A Nodal Transmission Pricing Model based on newly developed expressions of Real and Reactive Power Marginal Prices in Competitive Electricity Markets

Ashish Saini and A.K. Saxena

Abstract**—**In competitive electricity markets all over the world, an adoption of suitable transmission pricing model is a problem as transmission segment still operates as a monopoly. Transmission pricing is an important tool to promote investment for various transmission services in order to provide economic, secure and reliable electricity to bulk and retail customers. The nodal pricing based on SRMC (Short Run Marginal Cost) is found extremely useful by researchers for sending correct economic signals. The marginal prices must be determined as a part of solution to optimization problem i.e. to maximize the social welfare. The need to maximize the social welfare subject to number of system operational constraints is a major challenge from computation and societal point of views. The purpose of this paper is to present a nodal transmission pricing model based on SRMC by developing new mathematical expressions of real and reactive power marginal prices using GA-Fuzzy based optimal power flow framework. The impacts of selecting different social welfare functions on power marginal prices are analyzed and verified with results reported in literature. Network revenues for two different power systems are determined using expressions derived for real and reactive power marginal prices in this paper.

Keywords**—**Deregulation, Electricity markets, Nodal pricing, Social welfare function, Short run marginal cost.

I. Introduction

In recent years, the electricity industry has been undergoing restructuring all over the world. A main feature of electric power industry deregulation is that the delivery of electric power (a service) must be decoupled from the purchase of the power itself (a product) and priced and contracted separately. In this price based competition, a fair, transparent and predictable transmission pricing framework of electricity is one of the major issues. From the economic point of view, a nodal pricing based on SRMC (Short Run Marginal Cost) presents a good potential for providing economic signals for system operation [1].

First, Schweppe *et al.* [2] proposed the concept of marginal price of microeconomics to be extended to power systems and taken as the nodal price of electricity to induce efficient use of both the transmission and generation resources by providing correct economic signals. The marginal prices are obtained within an OPF (Optimal Power Flow) framework, as they are the sensitivities (dual variables) associated with the active power balance equations. Further, as proposed in [3]-[5], reactive marginal price is defined as the sensitivity of the generation production cost to the reactive power demand with reactive power production cost neglected. It represents a small portion of the true cost, as it only includes the fuel costs of the generators. It is suggested by Chattopadhyay *et al.* [6] that reactive power price should recover operational cost and capital investments of capacitors, but the reactive power production cost of generators is neglected. In the studies [7] on reactive power services, it is stressed that the capital costs should be included in reactive power price. Dai Y. *et al.* [8] introduced an opportunity cost as a reactive power production cost of generator along with capital investment cost of capacitors. Both of these costs are included in the objective function of the total system operation cost and sequential quadratic programming is applied to solve the OPF problem to obtain real and reactive marginal prices for five-bus system.

The utility industry restructuring has enhanced the role and importance of OPF tools. Although Newton method is well developed method for OPF, but more recently advanced optimized techniques such as genetic algorithms (GAs), simulated annealing method and interior point (IP) methods have been employed to solve power system optimization problems.

In present paper, section 2 is a brief introduction of GA-Fuzzy optimization method is given. The GA-Fuzzy OPF is tested and found better than various OPF methods based on classical optimization techniques and GA variants by authors and already reported in reference [9]. A proposed nodal pricing model based on SRMC method is discussed in section 3. The new expressions of real and reactive power marginal prices for all buses are developed for final optimal values of all control variables obtained from GA-Fuzzy OPF. Section 4 deals with a computer study made for 5-bus system and IEEE 30-bus data, by using expressions of real and reactive marginal

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power prices in section 3. A study is made to know the impact of different social welfare functions (with base electric power loads and bilateral power transactions) on real and reactive marginal prices SRMC method for 5-bus power system data [8]. The first two cases have different social welfare functions with same base electric power loads. The last two cases represent actual electricity market scenarios having same welfare functions with same base electric power loads but two different bilateral power transactions. Optimal values of real power generation, reactive power generation of generators and reactive support of shunt capacitors are obtained by GA-Fuzzy OPF. Real and reactive power marginal prices using newly developed expressions are determined for nodal transmission pricing. Another computer study is made on completely deregulated IEEE 30-bus system with pool loads, bilateral and multilateral transactions. Network revenues are determined for both 5-bus and IEEE 30-bus power systems. Section 5 concludes the paper.

II. GA-Fuzzy approach for OPF solution

The GA-Fuzzy optimization technique has been already validated by Saini *et al.*, (2006) for OPF on 26-bus power system data, 6-bus power system data and IEEE 30-bus power system data. In this approach the ranges of crossover probability (P_c) and mutation probability (P_m) are divided into LOW, MEDIUM and HIGH membership functions and each function is given some membership values.

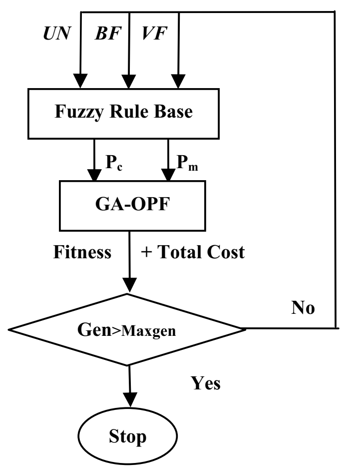

Fig. 1 GA-Fuzzy approach for OPF problem solving

Fig. 1 is a diagrammatic representation of an approach to incorporate fuzzy logic to GA based OPF solution. The GA parameters (P_c and P_m) are varied based on the fitness function values as per the following logic:

(1) The values of the best fitness for each generation (*BF*) is expected to change over a number of generations, but if it does not change significantly over a number of generations (*UN*) then this information is considered to cause changes in both P_c and P_m.

(2) The diversity of the population is one of the factors, which influences the search for a true optimum. The variance of the fitness values of objective function (*VF*) of the population is a measure of diversity which is used to change P_c and P_m.

In this approach the ranges of P_c , P_m , *BF*, *UN* and *VF* are divided into three triangular functions and each is given some membership values.

III. Proposed Nodal Transmission Pricing Model

In this model, all schedule firm electric power transactions are added to the system. The following assumptions are considered for proposed pricing model.

i) All the power pool generators are required to bid their generation cost characteristics to the power pool along with maximum generation.

ii) There are no non-firm bilateral electric power transactions.

iii) The real and reactive power of power pool loads are known from electric load forecasting and kept constant during optimization. Therefore, there is no bidding from single auction power pool demands shown in Fig.2. and instead of rectangular block bids from power pool generators quadratic generation cost bids are considered in the present paper.

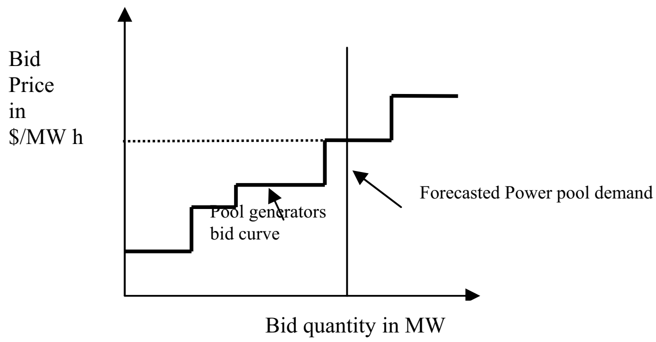

Fig. 2 Single Auction Power Pool

iv) The other costs of system like maintenance and different overheads etc. are not being included in proposed model.

v) The losses taking place in transmission network due to transactions as well as power pool are considered to be supplied from power pool itself. They are not supplied by electric power transactions generators or cope up with transaction loss supply contracts which are complex to setup and coordinate [10].

The proposed model has single auction power pool with bilateral and multilateral power transactions in which there are no power pool demand bids. Therefore, in this case a maximization of social welfare function becomes total system cost minimization problem.

A. Objective functions and constraints

The objective function for the optimization problem is to minimize the system cost. Based on the assumption of constant loads, the minimization of system cost is equivalent to maximize the social benefits. Therefore, two suggested objective functions in [8] to maximize social benefit are given by (1) and (2) as follows:

$$\min \sum_{i=1}^{ng}\left[C(Pg_i)+C(Qg_i)\right] \quad (1)$$

and

$$\min \sum_{i=1}^{ng}\left[C(Pg_i)+C(Qg_i)\right]+\sum_{j=1}^{ncap}C(Qc_j) \quad (2)$$

Let the real power generation cost curve bid of the generator at i^{th} bus = $C(Pg_i)$

Equivalent reactive power generation cost of generator at i^{th} bus = $C(Qg_i)$

where, ng = Total number of power pool generators

Equivalent reactive power production cost of j^{th} capacitor = $C_{cj}(Qc_j)$

where, j = 1,2,…..*ncap*, as *ncap* = Total number of capacitors operating in the system

For sake of simplicity cost curves for real power generation are modelled by following quadratic function:

$$C(Pg_i)=a+bPg_i+cPg_i^2 \quad (3)$$

Lamont and Fu [11], introduced reactive power cost based on opportunity cost and used by Dai Y. *et al.,* [8]. The reactive power output of a generator will reduce its real generation capability which can serve at least as spinning reserve and the corresponding implicit financial loss to generator is modeled as an opportunity cost. Therefore, expression of equivalent reactive power generation cost $C(Qg_i)$ is given by (4) as below.

$$C(Qg_i)=\left[C(Sg_{i,\max})-C\left(\sqrt{Sg_{i,\max}^2-Qg_i^2}\right)\right]k \quad (4)$$

where, $Sg_{i,max}$ is the nominal apparent power of the generator i ; k is the profit rate of active power generation, usually between 5 and 10%. Here we assume $Pg_{i,max} \approx Sg_{i,max}$.

The equivalent reactive production cost for capital investment return of capacitors in (2) can be expressed as their depreciated rate (the life span of capacitors is 15 years) as follows:

$$\begin{aligned} C(Qc_j) &= Qc_j \times \$11600 / MVAr \\ &\div (15\times 365\times 24\times h) \\ &= Qc_j \times \$13.24/(100\ MVArh) \end{aligned} \quad (5)$$

where, h represents the average usage rate of capacitors taken as 2/3. Qc_j is in per unit on 100 MVA base. Equation (5) is a linear cost function with the slope of $dC(Qc_j)/dQc_j = \$13.24/(100\ MVArh)$ representing approximately the capacitor investment impacts on reactive pricing.

The equality constraints are load flow equations:

$$g(V,\delta)=0 \quad (6)$$

where

$$g(V,\delta)=\begin{Bmatrix} Pg_i-Pd_i-P_i(V,\delta) \;\Rightarrow \textit{For each PV} \\ \textit{and PQ bus except slack bus} \\ Qg_i-Qd_i-Q_i(V,\delta) \Rightarrow \textit{For each PQ} \\ \textit{bus only} \end{Bmatrix}$$

P_i = real power injection into i^{th} bus

Q_i = reactive power injection into i^{th} bus

Pd_i = real power load on i^{th} bus

Qd_i = reactive power load on i^{th} bus

Pg_i = real power generation on i^{th} bus

Qg_i = reactive power generation on i^{th} bus

The inequality constraints are:

- Real power generation Pg_i at PV buses

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

where, $Pg_i^{\min}$ and $Pg_i^{\max}$ are respectively minimum and maximum value of active power generation at i^{th} PV bus.

- Reactive power generation Qg_i at PV buses

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

where, $Qg_i^{\min}$ and $Qg_i^{\max}$ are respectively minimum and maximum value of reactive power generation at i^{th} PV bus.

- Reactive power output limit of capacitor

$$0 \le Qc_j \le Qc_j^{\max} \quad (9)$$

where $Qc_j^{\max}$ is maximum value of output of capacitor at j^{th} bus.

- Voltage magnitude V of each PV and PQ bus

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

where, $V_i^{\min}$ and $V_i^{\max}$ are respectively minimum and maximum voltage at i^{th} bus

- Phase angle δ of voltage at all the buses.

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \quad (11)$$

where, $\delta_i^{\min}$ and $\delta_i^{\max}$ are respectively minimum and maximum allowed value of voltage phase angle at i^{th} bus

- Transmission power limit

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

where, $S_{ij}^{\max}$ is the maximum rating of transmission line connecting bus i and j

Based on the above mathematical model the corresponding Lagrangian function of this optimization problem can be expressed as (13):

$$\begin{aligned} L &= \sum_{i=1}^{ng}[C(Pg_i)+C(Qg_i)]+\sum_{j=1}^{ncap}C(Qc_j)- \\ &\sum_{i=1}^{n}\lambda_{pi}[Pg_i-Pd_i-P_i(V,\delta)]-\sum_{i=1}^{n}\lambda_{qi}[Qg_i-Qd_i-Q_i(V,\delta)]+ \\ &\sum_{i=1}^{ng}\mu_{pi,\min}(Pg_i^{\min}-Pg_i)+\sum_{i=1}^{ng}\mu_{pi,\max}(Pg_i-Pg_i^{\max})+ \\ &\sum_{i=1}^{ng}\mu_{qi,\min}(Qg_i^{\min}-Qg_i)+\sum_{i=1}^{ng}\mu_{qi,\max}(Qg_i-Qg_i^{\max})+ \\ &\sum_{j=1}^{ncap}\mu_{cj,\max}(Qc_j-Qc_j^{\max})+\sum_{i=1}^{n}\sum_{\substack{i=1\\ j\neq i}}^{n}\eta_{ij}(S_{ij}-S_{ij}^{\max})+ \\ &\sum_{i=1}^{n}\upsilon_{i,\min}(V_i^{\min}-V_i)+\sum_{i=1}^{n}\upsilon_{i,\max}(V_i-V_i^{\max}) \end{aligned} \quad (13)$$

The term $C(Qc_j)$ will be absent in above equation, if it is not considered as per objective function given by (1). According to the theory of microeconomics, in the above augmented

TABLE I
THE COMPARISON OF OPF BASED NODAL PRICING MODELS

Literature	OPF problem	Augmented LaGrange function	Expressions of nodal marginal prices
Baughman & Siddiqi (1991)	*Minimize* $\sum_{i\varepsilon G} C_i(P_{gi})$ *subject to* $P_{gi} - Pd_i - \sum_{j\varepsilon N} \lvert V_i \rvert \lvert V_j \rvert \lvert Y_{ij} \rvert \cos(\theta_{ij} + \delta_j - \delta_i) = 0$ $Q_{gi} - Qd_i - \sum_{j\varepsilon N} \lvert V_i \rvert \lvert V_j \rvert \lvert Y_{ij} \rvert \sin(\theta_{ij} + \delta_j - \delta_i) = 0$ $P_{g_{i,\min}} \le P_{g_i} \le P_{g_{i,\max}}$ $Q_{g_{i,\min}} \le Q_{g_i} \le Q_{g_{i,\max}}$ $P_{ij,\min} \le P_{ij} \le P_{ij,\max}$ $V_{i,\min} \le \lvert V_i \rvert \le V_{i,\max}$	$L = \sum_{i\varepsilon G} C_i(Pg_i)$ $- \sum_{i\varepsilon N} (MCp_i) \left[Pg_i - Pd_i - \sum_{j\varepsilon N} \lvert V_i \rvert \lvert V_j \rvert \lvert Y_{ij} \rvert \cos(\theta_{ij} + \delta_j - \delta_i) \right]$ $- \sum_{i\varepsilon N} (MCq_i) \left[Qg_i - Qd_i - \sum_{j\varepsilon N} \lvert V_i \rvert \lvert V_j \rvert \lvert Y_{ij} \rvert \sin(\theta_{ij} + \delta_j - \delta_i) \right]$ $- \sum_{i\varepsilon G} \lambda_{i,\min}(Pg_i - Pg_{i,\min}) - \sum_{i\varepsilon G} \lambda_{i,\max}(Pg_i - Pg_{i,\max})$ $- \sum_{i\varepsilon G} \mu_{i,\min}(Qg_i - Qg_{i,\min}) - \sum_{i\varepsilon G} \mu_{i,\max}(Qg_i - Qg_{i,\max})$ $+ \sum_{i\varepsilon N} \sum_{j\varepsilon N}^{j \ne i} \eta_{ij}(\lvert P_{ij} \rvert - P_{ij,\max}) - \sum_{i\varepsilon N} v_{i,\min}(\lvert V_i \rvert - V_{i,\min})$ $+ \sum_{i\varepsilon N} v_{i,\max}(\lvert V_i \rvert - V_{i,\max})$	Real power marginal price *Load bus* i: $\rho_{p_i} = MC_{P_i}$ *Generation bus* i: $\rho_{p_i} = \frac{\partial C_i(Pg)}{\partial Pg_i} - \lambda_{i,\min} + \lambda_{i,\max}$ Reactive power marginal price *Load bus* i: $\rho_{Q_i} = MC_{Q_i}$ *Generation bus* i: $\rho_{Q_i} = -\mu_{i,\min} + \mu_{i,\max}$
El-Keib & Ma (1997)	The P Subproblem *Minimize* $\sum_{i=1}^{m} C(P_{Gi})$ *subject to* $\sum_{i=1}^{m} P_{Gi} - \sum_{k=1}^{n} P_{Dk} - P_L = 0$ $P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$ $P_l \le P_l^{\max}$ The Q Subproblem *Minimize* $C_1(P_{G1})$ *subject to* $V_i^{\min} \le V_i \le V_i^{\max}$ $Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}$ $t_l^{\min} \le t_l \le t_l^{\max}$	For Real Power Subproblem $L = \sum_{i=1}^{m} C(P_{Gi}) - \lambda(\sum_{i=1}^{m} P_{Gi} - \sum_{k=1}^{n} P_{Dk} - P_L)$ $+ \sum_{l=1}^{N_l} \mu_l (P_l - P_l^{\max}) + \sum_{i=1}^{m} \{ \mu_i^{\min}(P_{Gi}^{\min} - P_{Gi}) + \mu_l^{\max}(P_{Gi} - P_{Gi}^{\max}) \}$ For Reactive Power Subproblem $L = C_1(P_{G1}) + \sum_{i=1}^{m} \{ v_{VGi}^{\min}(V_i^{\min} - V_i) + v_{VGi}^{\max}(V_i - V_i^{\max}) \}$ $+ \sum_{k=m+1}^{n} \{ v_{VDi}^{\min}(V_i^{\min} - V_i) + v_{VDi}^{\max}(V_i - V_i^{\max}) \}$ $+ \sum_{i=1}^{m} \{ v_{QGi}^{\min}(Q_{Gi}^{\min} - Q_{Gi}) + v_{QGi}^{\max}(Q_{Gi} - Q_{Gi}^{\max}) \}$ $+ \sum_{l=1}^{N_t} \{ v_{t,l}^{\min}(t_l^{\min} - t_l) + v_{t,l}^{\max}(t_l - t_l^{\max}) \}$	At any bus i, Real power marginal price $\rho_{P_i} = \lambda - \lambda \frac{\partial P_L}{\partial P_i} - \sum_{l=1}^{N_l} \mu_l \frac{\partial P_l}{\partial P_i}$ Reactive power marginal price $\rho_{Q_i} = -\lambda \frac{\partial P_{G_1}}{\partial Q_i} + \sum_{k=m+1}^{n} \mu_i \left[-v_{VD_k}^{\min} + v_{VD_k}^{\max} \right] \frac{\partial V_k}{\partial Q_i} - v_{QGi}^{\min} + v_{QGi}^{\max}$
Choi *et al.*, (1998)	$Max \left\{ \sum_{i\varepsilon C} B_i(x_i) - \sum_{j\varepsilon G} C_j(x_j) \right\}$ *subject to* $P_i - \sum_{j\varepsilon N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) = 0$ $Q_i - \sum_{j\varepsilon N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) = 0$ $P_{g,\min} \le P_g \le P_{g,\max}$ $Q_{g,\min} \le Q_g \le Q_{g,\max}$ $P_{c,\min} \le P_c \le P_{c,\max}$ $Q_{c,\min} \le Q_c \le Q_{c,\max}$ $Q_c = \frac{\sqrt{1 - pf_c^2}}{pf_c} \times P_c$ $P_{ij,\min} \le P_{ij} \le P_{ij,\max}$ $\delta_{ij,\min} \le \delta_i - \delta_j \le \delta_{ij,\max}$ $V_{i,\min} \le V_i \le V_{i,\max}$	$L = \left\{ \sum_{i\varepsilon C} B_i(x_i) - \sum_{j\varepsilon G} C_j(x_j) \right\}$ $+ \sum_{i\varepsilon C} \lambda_{ipf} \left[Q_c - \frac{\sqrt{1 - pf_i^2}}{pf_i} \times P_i \right]$ $+ \sum_{i\varepsilon C} \lambda_{ip} [P_i - \sum_{j\varepsilon N} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i)]$ $+ \sum_{i\varepsilon C} \lambda_{iq} [Q_i - \sum_{j\varepsilon N} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i)]$ $- \sum_{i\varepsilon G} \mu_{ip,\min}(P_i - P_{i,\min}) + \sum_{i\varepsilon G} \mu_{ip,\max}(P_i - P_{i,\max})$ $- \sum_{i\varepsilon G} \mu_{iq,\min}(Q_i - Q_{i,\min}) + \sum_{i\varepsilon G} \mu_{iq,\max}(Q_i - Q_{i,\max})$ $- \sum_{i\varepsilon N} \sum_{j\varepsilon N}^{i \ne j} \eta_{ij,\min}(P_{ij} - P_{ij,\min}) + \sum_{i\varepsilon N} \sum_{j\varepsilon N}^{i \ne j} \eta_{ij,\max}(P_{ij} - P_{ij,\max})$ $- \sum_{i\varepsilon N} \lambda_{iV,\min}(V_i - V_{i,\min}) + \sum_{i\varepsilon N} \lambda_{iV,\max}(V_i - V_{i,\max})$ $- \sum_{i\varepsilon N} \lambda_{i\delta,\min}(\delta_i - \delta_{i,\min}) + \sum_{i\varepsilon N} \lambda_{i\delta,\max}(\delta_i - \delta_{i,\max})$	At any bus i, Real power marginal price $\lambda_{ip} = \frac{\partial \left(\sum_{i \in C} B_i(P_i) - \sum_{j \in G} C_j(P_j) \right)}{\partial P_i}$ $+ \lambda_{ipf} \times \sqrt{\frac{1 - pf_i^2}{pf_i^2}} + \mu_{ip,\min} - \mu_{ip,\max}$ Reactive power marginal price $\lambda_{iq} = -\lambda_{ipf} + \mu_{iq,\min} - \mu_{iq,\max}$

Lagrangian function the marginal prices for real and reactive power on i^{th} bus are λ_{pi} and λ_{qi} respectively, which are taken as the corresponding nodal prices in [3], [5] and [12]. Similar to vector λ, the vectors μ, η and υ contain marginal change in cost with respect to the corresponding constraints. The elements of vectors μ, η and υ respectively are different than zero only in case that the corresponding constraints are active. The expressions of real and reactive power marginal prices reported in the literature are listed in Table I.

Optimization of either (1) or (2), with power flow relations included as equality constraints (6), inequality constraints (7) to (12) and generation bidding constraints using GA-Fuzzy approach is done. All the line flow limits and control variables e.g. V at PV bus, tap ratio of tap setting transformers and shunt capacitor settings are also taken care in this optimization process. The solution to this optimization problem provides the power pool generations, shunt capacitor settings, transformer tap settings, bus voltages and line flows. GA-Fuzzy approach does not provide Lagrange multipliers required for determination of SRMC during optimization process directly. Therefore, expressions of real and reactive power marginal prices for the proposed nodal pricing model are explained in the next subsection.

B. Expressions of Real and Reactive power marginal prices for nodal transmission pricing model

The optimization problem is solved, if the following equations from (14) to (19) of optimality are satisfied for (13).

$$\frac{\partial L}{\partial Pg_i} = \frac{\partial C_i(Pg_i)}{\partial Pg_i} - \lambda_{pi} = 0 \qquad i = 1,......ng \tag{14}$$

$$\frac{\partial L}{\partial Qg_i} = \frac{\partial C_i(Qg_i)}{\partial Qg_i} - \lambda_{qi} = 0 \quad i = 1,.......ng \tag{15}$$

$$\frac{\partial L}{\partial \delta_i} = \sum_{j=1}^{n} [\lambda_{pj} \frac{\partial P_j}{\partial \delta_i}] + \sum_{j=1}^{n} [\lambda_{qj} \frac{\partial Q_j}{\partial \delta_i}] = 0$$

$$= \left(\lambda_{ps} \frac{\partial P_s}{\partial \delta_i} + \sum_{\substack{j=1 \\ j \neq s}}^{ng+nload} \lambda_{pj} \frac{\partial P_j}{\partial \delta_i} \right) + \left(\lambda_{qs} \frac{\partial Q_s}{\partial \delta_i} + \sum_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} + \sum_{\substack{j=1 \\ j \neq s}}^{nload} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} \right)$$

$$= \left(\lambda_{ps} \frac{\partial P_s}{\partial \delta_i} + \lambda_{qs} \frac{\partial Q_s}{\partial \delta_i} + \sum_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} \right) + \left(\sum_{\substack{j=1 \\ j \neq s}}^{ng+nload} \lambda_{pj} \frac{\partial P_j}{\partial \delta_i} + \sum_{\substack{j=1 \\ j \neq s}}^{nload} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} \right) \tag{16}$$

where $i = 1,2,.....(ng + nload)$ *and* $i \neq s$

$$\frac{\partial L}{\partial V_i} = \sum_{j=1}^{n} [\lambda_{pj} \frac{\partial P_j}{\partial V_i}] + \sum_{j=1}^{n} [\lambda_{qj} \frac{\partial Q_j}{\partial V_i}] = 0$$

$$= \left(\lambda_{ps} \frac{\partial P_s}{\partial V_i} + \sum_{\substack{j=1 \\ j \neq s}}^{ng+nload} \lambda_{pj} \frac{\partial P_j}{\partial V_i} \right) + \left(\lambda_{qs} \frac{\partial Q_s}{\partial V_i} + \sum_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} + \sum_{j=1}^{nload} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} \right)$$

$$= \left(\lambda_{ps} \frac{\partial P_s}{\partial V_i} + \lambda_{qs} \frac{\partial Q_s}{\partial V_i} + \sum_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} \right) + \left(\sum_{\substack{j=1 \\ j \neq s}}^{ng+nload} \lambda_{pj} \frac{\partial P_j}{\partial V_i} + \sum_{\substack{j=1 \\ j \neq s}}^{nload} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} \right)$$

where $i = 1,2,..... nload$ *and* $i \neq s$ (17)

$$\frac{\partial L}{\partial \lambda_{pi}} = P_i(V,\delta) - Pg_i + Pd_i = 0 \ (i = 1,.......n) \tag{18}$$

$$\frac{\partial L}{\partial \lambda_{qi}} = Q_i(V,\delta) - Qg_i + Qd_i = 0 \quad (i = 1,.......n) \tag{19}$$

where n = total no. of buses
s = slack bus
ng = total no. of generator buses
$nload$ = total no. of load buses

Equations (16) and (17) can be expressed in matrix form as follows:

$$\left[\begin{array}{l} \lambda_{ps} \frac{\partial P_s}{\partial \delta_i} + \lambda_{qs} \frac{\partial Q_s}{\partial \delta_i} + \sum\limits_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} \quad i = 1,...(ng+nload) \\ \hline \lambda_{ps} \frac{\partial P_s}{\partial V_i} + \lambda_{qs} \frac{\partial Q_s}{\partial V_i} + \sum\limits_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} \quad i = 1,...nload \end{array} \right] +$$

$$\left[\begin{array}{l|l} \frac{\partial P_j}{\partial \delta_i} \ j = 1,....(ng+nload) & \frac{\partial Q_j}{\partial \delta_i} \ j = 1,..nload \\ \quad i = 1,...(ng+nload) & \quad i = 1,...(ng+nload) \\ \quad i \ and j \neq s & \quad i \ and j \neq s \\ \hline \frac{\partial P_j}{\partial V_i} \ j = 1,....(ng+nload) & \frac{\partial Q_j}{\partial V_i} \ j = 1,..nload \\ \quad i = 1,...(ng+nload) & \quad i = 1,...(ng+nload) \\ \quad i \ and j \neq s & \quad i \ and j \neq s \end{array} \right] \times \left[\begin{array}{l} \lambda_{pj} \\ j = 1,...(ng+nload) \\ j \neq s \\ \hline \lambda_{qj} \\ \quad j = 1,..nload \\ \quad j \neq s \end{array} \right] = \left[\begin{array}{c} 0 \\ - \\ 0 \end{array} \right]$$

It can also be expressed as:

$$\left[\begin{array}{l} \lambda_{ps} \frac{\partial P_s}{\partial \delta_i} + \lambda_{qs} \frac{\partial Q_s}{\partial \delta_i} + \sum\limits_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} \quad i = 1,...(ng+nload) \\ \hline \lambda_{ps} \frac{\partial P_s}{\partial V_i} + \lambda_{qs} \frac{\partial Q_s}{\partial V_i} + \sum\limits_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} \quad i = 1,...nload \end{array} \right] +$$

$$\left[\quad J \quad \right]^T \left[\begin{array}{l} \lambda_{pj} \quad j = 1,...(ng+nload) \\ \qquad j \neq s \\ \hline \lambda_{qj} \qquad j = 1,...nload \\ \qquad\quad j \neq s \end{array} \right] = \left[\begin{array}{c} 0 \\ - \\ 0 \end{array} \right]$$

where, J = Jacobian obtained from Newton Raphson load flow method for final optimized results.

$$\left[\begin{array}{l} \lambda_{pj} \quad j = 1,...(ng + nload) \\ \hline \lambda_{qj} \qquad j = 1,... nload \end{array} \right] = - \left(\left[\quad J \quad \right]^T \right)^{-1} \times$$

$$\left[\begin{array}{l} \lambda_{ps} \frac{\partial P_s}{\partial \delta_i} + \lambda_{qs} \frac{\partial Q_s}{\partial \delta_i} + \sum\limits_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial \delta_i} \quad i = 1,...(ng + nload) \\ \hline \lambda_{ps} \frac{\partial P_s}{\partial V_i} + \lambda_{qs} \frac{\partial Q_s}{\partial V_i} + \sum\limits_{\substack{j=1 \\ j \neq s}}^{ng} \lambda_{qj} \frac{\partial Q_j}{\partial V_i} \quad i = 1,... nload \end{array} \right] \tag{20}$$

Equation (14) can be written for slack bus as:

$$\lambda_{ps} = \frac{\partial C(Pg_s)}{\partial Pg_s} \tag{21}$$

and (15) can be written for slack and PV buses respectively as:

$$\lambda_{qs} = \frac{\partial C(Qg_s)}{\partial Qg_s} \tag{22}$$

$$\lambda_{qi} = \frac{\partial C(Qg_i)}{\partial Qg_i} \quad i = 1,...... ng \tag{23}$$

Therefore, real *(λ_p)* and reactive *(λ_q)* marginal prices for slack bus, PV buses and PQ buses are obtained solving (20)-(23). The above expressions of real and reactive power marginal prices do not include μ, η and υ used in (13) as all inequality

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:3, No:4, 2009

constraints corresponding to (7) to (12) are taken care in optimization process.

Short run marginal cost of real power wheeling PWC_{ij} and reactive power wheeling QWC_{ij} for transaction from bus i to j are calculated by following equations:

$$PWC_{ij} = PW_{ij} \text{ x } (\lambda_{pj} - \lambda_{pi}) \quad (24)$$

$$QWC_{ij} = QW_{ij} \text{ x } (\lambda_{qj} - \lambda_{qi}) \quad (25)$$

where, PW_{ij} and QW_{ij} are real power and reactive power to be wheeled from bus i to j respectively.

C. *Algorithm for proposed nodal transmission pricing model*

Step 1: All system voltages and power pool loads are set to initial conditions. All feasible (scheduled) firm power transactions are added to the system.

Step 2: The optimization of objective function either (1) or (2) is carried out satisfying all constraints (6) to (12) using GA-Fuzzy approach.

Step 3: After the optimization bus voltages, line flows, transformer tap settings (if present in the power system), capacitors reactive supports and power pool generations are obtained.

Step 4: Marginal prices for both real and reactive power at all buses are calculated using (20)-(23).

Step 5: Short run marginal cost of wheeling for bilateral power transactions are calculated using (24) and (25) respectively.

Step 6: The amount to be paid by each demand and amount to be received by each generation company is determined based on marginal cost. Similarly, multilateral power transaction is treated.

Step 7: The marginal network revenue is determined based on total payments and receipts.

IV. Computer Test Results

A. *For 5-bus system*

A 5-bus power system [8] is used for computer study. The following four cases are considered to study the impacts of various factors on real and reactive marginal prices.

Case 1: The objective function has total cost of real and reactive power generations with base loads only i.e. ($\sum_{i\in G} C(Pg_i) + C(Qg_i)$ .with base loads).

Case 2: The objective function has total cost of real and reactive power generations and capacitor cost with base loads only i.e ($\sum_{i\in G}[C(Pg_i) + C(Qg_i)] + \sum_{j\in C} C(Qc_j)$ with base loads).

Case 3: The objective function has total cost of real and reactive power generations and capacitor cost. Here base loads with two bilateral transactions of 50 MW each are considered i.e. ($\sum_{i\in G}[C(Pg_i) + C(Qg_i)] + \sum_{j\in C} C(Qc_j)$ with base loads and two bilateral transactions of 50 MW each).

Case 4: The objective function has total cost of real and reactive power generations and capacitor cost. Here base loads with two different bilateral power transactions of T1= 80 MW and T2= 50 MW respectively are considered i.e. ($\sum_{i\in G}[C(Pg_i) + C(Qg_i)] + \sum_{j\in C} C(Qc_j)$ with base loads and two different bilateral transactions of 80 MW and 50 MW respectively).

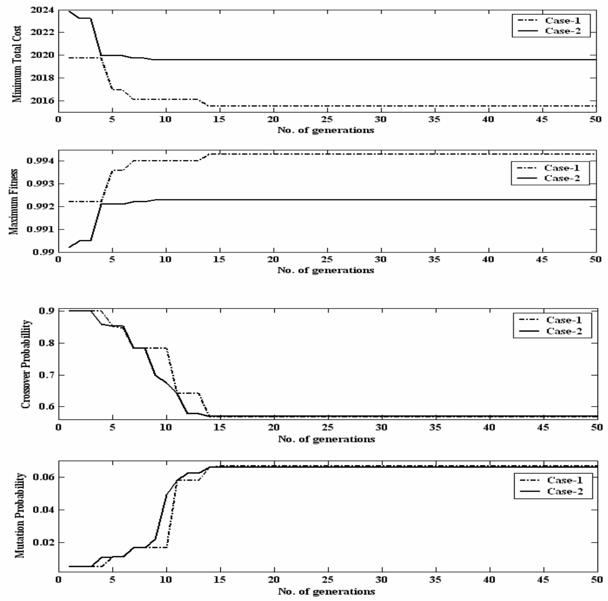

Fig. 3 Convergence of minimum total cost, maximum fitness and variations of crossover and mutation probabilities using GA-Fuzzy approach for Case-1 and Case-2 for 5 bus system.

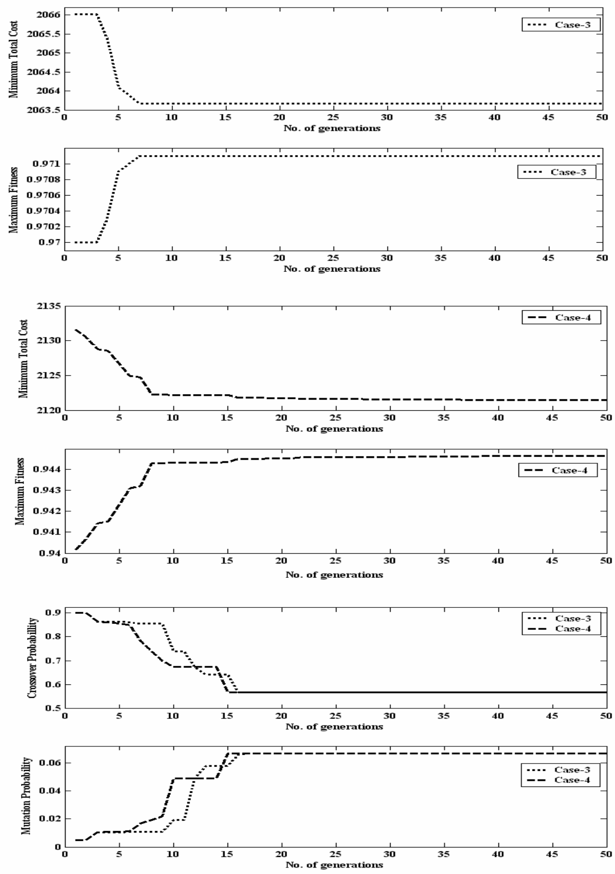

Fig. 4 Convergence of minimum total cost, maximum fitness and variations of crossover and mutation probabilities using GA-Fuzzy approach for Case-3 and Case-4 of 5 bus system.

TABLE II
TEST RESULTS OF CASE 1-4

	Case-1	Case-2	Case-3	Case-4
Objective function	$\sum_{i\in G} C(Pg_i) + C(Qg_i)$ (with base loads)	$\sum_{i\in G}[C(Pg_i)+C(Qg_i)]+ \sum_{j\in C} C(Qc_j)$ (with base loads)	$\sum_{i\in G}[C(Pg_i)+C(Qg_i)]+ \sum_{j\in C} C(Qc_j)$ (with base loads and bilateral transactions T1 and T2 = 50 MW)	$\sum_{i\in G}[C(Pg_i)+C(Qg_i)]+ \sum_{j\in C} C(Qc_j)$ (with base loads and bilateral transactions T1=80 MW and T2=50 MW
$S_{Gi} = P_{Gi} + Q_{Gi}$ (i=1,2) (in MW & MVAr)	85.02+0.266j 83.824+13.529j	84.085+4.264j 84.647+16.908j	82.447+8.044j 89.176+18.151j	83.735+5.924j 91.647+24.967j
Reactive power output of capacitor on bus 4 (MVAr)	47.412	39.305	43.145	49.939
Total cost	2015.3808 US$/h	2019.5978 US$/h	2063.7025 US$/h	2121.4116 US$/h
Marginal price λp of real power at buses 1-5 (US$/MW h)	14.6401 14.9536 15.4516 15.5009 15.6571	14.5631 14.8631 15.3570 15.4056 15.5565	14.4256 14.9707 15.2451 15.2607 16.0726	14.5338 15.2524 15.5535 15.5958 16.7446
Marginal price λp of real power at buses 1-5 (US$/MW h)	0.0019 0.0976 0.0910 0.0383 0.3307	0.0307 0.1222 0.1539 0.1129 0.3673	0.0580 0.1313 0.1617 0.1208 0.4513	0.0427 0.1813 0.1949 0.1512 0.5838

Figures 3 and 4 demonstrate the convergence of minimum total cost, maximum fitness and variations of crossover and mutation probabilities using GA-Fuzzy approach for Case-1 to Case-4.

The results obtained for all the four cases are listed in Table II. The real power marginal prices at various buses are in the same order for all cases but higher values are obtained at bus 5 for Case 3 and 4. Reactive power marginal prices are ~ 1/100 times real power marginal prices for all cases, but from Case 1 to 4 reactive power marginal prices at bus 4 and 5 rise significantly. In Case 1, when the capacitor cost *C(Qc)* of capacitor connected at bus 4 is neglected, the corresponding reactive power source bus(es) have very little reactive power marginal prices for the free reactive power available locally. When all the reactive power production costs (see Case 2-4) are taken into consideration, the reactive power marginal prices increase noticeably at all buses which send economic signals to electric loads in the form financial incentive to reduce their reactive power demand. Case 4 and 5 are cases of deregulated environment where system becomes more stressed due to bilateral power transactions along with base loads. It is also clear from Table II, reactive power marginal prices increase with greater proportion along with real power marginal prices.

The results obtained from Case-1 and Case-2 are closely matching with Dai Y. et al. [8], as shown in Fig. 5, hence verify the determination of real and reactive power marginal prices using mathematical expressions proposed in section 3.

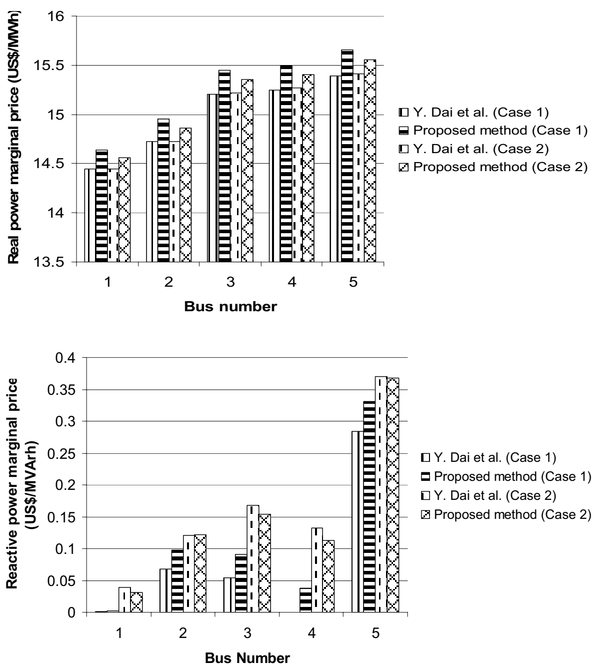

Fig. 5 Comparison of real and reactive power marginal prices for 5-bus system

TABLE III
NETWORK REVENUE OBTAINED FOR CASE-3 AND CASE-4 USING PROPOSED NODAL TRANSMISSION PRICING MODEL

Revenue from base loads

Bus No.	Real Demand Pd_i (MW)	Revenue (in \$/h) = $\lambda_{pi} \times Pd_i$		Reactive Demand Qd_i (MVAr)	Revenue (in \$/h) = $\lambda_{qi} \times Qd_i$	
		Case-3	Case-4		Case-3	Case-4
1	0	0	0	0	0	0
2	20	299.414	305.048	9.7	1.27361	1.75861
3	45	686.0295	639.9075	22	3.5574	4.2878
4	40	610.428	623.832	19	2.2952	2.8728
5	60	964.356	1004.676	29	13.0877	16.9302
	Total	2560.2275	2573.4635		20.21391	25.84941

Revenue from Bilateral Transactions

Transa-ction	From bus *i*	To bus *j*	Size (MW)		Revenue obtained (in \$/h) = $(\lambda_{qi} - \lambda_{pi}) \times$ Transaction Size	
			Case-3	Case-4	Case-3	Case-4
T1	1	5	50	80	82.35	176.864
T2	4	2	50	50	-14.50	-17.17
			Total		67.85	159.694

Expenditure for real and reactive power generations

Bus No.	Pg_i (MW)		Expenditure = $\lambda_{pi} \times Pg_i$ (in \$/h)		Qg_i (MVAr)		Expenditure = $\lambda_{qi} \times Qg_i$ (in \$/h)	
	Case-3	Case-4	Case-3	Case-4	Case-3	Case-4	Case-3	Case-4
1	82.447	83.735	1189.3474	1216.9877	8.044	5.924	0.4666	0.2529548
2	89.176	91.647	1335.0271	1397.8367	18.151	24.967	2.3832	4.5265171
	Total		2524.3745	2614.8244			2.8498	4.7794719

Summary of Results

S. No.		In (\$/h) Case-3	Case-4
1.	Revenue received from Base Real demand	2560.2275	2573.4635
2.	Revenue received from Base Reactive demand	20.21391	25.84941
3.	Revenue received from Bilateral transactions	67.85	159.694
4.	Expenditure for Real Generation	2524.3745	2614.8244
5.	Expenditure for Reactive Generation	2.8498	4.7794719
6.	Total Revenue (S.No. 1+2+3)	2648.29141	2759.00691
7.	Total Expenditure (S.No. 4+5)	2527.2243	2619.60387
	Network Revenue (S.No. 6-7)	*121.06711*	*139.40304*

Table II shows that real and reactive marginal prices at many load buses are higher than at generator buses and reactive marginal prices are smaller than real marginal prices at all the buses. These marginal prices can be used to calculate significant wheeling charges of real and reactive power (marginal network revenue) as difference of revenue received from real and reactive demand and expenditure for real and reactive generation (Table 3). Obviously, in Case-4 network revenue should be more in comparison to Case-3 as total generation exceeds in order to meet the requirement of increased size of bilateral power transaction T1 (= 80 MW) and transmission losses.

B. For IEEE 30-bus system

The proposed pricing model is tested for IEEE 30-bus system data [9], bilateral and multilateral power transactions [13] are presented here. The optimal values of pool generations and shunt capacitor values as obtained through GA-Fuzzy approach alongwith minimum total cost are tabulated in Table IV. The convergence of minimum total cost, maximum fitness and variations of crossover and mutation probabilities using GA-Fuzzy approach for IEEE 30-bus system are demonstrated in figure 6. The results summarized in Table V shows that due to implementation of marginal prices, marginal network revenue of 40.301905 \$/hr is obtained.

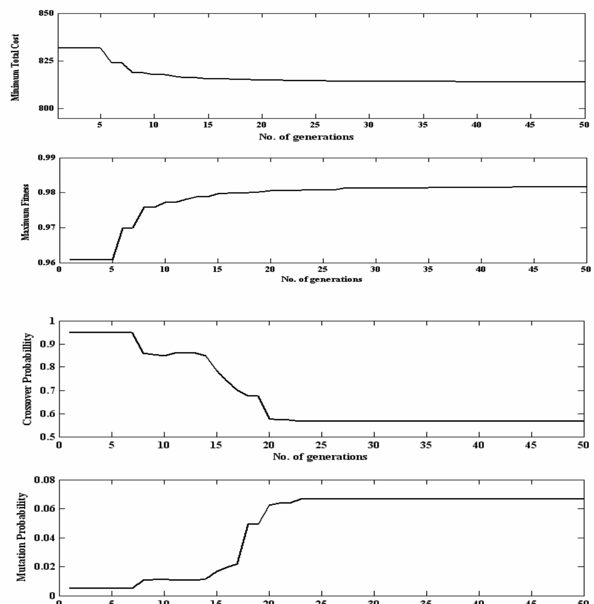

Fig. 6 Convergence of minimum total cost, maximum fitness and variations of crossover and mutation probabilities using GA-Fuzzy approach for IEEE 30 bus system (pool loads, bilateral and multilateral transactions)

TABLE IV
OPTIMAL VALUES OF POOL GENERATIONS, SHUNT CAPACITORS AND TOTAL COST FOR IEEE 30-BUS SYSTEM USING GA-FUZZY APPROACH

Bus No.	Real Generation (MW)	Reactive Generation (MVAr)	Bus No.	Capacitor size (MVAr)
1	174.961	11.902	10	4.726
2	47.529	15.599	12	1.967
5	21.176	36.06	15	4.168
8	24.51	34.885	17	0.89
11	12.039	15.297	20	4.618
13	12.329	21.845	21	4.589
			23	4.873
			24	3.513
			29	0.806
		Total Real power cost of generators		US 801.82529/h
		Total Reactive power cost of generators		US 13.466144/h
		Total capacitors cost		US 3.991976/h
		Total cost		US 819.28341/h

TABLE V
NETWORK REVENUE OBTAINED FOR IEEE 30-BUS SYSTEM USING PROPOSED NODAL TRANSMISSION PRICING MODEL

Revenue from Pool loads

Bus No.	Real Demand Pd_i (MW)	λ_{pi} (\$/MW h)	Revenue (in \$/h) = $\lambda_{pi} \times Pd_i$	Reactive Demand Qd_i (MVAr)	λ_{qi} (\$/MVAr h)	Revenue (in \$/h) = $\lambda_{qi} \times Qd_i$
1	0	3.31921	0	0	0.049762	0
2	21.7	3.435997	74.56113	12.7	0.042547	0.540345
3	2.4	3.513915	8.433397	1.2	0.101652	0.121983
4	7.6	3.570239	27.13382	1.6	0.110167	0.176267
5	94.2	3.690331	347.6292	19	0.127005	2.413096
6	0	3.612632	0	0	0.129748	0
7	22.8	3.66913	83.65617	10.9	0.144936	1.579805
8	30	3.626385	108.7916	30	0.150447	4.513415
9	0	3.616505	0	0	0.123827	0
10	5.8	3.621814	21.00652	2	0.13621	0.27242
11	0	3.61415	0	0	0.094843	0
12	11.2	3.599261	40.31173	7.5	0.126418	0.948136
13	0	3.598323	0	0	0.123478	0
14	6.2	3.676129	22.792	1.6	0.141555	0.226487
15	8.2	3.685928	30.22461	2.5	0.134784	0.336961
16	3.5	3.634265	12.71993	1.8	0.141915	0.255447
17	9	3.64232	32.78088	5.8	0.143435	0.831922
18	3.2	3.723113	11.91396	0.9	0.142798	0.128519
19	9.5	3.728377	35.41958	3.4	0.142602	0.484848
20	2.2	3.704354	8.149579	0.7	0.13277	0.092939
21	17.5	3.662132	64.08731	11.2	0.159024	1.78107
22	0	3.659034	0	0	0.156488	0
23	3.2	3.722763	11.91284	1.6	0.12908	0.206529
24	8.7	3.736867	32.51075	6.7	0.158234	1.060166
25	0	3.746257	0	0	0.152652	0
26	3.5	3.822748	13.37962	2.3	0.203776	0.468684
27	0	3.674906	0	0	0.128106	0
28	0	3.640752	0	0	0.140059	0
29	2.4	3.783965	9.081516	0.9	0.116025	0.104422
30	10.6	3.858995	40.90535	1.9	0.147013	0.279325
Total			1037.401	Total		16.82278

Revenue from Bilateral Transactions

From bus i	To bus j	Size (MW)	Revenue obtained (in \$/h) = $(\lambda_{qi} - \lambda_{pi}) \times$ Transaction Size
9	13	5	-0.09091
22	25	5	0.436115
		Total	0.345205

Revenue from Multilateral Transactions

Bus No.	MW	λ_{pi} (\$/MW h)	Expenditure (\$/h)	Bus No.	MW	λ_{pi} (\$/MW h)	Revenue Received (\$/h)
6	4	3.612632	14.450528	11	2	3.61415	7.2283
7	2	3.66913	7.33826	13	3	3.598323	10.794969
				14	1	3.676129	3.676129
			21.788788				21.699398
			Total = 21.699398 - 21.788788 = -0.08939				

Contd.

Contd. Table V

Bus No.	Pg_i (MW)	Expenditure = $\lambda_{pi} \times Pg_i$ (in \$/h)	Qg_i (MVAr)	Expenditure = $\lambda_{qi} \times Qg_i$ (in \$/h)
Expenditure for Real and Reactive power generations				
1	174.961	580.7323	11.902	0.592267
2	47.529	163.3095	15.599	0.663691
5	21.176	78.14645	36.06	4.5798
8	24.51	88.8827	34.885	5.248344
11	12.039	43.51075	15.297	1.450813
13	12.329	44.36372	21.845	2.697377
	Total	998.9454	Total	15.23229

Summary of Results

S. No.		In (\$/h)
1.	Revenue received from Pool Real demand	1037.401
2.	Revenue received from Pool Reactive demand	16.82278
3.	Revenue received from Bilateral transactions	0.345205
4.	Revenue Received from Multilateral Transactions	-0.08939
5.	Expenditure for Real Generation	998.9454
6.	Expenditure for Reactive Generation	15.23229
7.	Total Revenue	1054.479595
8.	Total Expenditure	1014.17769
	Marginal Network Revenue	*40.301905*

V. Conclusion

In this paper new expressions for real and reactive power marginal nodal prices are derived and GA-Fuzzy OPF is used for successful implementation of proposed nodal transmission pricing method. The real power marginal price is usually much higher than the reactive marginal price in non-stressed system (Case-1 and Case-2). Reactive power marginal price is affected by the reactive power production costs of generations and the capital investment cost of capacitors (Case-1 to Case-4). Reactive power marginal prices can be related to the urgency of the reactive power supply and an incentive can be given to improve load power factor and reduce power demand. The proposed nodal transmission pricing model forms a basis to calculate network revenue for bilateral and multilateral power transactions in deregulated power systems (Case-3 and Case-4) to wheel the power between the buses.

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