Multilateral Trading and Congestion Management in Deregulated Power Systems

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Abstract—Two market models, viz the bilateral trading model and pool trading model are in use in one form or other in the deregulated power systems. However the market models are still in the development stage and they have some inherent problem associated. To overcome some of the problems of bilateral and pool model another market model was proposed[1]. Congestion is a common problem in deregulated power systems. To relieve the congestion curtailment of load and generation may be necessary. A uniform curtailment procedure was proposed in [1], that ISO will adopt remaining neutral and allowing the brokers to find other profitable trades. An optimal congestion management algorithm in the multilateral trading model using sensitivity of the congested lines to the bus injections is proposed in this paper. Some results of the study are presented.

Keywords—power systems, deregulation, multilateral trading, congestion management

I. INTRODUCTION

In a traditional power system, the generation, transmission and distribution are managed or controlled by a single central entity, the utility. All financial and operational decisions are within the control of the energy management system of the utility. Such a power system is termed as Vertically Organized Utility (VOU).

The steady state characteristics of a power system are governed by the following equations.

\[ P_D + P_L - \sum P_i = 0 \]  
\[ P_{G_{\text{max}}} \leq P_{G_i} \leq P_{G_{\text{imin}}} \]  
\[ I_{km} = (V_k - V_m)y_{km} + V_k \frac{y_{km}}{2} \]

(1) represents the power balance in a system. (2) signifies that for every generator the generation must be within maximum and minimum limits. (3) represents the current flow in the line from bus \( k \) to bus \( m \). Each transmission line has a maximum capacity of carrying current mainly because of its thermal or stability limits. A line is said to be congested when it is carrying current above its limit.

II. POWER SYSTEM DeregULATION

The deregulation of industries, such as telecommunications, air-lines, gas etc, yielded economic benefits to a great extent in developed countries like USA, UK, Norway, Sweden, Australia, etc.[2] As a result the concept of deregulation of Electric Power System has also been conceived. In India restructuring of the SEBs have already started towards an ultimate goal of deregulation of the power system.

When the generation, transmission, distribution, and system control are separated in terms of management and ownership, the power system is said to be deregulated. A typical deregulated power system can be represented as a block diagram as shown in Fig I. [3]

The generation utilities designed as GenCo will compete in the free market to sell the electricity they produce. The bulk power purchasers, industrial power users and the local distribution companies will be termed as DisCo. The entity that will carry power from GenCo to DisCo or from one utility to another via transmission lines are termed as TransCo. There may be one TransCo in the whole country as in Norway or may be more than one TransCos as in USA. In the deregulated environment of the power system, there may be transfer of power directly between a GenCo and DisCo or GenCo to DisCo via TransCo or from one GenCo to TransCo to another TransCo via tie lines to a DisCo connected to the other TransCo.

As the transactions of electric power will take place among more than one entities (GenCo, DisCo, TransCo), there must be some entity to oversee the technical feasibility of these transactions. So it is necessary to have an independent central controlling authority for the entire system called the Independent System Operator (ISO) or Power System Operator (PSO). Normally the ISO/PSO does not have any financial controlling authority, but it validates all the transactions before the actual operation takes place from the points view of the security of the system, congestion management, real time operation, etc.

It is advocated that deregulation of power system will bring benefits to all those involved in the electric energy market (i.e. power producer, consumer and system operator). However, the electric energy market has plenty of problems as it is different form other markets. Electric energy can not be stored in bulk quantities unlike other commodities. Hence the supply and demand must be balanced at all the times. In power system operation emergency situation such as line outages, load disconnections, generation loss may happen at any time. The system operation must be able to cope up with that more efficiently in the deregulated power system. Power flow obeys the physical
relation viz. KCL and KVL. The physical nature of the electric network dictates the flow of power that may jeopardizes some aspect of deregulation.

III. ELECTRICITY MARKETS IN DEREGULATED ENVIRONMENT

Two electricity market model viz. bilateral trading model and pool trading model are currently prevailing in practice in the deregulated environment. In the bilateral trading model, sellers and buyers enter into contract for electrical energy. Both parties request the ISO to provide transmission. If security of the system is not threatened, the ISO/PSO dispatches all the requested amount. In the pool trading model, a central pool operator receives price and quantity offers from generators and consumers in the form of bid curves. From the bid curves the pool operator decides on the price for electricity and the quantity to be traded.

The advantages of bilateral trades are, there is no third party involved that can influence the economic decisions of the participating parties. However, as too many transactions are involved, there may be coordination problem from ISO’s point of view. In the pool concept the system controlling authority, the ISO, has enough control over the market as well as in the operation of the system. A large generator having sufficient capacity may use its market power, specially if there is zero elastic demand.

A. Coordinated Multilateral Trading Model

Varaiya and Wu [1] proposes a new operating paradigm which is compatible to the deregulated structure of the power systems. In the traditional power system as well as in bilateral and pool model, the coordination of the transmission operation is centralized. However, this new operating paradigm, tries to develop the same level of coordination without making the information and decision making process centralized. The new model is termed as Coordinated Multilateral Trading (CMT) model. It is claimed that in this model, problems of the system reliability/security and loss allocation that weaken the bilateral model have been solved. Similarly, it is also claimed that this model can achieve the same economic efficiency as the pool model, but without the interference of the ISO on the economic decisions.

While [1] developed the theory considering only the real power flow in the network. D. Quet et al. [4] has extended the work considering the reactive power as well in the development of the model and the theory.

IV. CONGESTION MANAGEMENT

Maintaining the transmission flow limits is a major challenge in the deregulated environment. When the producers and consumers of electric energy desire to produce and consume in amounts that would cause the transmission system to operate at or beyond transfer limit for one or more lines, the transmission system is said to be congested [2]. In a deregulated market there can be bilateral contracts, pool contracts and multilateral contracts. The contracts may be firm (i.e. can not be curtailed in normal circumstances) or non-firm (which may be curtailed if necessary). So the system controlling authority (ISO) has to make considerations of the contractual obligations of the participating parties. The other constraints are the priority of transactions, curtailment of an already confirmed transaction, the financial consequence of the action, etc. In other words congestion management is a task of the ISO to meet the constraints with economic consideration.

Glavitsch and Alvarado [5] discussed the congestion issues in transmission line at length. They considered that though some means such as use of FACTS devices, phase shifters etc. (which they termed as "cost free" means) are already being exercised, congestion still can not be completely alleviated. So the “not-cost-free” means of congestion relief such as modifications of dispatch of generation from the natural settling point of the market, curtailment of loads are to be used. In reference [5] it is assumed that the entire responsibility of congestion relief is on the generation (supply) side.

As there is little possibility of expanding transmission network in the short term, an efficient congestion management procedure is necessary for success of deregulation. David in his paper [6] has addressed the need to develop methodologies for imposing curtailment on all types of transactions, when the security of the system is threatened.

Yang and Anderson [7] presented a method to trace the flow of power in a transmission line contributed by each generator of the system. In the event of congestion it will help to locate the generators which are to be backed up or to be increased. However, in this method large number of computation is involved. If there are N number of generators in the system, at many as (N+1) load flow solutions are needed to determine the contributions of each generators to line flows. In the method presented by Gedra[8] a small amount of power ε is injected in a bus (say i\textsuperscript{th} bus). The injection at all other buses are kept constant except the slack bus and the bus voltage angle are computed. These changes in bus voltage angles due to injected power ε at the i\textsuperscript{th} bus the change in line flows are calculated. Thus this procedure gives an estimate of change of power required for removing congestion in a particular line. As voltage magnitudes are assumed to be remained constant the effect of change of reactive power is not considered.

With the increase of number and volume of bilateral contracts there may not be enough resources in the pool balancing market to manage congestion. In the procedure described by Wang and Song[9] the bilateral contract will also submit a price that both side of the contract willing to accept if the curtailment is imposed by ISO during congestion period. It is tried to minimize the total MW rescheduling, in light of cost which is determined by the bids in the balancing market and the compensative prices submitted by the participating bilateral contracts.

In the multilateral trading model proposed by Wu and Varaiya[1] there will be a number of brokers who will settle the load and generation on the basis of the bids it receives from the GenCos and the DisCos under its purview. They have also proposed that if the multilateral trades result congested transmission line, the ISO curtails the trades to a point when the line overload is eliminated. As ISO is only concerned with security of the system the curtailment does not rely on the cost-benefit information of the participants. After curtailment, the broker will look for additional feasible trades, that lead to improvement of the financial efficiency of the system.

However, in the above process i.e. when the ISO makes uni-
form curtailment there may be unnecessary curtailment of load and generation. Again after the curtailment the brokers will look for additional trades which may result congestion in some other lines. To overcome some of these problems, in the present work, we propose a congestion management algorithm in the multilateral trading environment using sensitivity of the congested lines to the bus injections. Here we are trying to find a trade settlement in such a way that brokers profit is maximized and at the same time congestion is relieved. The algorithm is described below.

V. OPTIMAL TRADE SETTLEMENT IN MULTILATERAL TRADING FOR CONGESTION MANAGEMENT

A. Load and generation settlement by individual broker

Each broker settles the trade of its own i.e. without considering the network constraints and the other brokers’ settlement in the following steps.

- Step 1: Broker receives the generation and load bids from GenCo and DisCo respectively.
- Step 2: The broker then formulates the cost curves from the bid curves it receives. For that, the broker finds the cost of each MW of generation from a GenCo or each MW of demand from the DisCo from the respective bid curves.
- Step 3: It will then adopt an optimization procedure to settle the generations and loads. In this optimization procedure the broker maximizes its profit subject to the constraint of the limits of the generations and loads it receives from the GenCo and DisCo as bids. Here the cost function is quadratic in nature with linear constraints. Hence a quadratic programming problem (QPP) is formulated and solved to find the optimized settlement from broker’s point of view.

However, at the end of these steps when each broker submits its schedule to the ISO, there is a possibility of congestion occurring.

B. Congestion management in the multilateral trading

Once each broker settles its load and generation and submit to the ISO, the ISO makes the necessary system studies. The ISO makes these result public. In the event of congestion, the brokers use these information to find a new schedule of the load and generation, so that the congestion is relieved.

In the proposed algorithm we try to reschedule the injections in such a way that no new line be overloaded while the rescheduling leads to minimum rise in electricity cost. We again use the QPP for a modified formulation of the problem that will reduce the congestion. In formulating the QPP, additional constraints are introduced such that the capacity of the lines, presently carrying power below it’s rated capacity, can only go to the maximum capacity.

The complete procedure is presented in Fig 2.

Recently, Hazarika and Sinha [10] [11] used sensitivity factor to alleviate line overload, controlling the power at the generation/load buses. If \( \Delta P \) be the vector for change in power in the generation/load buses, \( \Delta I \) be the change in current vector required to reduce the congestion in the line, then, \( \Delta I \) can be expressed as

\[
[\Delta I] \geq [F][\Delta P]
\]  

\( \text{Eqn 4 forms the additional constraints in the optimization process described in Step 3 of the previous subsection. This ensures that while alleviating the congestion of the congested lines, the flow in the other lines does not go above its maximum current carrying capacity.} \]

C. Mathematical formulation

Let there are \( G \) nos of GenCos and \( D \) nos of DisCos, that are doing business with the broker \( B_1 \). The bids received from the GenCo say,

\[
B(P_{gi}) = a_{gi} + b_{gi}P_{gi} \quad i \epsilon G
\]

Similarly the bid received from a DisCo is

\[
B(P_{dj}) = a_{dj} + b_{dj}P_{dj} \quad j \epsilon D
\]

From the bid curves the broker calculates the price it is to receive from the DisCos and to pay to the GenCos and maximizes the profit, i.e.

\[
\max \left( \sum_{j \in D} P_{dj}B(P_{dj}) - \sum_{i \in G} P_{gi}B(P_{gi}) \right)
\]

Subject to,

\[
P_{gmin} \leq P_{gi} \leq P_{gmax} \quad i \epsilon G
\]

\[
P_{dmin} \leq P_{dj} \leq P_{dmax} \quad j \epsilon D
\]
\[ [\Delta I] \geq [F][\Delta P] \]

where,

\[ [\Delta P] = [(P_{g1}^{old} - P_{g1}^{new}) \cdots (P_{gG}^{old} - P_{gG}^{new})(P_{d1}^{old} - P_{d1}^{new}) \cdots (P_{dD}^{old} - P_{dD}^{new})]^T \]

\[ [\Delta I] = [(I_{g1}^{old} - I_{g1}^{new}) \cdots (I_{L}^{old} - I_{L}^{new})]^T \]

L is the number of lines in the system.

D. Result and Discussion.

![Diagram](image)

Fig. 3. The example test system

Numerical studies are carried out for the example circuit shown in Fig 3. Two GenCos and two DisCos are doing trades with a broker as shown in the figure. We assume bid curves as follows:

For GenCo1: \( B(P_{g1}) = 60.00P_{g1} + 2000.00 \text{ Rs/MWh} \)
For GenCo2: \( B(P_{g4}) = 21.43P_{g4} + 15000.00 \text{ Rs/MWh} \)
For GenCo1: \( B(P_{g2}) = -11.11P_{g2} + 6000.00 \text{ Rs/MWh} \)
For GenCo2: \( B(P_{g3}) = -30.00P_{g3} + 5500.00 \text{ Rs/MWh} \)

The line flows at the optimum injection vector are shown in Table I. The last column of the table shows assumed values of the maximum current magnitude \( |I_m| \).

| Line no. | from bus | to bus | \( |I| \) [kA] | \( |I_m| \) [kA] |
|----------|----------|--------|-------------|-------------|
| 1        | 1        | 2      | 8.772       | 10.00       |
| 2        | 1        | 4      | 4.676       | 10.00       |
| 3        | 2        | 5      | 13.673      | 15.00       |
| 4        | 5        | 3      | 14.102      | 15.00       |
| 5        | 2        | 3      | 4.422       | 10.00       |
| 6        | 2        | 4      | 60.608      | 50.00       |
| 7        | 4        | 3      | 13.442      | 10.00       |

Table I

From the Table I it is seen that lines 6 and 7 are overloaded, but the flows through the other lines are below the maximum limit. After calculating the \([F]\) matrix and running the QPP with the new constraints of the line flow limit, new injection vector is found as follows.

\( P_{d2} = 65.52 \text{ MW}; P_{d3} = 7.60 \text{ MW}; P_{g4} = 62.60 \text{ MW} \) and \( P_{g5} = 10.52 \text{ MW} \) and the broker’s profit is 179934.00 Rs/hr

The line flows \( |I| \) at the new injection vector is shown in Table II

| Line no. | from bus | to bus | \( |I| \) [kA] | \( |I_m| \) [kA] |
|----------|----------|--------|-------------|-------------|
| 1        | 1        | 2      | 8.877       | 10.00       |
| 2        | 1        | 4      | 4.676       | 10.00       |
| 3        | 2        | 5      | 8.265       | 15.00       |
| 4        | 5        | 3      | 4.480       | 15.00       |
| 5        | 2        | 3      | 5.336       | 10.00       |
| 6        | 2        | 4      | 45.779      | 50.00       |
| 7        | 4        | 3      | 10.115      | 10.00       |

Table II

If uniform curtailment were made to relieve the congestion the line flows are shown in Table III for 15% 20% and 24% curtailment of the load and generation when broker’s profit is maximum. Form the line flows it is seen that at least 24% curtailment is needed to alleviate overload of the congested lines. However it is seen that even in 24% curtailment the overload of line between buses 3 & 4 is not completely removed though the overload is very less (within 5%). The injection vector at 24% curtailment is \( P_{d2} = 53.75 \text{ MW}; P_{d3} = 13.57 \text{ MW} \) \( P_{g4} = 51.98 \text{ MW} \) and \( P_{g5} = 15.38 \text{ MW} \) The broker’s profit at this injection vector would be 178688.35 Rs/hr. Moreover there would have been unnecessary curtailment of load and generation.

From the algorithm it can be ascertained that each GenCo and DisCo gets their due share that satisfies their bids while managing the congestion with optimum curtailment. It is seen from the results shown in Table II, that no new line is overloaded after relieving the congestion in the overloaded lines (line nos. 6 & 7).
TABLE III
LINE FLOWS AT DIFFERENT LEVEL OF CURTAILMENT

| Line No. | from bus | to bus | $|I_m|$ (kA) | $|I|$ at curtailment (kA) |
|----------|---------|-------|----------|------------------|
| 1 | 1 | 2 | 10.0 | 8.77 | 5.55 | 4.80 | 4.43 |
| 2 | 1 | 4 | 10.0 | 4.68 | 6.98 | 7.28 | 7.49 |
| 3 | 2 | 5 | 15.0 | 13.67 | 12.75 | 12.45 | 12.22 |
| 4 | 3 | 5 | 15.0 | 14.10 | 13.68 | 13.32 | 13.06 |
| 5 | 2 | 3 | 10.0 | 4.22 | 6.07 | 5.10 | 5.81 |
| 6 | 2 | 4 | 50.0 | 60.61 | 49.33 | 46.21 | 43.75 |
| 7 | 3 | 4 | 10.0 | 13.44 | 11.83 | 10.93 | 10.14 |

VI. SUMMARY

Congestion in transmission system may be a common problem in the deregulated power system. Hence, for the success of deregulation a proper congestion management procedure is necessary. In this paper an algorithm for congestion management in multilateral trading environment of deregulated power system is presented. The mathematical derivation as well as some result of system studies for a 5 bus test system are presented. The results show that congestion can be alleviated with minimum financial loss to the brokers. The present work is carried out assuming a single broker case. In the future it is planned to extend the work for a multi-brokers case.

REFERENCES