Analyzing the Interaction between Emission Trading Systems and Electricity Market

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Abstract— The emission trading system is one of the recent controlling tools for the greenhouse gases (GHG) emission. This policy was made in order to decrease the amount of emission from pollutant industries. One of the most challenging subject in this criteria is the mechanism of allowance allocation. The grandfathering and the allowance auction are two common approaches to allocate allowances to generation companies in electricity market. In grandfathering approach, the allocation is based on the historical output of generation units. Output-based and emission based allocation are two common methods for free allowance allocation in grandfathering approach. The auction is another mechanism that production units participate to buy enough allowances. In this paper, the emission market is modeled to investigate the interaction of the two market simultaneously. To model the behavior of the generation units in the presence of emission market, the Cournot model for electricity market and the allowance supply function for emission market is utilized. Furthermore, the impact of emission allowance auction, the approaches of allocating emission allowances to power plants and allowance trading in emission market on the profitability of production units in the electricity market is investigated.

Keywords— Electricity Market, Cournot Model, Emission Trading System, Allowance Allocation;

I. INTRODUCTION

During the last century, fossil fuel consumption for energy production in various industries caused a significant increase in greenhouse gases emission. According to the impolitic and irregular growth in the application of such fuels, the density of existing gas in the atmosphere is increased and cause the greenhouse effect. This effect increased the temperature of the earth, melting the glacier, significant climate changes and destroying the ecosystem and environment. Through the last decade by the increase of such concerns about the global warming and other dangerous effects of the greenhouse gases, several mechanisms have been developed throughout the world to control the emission. The Kyoto and Paris protocols are the international contract by which several countries guarantee to take steps in order to decrease their greenhouse gases emission [1].

Renewable energy support schemes such as Feed-in Tariff (FIT) and Renewable Energy Certificate (REC) are supporting mechanisms to increase the renewable energy production in the energy portfolio. These mechanisms decrease greenhouse gases emission indirectly. Since power plants in electricity industries are the main sources of greenhouse gases emission, several policies have been made to control and decrease the number of emissions such as carbon tax and cap and trade program. In some countries, these policies are applied simultaneously. The emission market is utilized in developed countries such as European Emission Trading System (EU-ETS) and US emissions trading markets for SO_2 and NOx [2]. According to the importance of this subject in future, the impact of emission market on power plants in electricity markets is studied in this paper.

In order to achieve emission reduction targets, the environment department set a cap on their annual greenhouse gases emission each year. The cap distributed among industries by their importance and contribution to emission in terms of emission allowances. In this mechanism, each power plants and other pollutant units must have emission allowances equal to their amount of emission. These allowances are able to be traded in emission markets. It is said that the emission reduction is done more efficiently than carbon taxes [3]. Meanwhile, the price of the emission allowances could be considered as an indirect supporting scheme for the renewable energy resources [4].

The allowances allocation is one of the most challenging subjects in this mechanism. Grandfathering and auction are two common approaches to allocate allowances to each company. In the primary phase of cap and trade program, it is recommended that the allowances are given to each company freely in grandfathering approach. Two common methods for free allocation of allowances to the power plants are output-based and emission-based. To avoid windfall profit and increase the efficiency of this program, it is recommended that in next phases of this program, the government sell a portion of the cap to the production units by using the auction mechanism.

To model generation unit's behavior in power market, various studies have been conducted on the structure of the power market and the market player's competition. These models are mostly based on the Nash equilibrium concept. The Nash equilibrium point in a market is the one in which market players do not have any tendency to change their bids in the markets unilaterally. The Nash equilibrium prices for several oligopolistic models such as Cournot, Bertrand, and supply function can be calculated. In several papers, the electricity market is modeled as a Cournot game and the generation companies are modeled as Cournot players. In Cournot game, the market players compete with each other by changing their production quantity. Electricity prices are determined by demand function, so prices are sensitive to changes in demand and usually overestimate the prices more than the real ones [5]. Because of detailed modeling capability, the Cournot model is used for analyzing the interaction of the electricity market with other markets such as emission market in this paper. In [6] the Nash-Cournot model is introduced to model the Genco's competition in electricity market as a pool market by considering the bilateral contracts and congestion in transmission lines. Cournot model is used in [7] to model the oligopolistic electricity market in presence of the emission trading system. The emission allowances allocation and its impact on competition between Gencos have been studied. In [5] and [8] the generation expansion planning in presence of emission permits and green certificate as a long-term environmental policy has been studied. It is shown that the green technologies development is not stable without economic incentives. In [9] the PJM electricity market and the NOx emission market are simulated by conjectured price response model. It is shown that the market power in each of these two markets can intensify the impact of the market power in the other one. It should be noted that the impact of various methods for the allowances allocation is not studied in this reference.

In [10], the impact of emission trading system on the profitability of Australian electric generation companies is studied. It is shown that the profit of some companies has decreased significantly. Those companies with more pollutant ones such as coal units loose more profit. Thus, an amount of allowances that should be allocated to each company to compensate the loss of profit have been calculated. It is concluded that emission market reduced the emission by increasing the price of the electricity. In this reference, it is assumed that all units have to provide their required allowances from the emission market. The price of allowances in the model is considered to be constant which is not a correct assumption.

In [14], the impact of the environmental policies including the emission trading system and the renewable energy resources support schemes in power system operation has been studied. It is shown that the renewable energies support schemes affect the emission trading system and power plants production. It is also deduced that there has to be a coordination between renewable energy support schemes and emission reduction regulations. This paper discussed allowance allocation as a challenging problem and a crucial factor in designing and efficiency of emission trading system.

In this paper, the electricity market and emission market are modeled simultaneously in order to study the effect of emission allowance allocation approaches on the price of the emission allowance, electricity price and profit of units. In the remaining of the paper, in section 2 the mathematical model is presented and in section 3 we present the results and analysis of the simulations and discuss the achievements.

II. Problem Formulation

In this study, the Cournot model is used in order to model the electricity market as a pool market in which the market players maximized their profits by changing their production level. The monthly load is divided into three levels of low, medium and peak. The price of the electricity market is determined according to the demand function and production level of units. The production of each unit is calculated in Nash equilibrium point in which profit of all units should be maximized simultaneously. The transmission limits and unit commitment constraints are neglected to study the interaction of electricity and emission market in the mid-term horizon.

The initial allocation of the emission allowances to units (N_f) affects their profitability and the price of electricity and emission allowances. Additional allocation of initial allowances would bring windfall profits for units and have a negative effect on market efficiency, emission reduction and electricity price. Initial free allocation of emission allowances to units is done in two ways. In this approach, the history records of emission and production of units were used. In the emission-based allowance allocation method, the amount of emission has been measured over the past few years and after that, the emission allowances are allocated to units based on their historical emission. In another method which is named as the output-based allowance allocation, the amount of electric energy production for each unit over the past few years is considered as a standard for allocation of emission allowances to units.

In this paper, it is assumed that 90% of the emission cap is allocated freely to units. First of all, due to lack of information about the historical records of production and emission, the market equilibrium point is determined without considering the emission market. The production and emission of each unit at the equilibrium point is considered as a historical record of production and emission over the same month of the past year and such records are utilized in order to allowance allocation to each unit. It is so obvious that the remaining 10% of the emission cap is sold in the auction. The auction of emission allowances is held monthly. The production units are offering their bid to buy allowances in addition to what was allocated freely to them. In another word, each company could participate in the auction and buy the additional allowances based on its requirement and prediction.

To model the emission market it is assumed that each company trades its deficit or surplus of allowances monthly. The price of the emission allowances is determined according to the supply function of emission allowances. The supply function of emission allowances is an increasing linear function and it shows that the price of the emission allowances is dependent on the allowances demand. Other pollutant industries are also participating in this market as price-takers players. These industries are modeled as a fixed allowances demand in the supply function of emission allowances.

Each company maximizes its monthly profit. This monthly profit is the function of energy price, allowance price, auction price, energy production cost, the free allowance allocated, the purchased allowances from the auction and the amount of traded allowances in the emission market. The electricity market, emission market, and the auction are simulated hourly, daily and monthly respectively and free allowance allocation is done based on the historical record from the same month of the previous year.

In profit maximization of each company, emission allowance price is an unknown parameter which is obtained from auction optimization problem. On the other hand, in the maximizing of auction function, the amount of allowances for each company is unknown which is obtained from optimizing the profit maximization problem of generation units. So, we are faced with a bi-level optimization problems. In each optimization problem, an unknown problem is dependent on another optimization problem. In the remaining part of this paper, profit maximization problem of generation companies and social welfare of auction problem is formulated.

A. Profit Maximization of Generation Companies

The optimization problem of Generation Company is as follows:

$$Max_{q_{i,f,t}} \quad \pi_f = \sum_i \Big(30 \sum_t D_t \big(p_{i,t} q_{i,f,t} - C_f(q_{i,f,t})\big) - 30 p_{i,co2} E_{i,f}\Big), \tag{1}$$

Subject to:

$$p_{i,t} = a_t - b_t \left(\sum_f q_{i,f,t} \right) \quad , \qquad \forall t \epsilon T \ , \forall i \tag{2}$$

$$C_f(q_{i,f,t}) = \alpha_f q_{i,f,t} + \frac{1}{2} \beta_f q_{i,f,t}^2 \quad , \qquad \forall t \epsilon T \ , \forall i \tag{3}$$

$$q_f^{min} \le q_{i,f,t} \le q_f^{max} \ , \qquad \forall t \epsilon T \ , \forall i \tag{4}$$

$$p_{i,co2} = a' + b' \left(E_0 + \sum_f E_{i,f} \right) \quad , \qquad \forall i \tag{5}$$

$$E_{i,f} = \left(\sum_t D_t \eta_f q_{i,f,t} \right) - \frac{N_{i,f}}{30} \quad , \qquad \forall t \epsilon T \ , \forall i \tag{6}$$

In this model π_f indicate profit of company f in the studied month in terms of dollar, T is load level set, D_t is duration of load level t in terms of hour, p_t is price of the electrical energy in load level of t in terms of MWh, q_{ft} is production of the company f in load level t in terms of MW, C_{ft} is production price of the company f in load level t in terms of dollar per hour. Constraint (2) is shown the electricity demand function and determine the price of electrical energy according to the total production of all units. Equation (3) indicates the electricity production cost which is considered as a second order curved function. Constraint (4) shows upper and lower limit of the production units.

In presence of emission market, the cost (income) of buying (selling) the deficit (surplus) of emission allowances is also added to the objective function of each company. P_{co2} is price of emission allowances in terms of dollar per ton, E_f is the amount of deficiency or surplus of emission allowances for each company f in each day in terms of ton, η_f is emission rate for the company f in terms of ton per MWh, N_f is initially allocated allowances to the company f for duration of one month in terms of ton and E_0 is the amount of deficiency (surplus) of the emission allowances of other industries such as the industrial, petrochemical and cement companies. Price of emission allowance in emission market is determined by supply function and amount of emission allowance demand. Constraint (5) show emission allowance function. The positive E_f indicates the daily deficiency of the emission allowance and the negative E_f is shown the surplus quantity. The fourth term in (1) explained the cost of purchasing allowances from auction. N_{bf} is the purchased allowance of company f in the auction in terms of ton per month, λ_{auc} is equilibrium price of the auction in terms of dollar per ton which is derived from the optimization problem of the social planner.

B. The Optimization of The Auction Objective Function

The objective function which is maximized by the operator is equal to the total offered price by companies to get allowance in auction minus the cost of buying allowance in the emission market by power plants,

$$Max \, J_{sp_{N_{bf}}} = \sum_f bid_f \times N_{bf} - 30 \sum_f p_{co2} \times E_f \ , \tag{7}$$

Subject to:

$$\sum_f N_{bf} < 10\% \, CAP \ , \qquad (\lambda_{auc}) \tag{8}$$

bid_f is the bid of the allowance for the company f in the auction in terms of dollar per ton and CAP is the upper limit of the emission in one month. In (8) total sold allowances in the auction is considered to be less than 10% of the emission upper limit. In this paper, we use a numerical method to calculate the equilibrium point in auction. In this method, we assume that each unit maximize its profit by changing its bid unilaterally. This action is done repeatedly for all units in the market until no units exist to change their bids. But nothing can be said about the existence and uniqueness of the auction equilibrium point.

III. Simulation Results

In this section, the proposed model is applied to the 30-BUS IEEE test system by withdrawing of the network constraints to investigate the emission market impact on the electricity market. In order to determine the equilibrium point, we should solve the coupled optimization problem of various companies together. In order to solve the bi-level optimization problem, the Lagrange function of each optimization problem is derived and the Karush–Kuhn–Tucker optimality conditions for all units and the social operator is solved together by using GAMS software.

Table I shows cost function parameters, emission rate and capacity limits of generation units. As can be seen in this system, units 1 and 2 have equal and the lowest emission rates. The most polluted unit is unit 3. Because of different slope and intercepts of the marginal cost function, we are not able to say which unit is cheap and which of them is expensive. The cheapness of a unit depends on its production quantity in comparison with other units. Electricity demand function end emission market supply function are given in table II and III respectively.

TABLE I. IEEE 30-bus test system Generation units characteristics.

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
α_f	20	17.5	10	32.5	30	30
β_f	0.2	0.175	0.625	0.0834	0.25	0.25
η_f	0.4	0.4	0.9	0.8	0.72	0.78
q_f^{max}	80	80	50	55	30	40
q_f^{min}	0	0	0	0	0	0

TABLE II. Electricity market parameters.

	D_t	a_t	b_t
Low load	8	40	0.05
Medium load	10	46	0.05
Peak load	6	50	0.05

TABLE III. Emission market parameters.

E_0	a'	b'
7000	10	0.05

A. Electricity Market

The monthly power production in low, medium and peak load level for different allocation schemes is depicted in Fig. 1. As the figure shows, in the medium and peak load level, the total power production is decreased in presence of emission market; but it is increased in output based allocation in low load level. Generally, the power production in the output based allowance allocation is more than the emission base allowance allocation.

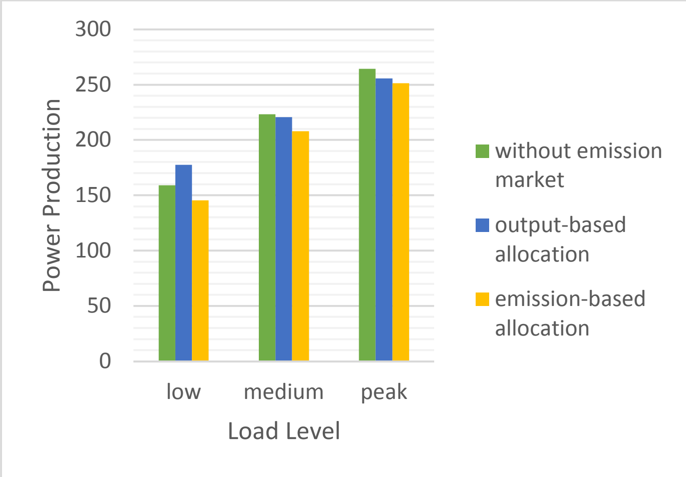

Fig. 1. Power production in different scenarios.

The electricity price in different scenarios is depicted in Fig. 2, the electricity price is increased in presence of emission market in medium and peak load level. The price of electricity in emission-based allocation is higher than the output based allocation.

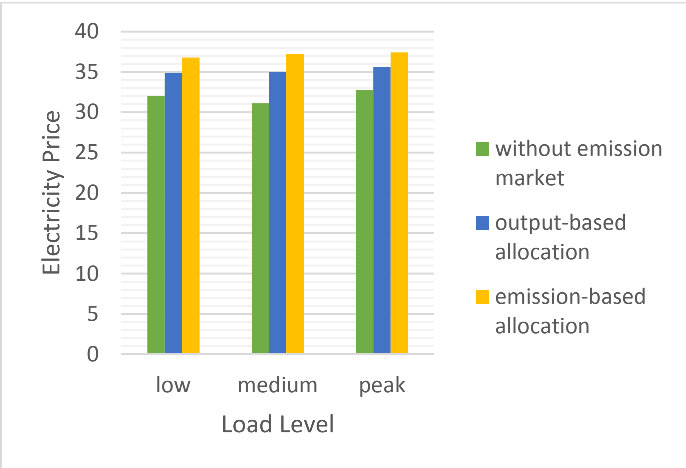

Fig. 2. Electricity price in different scenarios.

So we can conclude that emission market has 2 impacts on the electricity market. First, power production is reduced in presence of emission market and power production reduction in output based allowance allocation is lower than emission based allowance allocation. Second, electricity price is increased in presence of emission market and the amount of increase is higher in emission based allocation. So, the lower power production and higher electricity price in emission based allocation, decrease the social welfare objective function in comparison with output based allowance allocation. Emission reduction targets are reached in presence of emission market by the cost of increasing electricity price and decreasing the power production of polluting units.

B. Emission Market

The auction and emission price is shown in the table IV It can be deducted from the results that the auction and emission price are lower in output based allowance allocation than emission based allowance allocation.

TABLE IV. AUCTION AND EMISSION PRICE.

	Emission market	Emission auction
Allowance price in output based	28.53	3.28
Allowance price in emission based	35.67	7.42

The allowance deficit (surplus) of each unit is shown in Fig. 3. Those units that are cleaner and cheaper such as unit 1 and 2, have more surplus allowance than others. Unit 3 which has the highest emission rate, should purchase its allowance deficit in emission market. So in output based allowance allocation, the units with lower production cost have advantages of getting more allowances and increase their profit by selling the surplus. In emission based allocation, all the units have surplus allowance almost at the same level. So in this scenario, all units can sell their surplus in the market irrespective of their emission rate.

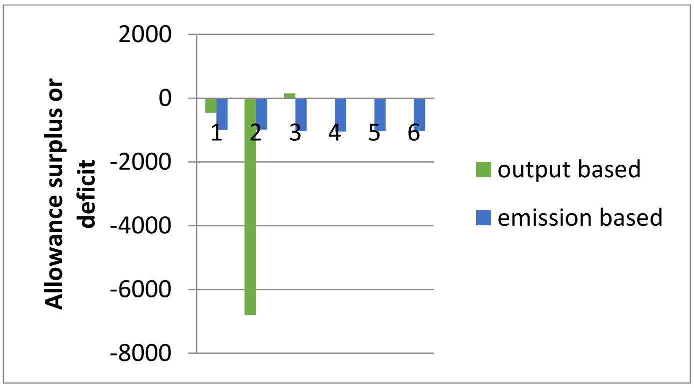

Fig. 3. Allowance surplus or deficit of power units.

IV. CONCLUSION

In this paper, the electricity market is simulated in presence of emission market. By introducing CAP and the resulting emission trade in developed countries, in the first phase of this program, emission allowances are allocated freely to provide an environment for generating units to be acquainted with allowance trading and its mechanism. In next stages, usually, the governments reduced the emission cap to decrease the emission effectively. Gradually, allowance allocation change from free allocation to auction; in which a percentage of the cap will be sold.

Generally, it can be inferred from the simulation results that the cleaner generation units are motivated in the emission based allowance allocation by acquiring more allowances in the market. The allowance price in emission market and auction is higher in emission-based allocation in comparison with output-based allocation. The profit of the cleaner and more pollutant units are more in the output-based and emission-based approach respectively. Thus it could be claimed that the auction mechanism plus the output-based allocation method motivate the cleaner units, however, auction next to the emission-based allocation is more beneficial for pollutant units.

According to the above mention results, emission-based allowance allocation is a better option in order to maintain companies' competitiveness condition than in the first phase of CAP. However, in order to force units to take steps toward emission reduction in long-term, the output-based allowance allocation plus auction will be the suggested option.

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