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Power flow tracing based transmission congestion pricing in deregulated power markets

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ABSTRACT

The objective of this paper is to propose a simple transmission congestion pricing scheme based on tracing principle by considering generator fixed cost, cost for incurring loss and transmission congestion cost. Restructuring has brought about considerable changes by the virtue of which electricity is now a commodity and has converted into deregulated type. Such a competitive market has paved way for innumerable participants. This concept of restructuring has led to overloading of transmission lines. In this paper, power flow tracing has been employed by using suitable optimization algorithm, where the real power generation has been maximized. Congestion in the transmission line has been produced in a new fashion by maximizing the real power demand. The power flow under normal operating condition and congestion is determined and hence the difference in power flow is estimated. Based on the estimated power flow difference, the transmission line congestion cost is computed. Pool model and bilateral model has been considered in simulation study to introduce the concept of deregulation. The proposed method is tested and validated on Modified IEEE 30 bus test system and Indian utility 69 bus test system.

Introduction

The vertically integrated structure of power industry is being replaced by market structure in the world range. In such a structure, a transmission system is being used by multiple generation and load entities that do not own the transmission system. Formerly, when the electric network was operated by one vertically integrated utility, there was not much interest in this subject. However, with the unbundling of generation and transmission facilities, and with accompanying deregulation of the power, the topic has acquired new significance as the different parties acting in the power grid are interested in a fair operation and fair allocation of transmission costs. In view of market operation it becomes more important to know the contribution of individual generators and loads to transmission lines and power transfer between individual generators to loads.

Rosado et al. explain the tracing of power flow using commons method and node method. The results obtained from these methods are not perfect and time required is more [1]. Bialek proposes a topological approach for allocating the power flow from a particular generator or a load in every branch flow based on an electricity tracing method [2].

Bialek and Kattuman recommend a tracing methodology is based on the assumption that the incoming flows are proportionally distributed among the out coming flows at any network node [3]. Panto et al. introduce modified Topological Load Distribution Factor (TLDF) based method to trace the power flow in the transmission losses to enable the decoupling of the extended matrices [4]. Xie suggests a new method using direct path from buses to buses by multiplying with the incidence matrix and to find the power transfers from individual generators to loads and branches. [5].

Abhyankar et al. discusses optimization technique based tracing algorithms using the continuity equations for the lossy flow networks with modified bus incidence matrix to discriminate the power flow between the sending end and the receiving end. [6]. Mustafa and Shareef elaborates about graph method, node method and common method for the allocation of power flow in the power system network. [7].

Hamid et al. introduces a concept of load tracing and generator tracing using Evolutionary Programming (EP). The power flow from generator to all system loads is traced and losses are allocated in the transmission lines. These method have the advantage of no assumption to formulate the tracing of power flow [8,9].

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Yang and Anderson explain the congestion management using Power Flow Comparison Method and the Proportional Sharing Method. The congestion management in two generators has conflicts of the one generator with higher MW contribution than the other [10].

Congestion [12] takes place when the transmission lines are not sufficient to transfer the power according to the market desires. Farahani et al. demonstrates the operation of restructured power system in bilateral power market and pool market. Singla et al. explains the causes for congestion and various congestion pricing calculations in the transmission network [16].

Murali et al. explains GA based congestion cost calculation using LMP for various generation bids and load bids. GA is implemented to find the fuel cost of generators. The main drawback of this paper is that time consumption for the convergence of GA is more [14]. Manikandan et al. proposes a power flow tracing algorithm using the new set of equations based on the concept of dominions and proportional sharing principle [15].

Modi and Parekh explain a method using game theory to determine the Congestion pricing with different zones using Locational marginal price (LMP) [17]. Jana explains the calculation of transmission congestion cost using Line Wise Cost and Line Impact Cost from the distribution of power flow among the congested lines [18]. Nikoukar and Haghifam propose a simple transmission pricing scheme using tracing based proportional tree, in which transmission fixed cost, congestion cost and loss cost are considered [19]. Liu et al. explains a method in which the incentives are provided to use and build a transmission line [20].

The basic power flow tracing methods include Node method, graph method and commons methods. Results obtained from commons methods are not accurate and this method takes more time for computation. The proportion sharing principle based power flow tracing provides rationalized results. By using the topological factors, the power flow tracing yield more computational time and memory. With matrix multiplication using directed path, the power flow tracing has been done which gives complexity in matrix multiplication. Evolutionary based algorithm has the capability to allocate losses and generated power to all loads with satisfaction of power system constraints. But this method cannot identify which transmission line causes the highest losses to the load.

To overcome above mentioned drawbacks, this paper presents a new method for evaluating the transmission congestion cost in pool power market and bilateral power market. The power flow in these markets is computed using power flow tracing principle. The power flow from generator to load and from generator to transmission lines has been traced by employing optimization technique. The congested power flow in these markets has been estimated by maximizing the real power demand. The fixed cost of generator, fixed cost of load and fixed cost due to the occurrence of loss in the transmission lines have been determined based on the power flow. Using these costs, the transmission congestion pricing (TCP) and congestion pricing (CP) in pool market and bilateral market has been calculated. This method of congestion cost calculation has been tested on Modified IEEE 30 bus system and Indian Utility 69 bus system.

This paper is organized as follows. The proposed methodology with block diagram is given in section 'Proposed methodology'. The discussion on concept of power flow tracing is shown in section 'Power flow tracing concepts'. A generic class of optimal tracing problem is introduced in section 'Problem formulation' with the detailed problem formulation. The implementation of PSO for maximizing the real power generation and real power load is given in section 'PSO algorithm for maximization of real power'. PSO constraint handling mechanism is given in section 'PSO constraint handling mechanism'. The detailed discussion of the test results are explained in 'Results and discussions'. The section 'Pool market' deals with the maximization of real power generation and load in Pool market. The maximization of real power generation and load in bilateral market is conferred in section 'Bilateral market'. The power flow tracing results for generator tracing and load tracing are given in section 'Power flow tracing results'. The transmission fixed cost calculation is shown in section 'Transmission fixed cost calculation'. The congestion cost estimation is discussed in section 'Congestion cost estimation'. The summary of the test results are discussed in section 'Summary'. Section 'Conclusions' draws the conclusion of the paper.

Proposed methodology

This paper intends to propose a new method for determining the transmission congestion cost. The congestion cost has been calculated based on power flow tracing principle. Bialek's tracing principle is implemented in this paper to find the power flow from generator to transmission lines and from generator to load. Basically, upstream algorithm and downstream algorithm is used in this work. The power flow tracing problem is formulated in two ways; one is generator tracing and another is load tracing. The real power generation is kept as similar in the load buses. The congestion in deregulated market is created by maximizing the real power demand at load buses. The power flow in base case and in congested condition is found using the optimization technique. The transmission congestion pricing and congestion pricing is estimated from the fixed cost of generator, load and loss occurrence in the transmission lines. The basic block diagram of the proposed methodology is given in Fig. 1.

The power flow from generator to load and from generator to transmission lines has been obtained using power flow tracing principle. Power flow tracing is achieved by maximizing the real power generation. The power flow at congested condition is obtained by maximizing the real power demand. The congested power from the load to the transmission lines has been found using downstream algorithm. The difference between power flow at basecase condition and power flow at congested condition is computed. The fixed cost of generation, fixed cost of load and fixed cost due to the occurrence of loss is determined based on the congested power flow.

Power flow tracing concepts

Tracing is the important process in a power system network. Due to the unbundling of the power system network, the power flow from the generator to load and from the generator to transmission lines become an important issue. Tracing gives a clear picture about the total power flow of the power system network. Power flow tracing comprises of two cases namely generator tracing and load tracing. In generator tracing, power transfer from generator to transmission lines are found. In load tracing, the power transfer from the load to transmission lines is determined.

Concept of generator tracing

An optimization technique based power flow tracing is implemented to determine the power flow from generator to transmission lines and from generator to load. The contribution of line flow by the generator is given as,

$$P_{gi} = \sum_{L1}^{Lm} P_{Lm} \tag{1}$$

$$P_{Lm} = P_{Lm}^{g1} + P_{Lm}^{g2} + \ldots + P_{Lm}^{gi} \tag{2}$$

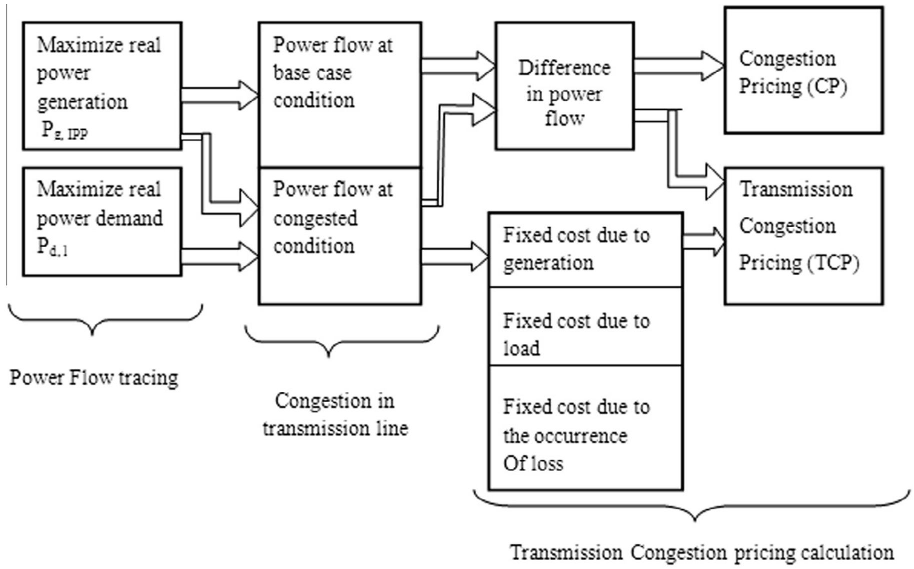


Fig. 1. Block diagram of the proposed work.

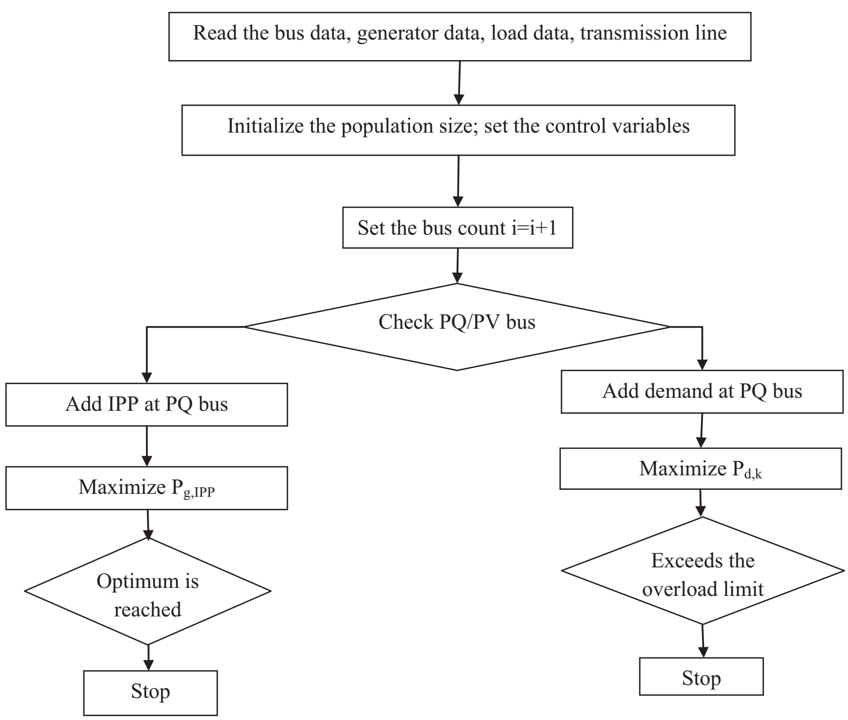


Fig. 2. Flow chart for maximization of real power using PSO.

The summation of power flow by all the generators in the transmission lines are given in Eqs. (1) and (2).

P_{Lm} – real power transfer in transmission line *Lm* in *MW*.
P_{gi} – total power flow in *MW* from all generators *gi*.
P_{gi}^{Ln} – total real power demand in *MW* from generator *gi* to load *Ln*.

Concept of load tracing

The generator that is connected to the line is categorized as an involved generator of that load. The involved generators and lines can be interpreted as the source and path used by a load in extracting real power from generation to load side

The extraction of power flow from the generator to load is given as,

$$P_{Ln} = \sum_{gi=L1}^{Ln} P_{gi} \quad (3)$$

$$P_{gi} = P_{gi}^{L1} + P_{gi}^{L2} + \ldots + P_{gi}^{Ln} \quad (4)$$

where

P_{Ln} – total power flow in the load due to the generator *gi*.
P_{gi} – total power flow in *MW* from all generators *gi*.
P_{gi}^{Ln} – total real power demand in *MW* from generator *gi* to load *Ln*.

Problem formulation

Objective function

The share of each generator and load on each line flow is determined using the power flow tracing method. The power flow tracing has been achieved using optimization technique. The real power generation and real power demand has been optimized to trace the power flow from generator to transmission lines and from generator to load. The objective function is decomposed in two forms, one with respect to the generator tracing and the other with respect to load tracing.

The objective function is formulated as,

$$Max\ (x, y) \tag{5}$$

where x is the maximization of real power generation $P_{g,IPP}$ and y is the maximization of real power demand $P_{d,k}$.

The above objective function has to satisfy the following constraints,

Equality constraints,

$$(P_{gi} + P_{g,IPP}) - P_{di} - \sum_{i=1}^{n} |V_i||V_j||Y_{ij}| \cos\ (\theta_{ij} + \delta_i - \delta_j) = 0 \tag{6}$$

$$P_{gi} - (P_{di} + P_{d,k}) - \sum_{i=1}^{n} |V_i||V_j||Y_{ij}| \cos\ (\theta_{ij} + \delta_i - \delta_j) = 0 \tag{7}$$

$$Qgi - Qdi - \sum_{i=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} + \delta_i - \delta_j) = 0 \tag{8}$$

where
n – number of buses.
δ_i, δ_j – bus voltage angle of i, j bus.
θ_{ij} – admittance angle.
P_{gi}, Q_{gi} – real and reactive power generation at i th bus.
P_{di}, Q_{di} – real and reactive power demand at ith bus.
$P_{g,IPP}$ – real power generation of IPP.
$|V_i|$ – voltage magnitude at ith bus.
$|V_j|$ – voltage magnitude at jth bus.
$|Y_{ij}|$ – admittance value between ith and jth buses.
δ_i – voltage angle at ith bus.
δ_j – voltage angle at ith bus.
θ_{ij} – admittance angle between ith and jth buses.

Inequality Constraints

(i) Real Power Limits:

$$P_{gi}^{\min} \leqslant P_{gi} \leqslant P_{gi}^{\max} \tag{9}$$

where
$P_{gi}^{\min}, P_{gi}^{\max}$ – minimum and maximum limits of real power at bus i.

(ii) Reactive Power Limits:

$$Q_{gi}^{\min} \leqslant Q_{gi} \leqslant Q_{gi}^{\max} \tag{10}$$

where
$Q_{gi}^{\min}, Q_{gi}^{\max}$ – minimum and maximum limits of reactive power at bus i.

(iii) Bus Voltage Limits:

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \tag{11}$$

where
$V_i^{\min}, V_i^{\max}$ – minimum and maximum limits of voltage at bus i.

(iv) Line Flow Limits:

$$S_{ij} \geqslant S_{ij}^{\max} \tag{12}$$

S_{ij} – line flow capacity in MVA.
$S_{ij}^{\max}$ – maximum Line capacity in line i–j.

Based on the results obtained for power flow tracing from the optimization technique, the loss occurrence in the transmission lines has been derived using the formula given as,

$$P_{Lm} = \sum_{g=1}^{i} P_g^i - \sum_{l=1}^{b} P_{loss,l} \tag{13}$$

where
P_{Lm} – real power transfer in transmission line Lm in MW.
P_g^i – total real power generation in MW from generator g to i.
$P_{loss,l}$ – total power loss in transmission lines due to load l in MW.

The equality constraints (6) and (7) satisfy the real power balance while adding real power generation using IPP at load buses and adding real power demand at load buses. The constraints (8) represent the reactive power balance at load buses. The inequality constraints (9) and (10) show the upper and lower limits of real and reactive power of generator. The voltage limit constraint (11) presents the upper and lower boundary limit of bus voltage magnitude. Constraint (12) ensures that the line loading should exceed its maximum line flow limit so as to create congestion in transmission lines.

PSO algorithm for maximization of real power

The power flow from generator to load and from generator to transmission line has been traced using optimization technique. In this paper, PSO has been employed for tracing the power flow in the test system. The traditional PSO [11] model was described by Dr. Kennedy and Dr. Eberhart in 1995. It consists of a number of particles moving around in the search space, each representing a possible solution to a numerical problem. Each particle has a position vector X_i^k, a velocity vector V_i^k. The usage of PSO does not require any derivatives. Within smaller time steps, the convergence will be reached. PSO has only fewer parameters to adjust and increase the speed of the search. PSO adopts the real number code and it is decided directly by the solution in which number of the dimension is equal to the constant of the solution (Fig. 2).

The step by step procedure for the implementation of PSO is given as follows,

Step1: Initialization:

Base case power flow for the standard system has been run. Real power generation and real power load is taken as control variables. The population size and number of iterations have been chosen. Initial searching points and velocities are randomly selected.

Step 2: Evaluation of fitness function

The real power generation has been maximized by adding IPP at each load buses. From the objective function, fitness values are evaluated. The new position and velocities are calculated using the equations.

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{14}$$

$$v^i_{k+1} = w_k v^i_k + c_1 r_1 \left(p^i_k - x^i_k\right) + c_2 r_2 \left(p^g_k - x^g_k\right) \quad (15)$$

where

V^i_{k+1} – particle's new velocity.
V^i_k – particle's previous velocity.
P^i_k –the past best position of particle i at time k.
P^g_k – the past global best position in the swarm at time k.
X^i_k – particle i's position at time k.
X^i_{k+1} – particles new position.
W_k – inertia weight.
c_1, c_2 – acceleration constant.
r_1, r_2 – uniform random numbers between 0 and 1.

Generally $C_1 = C_2 = 2$, K represents iteration number, r_1, r_2 are random values different for each particle and each dimension.

Step 3: Checking the convergence

If the optimum value of generation is reached, then the real power demand will be maximized. The real power load at each load buses has been maximized. The maximization of load has been made by exceeding the line flow limits. When the line flow limit exceeds its limits then stop the procedure. Update the position and velocity, until the objective function is reached. The power flow at maximized real power demand is considered as congested power flow. From this power flow, the transmission congestion cost is evaluated.

PSO constraint handling mechanism

PSO is constrained optimization techniques in which penalty functions are often used to meet the optimum solution. In the proposed method, the equality constraints are effectively handled by running Newton–Raphson power flow (NR) algorithm in repeated manner. The active power inequality constraints are after generation of new individual.

These constraints are handled as follows:

$$\text{If } \Delta P^i_g > \Delta P^i_{g,max};\ \Delta P^i_g > \Delta P^i_{g,max}; \quad (16)$$

$$\text{If } \Delta P^i_g < \ \Delta P^i_{g,min};\ \textit{Ignore} \quad (17)$$

If real power generation of any PQ bus gets maximized, then PQ bus is treated as PV bus by fixing real power generation at the threshold values.

The real power generation at load buses is maximized by adding IPP at load buses. From this maximized result, the maximum real power generated bus is identified and the real power demand at all load buses is maximized. This will create congestion in the transmission lines.

The real and reactive power balance should be satisfied while maximizing the real power demand at load buses. The real power flow limits and reactive power flow limits should be maintained within its upper and lower limits for the maximization of real power generation only. The voltage magnitude should be maintained within its upper and lower boundary limits. The line power flow limits exceed the prescribed power flow limit while maximizing the real power demand at load buses. As a result, the transmission lines are said to be congested.

Results and discussions

The power flow tracing based transmission congestion pricing is evaluated on Modified IEEE 30 bus Test system and Indian Utility 69 bus test system. The single line diagram, generator data, load

Table 1
Real power optimization in pool market-Modified IEEE 30 bus system.

Load bus number	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	24	25	26	28	29	30
Addition of IPP (MW)	122	130	122.8	110	**187.4**	67.1	128.3	133.4	75.1	115	45.3	52	40	38	36.3	42.1	38	70.6	20	31	19.4	70.3	30.9	36.4
Addition of Load (MW)	**222**	209.5	190	191.6	210.8	157	192.5	198	182.5	196	160	161.1	165	165	137.5	150.7	147.5	110	30	3	10	80	80	80

data and line data of the IEEE 30 bus test system and Indian Utility 69 bus test system is given in Appendices. The simulation study is done under MATAB 7.9 platform.

This paper proposes a new method to trace the power flow using optimization algorithm for solving non-linear problem. The basic power flow in the system has been run using Newton–Raphson method. The real power generation at each load bus has been maximized without violating the real power limits, reactive power limits, voltage limits and power transfer limits by using optimization algorithm. The real power is increased by increasing the value of IPP which is connected at load buses. While increasing the real power generation at IPP the real and reactive power of the generator has to be kept with its limits. The limits of voltage and real power transfer limits have also been within its limits. The power flow in the transmission lines have been found using optimization technique. So, the increase in real power at load bus is mentioned as maximization of real power.

The present work is demonstrated on the deregulated power market, so an Independent Power Producer (IPP) is added at load buses. The real power is already generated by the Generator bus (PQ bus) itself. In order to provide maximum real power to meet out the future demand, this paper proposes a concept of utilizing the real power generation at load buses for the deregulated power markets such as in pool market and bilateral power market.

Pool market

In pool market, required demand for each load bus can be supplied by more number of generators. Therefore, any generator delivers power to the load. In this market, the IPP is added at each load bus. The real power generation at the load buses has been maximized. The real power generation and real power demand at the pool market is shown in Table 1.

The IPP is added at load buses to increase the real power generation. The value of real power generation has been maximized by using Repeated Power Flow (RPF) to attain the maximum generation value. The real power is maximized without violating the equality and inequality constraints. The maximum generation for all the load buses has been found by using optimization algorithm. In pool market, the maximum value of IPP added at the load bus 7 is evaluated as 187.4 MW. With the addition of IPP at load buses, the standard system has been modified with 7 generator buses and 23 load buses.

Mostly the congestion has been created in the transmission line using line outage or by increasing the generation. This paper recommends a new method for producing congestion in power markets. The congestion in transmission line has been created when the line flow exceeds its power flow limit. The real power generation has been maximized by adding IPP at load buses. Simultaneously the real power demand at load buses has also been maximized to produce congestion in the transmission lines. At bus 3, the maximum real power demand has been attained as 222 MW. The power flow due to the addition of load from load side to transmission lines has been traced using power flow tracing principle.

Bilateral market

In bilateral market, each generator contributes power to each load. The power flow is determined from one generator to all the

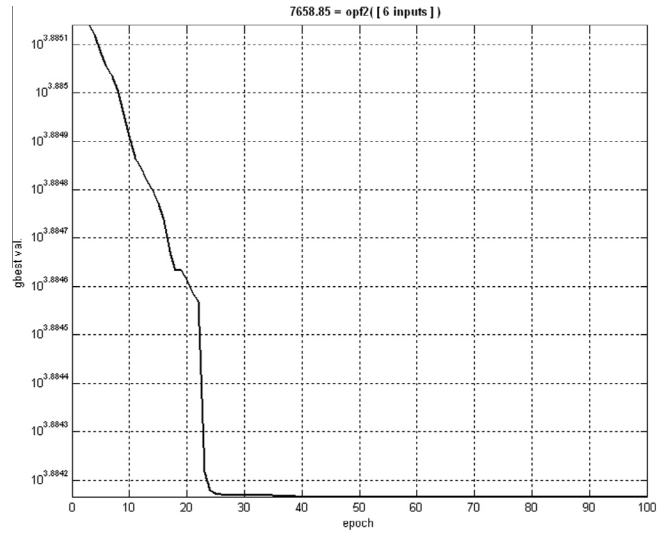


Fig. 3. Convergence characteristics of PSO – Modified IEEE 30 bus system.

loads connected in the system. In this type of market, the real power demand is only maximized at load buses. The real power generation is fixed as 187.4 MW in the load bus 7. The real power generation at load buses has been maximized using PSO. In this type of market, the real power demand at load buses are maximized except the load bus 7.

The maximization of real power generation and real power demand at each load buses is shown in Table 2. The congestion in transmission lines have been created by maximizing the real power demand at load buses. The real power demand is maximized at bus number 5 with the value of 98.75 MW. In the simulation study throughout, the IEEE 30bus test system has been modified with 7 generator bus and 23 load buses.

The parameters selected for getting optimal solution are given as follows, Population size is 60, C_1 and C_2 is 2, Inertia weight is varied from 0.4 to 0.9 and the number of iterations is taken as 100. The convergence characteristics of PSO for getting the fitness function is shown in Fig. 3.

Power flow tracing results

The power flow from generator to load and from generator to transmission lines is determined using generator tracing. The power flow is traced while increasing the real power generation by adding IPP. The contribution of power flow from generator to load for the deregulated power system with pool market is shown in Table 3. From Table 3, the power flow due to increase in real power from a particular generator bus to the connected load bus for the Modified IEEE30 bus system has been depicted. The loss occurrence in the transmission lines for the generator tracing of pool power market is given in Table 4. The power flow in the transmission lines is considered as loss incurred due to the maximization of real power at generator buses. This power flow is concerned for calculating the Congestion Pricing (CP) and Transmission Congestion Pricing (TCP) transmission. The transmission line loss at base case for the pool market is 610.9 Mw.

Table 2
Real power optimization in bilateral market-Modified IEEE 30 bus system.

Load bus number	3	4	5	6	8	9	10	11	12	14	15	16	17	18	19	20	21	24	25	26	28	29	30
Addition of IPP (MW)	**187.4**																						
Addition of Load (MW)	67.8	21.2	**98.75**	58.2	5	85	64.5	31.9	36.81	32	32.4	28.9	24.8	29.3	28	0.4	1.2	12	27	15.7	20.2	25.3	30.6

Table 3
Contribution of power flow from generator to load for pool power market (Base case) Modified IEEE 30 bus system.

Load bus ⟹ Generator bus ⇓	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L14	L15	L16	L17	L18	L19	L20	L21	L24	L25	L26	L28	L29	L30
G1	26.4	28.1	26.6	23.8	40.5	14.5	27.7	28.9	16.2	25.1	9.8	11.2	8.7	8.2	7.9	9.1	15.3	15.3	4.3	6.7	4.2	15.2	6.7	7.9
G2	35.2	37.5	35.4	31.7	54.1	19.4	37.0	38.5	21.7	33.5	13.1	15.0	11.5	11.0	10.5	12.1	20.4	20.4	5.8	8.9	5.6	20.3	8.9	10.5
G13	10.3	11.0	10.4	9.3	15.8	5.7	10.8	11.3	6.3	9.8	3.8	4.4	3.4	3.2	3.1	3.6	6.0	6.0	1.7	2.6	1.6	5.9	2.6	3.1
G22	14.4	15.4	14.5	13.0	22.2	7.9	15.2	15.8	8.9	13.7	5.4	6.2	4.7	4.5	4.3	5.0	8.4	8.4	2.4	3.7	2.3	8.3	3.7	4.3
G23	10.3	11.0	10.4	9.3	15.9	5.7	10.9	11.3	6.4	9.8	3.8	4.4	3.4	3.2	3.1	3.6	6.0	6.0	1.7	2.6	1.6	6.0	2.6	3.1
G27	25.4	27.0	25.5	22.9	38.9	13.9	26.7	27.7	15.6	24.1	9.4	10.8	8.3	7.9	7.5	8.7	14.7	14.7	4.2	6.4	4.0	14.6	6.4	7.6
Total	122.0	130.0	122.8	110.0	187.4	67.1	128.3	133.4	75.1	116.0	45.3	52.0	40.0	38.0	36.3	42.1	70.6	70.6	20.0	31.0	19.4	70.3	30.9	36.4

The power flow from load to generator and from load to transmission lines are found using load tracing principle. The extraction of power flow from load to generator for the deregulated power system at base case with pool market is shown in Table 5. The real power demand at the load buses is also maximized. From Table 5, it is shown that how much of real power has been extracted by the load buses. The loss occurrence in the transmission lines for the load tracing of pool power market is given in Table 6. Table 6 explains the real power loss occurrence in the transmission lines due to load tracing. From this Table 6, the power flow extraction in the transmission lines due to load buses has been obtained.

In this paper, the Congestion Pricing (CP) and Transmission Congestion Pricing (TCP) transmission has been calculated based on generator tracing only.

Transmission fixed cost calculation

The congestion cost is estimated by considering three types of costs such as fixed cost of generation, fixed cost of load, loss occurrence cost and cost due to transmission line congestion. Only fixed cost and congestion cost have been mentioned in some references [18,19]. The fixed cost is being evaluated by varying the bid rate.

The total fixed cost for all the participating generator buses is formulated as

$$FC_{Lm}^{gi} = \sum_{Lm=1}^{b} P_{Lm}^{gi} \tag{18}$$

The total fixed cost for all the participating load buses is formulated as

$$FC_{Lm}^{di} = \sum_{Lm=1}^{b} P_{Lm}^{di} \tag{19}$$

where

FC_{Lm}^{gi}, FC_{Lm}^{di} – fixed cost in \$/h in the transmission lines L–m for generator bus gi, Load bus di.

P_{Lm}^{gi} – real power generation due to bus gi in the transmission line L to m.

P_{Lm}^{di} – real power demand due to bus di in the transmission line L to m.

The real power generation, real power load and losses occurred by the addition of IPP at load buses for the base case and at various bid rates are shown in Table 7. Using power flow tracing principle, the power flow from generator to transmission lines have been found. From this power flow, the fixed cost is calculated. The fixed cost of generation, load and occurrence of loss for the base case and three cases have been got from the maximized power flow.

In case A, the bid rate is taken as 20 \$/MW and the generation, demand and losses occurred are 165989.7 \$/MW, 161,982\$/MW and 4007.72 \$/MW respectively. For a bid rate of 40 \$/MW, the generation is 331979.4 \$/MW, load is 323,964 \$/MW and losses occurred are 8015.44 \$/MW in CASE B. In case B, the generation, load and losses occurred are comparatively increased with CASE A & CASE B for a bid rate of 60 \$/h.

The comparison of fixed cost at base case and various bid rates are shown in Fig. 4. From the figure, the fixed rate due to congestion has been increased while increasing the bid rate. When the generator operating cost is increased, the fixed cost due to congestion also increases.

Congestion cost estimation

The transmission congestion cost is determined from the difference in power flow at base case and at congested condition. The

Table 4
Contribution from generator to transmission lines for pool power market (Base case) Modified IEEE 30 bus system.

From bus	To bus	Base case power flow	G1	G2	G13	G22	G23	G27	Total loss
1	2	110.491	23.9	31.9	9.3	13.1	9.4	23.0	110.5
1	3	39.775	8.6	11.5	3.4	4.7	3.4	8.3	39.8
2	4	15.192	3.3	4.4	1.3	1.8	1.3	3.2	15.2
3	4	41.08	8.9	11.9	3.5	4.9	3.5	8.5	41.1
2	5	60.887	13.2	17.6	5.1	7.2	5.2	12.7	60.9
2	6	23.612	5.1	6.8	2.0	2.8	2.0	4.9	23.6
4	6	36.187	7.8	10.4	3.1	4.3	3.1	7.5	36.2
5	7	34.351	7.4	9.9	2.9	4.1	2.9	7.1	34.4
6	7	27.982	6.0	8.1	2.4	3.3	2.4	5.8	28.0
6	8	13.499	2.9	3.9	1.1	1.6	1.1	2.8	13.5
6	9	5.815	1.3	1.7	0.5	0.7	0.5	1.2	5.8
6	10	3.355	0.7	1.0	0.3	0.4	0.3	0.7	3.4
9	11	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	10	5.805	1.3	1.7	0.5	0.7	0.5	1.2	5.8
4	12	17.278	3.7	5.0	1.5	2.0	1.5	3.6	17.3
12	13	48.485	10.5	14.0	4.1	5.7	4.1	10.1	48.5
12	14	0.148	0.0	0.0	0.0	0.0	0.0	0.0	0.1
12	15	6.734	1.5	1.9	0.6	0.8	0.6	1.4	6.7
12	16	0.622	0.1	0.2	0.1	0.1	0.1	0.1	0.6
14	15	2.783	0.6	0.8	0.2	0.3	0.2	0.6	2.8
16	17	0.893	0.2	0.3	0.1	0.1	0.1	0.2	0.9
15	18	2.822	0.6	0.8	0.2	0.3	0.2	0.6	2.8
18	19	1.628	0.4	0.5	0.1	0.2	0.1	0.3	1.6
19	20	1.377	0.3	0.4	0.1	0.2	0.1	0.3	1.4
10	20	2.649	0.6	0.8	0.2	0.3	0.2	0.6	2.6
10	17	3.217	0.7	0.9	0.3	0.4	0.3	0.7	3.2
10	21	22.848	4.9	6.6	1.9	2.7	1.9	4.7	22.8
10	22	15.316	3.3	4.4	1.3	1.8	1.3	3.2	15.3
21	22	24.632	5.3	7.1	2.1	2.9	2.1	5.1	24.6
15	23	15.2	3.3	4.4	1.3	1.8	1.3	3.2	15.2
22	24	0.393	0.1	0.1	0.0	0.0	0.0	0.1	0.4
23	24	4.452	1.0	1.3	0.4	0.5	0.4	0.9	4.5
24	25	2.449	0.5	0.7	0.2	0.3	0.2	0.5	2.4
25	26	0.839	0.2	0.2	0.1	0.1	0.1	0.2	0.8
25	27	2.78	0.6	0.8	0.2	0.3	0.2	0.6	2.8
28	27	2.094	0.5	0.6	0.2	0.2	0.2	0.4	2.1
27	29	2.095	0.5	0.6	0.2	0.2	0.2	0.4	2.1
27	30	2.584	0.6	0.7	0.2	0.3	0.2	0.5	2.6
29	30	1.58	0.3	0.5	0.1	0.2	0.1	0.3	1.6
8	28	1.153	0.2	0.3	0.1	0.1	0.1	0.2	1.2
6	28	5.791	1.3	1.7	0.5	0.7	0.5	1.2	5.8
Total loss (Mw)			132.0	176.3	51.5	72.2	51.9	126.9	610.9

transmission congestion cost is calculated from the congested power flow by optimizing the real power at load buses. The congestion cost estimation is explored in pool power market and bilateral power market. By using power flow tracing principle, the transmission congestion cost is determined. In general, congestion cost is computed by utilizing LMP calculations [14]. From these cost, transmission congestion pricing (TCP) and congestion pricing (CP) has been computed. Transmission congestion pricing (TCP) is the pricing due to congestion in the transmission lines. The congestion pricing (CP) is found from the fixed cost of generation and TCP. In this paper, TCP and CP have been used for calculating the transmission congestion costs.

Transmission congestion pricing (TCP) due to generator participation,

$$TCP^{gi}_{Lm} = \left(P^{base}_{Lm,gi} - P^{cong}_{Lm,gi}\right) \times C_{line} \tag{20}$$

Transmission congestion pricing (TCP) due to the contribution of load,

$$TCP^{di}_{Lm} = \left(P^{base}_{Lm,di} - P^{cong}_{Lm,di}\right) \times C_{line} \tag{21}$$

where

TCP^{gi}_{Lm} – transmission congestion pricing due to generator bus gi at branch Lm.

TCP^{di}_{Lm} – transmission congestion pricing due to load bus di in the branch Lm.

Table 5
Extraction of power from generator to load for pool power market (Base case) Modified IEEE 30 bus system.

Generator bus ⟹ Load bus ⇩	G1	G2	G13	G22	G23	G27
3	47.98	13.85	1.17	0.14	0.01	0.00
4	45.28	13.07	1.10	0.13	0.01	0.00
5	41.07	11.85	1.00	0.12	0.01	0.00
6	41.41	11.95	1.01	0.12	0.01	0.00
7	45.56	13.15	1.11	0.13	0.01	0.00
8	33.93	9.79	0.83	0.10	0.01	0.00
9	41.61	12.01	1.01	0.12	0.01	0.00
10	42.80	12.35	1.04	0.12	0.01	0.00
11	39.45	11.38	0.96	0.11	0.01	0.00
12	42.36	12.22	1.03	0.12	0.01	0.00
14	34.58	9.98	0.84	0.10	0.01	0.00
15	34.80	10.04	0.85	0.10	0.01	0.00
16	35.66	10.29	0.87	0.10	0.01	0.00
17	35.66	10.29	0.87	0.10	0.01	0.00
18	29.72	8.58	0.72	0.09	0.01	0.00
19	32.57	9.40	0.79	0.09	0.01	0.00
20	31.88	9.20	0.78	0.09	0.01	0.00
21	23.78	6.86	0.58	0.07	0.01	0.00
22	0.00	0.00	0.00	0.00	0.00	0.00
24	6.48	1.87	0.16	0.02	0.00	0.00
25	0.65	0.19	0.02	0.00	0.00	0.00
26	2.16	0.62	0.05	0.01	0.00	0.00
28	17.29	4.99	0.42	0.05	0.00	0.00
29	17.29	4.99	0.42	0.05	0.00	0.00
30	12.97	3.74	0.32	0.04	0.00	0.00

Table 6
Loss extracted from the transmission lines due to load tracing for pool power market (Base case) Modified IEEE 30 bus system.

From bus	To bus	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	24	25	26	28	29	30	TOT
1	2	7.2	6.8	6.2	6.2	6.8	5.1	6.2	6.4	5.9	6.4	5.2	5.2	5.3	5.3	4.5	4.9	4.8	3.6	1.0	0.1	0.3	2.6	2.6	1.9	110.5
1	3	2.6	2.4	2.2	2.2	2.5	1.8	2.2	2.3	2.1	2.3	1.9	1.9	1.9	1.9	1.6	1.8	1.7	1.3	0.4	0.0	0.1	0.9	0.9	0.7	39.8
2	4	1.0	0.9	0.8	0.9	0.9	0.7	0.9	0.9	0.8	0.9	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.5	0.1	0.0	0.0	0.4	0.4	0.3	15.2
3	4	2.7	2.5	2.3	2.3	2.5	1.9	2.3	2.4	2.2	2.4	1.9	1.9	2.0	2.0	1.7	1.8	1.8	1.3	0.4	0.0	0.1	1.0	1.0	0.7	41.1
2	5	4.0	3.7	3.4	3.4	3.8	2.8	3.4	3.5	3.3	3.5	2.9	2.9	2.9	2.9	2.5	2.7	2.6	2.0	0.5	0.1	0.2	1.4	1.4	1.1	60.9
2	6	1.5	1.5	1.3	1.3	1.5	1.1	1.3	1.4	1.3	1.4	1.1	1.1	1.1	1.1	1.0	1.0	1.0	0.8	0.2	0.0	0.1	0.6	0.6	0.4	23.6
4	6	2.4	2.2	2.0	2.0	2.2	1.7	2.0	2.1	1.9	2.1	1.7	1.7	1.8	1.8	1.5	1.6	1.6	1.2	0.3	0.0	0.1	0.8	0.8	0.6	36.2
5	7	2.2	2.1	1.9	1.9	2.1	1.6	1.9	2.0	1.8	2.0	1.6	1.6	1.7	1.7	1.4	1.5	1.5	1.1	0.3	0.0	0.1	0.8	0.8	0.6	34.4
6	7	1.8	1.7	1.6	1.6	1.7	1.3	1.6	1.6	1.5	1.6	1.3	1.3	1.4	1.4	1.1	1.2	1.2	0.9	0.2	0.0	0.1	0.7	0.7	0.5	28.0
6	8	0.9	0.8	0.8	0.8	0.8	0.6	0.8	0.8	0.7	0.8	0.6	0.6	0.7	0.7	0.5	0.6	0.6	0.4	0.1	0.0	0.0	0.3	0.3	0.2	13.5
6	9	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.1	0.0	0.0	0.1	0.1	0.1	5.8
6	10	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	3.4
9	11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	10	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.1	0.0	0.0	0.1	0.1	0.1	5.8
4	12	1.1	1.1	1.0	1.0	1.1	0.8	1.0	1.0	0.9	1.0	0.8	0.8	0.8	0.8	0.7	0.8	0.7	0.6	0.2	0.0	0.1	0.4	0.4	0.3	17.3
12	13	3.2	3.0	2.7	2.7	3.0	2.2	2.7	2.8	2.6	2.8	2.3	2.3	2.3	2.3	2.0	2.1	2.1	1.6	0.4	0.0	0.1	1.1	1.1	0.9	48.5
12	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
12	15	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.0	0.0	0.2	0.2	0.1	6.7
12	16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
14	15	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	2.8
16	17	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9
15	18	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	2.8
18	19	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.6
19	20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4
10	20	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	2.6
10	17	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1	3.2
10	21	1.5	1.4	1.3	1.3	1.4	1.1	1.3	1.3	1.2	1.3	1.1	1.1	1.1	1.1	0.9	1.0	1.0	0.7	0.2	0.0	0.1	0.5	0.5	0.4	22.9
10	22	1.0	0.9	0.9	0.9	0.9	0.7	0.9	0.9	0.8	0.9	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.5	0.1	0.0	0.0	0.4	0.4	0.3	15.3
21	22	1.6	1.5	1.4	1.4	1.5	1.1	1.4	1.4	1.3	1.4	1.2	1.2	1.2	1.2	1.0	1.1	1.1	0.8	0.2	0.0	0.1	0.6	0.6	0.4	24.6
15	23	1.0	0.9	0.8	0.9	0.9	0.7	0.9	0.9	0.8	0.9	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.5	0.1	0.0	0.0	0.4	0.4	0.3	15.2
22	24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
23	24	0.3	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.1	0.1	0.1	4.5
24	25	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	2.4
25	26	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
25	27	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	2.8
28	27	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	2.1
27	29	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	2.1
27	30	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.0	2.6
29	30	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.6
8	28	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2
6	28	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.2	0.1	0.0	0.0	0.1	0.1	0.1	5.8
Total loss(Mw)		39.78	37.54	34.05	34.33	37.77	28.13	34.49	35.48	32.70	35.12	28.67	28.85	29.57	29.57	24.6	27.00	26.43	19.1	5.38	0.54	1.79	144	14.3	10.7	611.0

Table 7
Fixed cost allocation at various bid rates Modified IEEE 30 Bus System.

Case study	Generation ($/MW)	Load ($/MW)	Loss occured ($/MW)
BASE CASE	14609.22	14261.1	348.115
CASE A	165989.7	161,982	4007.72
CASE B	331979.4	323,964	8015.44
CASE C	497969.2	485,946	12023.16

$P^{base}_{Lm,gi}$ – power flow at base case due to generator gi at transmission line *Lm*.
$P^{base}_{Lm,di}$ – power flow at base case due to load di at transmission line *Lm*.
$P^{cong}_{Lm,gi}$ – power flow due to congestion at generator gi at transmission line *Lm*.
$P^{cong}_{Lm,di}$ – power flow due to congestion at load di at transmission line *Lm*.
C_{line} – congested cost in the transmission line in $/h.

The variation in power flow by adding IPP at load buses are shown in Table 3. By maximizing the real power generation at load buses the total real power generated, real power demand and losses occurred in the transmission lines are presented for bilateral as well as pool power markets. The maximized value of real power is obtained at bus number 7 with the value of 187.4 Mw.

Summary

The fixed cost for the real power generation is obtained from the power flow at the generating buses. The fixed cost for the real power demand is also obtained from the power flow at the load buses due to the addition of IPP. The loss occurrence cost is calculated by obtaining the difference between the generator fixed cost and demand fixed cost. All the fixed cost is obtained only at the normal operating condition, not any congestion.

In pool market, loss allocation, transmission congestion pricing and congestion pricing is minimum. The Congestion Power flow is more in bilateral market. In this market, congested power flow can be reduced by minimizing the losses. The negative power flow in this market indicates that the consumers or buyer has to pay penalty for the losses. While maximizing the real power generation and demand, the real power losses in the bilateral market will be increased.

The congestion pricing and transmission congestion pricing at various power markets are tested on IEEE 30 bus system and Indian Utility-69 bus test system. The comparison of the results are shown in Table 8.

The base case power flow is 485.567 MW; the power flow due to congestion gives negative value as 10710.858 MW. In pool market, the power flow due to congestion is 4076.419 MW. As compared with bilateral market, the congested power in pool market is less. The power flow at base case is 610.876 MW for this pool market. In both power markets, the power flow in congested condition is in counter clockwise direction of the actual power flow.

The congestion pricing (CP) is calculated from the congested power flow and the cost of power flow in the transmission lines. The congested power in bilateral market for the test systems is 10710.858 MW and 27870532.39 Mw. This power is multiplied with power transfer cost (20 $/MW) for getting congestion pricing (CP). The transmission congestion pricing (TCP) is calculated by finding the difference between base case power flow and congested power flow. The change in power flow in pool market for the test systems is 4686.873 MW and 1527325.574 Mw. The TCP is calculated by multiplying the change in power flow value with cost of power flow (20 $/MW) in the transmission lines.

From the comparison of pricing results, it has been found that while increasing the number of buses, the power flow due to congestion has also increased. But, the variation in pricing in pool and bilateral market for IEEE 30 bus system provides less significant results. In case of Indian utility 69 bus system, the difference in pricing proves less variation. Therefore, by testing with large scale systems, the congestion pricing and transmission congestion pricing in pool market provides high significant results.

From the previous work, the congestion cost is calculated for one particular line to the generator and load. In this paper, all

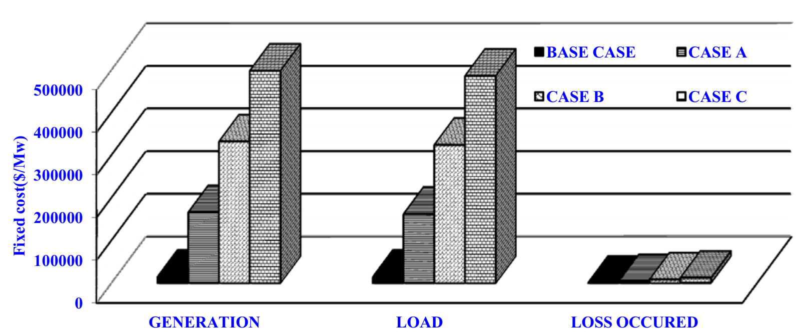


Fig. 4. Performance analysis at various bid rates – Modified IEEE 30 bus system.

Table 8
Congestion pricing and transmission congestion pricing in power markets.

Test system	Market type	Base case power flow (MW)	Power flow due to congestion (MW)	CP	TCP
Modified IEEE 30 BUS	Bilateral market	485.567	10710.858	2,14,217.16	2,23,928.5
	Pool market	**610.873**	**4076.419**	**81,528.38**	**93,745.84**
Indian Utility 69 BUS	Bilateral market	12369.29	27870532.39	55,74,10,647.7	55,76,58,034
	Pool market	15557.25134	1527325.574	3,05,46,511.49	3,08,57,657

the load buses are involved to supply for the transmission lines. The change in power flow in all the transmission line due to all connected load are determined.

From the pricing calculation, it is shown that the power transfer due to congestion in the higher order systems is more. The congestion cost in the transmission lines are less in 30 bus system in comparison with 69 bus system. The real power generation in pool market is more than the real power generation in bilateral power market. The occurrence of loss due to bilateral market is lesser than the loss occurred in the pool market.

The comparison of CP and TCP at various power markets are shown in Fig. 5. The fixed of the generation, load and loss allocations are calculated only for IEEE 30 bus test system. For validation of CP and TCP, the pricing calculations are done for Indian utility 69 test system. The convergence characteristics of Indian utility 69 test system for maximizing the real power demand is shown in Fig. 6.

In the reference papers, conventional tracing using matrix multiplication and Factors method are used. The power tracing has been done using either generator or load based tracing. Any one bus has been taken for testing the generation contribution or load extraction. The congestion pricing with line outage or N-1 contingency was analyzed using LMP [13,16]. The congestion cost calculation for IEEE-24 bus test system was explained [19] in which power transfer studies have been done due to the impact of only one transmission line.

The comparison of pricing in the proposed paper is done using optimization method and tested on Modified IEEE 30 bus test system and Indian utility 69 bus test system. This paper proposes a new method for calculating Congestion Pricing and Transmission Congestion Pricing using power flow tracing principle. The power flow in bilateral and pool power markets are obtained by maximizing the real power generation and real power load. The congestion pricing in pool market and bilateral markets are compared for showing the effectiveness of the proposed method. From the results obtained, it is clear that the power flow tracing based congestion pricing calculation is easily achieved without any assumptions and matrix inversion. The parameter selection details are shown in Tables 9–11.

The power flow due to congestion has negative values for both the market participants. The bilateral market gives more negative power under congested condition. This negative power flow refers to the amount of penalty to be paid by the consumer to the supplier. The real power losses in the transmission line can be reduced using FACTS devices. The presented paper does not focus on compensation of real power losses.

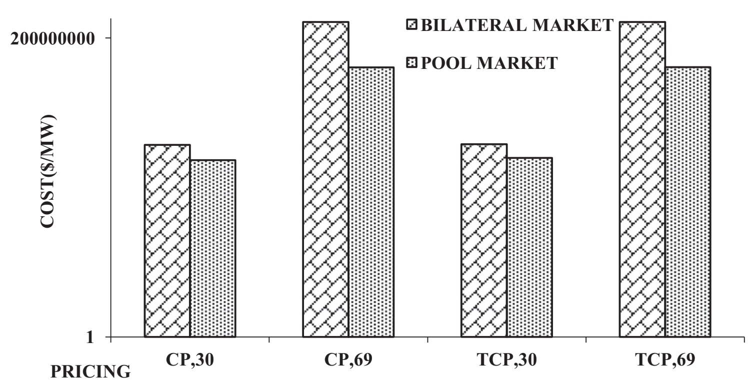


Fig. 5. Comparison of pricing in power markets. *CP,30-Congestion Pricing in 30 bus system. CP,69-Congestion Pricing in 69 bus system. TCP,30-Transmission Congestion Pricing in 30 bus system. TCP,69-Transmission Congestion Pricing in 69 bus system.

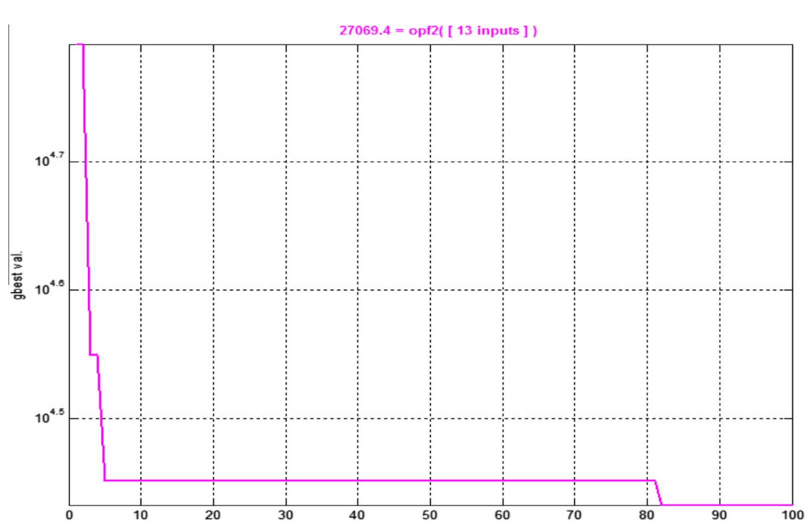


Fig. 6. Convergence characteristics of PSO for Indian Utility 69 bus system.

Table 9
Parameter verification for maximization of real power generation using PSO.

No. iteration	Gbest	Fitness value	Inertia weight	Standard deviation
20	2800.36	2.8004e+003	0.894	3.176874
40	2831.89	2.8319e+003	0.887	14.32441
60	2791.77	2.7918e+003	0.88065	0.13985
80	2782.06	2.7821e+003	0.87398	3.293153
100	2793.43	2.7934e+003	0.86731	0.726749
200	2774.18	2.7742e+003	0.83396	6.079154
300	2795.49	2.7955e+003	0.8006	1.455069
400	2776.91	2.7769e+003	0.76724	5.113953
500	2776.28	2.7763e+003	0.73389	5.336692

Table 10
Parameter verification for maximization of real power demand using PSO.

No. iteration	Gbest	Fitness value	Inertia weight	Standard deviation
20	2814.636	2.8021+003	0.889	1.058958
40	2768.588	2.7843+003	0.8831	4.774804
60	2764.0164	2.7765+003	0.8767	0.046617
80	2763.769	2.7537+003	0.8712	1.097718
100	2764.29	2.7643e+003	0.86731	0.24225
200	2760.944	2.7609e+003	0.83396	2.026385
300	2746.94	2.7469e+003	0.8006	0.485023
400	2753.12	2.7521e+003	0.7672	1.704651
500	2749.08	2.7491e+003	0.7338	1.778897

Table 11
PSO performance evaluation.

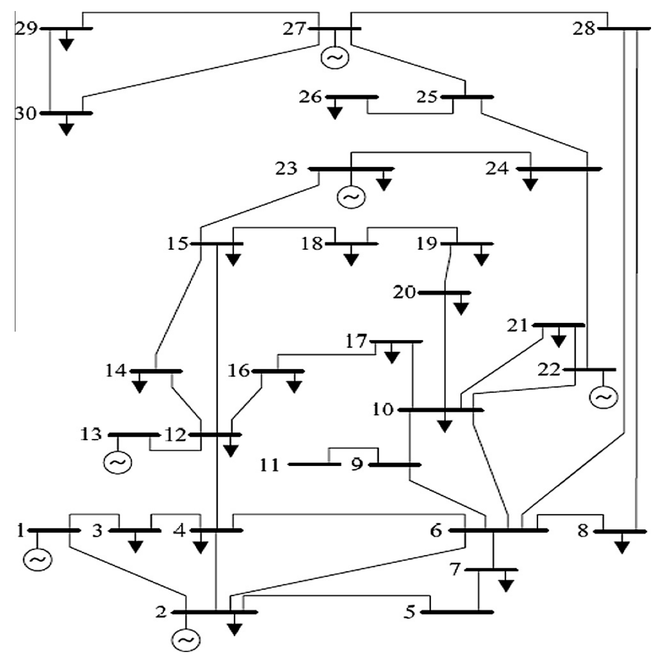
Parameter	Maximized real power generation	Maximized real power load
IEEE 30 bus system		
No. of trials	500	500
Mean value	2791.374	2765.043
Standard deviation	4.405101	13.2153
Best case	2.7742e+003	2.7469e+003
Worst case	2.8319e+003	2.8021e+003

Conclusions

This paper has presented a new scheme for estimating the transmission congestion pricing using tracing principle under deregulated electricity markets. The proposed work is solved in an optimization framework using PSO algorithm and the results are analyzed on Modified IEEE 30 bus system and Indian Utility 69 bus system. The transmission congestion cost is obtained from the fixed cost of generation/load and cost due to loss. The congestion pricing and transmission congestion pricing is obtained from the fixed and loss allocation costs. The various cost calculations are done in pool power market and bilateral power markets. From these pricing, pool power markets has proven to provide less congestion power flow and also less congestion pricing compared to bilateral model. The proposed method can also be applied for multilateral transaction to obtain the transmission congestion pricing. By maximizing the power flow at load bus, the congestion in the test system is created and congested power flow is obtained in bilateral and power pool markets. This proposed method of estimating the transmission congestion pricing can be extended for large scale power system networks.

Appendix A

A.1. Single line diagram of IEEE 30 bus system



A.2. Generator data for IEEE 30 bus system

Unit	Bus	Cost coefficients			P_{max} (MW)	P_{min} (MW)
		A ($/MW h)	*B* ($/MW h)	*C* ($/MW h)		
G1	1	0.200	15.00	0	80	15
G2	2	0.0175	14.75	0	80	15
G3	13	0.0250	16.00	0	50	10
G4	22	0.0625	14.00	0	50	10
G5	23	0.0250	16.00	0	30	5
G6	27	0.0083	15.25	0	55	10

A.3. Generator data for IEEE 30 bus system

Line no	From	To	*X*	Flow limit
1	1	2	0.06	130
2	1	3	0.19	130
3	2	4	0.17	65
4	3	4	0.04	130
5	2	5	0.2	130
6	2	6	0.18	65
7	4	6	0.04	90
8	5	7	0.12	70
9	6	7	0.08	130
10	6	8	0.04	32
11	6	9	0.21	65
12	6	20	0.56	32
13	9	11	0.21	65
14	9	10	0.11	65
15	4	12	0.26	65
16	12	13	0.14	65
17	12	14	0.26	32

(*continued on next page*)

Appendix A.3 (*continued*)

Line no	From	To	X	Flow limit
18	12	15	0.13	32
19	12	16	0.2	32
20	14	15	0.2	16
21	16	17	0.19	16
22	15	18	0.22	16
23	18	19	0.13	16
24	19	20	0.07	32
25	10	20	0.21	32
26	10	17	0.08	32
27	10	21	0.07	32
28	10	22	0.15	32
29	21	22	0.02	32
30	15	23	0.2	16
31	22	24	0.18	16
32	23	24	0.27	16
33	24	25	0.33	16
34	25	26	0.38	16
35	25	27	0.21	16
36	28	27	0.4	65
37	27	29	0.42	16
38	27	30	0.6	16
39	29	30	0.45	16
40	8	28	0.2	32
41	6	28	0.06	32

A.4. Load data for IEEE 30 bus system

Bus	Load (MW)	Bus	Load (MW)
1	0.0	16	3.5
2	21.7	17	9.0
3	2.4	18	3.2
4	67.6	19	9.5
5	34.2	20	2.2
6	0.0	21	17.5
7	22.8	22	0.0
8	30.0	23	3.2
9	0.0	24	8.7
10	5.8	25	0.0
11	0.0	26	3.5
12	11.2	27	0.0
13	0.0	28	0.0
14	6.2	29	2.4
15	8.2	30	10.6

Appendix B

B.1. Bus data for Indian 69 bus utility system

Bus number	Type of bus	V (p.u.)	P_d (MW)	Q_d (MVAR)	P_g (MW)	Q_g (MVAR)
1	Slack	1.00	85	51	–	–
2	PQ	1.00	56	34	0.0	0.0
3	PQ	1.00	97	58	0.0	0.0
4	PQ	1.00	0.0	0.0	0.0	0.0
5	PQ	1.00	98	59	0.0	0.0
6	PQ	1.00	99	60	0.0	0.0
7	PQ	1.00	142	85	0.0	0.0
8	PQ	1.00	89	54	0.0	0.0
9	PQ	1.00	36	22	0.0	0.0
10	PQ	1.00	61	37	0.0	0.0
11	PQ	1.00	52	31	0.0	0.0
12	PQ	1.00	48	29	0.0	0.0
13	PV	1.00	95	57	1050	–
14	PV	1.00	10	6	330	–
15	PV	1.00	100	60	460	–
16	PQ	1.00	5	3	0.0	0.0
17	PQ	1.00	68	41	0.0	0.0
18	PQ	1.00	28	17	0.0	0.0
19	PQ	1.00	69	42	0.0	0.0
20	PQ	1.00	0.0	0.0	0.0	0.0
21	PV	1.00	25	15	250	–
22	PQ	1.00	47	28	0.0	0.0
23	PQ	1.00	25	15	0.0	0.0
24	PQ	1.00	0.0	0.0	0.0	0.0
25	PQ	1.00	0.0	0.0	0.0	0.0
26	PQ	1.00	133	80	0.0	0.0
27	PQ	1.00	30	18	0.0	0.0
28	PQ	1.00	88	53	0.0	0.0
29	PQ	1.00	49	30	0.0	0.0
30	PQ	1.00	69	42	0.0	0.0
31	PV	1.00	170	102	190	–
32	PQ	1.00	144	87	0.0	0.0
33	PQ	1.00	82	49	0.0	0.0
34	PQ	1.00	56	34	0.0	0.0
35	PQ	1.00	14	6	0.0	0.0
36	PV	1.00	63	38	133	–
37	PQ	1.00	56	34	0.0	0.0
38	PQ	1.00	28	17	0.0	0.0
39	PV	1.00	40	24	420	–
40	PQ	1.00	45	27	0.0	0.0
41	PQ	1.00	119	72	0.0	0.0
42	PQ	1.00	54	33	0.0	0.0
43	PQ	1.00	137	82	0.0	0.0
44	PQ	1.00	155	93	0.0	0.0
45	PQ	1.00	140	84	0.0	0.0
46	PQ	1.00	20	12	0.0	0.0
47	PQ	1.00	69	42	0.0	0.0
48	PQ	1.00	105	63	0.0	0.0
49	PQ	1.00	59	36	0.0	0.0
50	PQ	1.00	62	37	0.0	0.0
51	PQ	1.00	143	86	0.0	0.0
52	PV	1.00	85	51	840	–
53	PV	1.00	0.0	0.0	55	–
54	PQ	1.00	90	54	0.0	0.0
55	PQ	1.00	56	34	0.0	0.0
56	PQ	1.00	230	138	0.0	0.0
57	PV	1.00	0.0	0.0	175	–
58	PV	1.00	0.0	0.0	165	–
59	PQ	1.00	108	65	0.0	0.0
60	PV	1.00	0.0	0.0	100	–
61	PQ	1.00	79	48	0.0	0.0
62	PQ	1.00	75	45	0.0	0.0
63	PQ	1.00	107	64	0.0	0.0
64	PQ	1.00	115	69	0.0	0.0
65	PQ	1.00	0.0	0.0	0.0	0.0

Appendix B.1 (*continued*)

Bus number	Type of bus	V (p.u.)	P_d (MW)	Q_d (MVAR)	P_g (MW)	Q_g (MVAR)
66	PQ	1.00	146	88	0.0	0.0
67	PQ	1.00	0.0	0.0	0.0	0.0
68	PQ	1.00	105	63	0.0	0.0
69	PQ	1.00	81	49	0.0	0.0

B.2. Line data for Indian 69 bus utility system

Line number	From bus	To bus	R (p.u.)	X (p.u.)	Half line charging susceptance	Thermal limit (MVA)
1	1	2	0.0004	0.0018	0.0068	150
2	1	3	0.0001	0.0001	0.0144	150
3	1	4	0.0067	0.0344	0.0067	150
4	1	5	0.004	0.0204	0.0751	90
5	1	20	0.021	0.1076	0.0821	90
6	1	22	0.022	0.113	0.0847	90
7	2	5	0.007	0.036	0.0993	50
8	3	20	0.022	0.113	0.1043	50
9	4	7	0.0018	0.009	0.0342	50
10	5	6	0.0172	0.0884	0.0867	50
11	5	7	0.0108	0.0552	0.0061	150
12	5	22	0.0198	0.1022	0.0727	50
13	6	1	0.0137	0.0706	0.051	90
14	7	22	0.0104	0.0536	0.0943	150
15	8	1	0.0179	0.0918	0.0495	130
16	8	9	0.0099	0.0509	0.047	90
17	9	10	0.0072	0.037	0.0339	90
18	9	11	0.0206	0.1057	0.0976	150
19	10	24	0.0061	0.0315	0.0317	90
20	11	12	0.016	0.082	0.0252	240
21	12	13	0.0008	0.0043	0.0556	150
22	12	14	0.0024	0.0126	0.0106	150
23	13	15	0.0013	0.0065	0.006	600
24	13	21	0.0007	0.0039	0.0102	295
25	14	19	0.0038	0.019	0.0325	295
26	15	16	0.0068	0.0348	0.0144	240
27	15	27	0.0151	0.0778	0.0968	295
28	15	28	0.0092	0.0474	0.0751	600
29	16	18	0.0137	0.0704	0.0578	240
30	17	21	0.0118	0.061	0.063	240
31	17	26	0.0094	0.0485	0.0436	240
32	18	26	0.0031	0.0157	0.015	240
33	19	24	0.0046	0.023	0.0433	240
34	20	22	0.001	0.0054	0.0198	150
35	20	25	0.0168	0.0861	0.0794	90
36	21	62	0.0138	0.0711	0.0621	295
37	22	23	0.0043	0.0223	0.0108	100
38	23	24	0.0154	0.0791	0.0325	150
39	24	25	0.0142	0.0728	0.0672	150
40	24	26	0.0017	0.0088	0.0144	150
41	25	63	0.0088	0.0454	0.0419	150
42	25	65	0.0148	0.0759	0.0622	150
43	27	48	0.0198	0.1017	0.0939	240

Appendix B.2 (*continued*)

Line number	From bus	To bus	R (p.u.)	X (p.u.)	Half line charging susceptance	Thermal limit (MVA)
44	28	29	0.0124	0.0638	0.065	500
45	29	30	0.0091	0.0469	0.0392	400
46	30	31	0.0084	0.043	0.0401	295
47	31	32	0.0034	0.0176	0.065	350
48	31	47	0.0156	0.0803	0.0741	100
49	32	41	0.0141	0.0722	0.0667	120
50	32	43	0.0074	0.0376	0.0134	150
51	33	44	0.0013	0.0069	0.0187	90
52	34	35	0.0029	0.0148	0.0255	150
53	34	39	0.0049	0.025	0.018	100
54	34	44	0.0043	0.0221	0.0339	150
55	34	45	0.0027	0.0141	0.0195	150
56	35	36	0.0004	0.0021	0.0195	150
57	36	38	0.0017	0.0086	0.0137	150
58	36	39	0.003	0.0157	0.0079	50
59	37	38	0.0012	0.0049	0.0144	150
60	38	39	0.0041	0.0211	0.0125	90
61	39	40	0.0114	0.0586	0.0195	100
62	39	42	0.0028	0.0146	0.0744	150
63	39	44	0.0109	0.0563	0.0108	90
64	40	41	0.0053	0.0275	0.1039	180
65	41	48	0.019	0.0978	0.0325	100
66	43	44	0.0071	0.0363	0.0903	295
67	44	32	0.004	0.0203	0.0335	180
68	44	45	0.0052	0.0267	0.0246	60
69	44	46	0.0003	0.0016	0.0195	150
70	44	47	0.0131	0.0675	0.0623	150
71	47	48	0.0154	0.0789	0.0729	295
72	48	49	0.0103	0.0527	0.0432	90
73	48	50	0.0157	0.0806	0.0687	90
74	48	51	0.0137	0.0701	0.0693	240
75	48	52	0.0121	0.0622	0.0574	350
76	51	52	0.0067	0.0344	0.0635	295
77	51	61	0.0024	0.0125	0.0462	195
78	52	53	0.0018	0.0094	0.0086	150
79	52	54	0.0026	0.0133	0.0122	90
80	52	55	0.011	0.0563	0.0436	90
81	52	59	0.0143	0.0733	0.0318	150
82	52	61	0.0021	0.0106	0.0195	150
83	53	54	0.0015	0.0078	0.0072	100
84	55	56	0.0113	0.0582	0.0536	100
85	55	61	0.0113	0.0579	0.0535	50
86	56	57	0.0098	0.0502	0.0564	150
87	56	58	0.0085	0.0437	0.0412	160
88	56	59	0.0053	0.0274	0.0178	90
89	57	58	0.0011	0.0055	0.0423	100
90	58	60	0.0011	0.0055	0.0412	150
91	60	64	0.0041	0.0209	0.0194	240
92	61	62	0.015	0.077	0.0678	240
93	61	63	0.0092	0.0473	0.0315	90
94	64	65	0.0125	0.0644	0.0594	90
95	65	66	0.0007	0.0034	0.0124	150
96	65	67	0.0037	0.0188	0.0693	150
97	65	68	0.0137	0.0704	0.065	195
98	66	67	0.0067	0.0344	0.0318	90
99	68	69	0.0101	0.0521	0.0123	100

B.3. Generator bus data for Indian 69 bus utility system

Bus no.	P_{min} (MW)	P_{max} (MW)	Q_{min} (MVAR)	Q_{max} (MVAR)	a_i (\$/MW^2-h)	b_i (\$/MW-h)	c_i (\$/h)
1	0	900	−300	200	0.0085	6.0	55
13	0	1100	−300	200	0.0085	6.0	55
14	0	350	−150	100	0.0080	5.5	90
15	0	500	−200	100	0.0055	4.0	45
21	0	250	−100	80	0.0045	1.6	25
31	0	200	−90	80	0.0045	1.6	25
36	0	150	−90	80	0.0045	1.6	25
39	0	450	−200	100	0.0055	4.0	45
52	0	850	−300	200	0.0085	6.0	55
53	0	60	−25	25	0.0025	0.85	15
57	0	200	−90	80	0.0045	1.6	25
58	0	200	−90	80	0.0045	1.6	25
60	0	100	−100	70	0.0045	1.6	65

References

[1] Rosado Sebastian P., Abdel-Rahman Khatib, HadjSaid Nouredine. Tracing the path of electric power flow – a study for deregulated power systems. In: IEEE power engineering society winter meeting, vol. 3; 2001. p. 1479–84.

[2] Bialek J. Tracing the flow of electricity. IEEE Proc Gen Transm Distrib 1996;143 (4):313–20.

[3] Bialek JW, Kattuman PA. Proportional sharing assumption in tracing methodology. IEE Proc Gener Transm Distrib 2004;151(4):526–32.

[4] Panto Milos, Verbic Gregor, Gubina Ferdinand. Modified topological generation and load distribution factors. IEEE Trans Power Syst 2005;20(4):1998–2005.

[5] Xie Kaigui, Li Chunyan, Liu Yenren. Tracing power flow from generators to loads and branches using incidence matrix multiplication. IEEE Power Energy Soc App Syst 1979;98(6):2047–54.

[6] Abhyankar AR, Soman SA, Khaparde SA. Optimization approach to real power tracing: an application to transmission fixed cost allocation. IEEE Trans Power Syst 2006;21(3):1350–61.

[7] Mustafa MW, Shareef H. A comparison of electric power tracing methods used in deregulated power systems. In: IEEE international power and energy conference. p. 156–60.

[8] Hamid Z, Musirin I, Othman MM, Rahim NA. Evolutionary programming based load tracing optimization in deregulated power system. In: International conference on communications, electrical & computer engineering. p. 160–5.

[9] Hamid Z, Musirin I, Othman MM, Rahim NA. A novel technique for generation tracing via evolutionary programming. In: IEEE power engineering and optimization conference. p. 381–6.

[10] Yang Jian, Anderson Max D. Tracing the flow of power in transmission network for use-of- transmission-system charges and congestion management. In: IEEE power engineering society winter meeting, vol.1; 1999. p. 399–405.

[11] Umarani DrR, Selvi V. Particle swarm optimization, evolution, overview and applications. Int J Eng Sci Technol 2010;2(7):2802–6.

[12] Pillay Anusha, Prabhakar Karthikeyan S, Kothari DP. Congestion management in power systems – a review. Int J Electr Power Energy Syst 2015;70:83–90.

[13] Farahani Vahraz Zamani, Kazemi Ahad. Comparing two ways of congestion management in bilateral based power market. In: IEEE CC conference (GCC).

[14] Murali M, Sailaja Kumari M, Sydulu M. LMP based electricity market simulation using genetic algorithm. In: IEEE conference on industrial electronics and applications. p. 1285–90.

[15] Manikandan BV, Charles Raja S, Venkatesh P, Mandala Manasarani. Comparative study of two congestion management methods for the restructured power systems. J Electr Eng Technol 2011;6(3):302–10.

[16] Singla Anu, Singh Kanwardeep, Yadav Vinod Kumar. Transmission congestion management in deregulated environment: a bibliographical survey. In: IEEE international conference on recent advances and innovations in engineering.

[17] Modi NS, Parekh BR. Transmission network congestion in deregulated wholesale electricity market. In: Proceedings of the international multi conference of engineers and computer scientists, vol II; 2009. p. 978–88.

[18] Jana Anup. A new approach to transmission congestion cost calculation. In: Power system technology and IEEE power india conference. p. 1–4.

[19] Nikoukar J, Haghifam MR. Transmission cost allocation based on the use of system and considering the congestion cost. Electr Power Energy Syst 2012;43 (1):961–8.

[20] Liu Bin, Liu Yafang, Inaba Tsuginon. A new wheeling price calculation method considering transmission line congestion and loss costs. International conference on power system technology, vol. 2. p. 1201–6.