^2 \sigma_{\lambda_i^S}^2 + \sum_{l=1}^n \left(P_{l,i}^B \right)^2 \sigma_{\lambda_{l,i}^B}^2 + Fuel_i^S \sigma_{\lambda_i^F}^2 + CO_{2i}^S \sigma_{\lambda_i^E}^2 \\ & + 2 \sum_{l=1}^n \left(P_i^S P_{l,i}^B \sigma_{\lambda_{0,i}^S, \lambda_{l,i}^B} - P_{l,i}^B Fuel_i^S \sigma_{\lambda_{l,i}^B, \lambda_i^F} - P_{l,i}^B CO_{2i}^S \sigma_{\lambda_{l,i}^B, \lambda_i^E} \right) \\ & - 2 P_i^S Fuel_i^S \sigma_{\lambda_{0,i}^S, \lambda_i^F} - 2 P_i^S CO_{2i}^S \sigma_{\lambda_{0,i}^S, \lambda_i^E} \\ & + 2 \sum_{l=1}^n \sum_{m=1}^n \left(P_{l,i}^B P_{m,i}^B \sigma_{\lambda_{l,i}^B, \lambda_{m,i}^B} \right)_{l \neq m} \\ & + 2 Fuel_i^S CO_{2i}^S \sigma_{\lambda_i^F, \lambda_i^E} \end{aligned} \right] \end{aligned} \quad (21)$$

D. Robustness Function

A risk-averse genco wishes to immune itself from losses. Robustness ensures that minimum profit would not be less than a targeted critical profit π_c for certain fall in market prices. It is the maximum uncertainty that the decision can tolerate without sacrificing π_c . For the considered uncertainty $U(\alpha, \pi)$, minimum profit from (17) would be

$$\min_P \pi = \tilde{\pi} - \alpha \sigma_\pi \quad (23)$$

For robustness, minimum profit should at least be equal to π_c

$$\tilde{\pi} - \alpha \sigma_\pi = \pi_c \quad (24)$$

$$\Rightarrow \alpha(\pi_c) = \frac{\tilde{\pi} - \pi_c}{\sigma_\pi} \quad (25)$$

Robustness and the consequent trading strategy P for critical profit π_c can be derived as the greatest value of uncertainty parameter α , such that profit in region $U(\alpha, \pi)$ is not be less than π_c .

$$\hat{\alpha}(\pi_c) = \max_P \alpha(\pi_c) = \max_P \frac{\tilde{\pi} - \pi_c}{\sigma_\pi} \quad (26)$$

where $\tilde{\pi}$ and σ_π can be evaluated from (20) and (22). Robustness (26) is maximized subject to limiting constraint on trading contracts.

$$P_i^G = P_i^S + \sum_{l=1}^n P_{l,i}^B \quad \forall i \quad (27)$$

$$Fuel_i = Fuel_i^B + Fuel_i^S \quad \forall i \quad (28)$$

$$CO_{2i} = CO_{2i}^B + CO_{2i}^S \quad \forall i \quad (29)$$

$$P_{l,Min}^B u_{l,i} \leq P_{l,i}^B \leq P_{l,Max}^B u_{l,i} \quad \forall l, \forall i \quad (30)$$

$$CO_2^{Min} v_i \leq CO_{2i}^B \leq CO_2^{Max} v_i \quad \forall i \quad (31)$$

$$Fuel^{Min} w_i \leq Fuel_i^B \leq Fuel^{Max} w_i \quad \forall i \quad (32)$$

$$u_i, v_i, w_i \in \{0, 1\} \quad \forall i \quad (33)$$

where (27), (28) and (29) are balancing constraints, while (30), (31) and (32) are limits on bilateral contracts of different

markets, if selected. Selection states of contract are decided by (33).

Profit function (11) is maximized with respect to decision variables P , subject to constraints (27) - (33). This is the maximum value of profit which a genco can have if prices of all uncertain trades remain same as expected and is represented as $\tilde{\pi}(P, \tilde{\lambda})$. Multiple values of critical profit π_c , are assumed less than maximum profit $\tilde{\pi}(P, \tilde{\lambda})$. Robustness from (26) is optimized for each value of π_c considering constraints (27) to (33). The considered portfolio optimization problem is MINLP in nature.

IV. CASE STUDY, RESULTS AND DISCUSSION

The proposed methodology is modeled as a case study for a typical coal fired genco, with specifications shown in Table I. The genco plans trading in all involved markets for some future month, considering each day as trading interval. To procure fuel and emission permits, it directly trades in their respective markets through contracts and spot trading (Table II). Genco situated at area NO1 ($l=0$), sells generation (assumed equal to its maximum capacity) in day-ahead spot market and through bilateral contracts made with customers of three different areas as shown in Table III. Spot market contracts in all three markets and inter-zonal bilateral contracts in electricity market are considered uncertain while local contract 1 and purchase contracts for fuel and EUA are deterministic. Based on fuel type, emission factors are estimated for CO₂ emissions [16]. Simulations are performed over several months, and one analysis as example is presented hence.

TABLE I
GENERATING UNIT SPECIFICATIONS

Fuel Type	Coal
Generation capacity	500 MW
Quadratic heat-rate coefficient	0.00037MBtu/MW ²
Linear heat-rate coefficient	4.76MBtu/MW
No-load heat-rate coefficient	683.91MBtu
Emission factor	0.0955 tCO ₂ /MBtu

TABLE II
SPECIFICATIONS OF FUEL AND EMISSION BILATERAL CONTRACTS

	Contract Prices	Min.	Max.
Coal	3.1 (€/MBtu)	200MBtu	1400 MBtu
EUA	15(€/tCO ₂)	20 tCO ₂	80 tCO ₂

TABLE III
SPECIFICATIONS OF ELECTRICITY BILATERAL CONTRACTS

Location Index	Area Name	Contract Prices (€/MWh)	Min. (MW)	Max. (MW)
0	NO1	34.7	50	400
1	NO5	40	50	400
2	SE3	35.5	50	400

Analysis is based on the historical data of month August from 2008 to 2012, of electricity from Nordpool [17] and emission permit (EUA) from Bluenext Exchange [18]. Coal prices are assumed random, due to their non-availability. For the different uncertain prices average values $\tilde{\lambda}_{l,i}^S, \tilde{\lambda}_i^{F,S}, \tilde{\lambda}_{l,i}^B$ and $\tilde{\lambda}_i^{E,S}$ and variance-covariance matrices are evaluated from statistical calculations using MATLAB. For

understanding of nature of prices an average variance-covariance matrix is presented in Table IV.

TABLE IV
VARIANCE-COVARIANCE MATRIX BETWEEN PRICES OF UNCERTAIN TRADES

	Spot Electricity	Contract 2	Contract 3	Spot Fuel	Spot Emission
Spot Electricity	147.98	-30.67	-1.12	3.79	56.98
Contract 2	-30.67	49.57	0.99	-1.87	-24.99
Contract 3	-1.12	0.99	1.79	-0.02	-0.57
Spot Fuel	3.79	-1.87	-0.02	0.23	1.69
Spot Emission	56.98	-24.99	-0.57	1.69	32.87

The considered optimization problem has been simulated with 501 real and 248 discrete variables, using SBB-CONOPT© solver of GAMS in a Core i5, 3.2 GHz processor and 4 GB RAM computer, with an average solution time of 0.655 seconds [17]. However, solution time increases with consideration of additional variables. SBB uses Branch and Bound algorithm to provide the initializing point for NLP sub-models which are solved using CONOPT.

From the simulation, the maximum obtained value of profit $\tilde{\pi}(P, \tilde{\lambda})$ is 3786851€. For presented analysis, π_c varies from 3786851€ to 2000000€ in small steps. For these values of π_c , robustness (26), subject to constraints (27)-(32) is maximized. The obtained results are shown in Fig. 1 to 5.

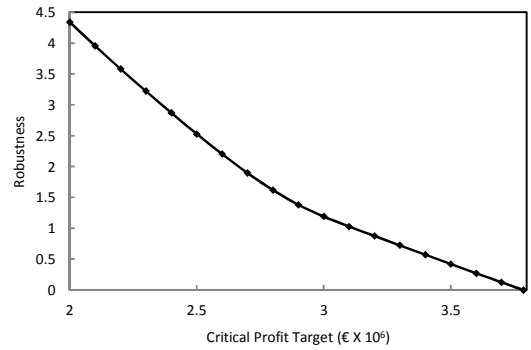


Figure.1 Robustness for different targeted profits

Robustness $\hat{\alpha}(\pi_c)$ is the maximum uncertainty or allowable range of unfavorable deviation in market prices, that the system can sustain without sacrificing the critical profit target π_c . At targeted profit $\pi_c=3786851€$ robustness $\hat{\alpha}(P, \pi_c)$ is zero and increases with reducing values of π_c (Fig. 1). This happens because for low profit targets, decision maker trades in contracts with low or no uncertainty, thereby enhancing the robustness of decision. This reduces profit's standard deviation (Fig. 2). This happens because higher variability contracts are accompanied with higher possibility of losses and a strong risk-averse genco would aim to reduce its exposure towards losses.

For the present case, genco enhances trading electricity in zero variability Contract 1 and low variability Contract 3 and at upstream, reduces purchase from spot market with reducing profit targets (Figs. 3 and 4). With this, expected purchase cost increases and revenue decreases, finally

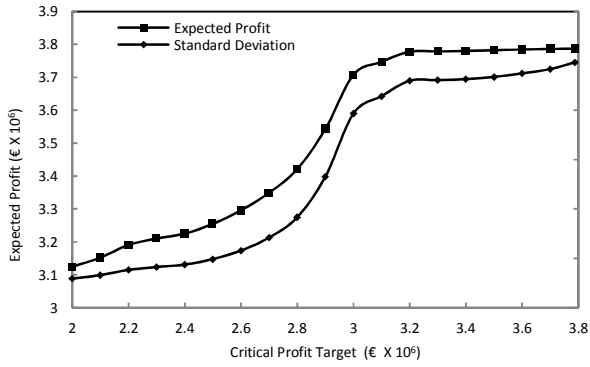


Figure.2 Expected profit and profit standard deviation

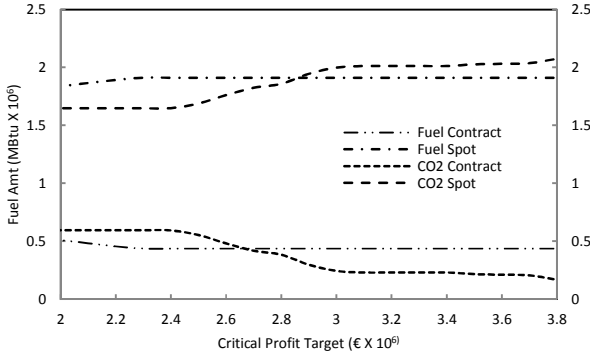


Figure.4 Fuel and EUA purchased from contracts and spot markets

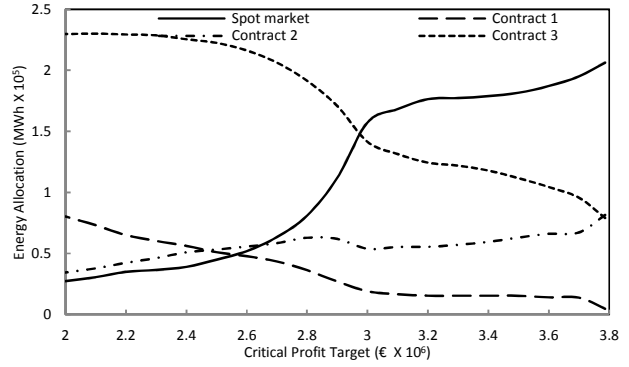


Figure. 3 Energy allocation in different trades of electricity market

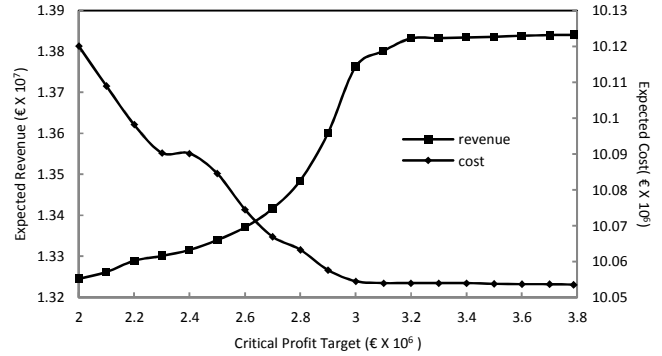


Figure. 5 Expected revenue and cost for different profit targets

reducing profit (Fig. 2 and 5). The reduced value of expected profit $\pi(P(\hat{\alpha}(\pi_c)), \tilde{\pi})$ represents the cost to robustness, *i.e.* if for a certain decision, prices do not move as per anticipation of the decision maker then he would get expected profit, which is always less than $\tilde{\pi}(P, \tilde{\lambda})$ (Fig. 2).

V. CONCLUSION

Considering the information gap that arises from market uncertainties, this paper proposes an IGDT based model for risk constrained trading decision making in three interactive markets. This integrated portfolio optimization model involves price uncertainty of electricity, congestion charges, fuel and emission permits, based on the covariance between uncertain trading options.

The proposed approach provides a robust trading strategy for a risk averse genco, which can guarantee profit under unfavorable price change, within the specified robustness range. The obtained results offer range of trading strategies, to assist genco in selecting the most appropriate, considering the trade-off existing between robustness and targeted profit. Robustness comes at a cost depending upon the tolerance of decision for market price deviations. Considering optimistic nature of genco, opportunistic performance can easily be included to secure windfall gains.

REFERENCES

[1] M. Denton, A. Palmer, R. Masiello and P. Skantze, "Managing market risk in energy", *IEEE Trans. Power Syst.*, vol. 18, no. 2, May 2003.
 [2] X.R. Li, C.W. Yu, F.J. Luo, S.Y. Ren, Z.Y. Dong, and K.P. Wong, "A multimarket decision-making framework for genco considering

emission trading scheme," *IEEE Trans. Power Syst.*, vol. 28, no. 4, pp. 4099-4108, 2013.
 [3] R. Bjorgan, Chen-Ching Liu and J. Lawarree "Financial risk management in a competitive electricity market", *IEEE Trans. Power Syst.*, vol. 14, no. 4, Aug. 1999.
 [4] J.Xu, P. B. Luh, F. B. White, E. Ni, and K. Kasiviswanathan, "Power portfolio optimization in deregulated electricity markets with risk management", *IEEE Trans. Power Syst.*, vol. 21, No.4, pp. 1653-1659, Nov. 2006.
 [5] M. Liu and F. F. Wu, "Managing price risk in a multimarket environment" *IEEE Trans. Power Syst.*, vol. 18, no. 2, May 2006.
 [6] F. A. Roques, D. M. Newbery, and W. J. Nuttall, "Fuel mix diversification incentives in liberalized electricity markets: a mean-variance portfolio theory approach", *Energy Eco.*, vol. 30, no. 4, pp. 1831-1849, July 2008.
 [7] P. Falbo, D. Felletti and S. Stefani, "Integrated risk management for an electricity producer", *Eur. J. Oper. Res.*, vol. 207, no. 3, pp. 1620-1627, 2010.
 [8] Y. Ben-Haim, Information Gap Decision Theory: Decisions under Severe Uncertainty, *Academic Press*, San Diego, CA, 2006.
 [9] K. Zare, M. P. Moghaddam, M. K. Sheikh El Eslami, "Demand bidding construction for a large consumer through a hybrid IGDT-probability methodology", *Energy*, vol. 35, no. 7, 2010.
 [10] K. Zare, M. P. Moghaddam, and M. K. Sheikh-El-Eslami, "Risk-based electricity procurement for large consumers", *IEEE Trans. Power Syst.*, vol. 26, no. 4, 2011.
 [11] P. Koenig, "Modelling correlation in carbon and energy markets", *Elect. Policy Res. Group Working Paper*, Uni. of Cambridge, Feb. 2011.
 [12] Factsheet of ETS 2013, "The EU Emissions Trading System (EU ETS)", available [Online] http://ec.europa.eu/clima/policies/ets/index_en.htm.
 [13] T. Gjengedal, "Emission constrained unit-commitment (ECUC)", *IEEE Trans. Energy Conversion*, vol. 11, no. 1, pp. 132-138, March 1996.
 [14] U. S. Energy Information Administration, Instructions for Form EIA-1605, Voluntary Reporting of Greenhouse Gases, Appendix H. Fuel Emission Factors, EIA-1605, OMB No. 1905-0194, p. 142, Oct. 2007.
 [15] <http://www.nordpoolspot.com>, accessed Nov. 2012.
 [16] <http://www.bluenext.eu>, accessed Nov. 2012.
 [17] The GAMS website, 2013, [Online] available: <http://www.gams.com/dd/docs/solvers/conopt.pdf>.