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SOCIAL WELFARE MAXIMIZATION IN DEREGULATED POWER SYSTEM

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Abstract - In power systems, transmission network provides the infrastructure to support a competitive electricity market, but congestion occurs frequently in the weakly connected networks. Transmission congestion can enhance the locational market power in the congested area and weaken the efficiency of electricity market. In this paper market dispatch problem in the pool-based electricity market is formulated so as to maximize the social welfare of market participants subject to operational constraints given by real and reactive power balance equations, and security constraints in the form of apparent power flow limits over the congested transmission lines. The comparisons of the real and reactive power costs of generators, benefit value of consumers, producers surplus, locational marginal prices (LMPs) under uncongested or congested conditions are evaluated by using a five-bus system.

Keywords - *Transmission Congestion, market power, locational marginal prices, social welfare.*

I. INTRODUCTION

With the introduction of deregulation in the power industry open access is provided to the transmission system. Due to transmission open access (TOA) the flow in the lines reach the power transfer limit and thereby creating a condition known as congestion [1-3].

The congestion may be caused due to various reasons, such as transmission line outages, generator outages and change in energy demand. Transmission congestion has impact on the entire system as well as on the individual market participants i.e. sellers and buyers. Without congestion lowest-priced resources are used to meet the demand but if congestion is present in the transmission network then it prevents the demand to be met by the lowest-priced resources due to transmission constraints and some energy is purchased from alternative sources at higher prices. The suppliers at the import side may raise their prices as high as they want and thus creates market power, (the conditions where a market participant can profitably maintain prices above a competitive level for a significant period of time) [4-5].

Congestion results an increase in locational marginal prices (LMP), defined as the marginal cost of supplying the next MW of load to the location using the lowest production cost of all available generation without violating any system security limit. If the lowest priced electricity can reach all locations, prices are the same across the entire grid. When there is transmission congestion, energy cannot freely flow to certain locations. In such cases, more expensive electricity is needed to meet that demand and so the locational marginal price is higher in those locations. So its management becomes necessary and this task is performed by Independent System Operator (ISO) [7].

In pool-based electricity market ISO collects hourly/half-hourly supply and demand bids from generator serving traders (GSTs) on behalf of GenCos and load serving traders (LSTs) on behalf of pool consumers. ISO determines the generation and demand schedule as well as LMPs based on maximization of social welfare, subject to system operational and security constraints [8-10].

The supply bids collected by ISO from GenCos are generally for real power generation and reactive power generation is assumed to be produced at negligible cost. In recent developments, the use of reactive power pricing is emphasized in parallel to active power pricing. Many authors have explored the opportunity cost of generators based on P-Q capability curve to develop reactive power generation cost function. Bhattacharya and Bollen *et. Al.* [1] explained the emergence of deregulation from the traditional power industry. Authors of References [2-3] explained the transmission open access in deregulated structure. Li and Bo [6] explained how LMPs are calculated with DC optimal power flow and then comparison is made with AC optimal power flow. Caramanis *et al.* [8] developed the theory of optimal spot pricing, according to which suppliers should be paid real-time price more than or equal to their cost incurred, and consumers should be charged real-time price less than or equal to their benefit, such that overall welfare is obtained. Authors in Ref. [11] discussed technical and economic issues for determining the reactive power pricing structure under an open-access environment. Dai *et al.* [12] modeled the lost spinning reserve of synchronous generators and depreciation charges on capital investment of capacitor banks to develop a reactive power production cost function. It includes this function into the OPF problem to determine LMPs of real and reactive power. Choi *et al.* [13] performed the maximization of social benefit, representing response (or marginal benefit) of consumers as the inverse of demand function. Singh *et al.* [14] modifies the reactive power generation cost function, as given in [12], by making use of an approximate P-Q capability curve of synchronous generators. The reactive power generation cost function obtained from the P-Q capability curve is added to the real power generation cost function to get total generation cost.

II. PROBLEM FORMULATION

In pool-based electricity market ISO collects hourly/half-hourly supply and demand bids from generator serving traders (GSTs) on behalf of GenCos and load serving traders (LSTs) on behalf of pool consumers. The supply bids provided by a GenCo (or related GST) is its minimum asking price which it would accept for supplying a particular amount of power. Similarly, demand bid of a consumer is its maximum willing price, which it would pay for consuming a particular amount of power. ISO determines the generation and demand schedule as well as locational marginal prices (LMPs) based on maximization of social welfare, subject to system operational and security constraints

The objective function for the optimization problem is to maximize the social welfare, which is the difference of benefit of consumers and the overall cost of active and reactive power production of suppliers. The objective function can be expressed as:

Max. Social Welfare

$$=\sum_{i\in D} B_i(P_{di}) - \sum_{i\in G} C_{pi}(P_{gi}) - \sum_{i\in G} C_{qi}(Q_{gi}) \qquad (1)$$

where {G} is the generator set, {D} is the consumer set, $C_{pi}(P_{gi})$ is the active power production cost of generator $i, C_{qi}(Q_{gi})$ is the reactive power production cost of generator i; $B_i(P_{di})$ is the benefit of the consumer, P_{gi} and Q_{gi} are the active and reactive power output of the generator on bus *i*, P_{di} is the active power demand on bus *i*.

The real power generation cost function of each generator is modeled by a quadratic function where a, b and c are predetermined coefficients:

$$C_i(P_{gi}) = a + bP_{gi} + cP_{gi}^2 \text{ (\$/h)} \qquad (2)$$

The reactive power cost of generator is also called as opportunity cost. The reactive power output of a generator will reduce its active power generation capability which can serve at least as spinning reserve, and the corresponding implicit financial loss to generator is modeled as an opportunity cost. For simplicity, the reactive power cost of generator from the approximated capability curve can be modeled as:

$$C_{qi}(Q_{gi}) = [C_i(P_{gi}^{\max}) - C_{qi}(\sqrt{P_{gi}^{\max^2} - Q_{gi}^2})]k$$
(3)

Where k is the profit rate of active power generation, usually lies between 5 to 10%.

Consumers' benefit as a function of real power demand is considered to follow a straight line passing through origin between $P_{di}^{\min}$ and $P_{di}^{\max}$ which specifies a fixed marginal benefit equal to the slope of line. Using Fig. 1., the benefit of consumer can be written as

$$B_i(P_{di}) = b_{di} * P_{di} \qquad (4)$$

where b_{di} is the slope of benefit curve of consumer at *i*th bus.

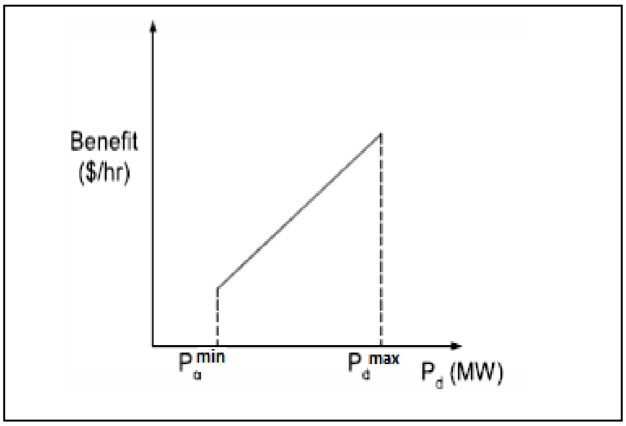

Fig. 1 : Benefit curve of a consumer

CONSTRAINTS

1) Power Flow Equations (Equality Constraints): **A** set of equations that characterizes the flow of real and reactive powers through a system are given by

$$P_{gi} - P_{di} - \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0$$
(5)

$$Q_{gi} - Q_{di} - \sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0$$
(6)

where N is total number of buses in the system, $\dot{V}_i$ and V_j are the magnitudes of the voltages of bus *i* and *j*, δ_i and δ_j are the voltage angles of bus *i* and *j*, and Y_{ij} and θ_{ij}, are the magnitude and angle of ijth element of the bus admittance matrix.

2) Generation Limit: The generators have a maximum generating capacity, above which is not feasible to generate due to technical or economic reasons. Generating limits are usually expressed as maximum or minimum real and reactive power outputs,

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max} \quad (7)$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad (8)$$

3) Load Limit: Consumers also have their capacity limits of consumption. Load limits are expressed as follows in the formulation,

$$P_{di}^{\min} \le P_{di} \le P_{di}^{\max} \quad (9)$$

$$Q_{di}^{\min} \le Q_{di} \le Q_{di}^{\max} \quad (10)$$

4) Constraint on constant power factor of loads: The real and reactive power consumption at any bus i are tied together by constant power factor.

$$Qdi = Pdi \tan\alpha i \quad (11)$$

5) Transmission line limits: Transmission limits refer to the maximum power that given transmission line is capable of transmitting under given conditions.

$$S_{ij} \le S_{ij,\max} \quad (12)$$

6) Voltage limits: The voltage at each bus should be within the specified range.

$$V_{i,\min} \le V_i \le V_{i,\max} \quad (13)$$

7) Additional constraint due to capability curve: The apparent power generated by the generator should lie within the boundaries of capability curve.

$$P_{gi}^2 + Q_{gi}^2 \le P_{gi}^{\max\,2} \quad (14)$$

The proposed market dispatch problem is a nonlinear programming problem and is solved with Sequential quadratic programming method in AMPL.

III. RESULTS

Five-Bus System:

The methodology described above has been applied on a five-bus system. There are two Gencos at buses 1 and 2, each having lower and upper power generation limits of 10 MW and 200 MW, respectively. The real power generation cost of each Genco is

$$Ci(Pgi) = 75 + 7.5Pgi + .042\,P_{gi}^2 \quad (\$/h)$$

The nominal apparent power output of each generator is 125 MVA. The reactive power generation costs of Gencos are modelled using eq. (3), taking k = 5%. In base case, values b_{di} of for all the consumers are set to be fairly high (50 $/MWh), such that these do not affect generation and demand schedules produced by OPF.

A capacitor bank is installed on bus 4 with total capacity of 50 MVAR can inject capacitive power between 0 to 50 MVAR. The systems loads on buses 1-5 are listed in Table A1 of the Appendix A with a common power factor of 0.9. The transmission line impedance and charging admittance are given in Table A2 of the Appendix A. Lower and upper bus voltage limits are considered to be 0.95 p.u. and 1.05 p.u. Apparent power flow limit of lines is taken to be 180 MVA.

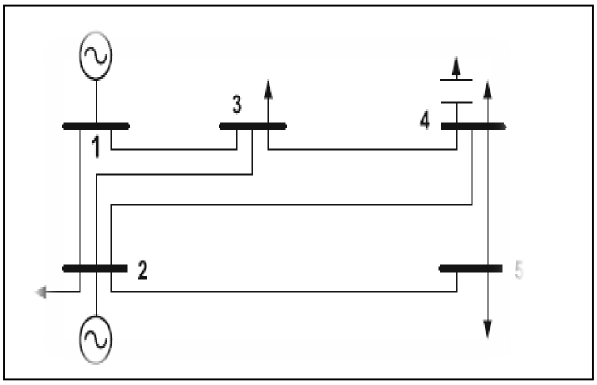

Fig. 2 : Five-bus system

Under heavy loading condition loads on buses 1-5 increase to [0, 0.6, 0.9, 0.8, 1.0] per unit with same power factor of 0.9 and the power generation limits of two Gencos are set to 250 MVA. The system is quite stressed. Now congestion can be created by reducing the flow over line 1-2 by 60 MVA.

Social Welfare Maximization Considering Reactive Power Procurement:

In Table total generation cost, real and reactive power generation costs, power generated values, producers surplus, LMP of real and reactive power at system buses under congested and un-congested conditions are obtained by the proposed methodology.

As depicted in Table I the benefit values of LSTs become twice with a two fold increase in demand under heavy loading from that of normal loading, because of assumed linear benefit characteristic. But, the social welfare value becomes less than double under heavy loading due to the nonlinear cost characteristics of generators. Although, the reactive power generation cost is small under normal loading, but it increases significantly with increase in loading. This illustrates that there is an utmost need of inclusion of reactive power cost in social welfare maximization.

Table I

Comparison of Results

	Uncongested	**Congested**
Social Welfare ($/h)	6236.90	11045.74
Total Generation Cost ($/h)	2013.1	5454.26
Real Power Generation Cost ($/h)	2012.89	5419.36
Reactive Power Generation Cost ($/h)	0.21	34.90
Benefit Value of Consumer ($/h)	8250.00	16500.00
Power Generation (MW+ j MVAR)	82.84 + j 0.73 85.85+ j10.00	118.83+j8.67 223.91+j 109.89
Producers Surplus	447.81	2548.80

The system bus voltage profiles under normal and congested conditions corresponding to proposed results of Table I are shown in Figure 3.

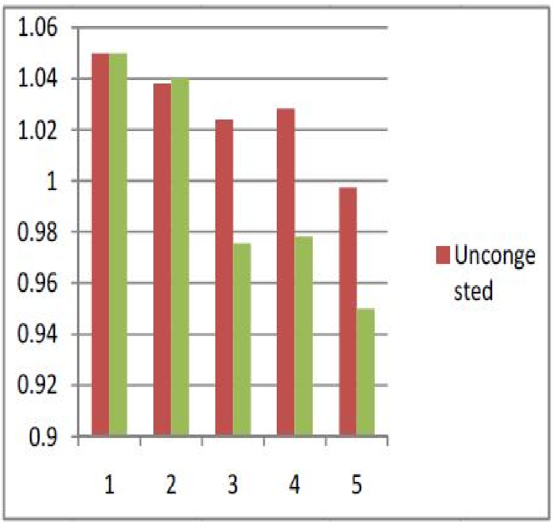

Fig. 3: System Bus Voltage Profile for Uncongested and Congested System

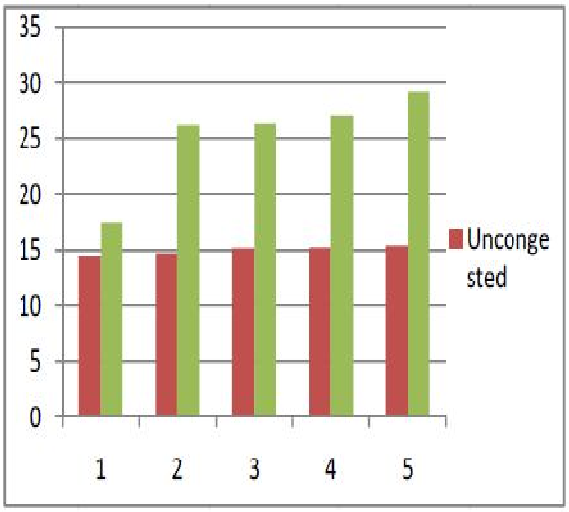

Fig. 4 : LMPs of Real Power for Uncongested and Congested System

From Fig. 4. It can be seen that for uncongested system LMPs for real power and reactive power are low, but when congestion occurs then generators have ability to create market power thereby there will be so LMPs become higher in congested system.

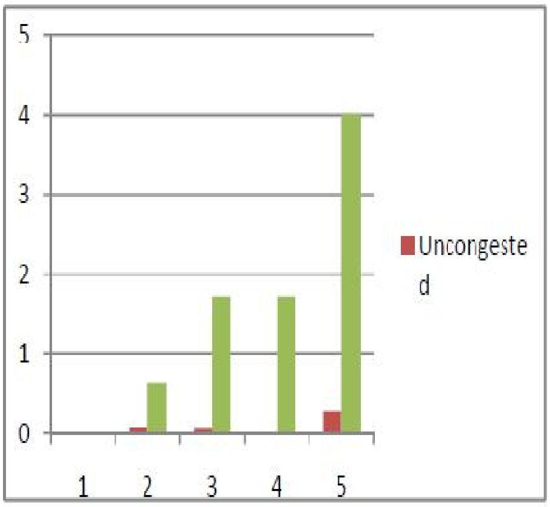

Fig. 5 : LMPs of Reactive Power for Uncongested and Congested System

IV. CONCLUSION

In this paper, market dispatch problem with the objective of maximization of social welfare is solved in the pool-based electricity market. From the optimization results given of five-bus system it can be concluded that although the presence of congestion results in an increase in market power along with producer surplus but with the given methodology there is also increase in consumers benefit value. So with the proposed method each market participant i.e. sellers or buyers are getting benefit in the case of congestion in the electricity market.

Appendix A

Table A1 Test system loads

Bus	Active Power	Reactive Power
1	0.0	0.0
2	0.20	0.097
3	0.45	0.22
4	0.40	0.19
5	0.60	0.29

Table A2 Test system line data

Bus node	Line impedance z_{ij}	Line charging y_{ij}
1-2	0.02 + j0.06	0.0 + j0.030
1-3	0.08 + j0.24	0.0 + j0.025
2-3	0.06 + j0.18	0.0 + j0.020
2-4	0.06 + j0.18	0.0 + j0.020
2-5	0.04 + j0.12	0.0 + j0.015
3-4	0.01 + j0.03	0.0 + j0.010
4-5	0.08 + j0.24	0.0 + j0.025

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