Paper

Market Mechanism for Line Congestion Clearance

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This paper proposes a mechanism for clearance of line congestion and power flow control in a deregulated market environment. The mechanism applies penalties to the bilateral transactions that cause line congestion by increasing the prices of such transactions. The market regulates itself by redefining the transactions and checking again for violations, applying penalties if necessary and repeating the process until all the demand is satisfied without causing line congestion to the system. A bilateral transaction matrix (BTM) creation algorithm developed by the authors and a DC power flow program are integrated as parts of the market mechanism proposed in this paper. The congestion is cleared by the market participants when they reschedule their transactions. This mechanism is useful to study the effects of bilateral transactions on a power system and helps the Independent System Operator (ISO) to create rules and market mechanisms for line congestion clearance and power flow control.

Keywords: bilateral transactions, deregulation, ISO, line congestion, power flow control

1. Introduction

The topic of deregulation has gained a lot of attention recently and several countries have decided to deregulate their electric utility industry (1). The vertically integrated electric utility is being divided into separate companies that perform the activities of power generation, transmission and distribution in a competitive market environment in which generation companies (GENCOs) compete with each other to sell their energy to distribution companies (DISCOs) and big users. DISCOs and big users constitute the buying participants of the market and they want to satisfy their demand as cheaply as possible and compete as market participants in the deregulated market environment.

Before deregulation the utility or power system operator would simply make adjustments to control congestion by rescheduling the generators. While in a free market environment for electricity, each GENCO may be allowed to self-commit according to the demand for its energy and market prices, therefore transmission congestion presents a challenging aspect in a deregulated environment and mechanisms to prevent congestion must be developed.

The growing interest in deregulation has stimulated research and new concepts have been created like the Transaction Matrix (TM) in Ref. (2) and (3). The transaction matrix is the expression of the physical generation and load in terms of the contracts defined by the market participants when they decide to trade electricity in the bilateral transaction market (3). The transaction matrix is the expression of the physical generation and load in terms of the contracts defined by the market participants when they decide to trade electricity in the bilateral transaction market (3). Security analysis using the Monte Carlo simulation method to create TMs have been made in Ref. (4) and (5), but a bidding or an auction is not considered as a part of the process to create a feasible TM. Therefore a method that incorporates a bidding process must be considered in a simulation of a free market environment for electricity.

A game theoretic evaluation of nodal prices in the pool model and cost allocation for the bilateral transaction model is analyzed in Ref. (7). The advantages and disadvantages of the pool and bilateral/multilateral dispatches are analyzed in Ref. (9). A locational pricing proposal for the New England power system is analyzed in Ref. (10). Transmission loss allocation is analyzed in Ref. (11)~(13). A technique to split the terms of transmission losses using a geometric allocation method is suggested in Ref. (11). A physical-flow-based approach to allocate the system losses as a linear expression of the system's transactions using a DC power flow is proposed in Ref. (12). A linear programming approach to calculate loss compensation in multiple transaction networks is proposed in Ref. (13).

Bilateral transactions are financial contracts between buyers and sellers, written on the basis of physical energy transfers, where the quantities traded and the prices are at the discretion of the market participants, therefore there is not a single system price nor a market clearing price in the bilateral model. The maximum benefit to society and economic efficiency are obtained

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by the market participants when generators try to maximize their profits by offering their power to the highest bidder and nodes try to minimize their costs by competing with other nodes to buy energy as cheaply as possible. This property has been implemented in a Bilateral Transaction Matrix (BTM) creation algorithm developed by the authors.

The BTM creation algorithm includes a bidding process which allows both buyers and sellers to bid a price in the market administrated by the Independent System Operator (ISO). The prices of the transactions are set by bilateral negotiations between sellers and buyers according to the buyer's demand and the seller's availability of power. All transactions are restricted to the suppliers (GENCOs) and consumers (DISCOs and big users) as it is suggested in Ref. (5), this simplifies the TM to a BTM which shows in a table form the trade in MW between the GENCOs and nodes that represent either DISCOs or big users. Table 1 shows the initial BTM used for the simulation.

Three different dispatch co-ordination strategies are analyzed in Ref. (16), the power pool, bilateral transactions and multilateral transactions, pointing out that the multilateral transaction model has not been sufficiently developed. The author of Ref. (16) also mentions that the pool dispatch in the UK has an estimated 80% of its transactions covered by a form of bilateral trade that stands outside of the pool pricing process.

In this paper the authors propose a market mechanism for congestion clearance using the bilateral transaction model. The only type of transaction considered is between generators and distributors or big users with a demand of at least 1 MW, other market entities are not considered.

The BTM obtained by the algorithm is used as the transactions schedule for a DC power flow program. A congestion allocation algorithm to determine the contribution of each transaction to congestion and to calculate the corresponding penalties was created, using an approach similar to Ref. (6).

The market mechanism consists of the BTM creating algorithm, a DC power flow program and the congestion allocation algorithm. A day ahead load forecast and starting prices for each node are used as input data for the BTM creation algorithm. The obtained BTM is used as the transactions schedule for the DC power flow program, which provides the corresponding power flows and branch monitoring for each transaction. This data is used to calculate the congestion contribution, then penalties are calculated and applied to the corresponding transactions by changing the prices of those transactions. These new prices are used as feedback for the BTM creation algorithm and the process is repeated until a feasible BTM that causes no line congestion is obtained.

The proposed mechanism is intended as a simulation tool for countries and regions that are in the process of deregulating their electric utilities. This mechanism helps to understand the effects that each bilateral transaction causes on the transmission system and is useful in the creation of rules for a reliable power system operation that benefits all participants in a deregulated market. In the most advanced electricity markets around the world, bid prices are kept confidential and there is no means to know the prices or the amounts of each individual transaction. This causes a limitation for the countries and regions that are in the process of deregulating their electricity markets, because they do not have access to the market data. This limitation is solved by the method proposed in this paper by providing the ISO with the price data and transaction amount in a simulation tool that simulates the behavior of market participants in a free market environment. Bid prices and the amounts of the transactions are shown to help the readers of this paper to understand the mechanisms necessary to implement a bilateral transaction electricity market and understand the effects of bilateral transactions and the application of penalties to the transactions that cause line congestion.

The ISO is the entity responsible for guaranteeing non-discriminatory access to transmission and establishes rules and pricing policies. The ISO is also responsible for guaranteeing market participants a secure and reliable operation of the power system. A secure system operation includes, line congestion clearance, voltage regulation, generation control and other means necessary for a stable and secure operation of the power system. Before deregulation, the system operator was in charge of generation dispatch, which was made based on an economic dispatch or a unit commitment. Line congestion and other system constraints were managed by rescheduling the generators. After deregulation, generators are allowed to self-commit and the ISO has little intervention in the transactions between market participants, but the ISO is the entity that authorizes and manages the transactions. For this reason the ISO is entitled to know the bidding prices and the amount of the transactions.

The ISO receives the transaction information from the market participants and this information is what constitutes the BTM. The BTM is created by the bilateral transactions of the market participants when the market participants define their transactions.

The BTM is the transaction matrix that is formed by the transactions defined by the market participants. The ISO keeps and maintains this information and uses it as the dispatch schedule when the ISO has confirmed that all transactions in the BTM do not cause line congestion or other problems to the power system. To achieve this, the ISO also has the authority to authorize or deny the transactions, apply penalties to the transactions that cause line congestion and maintain the information system necessary for a reliable and smooth bidding process and power allocation process.

The ISO does not participate in the decision of the price of each transaction and it does not decide the amount of transactions. The price and the amount of the transactions is a decision of the market participants, the ISO administrates the market information system that allows market participants to place bids and define their transactions in a free market environment.

The next section describes the BTM creation algorithm, and the market mechanism is described in the following section.

2. BTM Creation Algorithm

The BTM creation algorithm consists of two parts. One is the bidding process itself and the other is the demand allocation. Figure 1 shows the first part of the algorithm, where prices are decided in a bidding process that allows buyers and sellers to bid a price for each node. The price is decided in an iterative manner with buyers starting their offers with a low price and incrementing the offer gradually until a price is decided. At the same time sellers make an initial offer at a high price and adjust their offers by gradually reducing their price until a price is decided. The selling price is decided when the price offered by the buyer is equal to or greater than the price offered by the seller, each node obtains a price for each generator and each generator obtains a price for each node. The bidding prices are based on the node's total demand for a particular hour and are determined in \$/MWh.

The bidding process begins with a day ahead load forecast provided by the ISO to the GENCOs, then the GENCOs provide the ISO with initial nodal bidding prices. This information is made available to the market participants and buyers make an initial offer to GENCOs. The information that is provided by the ISO to the market participants is the load forecast and the starting price for each hour for each node in the case of generators. In the case of nodes, the ISO provides them with the amount of power that each generator has available for sale and the starting price of each generator. The starting price for each generator is the price at node i, therefore each node knows only the price at which each generator is willing to sell power to that particular node and each generator knows only the prices at which each node wants to buy power from that particular generator. In addition to this, the ISO knows the prices of all nodes and generators, the load forecast, the amount of power that each generator has available for sale and the amount of power of each transaction that forms the BTM.

In a competitive market environment, participants must have sufficient incentive to reveal their private information, such incentive can be in the form of unconstrained transmission access for each market participant [14] or in the form of a technique developed by economists called mechanism design [15]. This information can be made available by means of an Open Access Same-time Information System (OASIS) as it is suggested in Ref. (8).

The market model presented in this paper has a centralized bidding, but the transactions are bilateral transactions defined by the market participants, which is different from the pool model. In the pool model the market participants bid a price for the spot market and generators are dispatched by the ISO from the cheapest to the most expensive. The price being paid to all participants is the same and it is determined by the spot price, which is defined by the most expensive generator that had to be dispatched to satisfy the demand. This differs from the market model presented in this paper, because this paper considers only bilateral transactions that are defined by the market participants. The price and the amount of those transactions are determined by the market participants with little intervention from the ISO. The ISO administers the bidding process and authorizes or denies the transactions depending on the system conditions at the time the transactions are scheduled to be dispatched. In a deregulated environment, market participants are free to make a particular bilateral or multilateral transaction, even the pool can be considered an individual participant of the transmission system as it has been demonstrated in Ref. (18), which considers the pool as a multilateral transaction comprising the entire system.

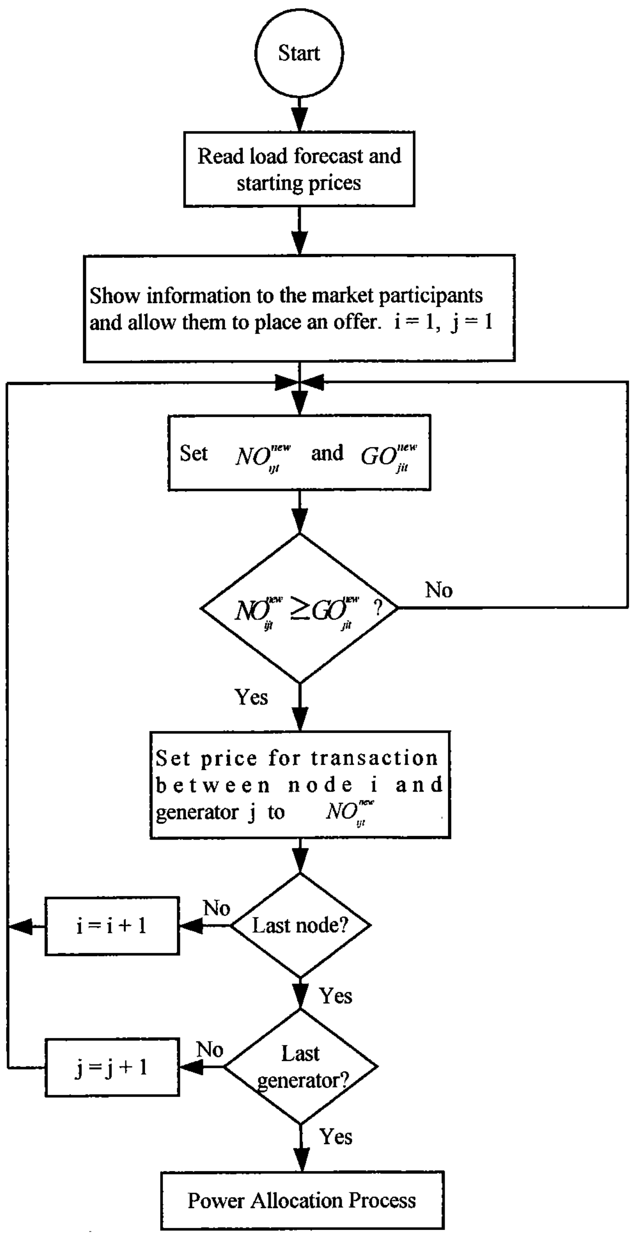

Fig. 1. First part of BTM creation algorithm

In this paper, the bidding process is a market simulation in which prices reflect the law of supply and demand. If the demand increases, the market prices also increase, and if the demand decreases, the market prices decrease. GENCOs want to sell their energy at the highest price and buying participants want to satisfy their demand at the lowest price; therefore market participants place their offers and make adjustments by increasing or decreasing their offer according to the market and the competition from other participants. Initially market participants offer only a price in \$/MWh for each node, according to the node's demand. The initial buying and selling offer prices are determined by Eqs. (1) and (2) respectively.

$$NO_{ijt} = NP_{ijt} + W_i * \Delta P_{it} \quad \cdots\cdots (1)$$

$$GO_{jit} = NP_{ijt} + W_j * \Delta P_{it} \quad \cdots\cdots (2)$$

where NO_{ijt} is the bidding offer made by node i to generator j at time t. GO_{jit} is the bidding offer made by generator j to node i at time t. NP_{ijt} is the start asking price for time t, at which generator j is willing to sell its energy to node i, which is the same price as the price at which power was sold in the previous hour. ΔP_{it} is the change in the demand of node i between time t and time t-1. W_i and W_j are the weights of node i and generator j respectively. These weights represent the price adjustments made by node i and generator j to adjust their offer to the change in demand. W_i and W_j are generated randomly to simulate the behavior of buyers and sellers during the price offering process at the beginning of the bidding process for each hour of the load forecast. These weights are generated using the random number function of FORTRAN 90 which returns a pseudo random number for the uniform distribution. W_i and W_j can have any value between 0 and 0.001, these values where found to be adequate to adjust the dimensions of the demand in MW to a \$/MWh value and to add the supply and demand component to the price offering process.

Equations (1) and (2) reflect the changes in demand and the prices increase or decrease according to the increments or decrements in the demand, considering both the amount of power and the price of that power amount at the same time. After an initial offer is made by buyers and sellers, Eqs. (3) and (4) are used to determine the final price for a transaction between node i and generator j. The price is decided by the iterative process of Fig. 1, which is an algorithm that considers the seller's profit and the buyers cost at the same time. The price is decided when the sellers bidding curve and the buyers bidding curve intercept each other, guaranteeing in this way the price that is decided is the maximum price possible for the sellers and the minimum price possible for the buyers.

After an initial offer is made, node i and generator j adjust their offer by increasing or decreasing the price until a price is set. Equations (3) and (4) describe the bidding price adjustment made by node i and generator j respectively.

$$NO_{ijt}^{new} = NO_{ijt} + \Delta NO_{ijt} \quad \cdots\cdots (3)$$

$$GO_{jit}^{new} = GO_{jit} - \Delta GO_{jit} \quad \cdots\cdots (4)$$

where NO_{ijt}^{new} and GO_{jit}^{new} are the new offer prices of node i and generator j respectively for time t. ΔNO_{ijt} and ΔGO_{jit} are the changes in price that node i and generator j make at each moment during the iteration process. The price between node i and generator j is set to NO_{ijt}^{new} when $NO_{ijt}^{new} \geq GO_{jit}^{new}$. If the price is not set, ΔNO_{ijt} and ΔGO_{jit} are generated randomly, using the random number function, every time that a new price is required in the iterative process until $NO_{ijt}^{new} \geq GO_{jit}^{new}$. ΔNO_{ijt} and ΔGO_{jit} can have values between 0 and 0.01 \$/MWh, this range of values was used so that the price setting process has a fast convergence. If the generator's price is too high, then the generator lowers its price by ΔGO_{jit}. If the node's offer is too low, then the node increases its offer by ΔNO_{ijt}. These price adjustments continue until the price of the transaction between generator j and node i is set. Then the price setting process continues with the next node until all nodes have a price that corresponds to generator j. The same process is repeated for the next generator, until all generators have set a price for each and every node in the system.

Each node obtains bid prices for all GENCOs and each GENCO obtains bid prices for all nodes. This allows market participants to decide to which node a GENCO sells its energy and from which GENCO a node buys its energy, maintaining the policy that GENCOs want to sell to the highest bidder and nodes want to buy from the cheapest GENCO.

After all nodal prices for all generators have been set, the power allocation process starts. In this part of the algorithm nodes and generators decide the amount of power that they buy and sell; nodes decide from which generators they buy and generators decide to which nodes they sell. Figure 2 shows the second part of the BTM creation algorithm, which corresponds to the demand allocation. In the proposed mechanism the price of transactions is freely determined by the market participants through bilateral transactions, therefore the price of each transaction is different from other transactions. Each generator is paid the price set by the bidding process for each node, depending on the amount of power that each generator sells to each node.

The algorithm shown in Fig. 2 is where the power amounts of each transaction are decided, nodes and generators decide the amount of power that they buy and sell; nodes decide from which generators they buy and generators decide to which nodes they sell.

The reason for determining the price of each transaction in the bidding process before the specific amount of power is allocated in the power allocation process is based on Sheblé's model for a double sided auction for electricity Ref. (17), where the price of electricity is independent of who is buying the electricity at node i. The price is determined by the rules of the bidding process, which is a sub-problem of the power allocation process. The price at node i is the price of 1 MWh sold by generator j to node i independently of who the buyer is (a distribution company, a big user or an electricity

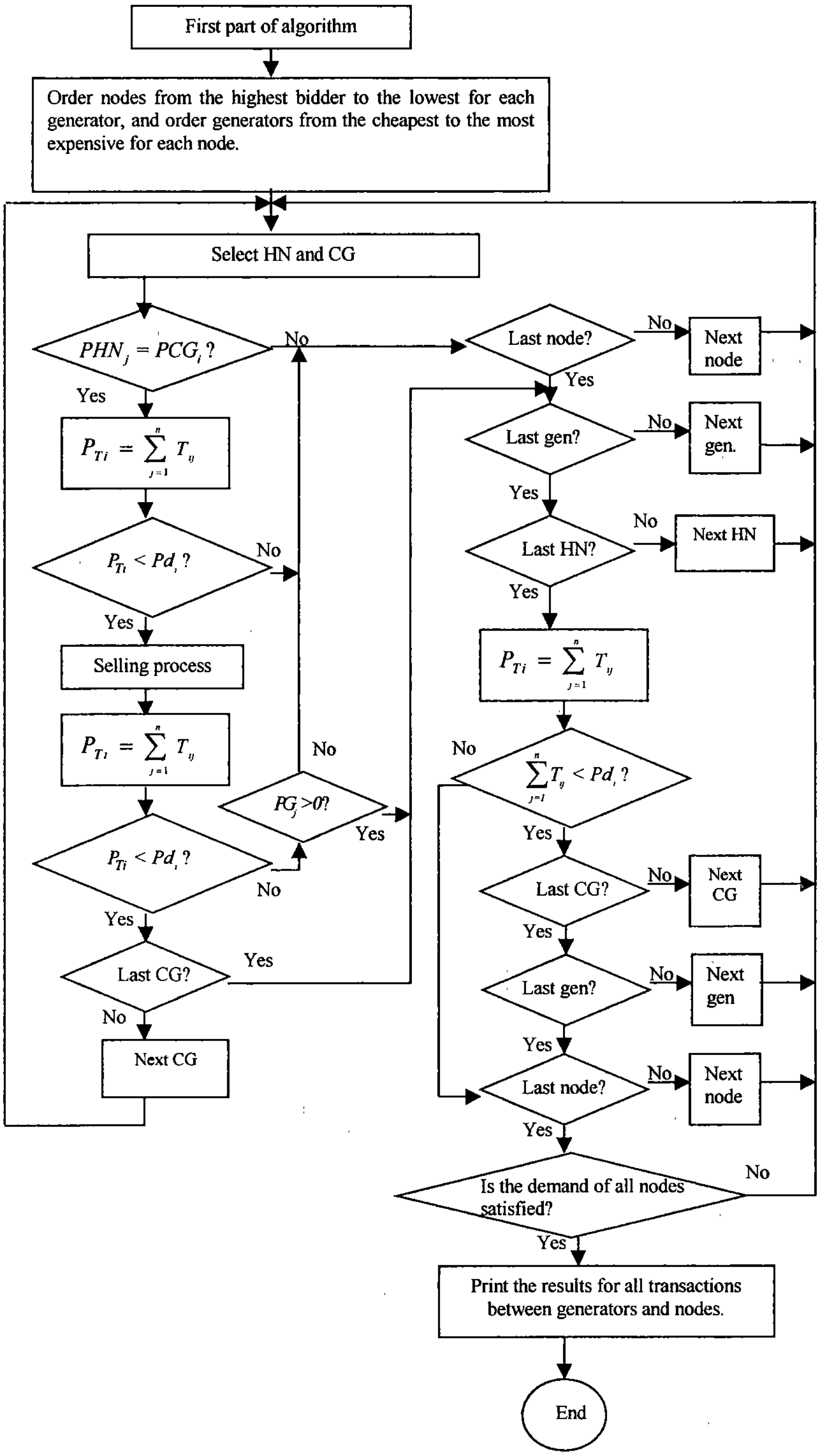

Fig. 2. Demand allocation algorithm (second part of BTM creation algorithm)

broker). The result is the sale of x_{ij} amount of power from generator j to node i at a price previously determined in the bidding process. The double sided electricity auction is defined as a power allocation problem with a different price for each node allowing buyers to buy power from different generators. Each generator has a different unit price for each node, which is determined by buyers and sellers during the bidding process.

Power balance is always obtained by the power allocation process of Fig. 2 because the process is repeated until all demand is satisfied and the generators available power is always checked before a transaction takes place. The process is an iterative process that does not stop until power balance is obtained. The process of Fig. 1 is not repeated because in the demand allocation algorithm power balance is always obtained.

Once prices have been set by the bidding process, GENCOs order nodes from the highest bidder to the lowest and nodes order generators from the cheapest to the most expensive. This sorting is necessary to assure that the selection of the highest priced node (HN) for each generator always starts from the highest bidder and the selection of the cheapest generator (CG) for each node always starts from the cheapest generator. This sorting is also needed every time the nodal prices change after penalties have been applied to the transactions that cause line congestion.

After the sorting process, the highest priced node (HN) and the cheapest generator (CG) are compared for each generator and each node respectively. The process continues until HN of generator j corresponds with CG for node i, that is if HN for generator j is node i and CG for node i is generator j, then HN and CG correspond to each other. If HN and CG do not correspond then each generator and each node continues searching with the next HN in the case of generators and with the next CG in the case of nodes, until a corresponding HN and CG pair is found.

In Fig. 2, PHN_j is the price of the highest node for generator j and PCG_i is the price of the cheapest generator for node i. These two prices should be equal for a transaction to be considered, since the prices have been set by the bidding process and they do not change during the demand allocation. The total amount of power bought by node i is determined by Eq. (5).

$$P_{Ti} = \sum_{j=1}^{n} T_{ij} \quad \cdots\cdots (5)$$

where P_{Ti} is the summation of all transactions made by node i and T_{ij} is the amount of power for the transaction between node i and generator j. In Fig. 2, Pd_i is the real power demand of node i. If $P_{Ti} < Pd_i$, the selling process starts and a transaction can be made.

The selling process is shown by Eqs. (6) and (7), where generator j sells its energy to node i. If generator j has more power than the demand of node i, then generator j satisfies all of the demand for node i. If the demand of node i is greater than the power that generator j has available, then node i buys all of the available power from generator j and a transaction is made.

$$\text{If } PG_j > Pd_i \text{ then } \begin{cases} T_{ij} = Pd_i \\ PG_{j,new} = PG_j - Pd_i \\ Pd_{i,new} = 0 \end{cases} \quad \cdots\cdots (6)$$

$$\text{If } PG_j < Pd_i \text{ then } \begin{cases} Pd_{i,new} = Pd_i - PG_j \\ T_{ij} = PG_j \\ PG_{j,new} = 0 \end{cases} \quad \cdots\cdots (7)$$

where PG_j is the power that generator j has available for sale, $PG_{j,new}$ is the power of generator j after a sale is made and $Pd_{i,new}$ is the new demand of node i after node i has bought power from generator j.

After the selling process, the summation of all transactions for node i is recalculated and compared with the new demand for node i. If the demand is satisfied and generator j still has power available ($PG_j > 0$), then generator j offers its energy to the next HN. If node i has satisfied its demand, the process continues with the next node. If not, node i tries to buy energy from the next CG. The process continues for all nodes and generators until all the demand has been satisfied assuring in this way that a feasible BTM is always obtained.

3. Market Mechanism

The market mechanism is shown in Fig. 3. It starts with a BTM created by the BTM creation algorithm. The BTM is used as transaction schedule for a DC power flow program, which calculates line power flows, monitors congestion and provides the data for the calculation of the contribution to congestion that each transaction makes.

The contribution to congestion is calculated in an approach similar to Ref. (6), which proposes a method for allocating transmission services to individual transactions using an AC power flow to obtain the data for reactive power allocation for each generator. The authors of Ref. (6) extensively tested their method on a real life system and their results provide a very accurate assessment of the impact of transactions on the transmission system. Two power flows are performed for each transaction, one including only transaction t and the other including all transactions except transaction t. A base case power flow without transactions and a power flow including all transactions are also performed. The accuracy of this method justifies its computational burden.

The base case power flow refers to the power flow of the system at the time when the bilateral transactions start. For example, Assume that at this moment there is no bilateral transactions in the power system and the system is operating at a stable operation point with a perfect power balance, then a group of market participants inform the ISO that they want to make some transactions one hour from now, then the power flow at this moment becomes the base case power flow which are the initial conditions before bilateral transactions take place. The ISO then runs a power flow to determine if the intended bilateral transactions do not cause any system constraint violations (line congestion, voltage regulation problems, etc). If there are no violations then the ISO authorizes those transactions and operates the system until it reaches a new stable operation point. If another group of market participants want to make some transactions, the power flow at that moment becomes the new base case power flow and the process is repeated.

In this paper the bilateral transactions considered are real power transactions. Reactive power is not considered, therefore a DC power flow is used to produce the data for calculation of the contribution that each transaction makes to line congestion, by identifying which lines are congested, and indicating the amount of such congestion.

Using a DC power flow model it is relatively simple to calculate the participation factors, therefore the simplest approach to allocate congestion penalties is to apply these penalties to all transactions by dividing the excess flow in a pro-rata manner among the bilateral

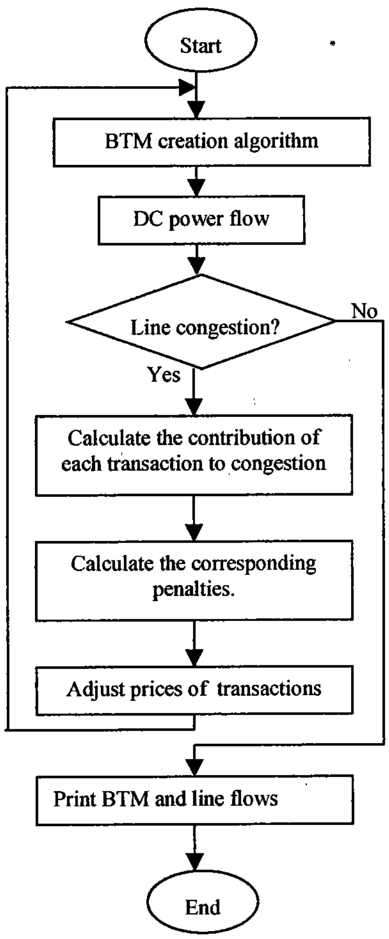

Fig. 3. Market mechanism

transactions weighted by the participation factors. This approach is acceptable if the price of congestion is small, or if congestion is not frequent, but as the number of bilateral transactions increase in the deregulated environment congestion and other constraint violations might be frequent. Therefore it is necessary to determine the contribution of each transaction to congestion in an accurate and efficient way. The method proposed in Ref. (6) is applied in this paper to the DC model by deducting the corresponding equations for real power from the equations of the AC model. The transaction contribution to the line flow is shown by Eq. (8).

$$\Delta P_{ij,t} = \frac{1}{2}(\Delta P^1_{ij,t} + \Delta P^T_{ij,t}) + mc_{ij} \cdots\cdots\cdots (8)$$

where $\Delta P_{ij,t}$ is the contribution to the line flow from node i to node j due to transaction t. $\Delta P^1_{ij,t}$ is the change in the line flow between the base case and the power flow resulting from adding transaction t. $\Delta P^T_{ij,t}$ is the change in the line flow between the base case and the power flow resulting from adding all transactions except transaction t. mc_{ij} is the minor component for line from node i to node j, which is explained later in this paper. The units of $\Delta P_{ij,t}$, $\Delta P^1_{ij,t}$, $\Delta P^T_{ij,t}$ and mc_{ij} are in MW. The major component is the average of $\Delta P^1_{ij,t}$ and $\Delta P^T_{ij,t}$, this component is shown by Eq. (9).

$$\Delta \overline{P_{ij,t}} = \frac{1}{2}(\Delta P^1_{ij,t} + \Delta P^T_{ij,t}) \cdots\cdots\cdots (9)$$

The summation of Eq. (9) is represented in Eq. (10) by $\Delta \overline{P_{ij}}$, which is the total amount of aggregated power allocated to each transmission line necessary to calculate the minor component.

$$\Delta \overline{P_{ij}} = \sum_t \Delta \overline{P_{ij,t}} \cdots\cdots\cdots (10)$$

The minor component is shown by Eq. (11) where ΔP_{ij} is the change in the line power flow between the base case and the flow when all transactions are considered.

$$mc_{ij} = \Delta P_{ij} - \Delta \overline{P_{ij}} \cdots\cdots\cdots (11)$$

The minor component is the difference between the total amount of aggregated power obtained in Eq. (10) and the actual power flow, this mismatch is small compared to the major component. The minor component calculated in Eq. (11) is the mismatch in Eq. (8) and occurs because the calculated amounts are the difference in power not the difference in current and the law of superposition is not satisfied in the case of calculating the differences in power. The amount of this mismatch is in the order of 0.001 to 0.01 MW and is evenly distributed among all transactions.

After the contribution of each transaction to the line power flow has been calculated for all lines, the contribution to congestion is calculated. If there is no congestion in the line from node i to node j, the contribution to congestion for all transactions is 0, but if the line has congestion, then the contribution of each transaction is calculated. The total power flow for line from node i to node j is calculated using Eq. (12).

$$TPF_{ij} = \sum_{t=1}^{T} \Delta P_{ij,t} + P_{bij} \cdots\cdots\cdots (12)$$

where TPF_{ij} is the total power flow in MW for line from node i to node j, $\Delta P_{ij,t}$ is the transaction contribution calculated in Eq. (8), T is the total number of transactions, P_{bij} is the base power flow in MW for line from node i to node j. Line congestion exists when TPF_{ij} is greater than the line limit. If line congestion is found then the amount of congestion is calculated using Eq. (13).

$$LC_{ij} = \begin{cases} 0, \text{ if } |TPF_{ij}| \leq LPL_{ij} \\ |TPF_{ij}| - LPL_{ij}, \text{ if } |TPF_{ij}| > LPL_{ij} \end{cases} \cdots\cdots\cdots (13)$$

where LC_{ij} is the line congestion and LPL_{ij} is the line power limit for line from node i to node j. LC_{ij} and LPL_{ij} are in MW. The contribution to congestion for each transaction is calculated using Eq. (14).

$$CTC_{ij,t} = \frac{\Delta P_{ij,t}}{\sum_{t=1}^{T} \Delta P_{ij,t}} * LC_{ij} \cdots\cdots\cdots (14)$$

where $CTC_{ij,t}$ is the contribution to congestion of line from node i to node j, caused by transaction t.

After the contribution to congestion of each transaction has been determined, the corresponding penalties are calculated by multiplying the price of congestion and the $CTC_{ij,t}$ as shown in Eq. (15).

$$Pen_{ij,t} = CTC_{ij,t} * CP_{ij} \cdots\cdots\cdots\cdots\cdots\cdots (15)$$

where $Pen_{ij,t}$ is the penalty applicable to the contribution to line congestion made by transaction t for line from node i to node j and CP_{ij} is the congestion price in \$/MWh.

The prices of congestion are based on contracts previously signed between GENCOs and the Transmission Provider (TP). These prices are defined in a \$/MWh basis and the rates are agreed in advance with the ISO which calculates the congestion and the corresponding penalties for each line that must be applied to transactions contributing to congestion. If there is no congestion, then no penalties are applied and the ISO dispatches all the transactions scheduled. If congestion exists then the ISO calculates the corresponding penalties and provides this data to all participants in the market to allow them to reschedule their transactions.

Congestion penalties are the difference in the new nodal bidding prices of the transactions that cause congestion. If the total line flow is positive, the transactions that contribute with a positive flow pay the corresponding penalty and the transactions with a negative flow are allowed to lower their price, as a compensation for contributing to clear congestion. The opposite happens if the total line flow is negative. These changes are applied to the original prices obtained by the bidding process and are used as feedbacks for the demand allocation part of the BTM creation algorithm. The prices after penalties are shown by Eq. (16).

$$PAP_{ij,t} = NO_{ijt}^{new} + Pen_{ij,t} \cdots\cdots\cdots\cdots\cdots (16)$$

where $PAP_{ij,t}$ is the price after penalties for transaction t between node i and generator j.

Once new prices have been defined for the transactions that cause congestion, the algorithm continues with the sorting process and the selection process to define new HN and new CG for generator j and node i respectively. Then the demand allocation algorithm continues with the rest of the process until a new BTM is obtained. The BTMs obtained by the demand allocation algorithm are always feasible due to the iterative process that continues until all the demand has been satisfied. Once a new BTM has been obtained, the process described in Fig. 3 is repeated until a BTM that causes no line congestion is obtained. The cost of each BTM to society can be calculated by Eq. (17).

$$CTS = \sum_{t=1}^{T} T_{ijt} * PAP_{ijt}$$
$$(i = 1, 2, \cdots m, j = 1, 2, \cdots, n) \cdots\cdots\cdots (17)$$

where CTS is the cost to society, T_{ijt} is the amount in MW of transaction t, m is the number of nodes and n is the number of generators. The cost to society that is calculated by Eq. (17) represents the total cost of the BTM. This calculation is used in this paper as a means to compare the benefits obtained by the market mechanism when congestion has been eliminated. This comparison is shown in Table 9. The calculation of the benefits and profits of each market participant is outside the scope of this paper.

4. Simulation

The simulation was made using the IEEE 14 bus sample system with 5 generators and 11 nodes with demand and the IEEE 300 bus system with 69 generators and 193 nodes with demand. The first part of the simulation consists of the use of the BTM creation algorithm and a DC power flow program to find a BTM that causes line congestion. Table 1 shows the initial BTM for the IEEE 14 bus system, which is used as the starting point for the market mechanism. The BTM is shown in a table form, which shows the amount in MW of the transaction between node i and generator j. The row labeled Gen Capacity is the maximum generation that each generator has. Gen Sale is the total amount of power sold by generator j and Gen Margin is the total amount of unsold energy.

Table 2 shows the initial nodal prices for the same system obtained by the bidding process of the BTM creation algorithm. Each node has a different price for each GENCO as a result of bilateral negotiations between market participants, then the actual transactions are decided by the demand allocation algorithm shown in Fig. 2. The result of this algorithm is the initial BTM shown in Table 1. The demand allocation algorithm always produces a feasible BTM because the process is repeated until all demand is satisfied; in some cases the nodes have to buy power at a higher price for example in the case of NOD-4, it is buying energy from GEN-3 at a higher price, because GEN-2, GEN-6 and GEN-8 have

Table 1. Initial BTM for the IEEE 14 bus system (Figures are in MW)

Node	GEN-1	GEN-2	GEN-3	GEN-6	GEN-8	Demand
NOD-1	0.000	0.000	0.000	0.000	0.000	0.000
NOD-2	45.058	0.000	22.529	38.177	0.000	105.764
NOD-3	135.586	0.000	0.000	0.000	0.000	135.586
NOD-4	0.000	0.000	114.478	0.000	0.000	114.478
NOD-5	16.684	0.000	0.000	0.000	0.000	16.684
NOD-6	26.716	0.000	0.000	0.000	0.000	26.716
NOD-7	0.000	0.000	0.000	0.000	0.000	0.000
NOD-8	0.000	0.000	0.000	0.000	0.000	0.000
NOD-9	10.699	40.000	17.935	0.000	0.000	68.634
NOD-10	25.052	0.000	0.000	0.000	0.000	25.052
NOD-11	0.000	0.000	0.000	8.507	2.975	11.482
NOD-12	0.000	0.000	0.000	13.316	0.000	13.316
NOD-13	0.000	0.000	0.000	0.000	32.607	32.607
NOD-14	0.000	0.000	0.000	0.000	24.419	24.419
Total	259.795	40.000	154.942	60.000	60.000	574.737
Gen capacity	300	40	200	60	60	
Gen margin	40.205	0.000	45.058	0.000	0.000	
Gen sale	259.795	40.000	154.942	60.000	60.000	

Table 2. Initial nodal prices in $/MWh for the created BTM (IEEE 14 bus system)

	GEN-1	GEN-2	GEN-3	GEN-6	GEN-8
NOD-1	0.000	0.000	0.000	0.000	0.000
NOD-2	11.286	13.684	15.918	20.243	13.676
NOD-3	15.686	17.361	20.271	24.410	17.281
NOD-4	15.807	16.957	19.768	22.372	14.516
NOD-5	13.534	14.536	16.853	19.029	12.337
NOD-6	14.386	15.454	17.540	17.655	14.326
NOD-7	0.000	0.000	0.000	0.000	0.000
NOD-8	0.000	0.000	0.000	0.000	0.000
NOD-9	16.418	17.639	20.048	21.169	15.179
NOD-10	15.447	16.586	18.856	20.016	14.260
NOD-11	13.879	14.880	16.952	16.951	13.740
NOD-12	13.552	14.451	16.423	16.397	13.479
NOD-13	16.593	17.787	20.109	20.094	16.557
NOD-14	14.620	15.639	17.318	18.587	13.557

Table 3. Line flows and congestion in MW for the IEEE 14 bus system

Line	FN-TN	Rating	Initial Flow	Congestion	Final Flow
1	1-2	200	181.5	0	147.8
2	1-5	100	80.4	0	69
3	2-3	50	17.7	0	-6.3
4	2-4	50	55.5	5.5	49.1
5	2-5	50	41.9	0	38.7
6	3-4	60	37	0	58.1
7	4-5	50	-59.5	9.5	-45.7
8	4-7	30	16	0	16.6
9	4-9	22	21.1	0	21.4
10	5-6	50	46.1	0	45.2
11	6-11	20	17.7	0	17.3
12	6-12	20	18.3	0	18.2
13	6-13	50	43.2	0	42.8
14	7-8	80	-60	0	-60
15	7-9	80	76	0	76.6
16	9-10	20	18.9	0	19.3
17	9-13	12	9.2	0	9.7
18	10-11	12	-6.2	0	-5.8
19	12-13	12	4.9	0	4.8
20	13-14	25	24.6	0	24.6

sold all of their available power before NOD-4 can satisfy its demand and GEN-1 does not have enough available power to cover all of the demand of NOD-4.

Table 3 shows the congestion caused by the transactions of Table 1, the initial power flow corresponding to the initial BTM and the final power flow that corresponds to the new BTM shown in Table 5. In Table 3 each line is shown by from node (FN) and to node (TN). The rating column represents the line power limits. Fig. 4 shows the diagram of the IEEE 14 bus system, congestion caused by the initial BTM is shown by the bold lines.

The transactions of Table 1, cause congestion, therefore a BTM that does not cause congestion has to be found, this is done by using the market mechanism shown in Fig. 3. Table 4 shows the new prices after

Table 4. New prices in $/MWh (IEEE 14 bus system)

	GEN-1	GEN-2	GEN-3	GEN-6	GEN-8
NOD-1	0.000	0.000	0.000	0.000	0.000
NOD-2	**10.732**	13.684	**16.192**	**19.062**	13.676
NOD-3	**12.749**	17.361	20.271	24.410	17.281
NOD-4	15.807	16.957	**18.817**	22.372	14.516
NOD-5	**14.181**	14.536	16.853	19.029	12.337
NOD-6	**14.704**	15.454	17.540	17.655	14.326
NOD-7	0.000	0.000	0.000	0.000	0.000
NOD-8	0.000	0.000	0.000	0.000	0.000
NOD-9	**16.163**	**17.935**	**20.386**	21.169	15.179
NOD-10	**15.201**	16.586	18.856	20.016	14.260
NOD-11	13.879	14.880	16.952	**16.905**	**13.858**
NOD-12	13.552	14.451	16.423	**16.393**	13.479
NOD-13	16.593	17.787	20.109	20.094	**17.497**
NOD-14	14.620	15.639	17.318	18.587	**14.269**

Figures in bold show the transactions to which penalties were applied.

penalties have been calculated and applied to the transactions that cause congestion following the process described in Section 3. These new prices are used as a feedback for the demand allocation algorithm. The results of this algorithm are shown in Table 5, which shows the new BTM. The demand of every node is always satisfied in a feasible BTM, therefore a power balance is always obtained; generators compete with each other to sell their available power and nodes compete with other nodes to buy their energy as cheaply as possible, until all the demand is satisfied. The maximum power that generators can sell is limited by their maximum generation and the system's demand, for this reason some nodes might have to buy power from generators that have a high price, for example in Table 5, NOD-4 is buying power from GEN-6 because NOD-4 has not been able to satisfy all its demand and GEN-8 has sold all of its available power before NOD-4 can satisfy its demand. GEN-2 is also sold out and the other generators have already sold their energy to other nodes, this forces NOD-4 to buy its remaining energy from GEN-6 at the price that GEN-6 is selling its energy, even if GEN-6 is the most expensive generator for NOD-4. This is the result of the power allocation process explained in Section 2, which repeats the power allocation until all the demand is satisfied, even if a node is obligated to buy from the most expensive generator in order to satisfy its demand.

The new BTM causes no line congestion; this can be verified in Table 3 by comparing the final flow column with the rating column. All flows of the final flow column are smaller than the line limits, this indicates that there is no congestion.

The bilateral transaction model is based on the concept of free market competition, where market participants trade energy in their own financial terms then request the ISO to authorize the dispatch and provide access to the transmission system. The responsibility of the ISO is to assure a reliable system operation and authorize the transactions that do not cause line

Table 5. New BTM for the IEEE 14 bus system (Figures are in MW)

Node	NOD-1	NOD-2	NOD-3	NOD-6	NOD-8	Demand
NOD-1	0.000	0.000	0.000	0.000	0.000	0.000
NOD-2	105.764	0.000	0.000	0.000	0.000	105.764
NOD-3	27.205	40.000	68.381	0.000	0.000	135.586
NOD-4	0.000	0.000	0.000	54.478	60.000	114.478
NOD-5	16.684	0.000	0.000	0.000	0.000	16.684
NOD-6	26.716	0.000	0.000	0.000	0.000	26.716
NOD-7	0.000	0.000	0.000	0.000	0.000	0.000
NOD-8	0.000	0.000	0.000	0.000	0.000	0.000
NOD-9	0.000	0.000	63.112	5.523	0.000	68.634
NOD-10	25.052	0.000	0.000	0.000	0.000	25.052
NOD-11	0.000	0.000	11.482	0.000	0.000	11.482
NOD-12	13.316	0.000	0.000	0.000	0.000	13.316
NOD-13	0.000	0.000	32.607	0.000	0.000	32.607
NOD-14	0.000	0.000	24.419	0.000	0.000	24.419
Total	214.737	40.000	200.000	60.000	60.000	574.737
Gen capacity	300	40	200	60	60	
Gen margin	85.263	0.000	0.000	0.000	0.000	
Gen sale	214.737	40.000	200.000	60.000	60.000	

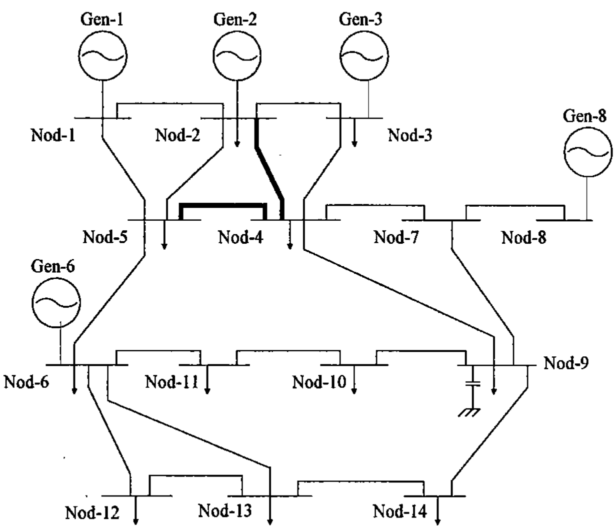

Fig. 4. IEEE 14 bus system: Congested lines are in bold

congestion therefore a BTM that does not cause line congestion is a sufficient condition for the ISO to authorize the transactions.

To determine the capability of the mechanism on large size power systems, the market mechanism was tested using the IEEE 300 bus sample system. The initial BTM required 243 transactions to obtain power balance and satisfy all of the system's demand. This BTM is very large therefore only some transactions are shown in Table 6. The 300 bus system has a total of 409 transmission lines and the initial BTM causes 177 lines to be congested. Table 7 shows some of the congested lines. The amount of congestion can be determined by subtracting the rating column from the initial flow column.

In Table 7, the final flow column indicates the flows that correspond to the final BTM, these flows are lower than the line limits indicated by the rating column; therefore there is no congestion on these lines.

The final BTM for the 300 bus system required 239

Table 6. Some of the initial transaction for the IEEE 300 bus system

Gen	Node	MW	Gen	Node	MW	Gen	Node	MW
7039	1	178.07	141	76	359.15	9054	152	33.64
7003	2	110.80	227	76	52.38	239	154	138.50
7130	3	39.57	190	77	146.41	241	155	146.41
7139	5	592.13	149	79	94.97	243	155	249.30
9051	5	106.30	191	80	55.40	238	156	74.96
7024	6	237.43	7012	84	73.21	9054	156	73.43
7001	8	114.76	7002	89	87.45	221	157	244.35
7166	9	189.94	84	90	130.58	186	159	65.29
222	10	292.82	7002	91	34.43	221	161	69.25
222	11	164.22	143	92	31.26	119	162	59.73
241	13	114.76	7166	94	119.31	143	162	108.44
236	14	316.57	7017	97	78.94	239	167	388.69
7049	15	250.68	221	98	131.97	7012	167	204.68
143	17	1109.96	91	99	165.21	7003	170	89.65
10	20	14.80	91	102	153.93	7062	170	863.61
124	20	712.30	7049	103	63.31	152	171	486.92
220	20	296.80	143	104	17.02	230	171	1023.90
7003	20	153.33	149	105	98.14	7001	172	52.43
7130	21	152.35	239	107	9.10	7062	173	323.49
138	22	160.26	7166	108	221.79	221	175	132.09
236	23	41.55	7139	109	60.74	239	175	216.14
236	25	89.03	152	110	124.65	7003	176	9.89

Table 7. Line flows and congestion in MW for the IEEE 300 bus system.

From	to	Initial	Rating	Final	From	to	Initial	Rating	Final
1	3	138.9	98	-95.6	59	61	-859.4	767	-746.1
1	5	1324.8	880	855.1	60	62	-1659.0	1039	-1010.9
1	7001	-1731.8	1058	-1027.5	62	64	544.5	530	514.8
2	8	1187.5	1179	1145.2	62	144	-569.8	230	221.3
3	4	2629.9	2123	2064.7	63	64	-538.1	523	-508.4
3	19	307.5	190	184.9	69	79	-173.1	116	-112.8
3	150	341.6	90	-65.5	69	201	135.1	128	124.2
3	7003	-2941.2	1534	-1490.2	69	211	38.1	23	-11.5
4	16	2629.9	2123	2064.7	71	73	-140.8	119	-116.1
5	9	276.8	148	90.2	73	74	-759.8	669	-649.5
7	131	270.4	38	-5.2	73	76	211.3	120	117.1
8	11	-53.0	21	-19.6	73	79	92.4	39	-38.8
8	14	1069.8	1023	994.2	74	88	687.7	323	314.4
10	11	-120.3	83	-80.9	77	80	257.0	145	140.8
11	13	497.9	395	384.1	79	211	95.6	40	39.7
12	21	981.9	815	792.0	80	211	173.6	59	57.4
13	20	323.3	216	209.5	81	88	-565.5	236	-174.5
14	15	581.9	520	506.2	81	194	1883.2	1228	1193.4
15	37	54.2	26	24.7	81	195	1623.0	1023	994.3
16	42	2057.9	1422	1383.4	85	86	-309.8	276	-268.8
17	7017	-984.7	907	-881.0	85	99	309.8	276	268.8
19	87	530.1	479	465.8	86	87	-363.7	324	-315.2

transactions to satisfy the system's demand, some of these transactions are shown in Table 8.

The results obtained using the IEEE 300 bus system show that the market mechanism proposed in this paper can handle a large size power system, a large number of transactions and a large number of congested lines.

Table 9 shows the cost associated with each BTM,

Table 8. Some of the final transactions for the IEEE 300 bus system

Gen	Node	MW	Gen	Node	MW	Gen	Node	MW
84	1	178.07	7071	71	229.51	7012	155	395.71
92	2	98.30	243	72	112.78	7002	156	148.39
9002	2	12.50	119	73	443.19	138	157	244.35
92	3	39.57	7039	76	411.54	91	159	65.29
143	5	595.81	7017	77	146.41	190	161	69.25
9051	5	102.62	149	79	94.97	63	162	6.40
241	6	8.60	191	80	55.40	138	162	161.77
7057	6	228.83	239	84	73.21	191	167	593.37
119	8	114.76	7023	89	24.69	7062	170	953.26
190	9	189.94	7130	89	62.76	152	171	486.92
7003	10	292.82	7001	90	130.58	230	171	1023.90
7166	11	164.22	63	91	10.73	236	172	52.43
7017	13	114.76	9055	91	23.70	143	173	200.84
92	14	316.57	170	92	31.26	177	173	88.64
119	15	250.68	7166	94	119.31	7049	173	34.01
76	17	19.80	7017	97	78.94	221	175	176.73
213	17	807.20	241	98	131.97	7002	175	171.49
7130	17	282.96	84	99	165.21	7166	176	9.89
10	20	14.80	141	102	153.93	7001	177	43.36
124	20	712.30	241	103	63.31	7062	177	12.04
220	20	296.80	7023	104	17.02	7049	178	845.63
7003	20	153.33	143	105	98.14	222	179	146.41

Table 9. BTM costs in $

	IEEE 14	IEEE 300
Initial BTM	9541.94	708551.16
New BTM	9519.63	689814.20

showing that the new BTM has a lower cost than the initial BTM. The new BTM is the result of congestion management using the proposed market mechanism. Table 9 shows that the total cost of the BTM after congestion management, represented by the new BTM is lower than the cost of the initial BTM that causes line congestion. This result is obtained because the transactions that contribute to relieve congestion are allowed to lower their price, this allows to increase the power amount of those transactions and reduce the power amount of the transactions that cause line congestion, stimulating in this way the transactions that do not cause line congestion. Since the transactions that contribute to congestion clearance have a lower price than the transactions that cause line congestion, the buying participants increase the amount of their transactions from the generators that have a lower price, for this reason the total cost of the BTM obtained after congestion clearance is lower than the total cost of the BTM before congestion. Therefore the BTM before congestion has a higher price for the transactions than the BTM after congestion clearance. The market participants have increased the transaction amount of the transactions that do not cause line congestion as shown in Table 5. For example GEN-1 was selling 45.058 MW to NOD-2 at 11.286 $/MWh before congestion management, but when penalties were applied to the transactions that cause line congestion and the transactions that contribute to relieve congestion were allowed to lower their price, then GEN-1 increased the transaction amount sold to NOD-2 to 105.764 MW at 10.732 $/MWh.

5. Conclusions

A mechanism for line congestion clearance in a deregulated market environment has been presented. This mechanism is useful to study the effects of bilateral transactions on a power system and helps the Independent System Operator (ISO) to create rules for line congestion clearance and power flow control in a deregulated market environment.

The line flows are the result of the power injections caused by the bilateral transactions defined by the market participants in the BTM creation algorithm. If congestion exists a new BTM is found after penalties are applied, the new BTM is affected by the price of congestion, which depends on the contracts between GENCOs and the transmission provider.

The market model proposed in this paper is based on the bilateral transaction model and includes a bidding process to determine the prices of the transactions that take place in the electricity market. Generators are allowed to self-commit and the ISO has little intervention in the transactions between market participants, but the ISO is the entity that authorizes and manages the transactions. Congestion management has been obtained by the application of penalties to the transactions that cause line congestion.

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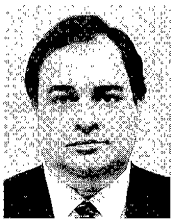

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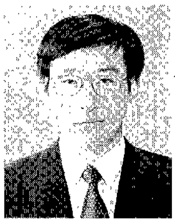

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