Cost Allocation of Reactive Power Using Matrix Methodology in Transmission Network

Gaurav Gupta, Manisha Dubey, Anoop Ayra
Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal, India

ABSTRACT
In the deregulated market environment as generation, transmission and distribution are separate entities; reactive power flow in transmission lines is a question of great importance. Due to inductive load characteristic, reactive power is inherently flowing in transmission line. Hence under restructured market this reactive power allocation is necessary. In this work authors presents a power flow tracing based allocation method for reactive power to loads. MVAr-mile method is used for allocation of reactive power cost. A sample 6 bus and IEEE 14 bus system is used for showing the feasibility of developed method.

Keywords: Kirchhoff matrix
Reactive power allocation
Tracing of reactive power flow
pricing of electricity

1. INTRODUCTION
A fair transmission pricing methodology should recover all the cost of the transmission system and provide profit to the transmission utility. So many methodologies have developed in past years for transmission cost allocation in transmission system.

The active power production capability of generator will reduced due to more reactive power. Hence, provision of pricing of reactive power becomes an important issue to be addressed in electricity market as similar to real power pricing [1]. The voltage of the system must be controlled as an component of reactive power supports so, the reliability can achieved but more pricing options required due to unrecovered obtained cost with inclusion of capital cost under scheme proposed in [2]. Reactive power transaction depends on indefinite sources such as susceptance of line, capacitor banks rating, generator capacity, installed FACT devices capacity and so on while real power flows depends on source and direction. Reactive power flow is continuously changing due to variable system operating condition. Further transmission of reactive power does not carry over longer distances because it needed to fulfill local requirements. So while locating reactive sinks, sources of reactive power identification became a big challenge. The scheme based on proportional sharing principal [3-4] offer an effectual computational tool but that concept neither discoverable nor verifiable for loss allocation. Power factor based reactive power costing methods are in traditional use but these methods are inappropriate for the restructured power systems, because they separately charged the cost of reactive power support. In addition, the tariff in current scenario only consider local charges and consumption of reactive power calculated with respect to those variables which do not judge the complete customer’s usage [3-6]. Relative electrical distance (RED) idea for transmission charge allocation based on nodal pricing method influences the operation condition and system variable has been discussed in [7]. The majority of the above referred solutions [3-7] show that transmission usage charge also
having cost of losses in transmission line as in form of their integral part so it does not required separate
calculation. The non-acceptability of these methods is due to the long computational time and nonlinearity
towards convergence. The Z-bus matrix and modified Y-bus matrix methods treated as circuit-based
allocation methods, all the computation in these methods are based on admittance matrix to solved power
flow [8], [9]. The cost allocation towards line losses based on complex power injection has been addressed
in [10]. The virtual flow methodology for assessment of flow of reactive power in transmission network due
to different sources and particular load involvement with consideration of counter and loop flows without any
difficulty has been addressed in [11]. Flow of electrical power based on tracing approach shows their
importance due to its explanatory and comprehensibility in transmission network process. A method based on
tracing of electrical power has been reported in [12], [13] which, having assumption that outflow and inflow
on nodes are proportionally shared. This permits one to outline power flow in meshed structure. A tracing
based reactive power flow is reported by Bialek with upward and downward looking principle. The upward
looking principle look at the balancing of incoming flows towards the nodes and the downward looking
principle look at the balancing of outgoing flows from the nodes, then compute the power spread among
different loads [15]. Power flow tracing methods dominate marginal participation method as there is full
recovery of cost by tracing flow [16]. It also depends on the Kirchhoff current laws and easy to implements
on larger power systems. Moreover it has very less volatility as compared to marginal participation methods.
It also provides uniformity and fairness in charge allocation due to depends on actual usage of system [17].
The locational marginal pricing for congestion cost with FACT controller by real power rescheduling for
pool based transaction has been discussed in [18]. Determination of generator contribution can be used for
congestion management as proposed in [19].

In this paper a reactive power flow allocation method has been proposed. After allocation of reactive
power, the total cost to be recovered from individual participant towards transaction of reactive power is also
allocated to different participant. For allocation power flow tracing technique is used while for cost allocation
MVAr-Mile method is used. Results are shown for 6 bus system and IEEE 14 bus system.

2. DEVELOPED METHODOLOGY

2.1. Model for Reactive Power Flow Allocation

The electrical power system network consists with different component so their behaviors towards
tracing of power flow become topological, so power flow by tracing theory is based on true flows in
transmission system with consideration of proportional sharing principle. It handles the common issue
regarding distribution of VAR (reactive power) flows in a meshed system [12-14]. To determine electricity at
the nodes, the nodal power flow based on tracing which generally use implementation of the KCL
(Kirchhoff’s current law).

To determine the correlation in conjunction with incoming and outgoing flows the proportional
sharing and nodal method is adopt. Hence this principle is similar for the validation of true power and
reactive power flows. The model proposed and implemented in this paper considered network is as
lossless [15], [16].

Let ln = 1,……,e shows entire transmission line in the power system structured, Gn = 1,……,g is
entire quantity of generating units and D = 1,……,d is the entire quantity of users in the structure. Again
PG = diag (PG1, PG2,……, PGG) represents generation in diagonal matrix. Thus from [16]

\[ U = K_m^{-1} P_L \]  
(1)

\[ UTP_{GG} = (P_G)^T \text{ or } P_G = P_{GG}U \]  
(2)

By combining equation (1) and (2)

\[ P_G = P_{GG}K_m^{-1} P_L \]  
(3)

Obtained matrix \( P_{GG}K_m^{-1} \) is called generation production matrix. The generation production matrix is
indicated by GPM = \( t_{ij} \), i.e., Where,

\[ \text{GPM} = P_{GG}K_m^{-1} \]  
(4)

\[ R_{i\rightarrow j} = t_{ij}R_{ij} \]  
(5)

Here \( t_{ij}R_{ij} \) represent the reactive flow contribution of generator situated at bus i to the load at bus j.
Reactive power allocated to generator placed at bus $i$ share the line $s - b$ can be calculated by,

$$RP_{i\rightarrow s-b} = t_{i\rightarrow s-b}$$

(6)

To obtaining the contribution of reactive power by loads similar procedure is repeat. Where the diagonal matrix $P_{LL} = \text{diag}(P_{L1}, P_{L2}, \ldots, P_{Ld})$ and EFM = $P_{LL}(K_m^{-1})^T$ is the extraction factor matrix of loads to generators [16].

2.2. Cost Allocation Model for Reactive Flows

For allocation of reactive power cost following algorithm is developed. For this purpose MVAr-mile method is used. In this model, reactive power charge is allocated with respect to the reactive power base capacity of the transmission line.

If the cost of the line is denoted as $TC_{s-b}$ (in Rs/hr) then Reactive power cost allocated to users is given by:

For generator $G_i$, full transmission usage cost allocation is given by,

$$FTRC^G_{s-b} Gi = RP_{i\rightarrow s-b} \times TC_{s-b}$$

(7)

2.3. Partial Recovery Model

Partial recovery model provide cost recovery with respect to rated reactive power capacity of transmission line.

If the cost of the line is denoted as $TC_{s-b}$ (in Rs/hr) then reactive power cost allocated to users is given by:

For generator $G_i$, partial transmission usage cost allocation is given by,

$$PRTC^G_{s-b} Gi = RP_{i\rightarrow s-b} \times TC_{s-b}$$

(11)
The mathematical formulation in Equation 4 shows the contribution of active power of generator’s to load in network. Contribution of reactive flow in line by generator can be obtained by mathematical formulation given in Equation 5.

3. RESULTS AND ANALYSIS

The presented model is implemented on standard 14 buses IEEE network and 6 bus sample network shown in Fig.1 to test their feasibility and effectiveness. The programming code is developed in MATLAB tool and results are obtained. Under MATLAB tool firstly power system components such as generator, transmission line and loads are modeled for the test system. Newton-Raphson method is used to determine power flow. The line flow limits were also checked out during the power flow. As the restructuring process in power system going on from a decade, trading of real power in power market are carried out while as a responsibility of system operator toward maintaining system security, stability and reliable operation play an important role. To achieve system operator importance, voltage and reactive power comes to the picture. In this paper, the reactive power contributions of demands have been determined using power flow tracing methods. In this perspective, the influence of total reactive power flow through the line is taken for the analysis.

The proposed model is implemented on test network with 6 buses and 14 buses to show their feasibility. First of all reactive power flows are allocated to loads at normal power flow condition by using modified Kirchhoff matrices methodology given in Table I for 6 bus system. For this purpose equation 5 is used. Allocation of the cost to be recovered from individual participant toward reactive power flow through the transmission network under normal operating condition is also done.

3.1. Sample 6 Bus System

The single line diagram of the sample 6 bus system is shown in Figure 1. It contains 3 generator buses and 3 load buses. The data is at 100 MVA base. Table 1 shows about line flows and cost for 6 bus system. Table 2 shows about allocated reactive power of different loads for 6 bus system. Table 3 shows about cost allocated to different loads for 6 bus system.

![Figure 1. Single line diagram of sample 6 bus system](image-url)

| Line  | Flow (pu) | Cost (Rs/hr) |
|-------|-----------|--------------|
| 1-2   | 0.142     | 223.61       |
| 1-4   | 0.227     | 206.16       |
| 1-5   | 0.149     | 310.49       |
| 2-3   | 0.075     | 254.95       |
| 2-4   | 0.496     | 111.8        |
| 2-5   | 0.185     | 316.23       |
| 2-6   | 0.153     | 211.9        |
| 3-5   | 0.269     | 286.36       |
| 3-6   | 0.645     | 101.98       |
| 4-5   | 0.023     | 447.21       |
| 5-6   | 0.063     | 316.23       |
| Total | 2786.92   |              |

| Allocated Reactive Power to Load 4 (pu) | Allocated Reactive Power to Load 5 (pu) | Allocated Reactive Power to Load 6 (pu) |
|----------------------------------------|----------------------------------------|----------------------------------------|
| 0.0046                                 | 0.0071                                 | 0.0169                                 |
| 0.1353                                 | 0.1232                                 | 0.0270                                 |
| 0.0888                                 | 0.0809                                 | 0.0178                                 |
| 0.0212                                 | 0.0130                                 | 0.0213                                 |
| 0.1403                                 | 0.0860                                 | 0.1412                                 |
| 0.0523                                 | 0.0321                                 | 0.0527                                 |
| 0.0433                                 | 0.0265                                 | 0.0435                                 |
| 0.0000                                 | 0.0793                                 | 0.1862                                 |
| 0.0000                                 | 0.1902                                 | 0.4465                                 |
| 0.0198                                 | 0.0012                                 | 0.0000                                 |
| 0.0000                                 | 0.0612                                 | 0.0015                                 |
3.2. IEE 14 Bus System

The single line diagram of the IEEE 14 bus system is shown in Figure 2. It contains 2 generator buses and 12 load buses. The data is at 100 MVA base. Table 4 shows about line flows and cost for 14 bus system. Table 5 shows about allocated reactive power of different loads for 14 bus system. Table 6 shows about cost allocated to different loads for 14 bus system.

![Figure 2. Single line diagram of IEE 14 bus system](image)

### Table 3. Cost Allocated to Different Loads for 6 Bus System

| S.No. | Charge allocated to Load1(Rs/hr) | Charge allocated to Load2(Rs/hr) | Charge allocated to Load3(Rs/hr) |
|-------|----------------------------------|----------------------------------|----------------------------------|
| 1     | 133.2212                         | 121.4108                         | 26.61274                         |
| 2     | 122.8786                         | 111.8895                         | 24.52123                         |
| 3     | 185.0437                         | 168.5815                         | 37.9209                          |
| 4     | 72.06587                         | 44.19133                         | 72.4058                          |
| 5     | 31.62407                         | 19.38468                         | 31.82694                         |
| 6     | 89.39908                         | 54.87018                         | 90.08282                         |
| 7     | 59.96908                         | 36.70163                         | 60.24608                         |
| 8     | 0                                | 84.41765                         | 198.2165                         |
| 9     | 0                                | 30.07224                         | 70.59546                         |
| 10    | 384.9895                         | 23.3327                          | 0                                |
| 11    | 0                                | 307.1949                         | 7.529286                         |

### Table 4. Line Flows and Cost for 14 Bus System

| S.No. | Flow (MVAR) | Cost (Rs/hr) | S.No. | Flow (MVAR) | Cost (Rs/hr) |
|-------|-------------|--------------|-------|-------------|--------------|
| 1     | 63.774      | 62.26        | 11    | 6.4         | 220.44       |
| 2     | 39.797      | 229.49       | 12    | 2.918       | 283.81       |
| 3     | 28.848      | 203.47       | 13    | 8.821       | 146.1        |
| 4     | 19.862      | 185.65       | 14    | 0           | 176.15       |
| 5     | 17.173      | 182.97       | 15    | 13.065      | 110.01       |
| 6     | 0.359       | 183.69       | 16    | 1.531       | 90.29        |
| 7     | 8.641       | 44.18        | 17    | 1.961       | 298.77       |
| 8     | 15.371      | 209.12       | 18    | 4.378       | 208.86       |
| 9     | 10.438      | 556.18       | 19    | 1.111       | 297.92       |
| 10    | 33.236      | 252.02       | 20    | 3.528       | 387.73       |

### Table 5. Allocated Reactive Power of Different Loads for 14 Bus System

| L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 | L10 | L11 | L12 | L13 | L14 |
|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|
| 24.0395 | 12.8888 | 2.185 | 3.22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15.0014 | 8.043 | 1.3635 | 2.004 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14.7957 | 5.5619 | 0.4933 | 0.727 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10.1869 | 3.8294 | 0.3397 | 0.5005 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8.8078 | 3.3109 | 0.2937 | 0.4328 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.359 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.7808 | 3.5804 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3.1677 | 6.369 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2.1511 | 4.325 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3.6432 | 7.325 | 2.2603 | 3.331 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1.6032 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0.731 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 2.2097 | 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 | 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 |

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In Opportunity cost method the total cost of reactive power including capacitor cost is 7.31 $/hr or 467.84 Rs/hr and in case of Triangle method total cost of reactive power including capacitor cost is 267 $/hr or 16020 Rs/hr reported in [20] while the total cost allocated obtained from proposed model as shown in Table VI for IEEE 14 bus system is 69.21$/hr or 4152.94 Rs/hr which is more acceptable to attract the investor in deregulated power market as compared to Opportunity cost method and Triangle method.

4. CONCLUSION

The main objective of the model proposed in this paper is to allocate reactive power for each load based upon the proportion of reactive power flow through the transmission line as per demand by the load. The reactive power flow tracing is done by constructing reactive power flow matrix.

The main reason behind the reactive power flow is the inductive loading at the load end; hence by using MVAr-Mile method the cost of this reactive power flow is allocated to loads. Power system network is very large so this need to have additional information regarding reactive power injected by different sources as well as shunt admittance of the transmission line, the tracing of power flow scheme becomes as effective tool to achieve that. For reliable and stable operation of power system the reactive power economics play a vital role. By allocating the reactive power flow cost by proposed model, total embedded cost associated with the transmission line can be recovered and the size of reactive power sources installations such as capacitor bank, SVC and FACTS devices can be easily done.

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Table 6. Cost Allocated to Different Loads for 14 Bus System

| L1  | L2  | L3  | L4  | L5  | L6  | L7  | L8  | L9  | L10 | L11 | L12 | L13 | L14 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 21.46 | 12.38 | 1.133 | 3.143 | 0 | 0 | 7.765 | 2.466 | 0.996 | 1.733 | 3.854 | 4.115 |
| 86.505 | 46.380 | 7.862 | 11.587 | 0 | 0 | 28.623 | 9.089 | 3.672 | 6.391 | 14.206 | 15.170 |
| 104.356 | 39.229 | 3.479 | 5.127 | 0 | 0 | 24.210 | 6.007 | 1.625 | 2.828 | 6.287 | 10.319 |
| 95.216 | 35.793 | 3.175 | 4.678 | 0 | 0 | 22.089 | 5.481 | 1.482 | 2.580 | 5.736 | 9.415 |
| 93.842 | 35.27603 | 3.12923 | 4.61274 | 0 | 0 | 21.7714 | 5.40183 | 1.4617 | 2.54322 | 5.65328 | 9.27901 |
| 639 | 1293 | 442 | 0 | 0 | 3761 | 9516 | 99569 | 2924 | 6089 | 7819 |
| 183.69 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9.104 | 18.305 | 0 | 0 | 0 | 0 | 11.297 | 1.942 | 0 | 0 | 0 | 3.528 |
| 43.096 | 86.649 | 0 | 0 | 0 | 0 | 53.476 | 9.194 | 0 | 0 | 0 | 16.704 |
| 114.619 | 230.453 | 0 | 0 | 0 | 0 | 142.226 | 24.452 | 0 | 0 | 0 | 44.4283 |
| 27.625 | 55.543 | 17.139 | 25.258 | 0 | 0 | 34.279 | 14.981 | 8.005 | 13.931 | 30.970 | 24.286 |
| 0 | 0 | 0 | 55.212 | 0 | 0 | 0 | 19.864 | 17.498 | 30.454 | 67.696 | 29.683 |
| 0 | 0 | 0 | 71.098 | 0 | 0 | 0 | 25.579 | 22.535 | 39.215 | 87.175 | 38.223 |
| 0 | 0 | 0 | 36.598 | 0 | 0 | 0 | 13.167 | 11.598 | 20.186 | 44.873 | 19.674 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 74.116 | 12.744 | 0 | 0 | 0 | 23.152 |
| 0 | 0 | 0 | 0 | 0 | 0 | 60.832 | 10.456 | 0 | 0 | 0 | 19.001 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 201.292 | 34.600 | 0 | 0 | 62.8772 |
| 0 | 0 | 0 | 0 | 0 | 0 | 208.86 | 0 | 0 | 0 | 0 | 9679 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 232.034 | 45.800 | 20.084 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 269.553 | 118.176 |

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