Journal of Engineering Science and Technology
Vol. 12, No. 1 (2017) 015 - 030

APPLICATION OF MODIFIED POWER FLOW TRACING METHOD FOR REACTIVE POWER PRICING IN PRACTICAL UTILITY SYSTEM

M. SUSITHRA[1,]*, R. GNANADASS[2]

[1]Department of Electrical and Electronics Engineering, Christ College of Engineering and Technology, Puducherry, India
[2]Department of Electrical and Electronics Engineering, Pondicherry Engineering College Puducherry, India
*Corresponding Author: ersusithra@gmail.com

Abstract

Competitive trend towards restructuring and unbundling of transmission services has resulted in the need to discover the impact of a particular generator to load. This paper initially presents the analysis of three different reactive power valuation methods namely, Modified Y_{bus} , Virtual flow approach and modified power flow tracing to compute the reactive power output from a particular generator to particular load. Among these methods, the modified power flow electricity tracing method is identified as the best method to trace the reactive power contribution from various reactive power sources to loads, transmission line, etc. Also this proposed method breakdown the total reactive power loss in a transmission line into components to be allocated to individual loads. Secondly, based on this Method a novel allocation method for reactive power service for practical system is proposed. Hence, this method can be useful in providing additional insight into power system operation and can be used to modify existing tariffs of charging for reactive power transmission loss and reactive power transmission services. Simulation and comparison results are shown by taking WSCC 9 and IEEE 30 bus system as test system.

Keywords: Modified Y_{bus} method, Virtual flow approach, Modified power flow tracing method, Reactive power pricing.

1. Introduction

The modern power industry is changing from one based on vertically integrated market to a new form based on competition and privatization. This results in the unbundling of the vertically integrated functions of generation, transmission and distribution. In deregulation sector, each electric power service should be

Nomenclatures

$C_{ci}(Q_{sci})$	Opportunity cost of capacitor
C_{PGK}	Real power production cost of k^{th} generator
C_{QGK}	Reactive power production cost of k^{th} generator
$C_{QGK}(Q_{GK})$	Opportunity cost of generator
$C_{sci}(Q_{sci})$	Opportunity cost of synchronous condenser
l	Total number of loads served by transmission line *i-j*
Q_{Dij}	Total reactive power loss in the transmission line *i-j*
$Q_{Dij,k}$	Reactive power loss allocated to the k^{th} load
r	Profit rate
$S_{GK,\ max}$	Complex power of k^{th} generator
SL_j	Apparent power of load on bus j
VL_j	Resultant voltage of bus j of power flow analysis
Y_a	Series admittance
Y_b	Half line charging susceptance
YL_j	Equivalent admittance of load on bus j

Greek Symbols

$\Delta S_{i-j}^{(1)}$	Virtual flows due to source at node 1
$\Delta S_{i-j}^{(2)}$	Virtual flows due to source at node 2

Abbreviations

VPFA	Virtual Power Flow Approach
VAR	Volt Ampere Reactive

economically valued and the fair rules for evaluation and compensation should be established. Reactive power service is one of the key ancillary services and its trading is becoming a reality for restructured electricity markets [1]. In [2] a cost-based reactive power pricing approach which integrates the reactive power cost minimization and the voltage security problem into the optimal power flow (OPF) is presented. The dynamic VAR support from generator is of much greater importance in the value assessment and evaluation [3, 4].

In view of market operation, it becomes more important to know the role of individual generators and loads to the networks and power transfer from individual generators to loads. Several methods have been developed to solve the allocation problem in the last few years. Y_{bus} or Z_{bus} matrix methods integrate the network characteristics and circuit theories [5] which are used to find the reactive power contribution. Contribution to bus voltages is computed as a function of each generator current injection by decomposing the network into different networks [6]. Evaluation of reactive power flow in the lines of the network due to individual sources and its contribution to each load are determined by using virtual flow approach. Counter flow components are easily determined and loop flows are handled without any difficulty [7]. Tracing of electricity gains importance as its solution could enhance the transparency in the operation of the transmission system. A straight forward method of allocating the costs of reactive power using modified Y-Bus matrix method is explained in paper [8].

A novel electricity tracing method has been proposed in [9] which assume that nodal inflows are shared proportionally between the nodal outflows. Bialek explains upstream and downstream looking algorithms for tracing reactive power flow. The upstream looking algorithm look at the nodal balance of inflows and it determines how the line flows are supplied from individual generators. The dual, downstream looking algorithm looks at the nodal balance of outflows and it determines how the generation is distributed between each of the loads [10]. Due to the addition of fictitious node the network size increases, thus requiring more computation memory. To overcome this problem a modify methodology for tracing reactive power is proposed in [10-12].

A methodology for the aggregation of nodal generation loss factors into zonal loss factor is presented in [13]. A power flow procedure is used to calculate power loss in the system. It is desirable to take network loss effect of injection power at each node for calculating contribution of transmission loss by each generator and loss allocated to loads based on its contractual obligations with consumer [14]. A new path-integral method is developed in paper [15] by integrating the partial differential of the system loss along a path reflecting the transaction strategy.

In this paper, at first, three different methods to solve the reactive power allocation problem are presented. The modified power flow tracing method considers the transmission losses and so, results in more accurate consequences than the other methods. Hence, according to this power flow tracing method, Reactive power production cost anchored in contribution of reactive power and different usage cost can also be estimated and is presented.

2. Modified Ybus Method

In this method, a new modified nodal equation has been developed for identifying reactive power transfer between generators and load. The purpose is to represent each load current as a function of the generator's currents and load voltages. In circuit theory which uses the modified admittance matrix to decompose the load voltage dependent term into generator component dependent term. By using these two decompositions of current and voltage terms, separate real and reactive power transfer between loads and generators are obtained [8].

The proposed methodology begins with the system node equation. In order to explain this concept, it is taken as that the power system has a total number of n buses, 'g' generators, and 'l' loads, among which bus number 1 to g are generation buses and bus number g+1 to n are load buses. Therefore, the Y_{bus} of n*n dimension can be divided into four sub matrixes as illustrated in Eq. (1).

$$\left[\begin{array}{cc|cc} Y_{1,1} & Y_{1,g} & Y_{1,g+1} & Y_{1,n} \\ \ddots & & \ddots & \\ Y_{g,1} & Y_{g,g} & Y_{g,g+1} & Y_{g,n} \\ \hline Y_{g+1,1} & Y_{g+1,g} & Y_{g+1,g+1} & Y_{g+1,n} \\ \ddots & & \ddots & \\ Y_{n,1} & Y_{n,g} & Y_{n,g+1} & Y_{n,n} \end{array}\right] \times \left[\begin{array}{c} V_1 \\ \vdots \\ V_g \\ \hline V_{g+1} \\ \vdots \\ V_n \end{array}\right] = \left[\begin{array}{c} I_1 \\ \vdots \\ I_g \\ \hline I_{g+1} \\ \vdots \\ I_n \end{array}\right] \qquad (1)$$

Equation (1) can be briefly represented as

$$\left[\begin{array}{c|c} YGG & YGL \\ \hline YLG & YLL \end{array}\right] \quad \left[\frac{VG}{VL}\right] = \left[\frac{IG}{IL}\right]$$

Equivalent admittance of each load bus is estimated as:

$$YL_j = \frac{1}{VL_j}\left(\frac{SL_j}{VL_j}\right)^* \tag{2}$$

Equation (2) helps to calculate the equivalent admittance of every load and the sub matrix [YLL] in the original Y_{bus} matrix is then modified. The modification is executed by adding the corresponding YL_j to the diagonal elements in the [YLL] matrix. Now, the original matrix [YLL] is replaced by matrix [YLL']. The load buses will not have any injection current, thus reducing the sub-matrix [IL] in to [0]. Now Eq. (1) is changed as shown:

$$\left[\begin{array}{c|c} YGG & YGL \\ \hline YLG & YLL \end{array}\right] \quad \left[\frac{VG}{VL}\right] = \left[\frac{IG}{0}\right] \tag{3}$$

In Eq. (2), the lower half part of the matrix is modified into:

$$[YLG][VG] + [YLL'][VL] = 0 \tag{4}$$

and then the relationship functions can be obtained as follows:

$$[YLL'][VL] = -[YLG][VG] \tag{5}$$

$$[VL] = -[YLL']^{-1}[YLG][VG] \tag{6}$$

In Eq. (6), it is assumed that

$$[YA] = -[YLL']^{-1}[YLG] \tag{7}$$

And Eq. (5) can be rewritten as

$$[VL] = [YA]\ [VG] \tag{8}$$

The voltage of all load buses consisting of the voltages supplied by individual generators is expanded and it is shown in the following equation:

$$VL_j = \sum_{i=1}^{g} YA_{j,i} * VG_i \tag{9}$$

and it is assumed that

$$\Delta VL_{i,j} = YA_{j,i} * VG_i \tag{10}$$

where ΔVL_j is the voltage contribution is that load acquires from generator. It may also be expressed as

$$VL_j = \sum_{i=1}^{g} \Delta VL_{i,j} \tag{11}$$

With Eq. (11), it can be recognized that the voltage contribution of each load bus received from individual generators is ΔVL. The reactive power contributions that load acquire from generator *i* is as follows:

$$QL_{i,j} = \mathrm{Im}aginary\{\Delta VL_{i,j} * IL_j^*\} \tag{12}$$

where IL_j is the load current which is to divide the power of the load by known load bus voltage and take the conjugate of the complex number on load bus *j*.

Reactive Power Contribution that load j acquires from generator *i* can be determined from Eq. (12). The calculation results might bring about some differences from those based on other methods if any static capacitor is added to load bus. Then, the power flows and voltages of this system have been changed. The bus voltage contributions from each generator are also changed, reflecting a change that can be seen as a reduced share on each load bus of the reactive power from existing generators. This method is much effective to find the contribution of reactive power including the effect of capacitor. However, the contribution of reactive power to the transmission line cannot be estimated.

3. Virtual Flow Approach

This approach presents the concept of virtual flows using the principle of superposition. The concept is applied to obtain virtual contributions of individual sources to line flows and loads. It is established that the virtual contribution to loads is by each source of the network in some proportion and the actual contribution is the superposition of the all the respective virtual contribution. The procedure of this method to find the contribution of an each generator to the line flow, loads and losses is given below.

Step 1. Perform load flow estimation of the network and read bus voltage phasors, real and reactive power injections at generator buses, loads and network parameters.

Step 2. Convert all the loads to equivalent admittances at the operating point by the relation,

$$y_i^{load} = \frac{\left(-P_i^{(o)} + jQ_i^{(o)}\right)}{\left|V_i^{(0)}\right|^2} \quad \text{i=g+1, g+2…n} \tag{13}$$

Step 3. Modify the network Y $_{\text{bus}}$ matrix to include loads as admittances and inject equivalent current from one source at a time to respective bus and obtain corresponding bus voltage profile.

$$I_i^{(o)} = \frac{S_i^{(0)*}}{V_i^{(0)*}} \quad \text{where } S_i^{(0)} = P_i^{(0)} + jQ_i^{(0)} \tag{14}$$

Step 4. Determine all the resulting branch currents for the voltage profile obtained from this source. The total complex power flow in the line *i-j* is given by,

$$S_{i-j}^{(0)} = \left\{(V_i^{(0)} - V_j^{(0)})y_a + V_i^{(0)} y_b\right\}^* V_i^{(0)}$$
$$= \left|V_i^{(0)}\right|^2 (y_a^* + y_b^*) - V_i^{(0)} V_j^{(0)*} y_a^* = \Delta S_{i-j}^{(1)} + \Delta S_{i-j}^{(2)} \quad (15)$$

Step 5. The total contributions to given load from all the sources is obtained by the summation of partial contribution by all individual sources and it agrees with load power as in base case. It can be ascertained that the load power.

$$S_i^{(0)} = \sum_{k=1}^{g} \Delta S_i^{(k)} \quad (16)$$

This method presents the concept of virtual flows using the principle of superposition. The concept is applied to obtain virtual contributions of individual sources to line flows and loads. Though the power flows computed by the proposed method is virtual, the line flows and counter flows gives information regarding extend of line usage by each sources. This information is valuable for redispatch of generation and overload alleviation based on economics, environment issues or any other criterion. However, the contribution of reactive power including line losses cannot be estimated. Also, this method does not calculate the reactive power generation due to static and dynamic sources.

4. Modified Power Flow Tracing Method

The electricity tracing methodology is based on actual flows in the network and proportionality sharing principle. It deals with a general problem of how to distribute flows in a meshed network [9]. The proportional sharing principle basically applies Kirchhoff’s current law at the node and applies proportionality principle to find the relationship between incoming and outgoing flows. Thus, this method is equally applicable to real and reactive power flows and direct currents. The only assumption that is made in this methodology is that the system is assumed as lossless [10]. This is achieved by averaging the sending and receiving end line flows and by adding half of the line loss to the power injections at each terminal node of the line.

4.1. Objective function

The main objective of reactive power tracing method is to calculate reactive power loss allocated to each line for particular load. In case of the responsibility share of k^{th} load for reactive power loss in transmission line *i-j* can be represented as

$$Q_{Dij,k} = QD_{ij,k} Q_{Dij} \quad (17)$$

where $QD_{ij,k} = \dfrac{\left(\dfrac{Q_{ij,k}}{\sin\phi_k}\right)^2}{\sum_{k=1}^{l}\left(\dfrac{Q_{ij,k}}{\sin\phi_k}\right)^2}$

Here, $Q_{Dij,k}$ is reactive power loss allocated to the k^{th} load for the total reactive power loss in the transmission line *i-j*, l is total number of loads served by transmission line *i-j* and $Q_{Dij,}$ is total reactive loss in the transmission line *i-j*. $QD_{ij,k}$ is reactive power loss distribution factor (QLDF).To obtain this main objective, the procedure is summarised below.

4.2. Algorithm

1. Obtain the Power Flow solution for given system.
2. The transmission line Π model shown in Fig. 1 is considered and the lossless system is obtained. Calculate new reactive power in each line due to the reactive power generated by shunt admittance Q_{shunt} which is connected to each bus, by assuming that voltage of shunt admittance is equal to the nearby nodal voltage. The nodal voltage can be obtained from power flow using the formula:

$$Q_{shunt,i} = V_i^2 B_{sh/2,ij} \qquad Q_{shunt,j} = V_j^2 B_{sh/2,ij}$$

$$Q_{ij,New} = Q_{ij} + Q_{shunt,i} \qquad Q_{ji,New} = Q_{ji} - Q_{shunt,j}$$

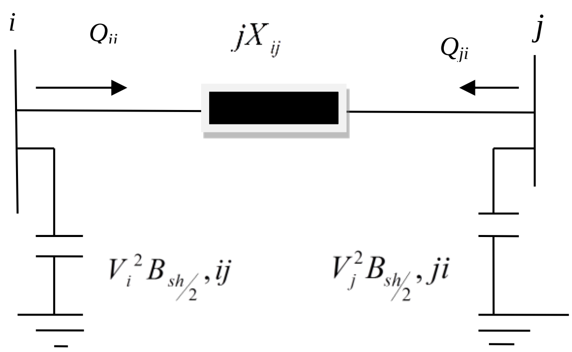

Fig. 1. Transmission line π model and the forward/ backward current.

3. Form the Lossless Network by dividing the line loss by

   a) Calculate the Reactive Power injection at each bus, i.e., equal to Total generated power (Σ half of the transmission line loss connected to that bus).

   b) Calculate the average value of sending and receiving end reactive power of each transmission line.

c).Calculate the reactive power at each bus, i.e., equal to sum of outflows of that bus.

4. Calculate the Upstream Distribution Matrix (**A$_u$**):

This can be calculated using Upstream Looking Algorithm; it states that total flows (inflows and outflows) in bus 'i', i.e., P_i can be expressed as

$$P_i = \sum_{j=\alpha_i^{(u)}} C_{ij|P_{i-j}|} + P_{Gi}$$

Let $c_{ij=|P_{j-i}|/P_j}$ and $A_u P = P_{Gi}$

The upstream distribution matrix elements can be calculated by

$$[A_u]_{ij} = \begin{cases} 1 & for \quad i = j \\ -C_{ji} = -|P_{j-i}|/P_j & for \quad l \in \alpha_i^{(u)} \\ 0 & otherwise \end{cases} \tag{18}$$

5. Obtain the inverse of upstream distribution matrix

6. The contribution of k^{th} generator to i^{th} load is found out using

$$P_{Li} = \frac{P_{Li}}{P_i} P_i = \frac{P_{Li}}{P_i} \sum_{k=1}^{n} \left[A_u^{-1}\right]_{ik} P_{GK} \text{ for } i=1,2,...n. \tag{19}$$

7. The contribution of k^{th} generator to i-l line is found out using

$$|P_{i-l}| = \frac{|P_{i-l}|}{P_i} P_i = \sum_{k=1}^{n} D_{i-i,k}^{G} P_{GK} \text{ for all } l \in \alpha_i^{(d)} \tag{20}$$

where $D_{i-j}^{G} = |P_{i-l}|\left[A_u^{-1}\right]_{jk} / P_i$ is generation distribution factor.

8. Calculate the Downstream Distribution Matrix (A_d):

This can be calculated using Downstream Looking Algorithm, it states that total flows (inflows and outflows) in bus 'i', i.e., P_i can be expressed as

$$P_i = \sum_{l\in\alpha_i^{(d)}} |P_{i-l}| + P_{Li} = \sum_{l\in\alpha_i^{(d)}} C_{li} P_i + P_{Li} \tag{21}$$

Let $C_{li} = |P_{l-i}| / P_l$. Therefore, $P_i - \sum_{j\varepsilon\alpha_i^{(d)}} C_{ij} P_i = P_{Li} (or) A_d P = P_L$

The Downstream distribution matrix elements can be calculated by

$$[A_d]_{il} = \begin{cases} 1 & for \quad i = l \\ -C_{li} = -|P_{l-i}|/P_l & for \quad l \in \alpha_i^{(d)} \\ 0 & otherwise \end{cases} \tag{22}$$

9. Find the inverse of downstream distribution matrix

10. Calculate reactive power loss allocated to each line for particular load by using

$$Q_{Dij,k} = QD_{ij,k} Q_{Dij} \tag{23}$$

An excellent feature of this method is that the introduction of fictitious node in each transmission line is avoided. Therefore, there is a reduction in size of the system. This method helps to deal with one of the ancillary services that is power loss and proposes a simple method to allocate transmission line losses to individual loads. It can also identify the amount of reactive power generated by transmission line and power components like capacitor, shunt admittance, etc.

5. Reactive Power Pricing Using Modified Power Flow tracing Method

5.1. Reactive power production cost

When generator is supplying reactive power, the amount of real power which is not supplied in the third region of reactive power capability curve is considered as real power loss [12]. The cost estimation for this loss is known as opportunity cost of reactive power production. The reactive power pricing to find the opportunity cost or production cost of various components of practical utility system is presented in Eqs. (25-29)

Objective Function:

Opportunity cost is estimated by using this expression:

$$Op.cost = \sum_{i \in NG} C_{QGK}(Q_{GK}) + \sum_{i \in Nl} C_{ci}(Q_{ci}) + \sum_{i \in Nl} Csci(Qsci) \tag{24}$$

The Production cost of generator can be given as

$$C_{QGK}(Q_{GK}) = \left[C_{PGK}(S_{GK,\max}) - C_{PGK}\left(\sqrt{S^2{}_{GK,\max} - Q_{GK}^2}\right) \right] r \tag{25}$$

The Production cost of capacitor can be given as

$$C_{ci}\left(Q_{ci}\right) = \frac{\alpha \times Q_{ci} \times \$IC_i \ / \ MVar}{8760} \tag{26}$$

The investment cost of capacitor is dependent upon its voltage rating. Let the investment cost of ‘v’ Kv rating of capacitor be \$IC/MVAR. If n is number of years for recovering the investment then production cost per hour is given in Eq. (26).

where $\alpha = \dfrac{r(1+r)^n}{(1+r)^n - 1}$ is recovery factor and IC_i is investment cost of i^{th} capacitor.

The production cost of synchronous condenser is ‘m’ times higher than the capacitor

$$C_{sci}\left(Q_{sci}\right) = \frac{m.\alpha \times Q_{sci} \times \$IC_i \ / \ MVar}{8760} \tag{27}$$

Based on the reactive power components present in the system, the overall production cost can be estimated. Then, different usage cost will be calculated using the following procedure.

5.2. Reactive power usage cost allocation

In power system, different type of power sources delivers reactive power to the loads in different rates. These sources utilize transmission line to transmit power to loads. The transmission line usage cost must be charged by the sources. The total transmission line usage cost is given by summing up individual shares multiplied by the charge C_{il} for the line use and divided by the net flow in the line.

Then transmission network usage cost can be calculated from Eq. (20) is

$$U_{Grk} = Q_{Grk} \sum_{i=1}^{n} \left\{ \frac{[A_u]_{ik}^{-1}}{Q_i} \sum_{l \in \alpha_i^d} C_{il} \right\} \tag{28}$$

where Q_{Grk} is reactive power generation by r^{th} reactive power source at k^{th} bus and C_{il} is the *i*-l line cost.

Reactive power loss occurring in transmission line to loads can be estimated by using Eq. (17). Then, the cost of reactive losses in transmission network can be allocated to the load is given by

$$U_{LK} = \sum_{i=1}^{n} \sum_{j \in \alpha_i^d} QD_{ij,k} \times C_{ij} \tag{29}$$

where $QD_{ij,k}$ is reactive power loss distribution factor, and C_{ij} is transmission line *i-j* cost for reactive power loss.

The contribution of reactive power from source to i^{th} load can be estimated by using Eq. (19). Thus, we can allocate reactive power production cost of each source to loads. The total cost of consuming reactive power by i^{th} load, U_{Di} can be calculated by summing up individual contribution of r^{th} reactive power source production charge C_{Grk} and divided by the total r^{th} reactive power source generation Q_{Grk} at k^{th} bus is given by

$$U_{Di} = \frac{Q_{Li}}{Q_i} \sum_{k=1}^{n} [A_u]_{ik}^{-1} \times C_{Grk} \tag{30}$$

where C_{Grk} is the reactive power production cost of r^{th} reactive power source at k^{th} bus. Opportunity cost and various usage cost result is shown in the following session.

6. Simulation Results and Discussion

The Western System Coordinated Council (WSCC) 9 bus system is taken to study and compare various tracing methods and IEEE 30 bus system is applied as test system to estimate reactive power opportunity cost and different usage cost. The modelling of the power system components (generator, transmission line and loads) of the test system was carried out in the MATLAB environment. Power flows in transmission lines were determined using N-R method. In this context, the influence of reactive power delivered by the generation sources alone is taken for the analysis.

6.1. Reactive power contribution

The following three case studies were carried out to demonstrate contribution of reactive power delivered by the sources by three computing methods.

1. Base case condition (315 MW).
2. Increased in load condition (120 %).
3. Contingency case (One transmission line contingency).

6.1.1. Comparison between modified Y_{bus} and virtual power flow approach

Table 1 shows the results of comparison of Modified Y_{bus} and Virtual Power Flow Approach (VPFA). Using Modified Y_{bus} method, the amount of reactive power absorbed by the load from generator sources is computed. But this method is not capable to identify counter flow components in a given branch of network produced by some other sources when subjected to different case studies.

In Virtual power flow method, by knowing the virtual power flows in each branch due to each source, the source contribution to each load can be obtained. It is established that the virtual contribution to load is by each source of the network in some proportion and the actual contribution is the superposition of the all the respective virtual contribution. This method is used to find contribution of an each generator to the line flow, loads and losses. But this method does not identify the amount of reactive power generated by transmission line and the amount of reactive power generated by static and dynamic reactive power sources. In order to overcome this above said drawbacks, power flow tracing method is used.

Table 1. Comparison of modified Y_{bus} and virtual power flow approach.

Modified Y_{bus} Method

Load Bus No.	Base Load Condition			Increase in Load Condition			Line Outage Condition		
	G_1	G_2	G_3	G_1	G_2	G_3	G_1	G_2	G_3
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	27.91	16.83	10.31	30.42	18.5	11.43	38.52	20.7	10.68
6	16.76	7.86	7.96	18.27	8.71	8.74	7.32	10.1	15.52
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	12.04	14.57	10.69	14.42	17.5	12.84	9.67	17.2	14.96
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

VPFA Method

Load Bus No.	Base Load Condition			Increase in Load Condition			Line Outage Condition		
	G_1	G_2	G_3	G_1	G_2	G_3	G_1	G_2	G_3
4	0.000	0.00	0.000	0.00	0.00	0.00	0.00	0.00	0.00
5	27.92	16.91	10.31	30.4	18.7	10.43	38.52	20.7	10.56
6	13.73	79.39	7.11	0.00	0.00	0.00	0.00	0.00	0.00
7	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	10.91	13.04	19.5	14.4	17.5	12.82	9.67	17.2	14.96
9	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

6.1.2. Modified power flow tracing method

Here, Loss distribution factor identifies the loads responsible for reactive power loss in a specific transmission line and indicates their responsibility share. Total amount of reactive power delivered to the load from the sources for three case studies by modified power flow tracing method is shown in Table 2. In this table, the generator G1 delivers the maximum amount of reactive power in all the three cases. In large scale power system, power flow tracing method gives additional information about reactive power generated by VAR sources, shunt admittance of transmission line and it is also given in Table 2. Table 3 shows the reactive power loss occurring in each line is allocated to each load according to Eq. (17) by taking the power factor (cos φ) of load is 0.85 respectively.

Table 2. Contribution of reactive power using power flow tracing method.

	Base case		Line Outage		Increased Load Condition	
Bus No.	Due to generator	Due to shunt admittance	Due to generator	Due to shunt admittance	Due to generator	Due to shunt admittance
1	26.7636	0	22.6891	0	35.5314	0.0000
2	6.3269	0	12.0828	0	11.4689	0.0000
3	10.3912	0	16.7795	0	8.8704	0.0000
4	0	17.57	0	9.3039	0	17.4120
5	0	23.89	0	24.0479	0	23.5407
6	0	26.47	0	15.9124	0	25.9708
7	0	23.94	0	23.7841	0	23.8014
8	0	18.48	0	18.1424	0	18.3172
9	0	30.25	0	29.3552	0	30.0711

6.2. Reactive power pricing

Reactive Power Pricing study has been conducted by taking IEEE-30 bus system as test system. It consists of 6 generator units, 24 load buses, and 41 transmission lines with four tap-changing transformers and two injected VAR sources. The system has a base case load of 283.4 MW and 126.2 MVAR. The cost coefficients data is taken from paper [16].

Table 3. Contribution of MVAR from each load to each line.

	Load5	Load6	Load8	Total
line 1- 4	0.20576	0.0771	0.007368	0.290307
line 2- 7	0.0000	0.0000	0.007411	0.007411
line 3- 9	0.0000	0.0000	0.037462	0.037462
line 4- 5	0.29888	0.0000	0.001089	0.299977
line 4- 6	0.0000	0.2230	0.009614	0.232709
line 5- 7	0.0000	0.0000	0.001821	0.001821
line 6- 9	0.0000	0.0000	0.025730	0.025730
line 7- 8	0.0000	0.0000	0.019880	0.019880
line 9- 8	0.0000	0.0000	0.184268	0.184268

According to generator capability curve it is necessary to set values for Q_{min}, Q_{base}, and Q_{max}. In this paper it is assumed that Q_{base} = 0.1×Q_{max} and

Q_A=0.8xQ_B.Then, the three regions for each generator of IEEE30 bus system are shown in Table 4. As seen in the Table 4, it is necessary to estimate Reactive power opportunity cost in the third region $(Q_A\ to\ \ Q_B)$. From the contributions of reactive power and by solving Eqs. (24) and (25), the production cost of generator and capacitor are obtained and are tabulated in Table 5.

Table 4. Reactive power supply region.

Buses having Generator	Classifications of regions for Q_G			Q_{min}	Q_{max}
	Q_1 (0to $Q_{\min}$)	$Q_2(Q_{base} to Q_A)$	$Q_3(Q_A to Q_B)$		
1	0 to -60	10 to 80	80 to 100	-60	100
2	0 to -40	5 to 40	40 to 50	-40	50
5	0 to -40	4 to 32	32 to 40	-40	40
8	0 to -10	1 to 32	32 to 40	-10	40
11	0 to -6	2.4 to 9.2	19.2 to 24	-6	24
13	0 to -6	2.4 to 9.2	19.2 to 24	-6	24

Table 5. Reactive power production cost of generator and capacitor.

Generator	Production cost in $/MVAR	Capacitor	Production cost in $/MVAR
1	854.640		
2	832.088	10^{th} bus	1.119
5	782.535		
8	876.861		
11	734.183	24^{th} bus	0.253
13	658.544		

Different usage cost is then estimated. Firstly, Transmission line usage cost is calculated using Equation 28 and the result is exposed in Fig. 2.

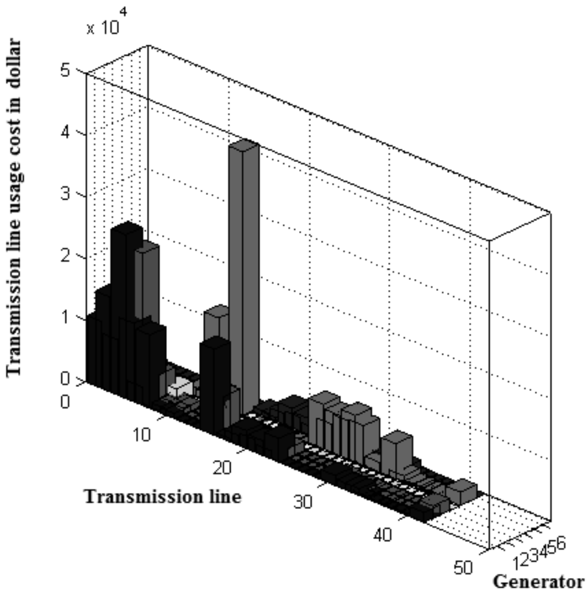

Fig. 2. Transmission line usage cost of generator.

Figure 2 obviously shows the transmission line usage cost of generator. This figure explains that when 11th (No. 5 in Fig. 2) generator supplies reactive power to 14th line then the transmission line usage cost is more compared to other generators and transmission lines.

The reactive power production cost of generator to each load is calculated by using Eq. (30) and the result is visualized in Fig. 3.

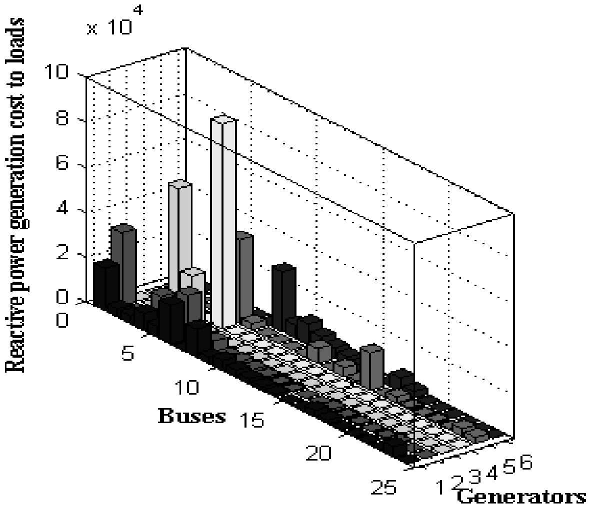

Fig. 3. Reactive power generation cost.

In reactive power management, reactive power loss is one of the important factors. Therefore, it is necessary to find losses allocated to the demand. Using Eq. (17) the reactive power loss is estimated and by using Eq. (29) the reactive power loss cost is evaluated and is illustrated in Fig. 4.

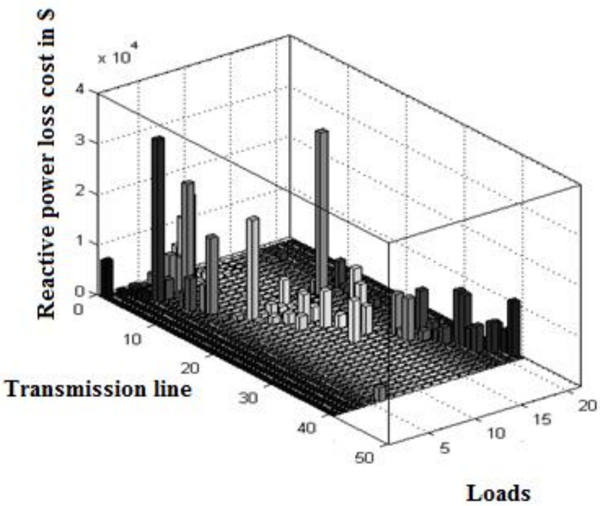

Fig. 4. Reactive power loss cost to each load.

7. Conclusions

The comparison of three different methods of reactive power valuation is reported in this paper. Different methods have different results. The modified Y_{bus} Method can identify the source and can calculate the amount of consumed reactive power on each load. Virtual flow approach is used to evaluate real and reactive power flow in the network due to individual sources and its contribution to each load using the principle of superposition. The Modified power flow tracing method could have wide applications in the deregulated electricity supply industry. Apart from giving additional insight into how power flows in the network, it can be used to set tariffs for transmission services based on the shared, as opposed to marginal costs.

As a result of power flow tracing method, the charging for the transmission loss and for the actual usage of the system by a particular generator or the load can be estimated. This method can also be used to assess the contribution of individual sources of reactive power in satisfying individual reactive power demands and therefore be used as a best tool for reactive power pricing.

References

1. Chattopadhyay, D.; Chakrabarti, B.B.; and Grant Read, E. (2003). A spot pricing mechanism for voltage stability. *International journal of electrical power & energy systems*, 25(9), 725-734.
2. Chung, C.Y.; Chung, T.S.; Yu, C.W.; and Lin, X.J. (2004). Cost based reactive power pricing with voltage security consideration in restructured power systems. *Electric Power Systems Research*, 70(2), 85-91.
3. Xu, W.; Zhang, Y.; Silva, L.C.P.; and Kundur, P. (2001).Assessing the value of generator reactive power support for transmission access, *IEE Proceedings generation, Transmission and Distribution*,148(4),337-342.
4. Fattahi, S.; Afsharnia, S.; and Javidi, M.H. (2008) A new AHP-Based reactive power valuation method. *IEEE Electric power Conference,'08,* Canada, 1-7.
5. Shareef, H.; Mohamed, A.; Khalid, S.A.; and Mustafa, M.W. (2012). A method for real power transfer allocation using multivariable regression analysis. *Journal of Central South University*, 19(1), 179-186.
6. Wu, F.F.; Ni, Y.; and Wei, P. (2000). Power transfer allocation for open access using graph theory-fundamentals and applications in systems without loopflow. *IEEE Transactions on Power System*, 15(3), 923-929.
7. Dhadbanjan, T. (2011).Comparison of Virtual Flow Approach with Proportional Sharing Methods for Tracing of Network Power Flows. *International Journal of Emerging Electric Power Systems*, 12(4).1-21.
8. Chu, W.C, Bin-Kwie Chen and Chung-Hsien Liao (2004). Allocating the costs of reactive power purchased in an ancillary service market by modified Y-bus matrix method," *Power Systems, IEEE Transactions on*, 19(1), 174-179.
9. Bialek, J. (1996). Tracing the flow of electricity. *IEE Proceedings-Generation, Transmission and Distribution*, 143(4), 313-320.

10. Tiwari, A.; and Ajjarapu, V. (2006). Modified methodology for tracing power flow. *38th North American Power Symposium, NAPS 2006*, 317-322.
11. Acha, E.; Fuerte-Esquivel, C.R.; Ambriz-Perez, H.; and Angeles-Camacho, C. (2004). *FACTS: Modelling and simulation in power networks*. John Wiley & Sons.
12. Rider, M.J.; and Paucar, V.L. (2004). Application of a nonlinear reactive power pricing model for competitive electric markets. In *Generation, Transmission and Distribution, IEE Proceeding*, 151(3), 407-414.
13. Biskas, P.N.; Tsakoumis, A.; Bakirtzis, A.G.; Koronides, A.; and Kabouris, J. (2011). Transmission loss allocation through zonal aggregation. *Electric Power Systems Research*, 81(10), 1973-1985.
14. Satyaramesh, P.V.; and Radha Krishna, C. (2010). Usage-based transmission loss allocation under open access in deregulated power systems. *IET Generation, Transmission & Distribution*, 4(11), 1261-1274.
15. Min, K.I.; Ha, S.H.; Lee, S.W.; and Moon, Y.H. (2010). Transmission loss allocation algorithm using path-integral based on transaction strategy. . *IEEE Transactions on Power Systems*, 25(1), 195-205.
16. Gnanadass, R.; Padhy, N.P.; and Manivannan, K. (2004). Assessment of available transfer capability for practical power systems with combined economic emission dispatch. *Electric Power Systems Research*, 69(2), 267-276.