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Power Loss Allocation in Deregulated Electricity Markets

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Abstract:- The restructuring of Electricity Supply Industry (ESI) all over the world thatstartedmainlyinthe 20th century introduces an open electricity marketfor trading electricity betweengenerators and suppliers in competitive environments. Market participants utilize thenetwork differently to maximize their profits. This transformation consists of two aspects that are related with each other; restructuring and privatization. However, dueto this change, some problems and challenges have risen. One of it is theissue of power losses allocation. When electrical power is transmitted throughanetwork, it will cause power losses. The generators must compensate this lossbygenerating more power. Under competitive electricity market environment, no generators would want to generate more to compensate this loss asit will increase their production cost. Logically both generators and consumers are supposed topayfor the losses because they both use the network and thus are responsible for the lossesincurred. If there is no specified method to handle this problem, there is a probability that the Independent System Operator (ISO) which is a non-profit entity and does not have source of income will be responsible for this losses. However, if ISO paid forthe losses, itis considered unfair. Thus, this analysis focuses on some existing allocating transmissionlosses.The selected methods are pro rata, postage stamp, and Current Adjustment Factor (CAF) and these methods have been tested using simple bus network and the IEEE standard 14 test bus system.

Keywords:- Individual system operator (ISO), Pro rata, post stampage, current adjustment factor (CAF), Restructuring.

I. INTRODUCTION

In electricity markets, the system operator assures security of the network whether it is a pool market or a bilateral market [1]. Power system must be balanced at every second, which means that generation equals loads plus losses at all times. Power dispatch does not take into consideration system losses and the system operator (SO) is the entity responsible for system security by providing the required real and reactive power. Since the power network is not lossless, entities providing the network losses must be compensated for their contribution, normally at the pool marginal price in a pool based market, or at their marginal cost in bilateral markets. The purpose of loss allocation is to assign each user of the network, whether a generator or a load, its share of the cost of transmission losses based on how much losses the user causes. Network losses cost millions of dollars every year as they can account for 5 to 10% of the total generation in the system. The development of a fair and accurate loss allocation scheme power loss is significant to avoid cross subsidies and to have the correct charge for each participant. A user who causes more network losses must be charged more while a user who helps to reduce the losses, due to counter flow, must be rewarded.

If there is no specified method to handle this problem, there is a probability that the Independent System Operator (ISO), which is a non-profit entity and does not have aSource ofincome, will beresponsible forthisloss. The main responsibilities of ISO are maintaining the security of thepower system, managing the market settlement process andoperating in a manner that does not favour or penalize one market participant over another. However if ISO paid for the losses, it is considered unfair and the market participants shouldcoverup the cost of losses. Thus, this project focuses on the comparative analysis in some existing allocating transmission losses methods and these methods will be tested using the IEEE standard test bus system.
Since transmission losses are nonlinear function of line flows, it is impossible to divide system losses to unique separate parts, i.e. each part is uniquely assigned to a generator or a load. So, any loss allocation approach has a certain degree ofarbitrariness. Any loss allocation algorithm should have most of the desirable properties stated below:

- To be consistent with the results of a power flow;
- To depend onthe amount of energy either produced or consumed.
- To depend on the relative location in the transmission network.
- To avoid volatility.

- To provide appropriate economic marginal signals.
- To be easy to understand.
- To be simple to implement.
- Reflects the amount produced or consumed by a user.
- Takes into consideration the relative location of a user within the network.
- The sum of all loss allocated terms is consistent with the results of the power flow

II. NETWORK AND LOSS ALLOCATION METHODS

Generally, in real power systems, the total power generation is always larger than the total load demand because the total power generation is equal to the total load demand counting the losses

$P_G = P_D + L$----------- (1)

$P_G = \sum_{i=1}^{NG} P_{Gi}$----------- (2)

$P_D = \sum_{j=1}^{ND} P_{Dj}$----------- (3)

Where,

P_G= total active power generated

P_{Gi}= power output of generators of bus i

P_D= total active power demand

P_{Dj}= active power demanded by consumers of bus j

L = transmission power losses

N_G= number of generating buses

N_D= number of demand buses

The purpose of loss allocation methods is to assign the cost of losses fairly among the market participants. Lately, although there a number of existing loss allocations methods this project only focuses on three methods based on the technical literature which are :-

A. Pro rata allocation.
B. Postage stamp allocation.
C. Current Adjustment Factor method.

A. Pro rata

The principle is simple and easy to understand. The losses allocates to consumers proportionally with the level of energy consumption [2].

$L_{Dj} = L\frac{P_{Dj}}{P_D}$----------- (4)

This equation represents the Pro ratamethodallocation of losses to the load at bus *j*.

P_D = total real power consumed

P_{Dj} =real power consumed by the loads of bus j.

L_{Dj} = losses allocated at the demandj.

The transmission loss is charged to the consumers through uniform pro rata charge. Uniform means that the same bid for each hour is being submitted.

B. Post stampage method

Post stampage method is the simplest and easy to implement the methodology of transmission loss allocation. It is a fixed charge per unit of power transmitted with in a particular zone. It is transparent and is easily understood by all. There is no mathematical rigor involved in this method. In this method 50% of losses are allocated to generators and 50% of losses to the loads. In this method network topology is never taken into account. Further it will not be beneficiary for two identical loads where one load is locating nearer to the load centre and another load is locating far away from load centre to allocate the loss with the same amount of cost.

i. Transmission loss allocation

Transmission loss allocation for generator is

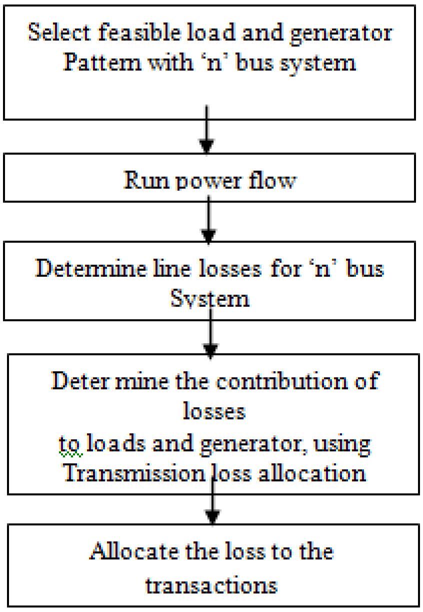
$L_{Gi} = \frac{L}{2} \times \frac{P_{Gi}}{P_G}$----------- (5)

Transmission loss allocation for load is

$L_{Dj} = \frac{L}{2} \times \frac{P_{Dj}}{P_D}$----------- (6)

Where,
P_{Gi}, P_{Dj} =Real power generation and load at buses i and j
P_G,P_D = Total power generation and loadof this system
L_{Gi} = Losses allocatedtothe generatori
L_{Dj} = Losses allocatedto the demand j
L= Total losses ofthe system

Algorithm for post stampagemethod:



C. Current Adjustment Factors (CAFs) Method:

In a deregulated energy system, every user should be responsible for the system losses that they caused. Every user contributes differently to system loss. The interaction between different user's losses causes allocation difficulty. To illustrate this difficulty, consider the following branch that carries two power flows; *PA* and *PB* as shown in Fig. 1

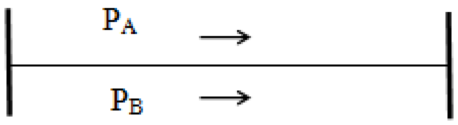


Fig.1

Real power losses can be easily calculated as follows [3] [4]

$P_{loss} = |\bar{I}_t|^2 \times R$
$= |I_A + I_B|^2 \times R$
$= |I_A^2 + I_B^2 + 2 \times I_A \times I_B| \times R$------------ (7)

Where,

$I_t$is the current vector,|*I*|is the magnitude of *I* and*R* isthelineresistance. But if the power loss of these flowsitis the current vector, |*I*|is the magnitude of *I* and *R* is the line resistance. But ifthe power losses of these flows are calculated individually, then

$$P_{loss,A} = |I_A^2| \times R \text{----------} (8)$$
$$P_{loss,B} = |I_B^2| \times R \text{----------} (9)$$

The summation illustrates that

$$P_{loss} \neq P_{loss,A} + P_{loss,B} \text{----------} (10)$$

There is a cross term difference ($2 \times I_A \times I_B \times R$) inside the absolute term. If one traces$I$'s of$A$ transaction and thoseof Btransaction.

Then

$$P_{loss} = |(I_{Ax} + I_{Bx}) + j(I_{Ay} + I_{By})|^2 \times R \text{----------}(11)$$

Where,

$I_x$andI_y are the real and imaginary parts of$I$respectively. But the squared absolute term of a vector is equalto the dot product of that vector, so,

$$P_{loss} = [(I_{Ax} + I_{Bx})^2 + (I_{Ay} + I_{By})^2] \times R$$
$$= [I_{Ax}^2 + I_{Ay}^2 + 2 \times I_{Ax} \times I_{Bx} + 2 \times I_{Ay} \times I_{By} + I_{Bx}^2 + I_{By}^2] \times R \text{-----------} (12)$$

Then it is fair enough to assign each contributor its shareof the losses as follows

$$P_{loss,A} = [I_{Ax}^2 + I_{Ay}^2 + 2 \times I_{Ax} \times I_{Bx} \times \frac{I_{Ax}^2}{I_{Ax}^2 + I_{Bx}^2} + 2 \times I_{Ay} \times I_{By} \times \frac{I_{Ay}^2}{I_{Ay}^2 + I_{By}^2}] \times R \text{----------} (13)$$
$$P_{loss,B} = [I_{Bx}^2 + I_{By}^2 + 2 \times I_{Ax} \times I_{Bx} \times \frac{I_{Bx}^2}{I_{Ax}^2 + I_{Bx}^2} + 2 \times I_{Ay} \times I_{By} \times \frac{I_{By}^2}{I_{Ay}^2 + I_{By}^2}] \times \text{----------} (14)$$

In equations (13) and (14), all terms are separated except the crosses terms which are assigned to each user according to the separated terms ratio on the same transmission line (not based on sharing on other lines).

Define $M_A$and $M_B$such that

$$P_{loss,A} = M_A \times R \text{----------} (15)$$
$$P_{loss,B} = M_B \times R \text{----------} (16)$$

The squared values of currents in fractions in equations (13) and (14) are used instead of the normal values as the transmission loss is proportional to the current squared and the separable terms of the expressions are already squared. So, when assigning each contributor its share of the cross term, it is logical to use the other squared terms in the expression rather than their normal values. In addition, using normal values instead of squared values of currents has been conducted on many test networks. The resultsmay yield negative allocations which may be interpreted as cross subsidy.

More generally, for any system, real and reactive power loss allocations can be determined through the following procedure:

1. From a constrained schedule calculations in a pool system where all participants deliver their shares of the market, each generator injects its dispatched real power and each load consumes its declared quantity (base case), calculate all currents in all branches of the network

$$\bar{I}_k = I_{kx} + jI_{ky} \qquad k = 1,\ldots\ldots\ldots NB \text{----------} (17)$$

Where,
NB = total number of branches
I_{kx} = real part of the complex current
I_{ky} = imaginary part of the complex current

2. With theparticipant of interest (generator or load) Tiinactivated, re-dispatch the system using OPF (or anyredispatchingscheme such as proportional dispatch) andcalculate resultedcurrents in all branches

$$\bar{I}_k^{Ti} = I_{kx}^{Ti} + jI_{ky}^{Ti} \; i = 1,\ldots\ldots\ldots NT \text{---------} (18)$$

Where

NT = total number of participants (generators andloads)

Load inactivation means disconnecting it, while fora generator it means resetting its real power output. In a pool-based market, when a generator real power is taken off or a load is disconnected from the network, the new system is re-dispatched. So, the marginal generator of the re-dispatched system makes up the real power shortage due to the loss of the real power output of generator *I* in this step. Also, it is the marginal generator that needs to reduce its output when a load is disconnected. In this step, we keep generator(or groups of generators under the same entity *i*) active with zero real power output while its reactive power is dispatched according to OPF. This ensures convergent solution, especially for the Must-Run generators. It is assumed that each generator submits its bids of real and reactive power to the system operator. It is also assumed that both bids are quadratic functions, ($b0$ + $b1p$ + $b2p2$) for real power and ($c0$ + $c1q$ + $c2q2$) for reactive power, with the reactive power cost being 10% of that of real power and the constant term of reactive power cost is zero. Other constructions of reactive power cost are out of the scope of this paper.

3. The contribution of each participant *Ti* in a branch current flow is equal to the corresponding current flow difference between the base case and that when *Ti* is inactive;

$$\bar{I}^{Ti}_{k,con\,t} = \bar{I}_k - \bar{I}^{Ti}_k, \qquad k = 1, \ldots\ldots\ldots\ NB \text{----------} \ (19)$$

Logically, the changes of current flows, both magnitude and direction, in branches due to system re-dispatch without a load or a generator is due to the effect of that load or generator. Inother words, the existence of a load or a generator inthe system creates these changes, so, it does make sense to say that these changes should be attributed to that load or generator. The simulation results presented in this paper and other results through simulations do support the justification of this idea as they are consistent with engineering experience.

4. The nonlinearity of the network due to the interactionbetween loads and generators when they are run at the same time makes the sum of currents obtained in step 3 does not matchthose in step 1, i.e.

$$\bar{I}_k \neq \sum_{i=1}^{NT} \bar{I}^{Ti}_{k,cont}, k = 1, \ldots\ldots\ldots\ NB \text{----------} \ (20)$$

So, Current Adjustment Factors (CAF's) are introduced toadjust theobtained currents in step3 as follows

$$CAF_k = \frac{\bar{I}_k}{\sum_{i=1}^{NT} \bar{I}^{Ti}_{k,cont}}, \ k = 1, \ldots\ldots\ldots\ NB \text{---------} \ (21)$$

Where,

CAF = Current Adjustment Factors matrixof kelements. *CAF*is generally a complex matrix which isexpected since the nonlinearity of the system is due to real and imaginary factors interactions.

5.Calculate the new adjusted currents

$$\bar{I}^{Ti}_{k,Adj} = CAF_k \times I^{Ti}_{k,cont}, \ k = 1, \ldots\ldots\ldots\ NB \text{---------} \ (22)$$

6. Calculate the real losses allocations for each participant, P^{Ti}_{loss}, as follows

$$P^{Ti}_{loss} = \sum_{k=1}^{NB} R_k \times \left\{\left[(I^{Ti}_{kx,Adj})^2 + (I^{Ti}_{ky,Adj})^2 + C^{Re}_k \times \frac{(I^{Ti}_{kx,Adj})2}{I^{Re,sum}_k} + C^{Im}_k \times \frac{(I^{Ti}_{ky,Adj})2}{I^{Im,sum}_k}\right]\right\} \text{----------} (23)$$

Where,

R_k= resistance of branch k.

$I^{Ti}_{kx,Adj}$ = real part of$I^{Ti}_{k,Adj}$.

$I^{Ti}_{ky,Adj}$ = imaginary part of $I^{Ti}_{k,Adj}$.

$I^{Re,sum}_k = \sum_{i=1}^{NT} (I^{Ti}_{kx,Adj})^2$

$I^{Im,sum}_k = \sum_{i=1}^{NT} (I^{Ti}_{kx,Adj})^2$

$C^{Re}_k = \sum_{i=1}^{NT} \sum_{\substack{i=1 \\ i \neq j}}^{NT} I^{Ti}_{kx,Adj} \times I^{Tj}_{kx,Adj}$

$$C^{Im}_k = \sum_{i=1}^{NT} \sum_{\substack{i=1 \\ i \neq j}}^{NT} I^{Ti}_{ky,Adj} \times I^{Tj}_{ky,Adj}$$

III. CASE STUDIES

The proposed methods is appliedon the IEEE-14-bus systemto allocate participants their shares of losses. The line data, load data, and generator outputs are shown in Table II.

Table-1IEEE-14 bus system line data

S.NO	SB	RB	R	X	B/2	TAPPPINGS	LINE CAPACITY
1	**1**	**2**	**0.01938**	**0.05917**	**0.0528**	**1**	**200**
2	**1**	**5**	**0.05403**	**0.22304**	**0.0492**	**1**	**110**
3	**2**	**3**	**0.04699**	**0.19797**	**0.0438**	**1**	**110**
4	**2**	**4**	**0.05811**	**0.17632**	**0.034**	**1**	**80**
5	**2**	**5**	**0.05695**	**0.17388**	**0.0346**	**1**	**70**
6	**3**	**4**	**0.06701**	**0.17103**	**0.0128**	**1**	**50**
7	**4**	**5**	**0.01335**	**0.04211**	**0**	**1**	**100**
8	**4**	**7**	**0**	**0.20912**	**0**	**0.978**	**50**
9	**4**	**9**	**0**	**0.55618**	**0**	**0.969**	**50**
10	**5**	**6**	**0**	**0.25202**	**0**	**0.932**	**70**
11	**6**	**11**	**0.09498**	**0.1989**	**0**	**1**	**30**
12	**6**	**12**	**0.12291**	**0.25581**	**0**	**1**	**30**
13	**6**	**13**	**0.06615**	**0.13027**	**0**	**1**	**50**
14	**7**	**8**	**0**	**0.17615**	**0**	**1**	**60**
15	**7**	**9**	**0**	**0.11001**	**0**	**1**	**60**
16	**9**	**10**	**0.03181**	**0.0845**	**0**	**1**	**50**
17	**9**	**14**	**0.12711**	**0.27038**	**0**	**1**	**50**
18	**10**	**11**	**0.08205**	**0.19207**	**0**	**1**	**50**
19	**12**	**13**	**0.22092**	**0.19988**	**0**	**1**	**50**
20	**13**	**14**	**0.17093**	**0.34802**	**0**	**1**	**50**

A case study of IEEE-14 Bus system is illustrated to test the performance of the three methodologies which is discussed in section II. The layout of IEEE- 14 bus system has 14 nodes and 20 branches and consists of one slack bus, 4 PV buses and 9 load buses and is represented by bus power injections, line power flows and line power losses obtained from the base case solution i.e. Newton Raphson method

Table-2IEEE-14 bus system load data

S.NO	BUS TYPE	VOLTAGE	ANGLE	PL	QL	PG	QG
1	1	1.06	0	0	0	232.2	-23.26
2	2	1.045	0	21.7	12.7	40	32.223
3	2	1.01	0	94.2	19	0	0
4	0	1	0	47.8	-3.9	0	0
5	0	1	0	7.6	1.6	0	0
6	2	1.07	0	11.2	7.5	0	0
7	0	1	0	0	0	0	0
8	2	1.09	0	0	0	0	0
9	0	1	0	29.5	16.6	0	0
10	0	1	0	9	5.8	0	0
11	0	1	0	3.5	1.8	0	0
12	0	1	0	6.1	1.6	0	0
13	0	1	0	13.5	5.8	0	0
14	0	1	0	14.9	5	0	0

A. PERFORMANCE INDEX

We would like to get some measures as to how much a particular outage might affect the power system. The idea of a performance index seems to fulfill this need.

The definition for the overload performance index(PI) is as follows

$PI_{(ij)}=\sum_k \left(\frac{P_{ij}}{Pmax_{ij}}\right)^2$

Where k = no of lines

TABLE-3

S.NO	Line between buses	Line flow(mw)	Line capacity	Performance index	Rank
1	1-2	158.46	200	0.7923	1
2	1-5	75.641	110	0.6876	3
3	2-3	73.136	110	0.6648	4
4	2-4	56.270	80	0.7033	2
5	2-5	41.566	70	0.5938	7
6	3-4	23.560	50	0.4718	10
7	4-5	62.966	100	0.62966	6
8	4-7	29.887	50	0.58704	8
9	4-9	16.052	50	0.32104	12
10	5-6	460188	70	0.6598	5
11	6-11	8.337	30	0.2779	14
12	6-12	8.203	30	0.2734	15
13	6-13	19.241	50	0.3848	11
14	7-8	17.750	60	0.2958	13
15	7-9	28.864	60	0.48106	9
16	9-10	6.511	50	0.13022	17
17	9-14	9.994	50	0.19988	16
18	10-11	4.269	50	0.08538	19
19	12-13	1.809	50	0.03618	20
20	13-14	6.001	50	0.12002	18

NOTE: A fault is created by removing line 2-4 which is given as rank 4 in the performance index table iii. If the line rank is selected below 4 congestion will comes into picture. In that case congestion is removed by using appropriate methods and solve for loss allocation by using following methods.

B. COMPARISION OF LOSSES

1. pro rata method loss results:

- Loss allocation is based on the load real power levels regardless of its relative location within the network.
- Losses allocated to generators compared to loads must be specified arbitrarily
- Always positive.
- Independent of the choice of the slack bus.

Table-4

Bus no	Pro rata (under normal case)	Pro rata (under fault case)
1	0	0
2	1.1204	1.2929
3	4.8638	5.6124
4	2.4681	2.8479
5	0.3924	0.4528
6	0.5783	0.6673
7	0	0
8	0	0
9	1.5232	1.7576
10	0.4647	0.5362
11	0.1807	0.2085

12	**0.3150**	**0.3634**
13	**0.6970**	**0.8043**
14	**0.7693**	**0.8877**
TOTAL	**13.738**	**15.431**

2 Post stampage method loss results:

- Loss allocation is based on the bus generation or load real power levels regardless of its relative location within the network.
- Losses allocated to generators compared to loads must be specified arbitrarily
- Always positive.

Table-5

Normal case				**Fault case**		
Bus no	**Post stampage L**	**Post stampage G**	**Total**	**Post stampage L**	**Post stampage G**	**Total**
1	**0**	**5.8630**	**5.8630**	**0**	**6.1847**	**6.1847**
2	**0.5758**	**1.0100**	**1.5858**	**0.6464**	**1.1338**	**1.7802**
3	**2.4998**	**0**	**2.4998**	**2.8062**	**0**	**2.8062**
4	**1.2685**	**0**	**1.2685**	**1.4239**	**0**	**1.4239**
5	**0.2017**	**0**	**0.2017**	**0.2264**	**0**	**0.2264**
6	**0.2972**	**0**	**0.2972**	**0.3336**	**0**	**0.3336**
7	**0**	**0**	**0**	**0**	**0**	**0**
8	**0**	**0**	**0**	**0**	**0**	**0**
9	**0.7828**	**0**	**0.7828**	**0.8788**	**0**	**0.8788**
10	**0.2388**	**0**	**0.2388**	**0.2681**	**0**	**0.2681**
11	**0.0929**	**0**	**0.0929**	**0.1043**	**0**	**0.1043**
12	**0.1619**	**0**	**0.1619**	**0.1817**	**0**	**0.1817**
13	**0.3582**	**0**	**0.3582**	**0.4022**	**0**	**0.4022**
14	**0.3954**	**0**	**0.3954**	**0.4439**	**0**	**0.4439**
TOTAL			**13.738**			**15.431**

3 *CAF method loss results*:

- Loss allocation is based on the actual network utilization by individual participants.
- No need for arbitrary sharing percentage.
- Always positive

Table-6

Normal case				**Fault case**		
Bus no	**CAF L**	**CAF G**	**Total**	**CAF L**	**CAF G**	**Total**
1	**0**	**3.509**	**3.509**	**0**	**3.5737**	**3.5737**
2	**0.0608**	**0.83**	**0.8908**	**0.9994**	**1.103**	**2.103**
3	**1.8997**	**0**	**1.8997**	**1.9866**	**0**	**1.9866**
4	**0.567**	**0**	**0.567**	**0.8794**	**0**	**0.8794**
5	**4.4914**	**0**	**4.4914**	**4.206**	**0**	**4.206**
6	**0.6879**	**0**	**0.6876**	**0.7978**	**0**	**0.7978**
7	**0**	**0**	**0**	**0**	**0**	**0**
8	**0**	**0**	**0**	**0**	**0**	**0**
9	**0.9264**	**0**	**0.9264**	**0.9479**	**0**	**0.9479**
10	**0.0093**	**0**	**0.0093**	**0.0075**	**0**	**0.0075**
11	**0.0273**	**0**	**0.0273**	**0.0615**	**0**	**0.0615**
12	**0.002**	**0**	**0.002**	**0.0621**	**0**	**0.0621**
13	**0.003**	**0**	**0.003**	**0.0692**	**0**	**0.0692**
14	**0.7242**	**0**	**0.7242**	**0.7364**	**0**	**0.7363**
TOTAL			**13.738**			**15.431**

IV. CONCLUSION

The required power to compensate losses should be allocated to all participants fairly according to their actual use of the network. The actual use of the system mainly depends on two factors; the nature of the traded commodity in electricity markets, which is until now real power, and the relative locations of participants within the network. This paper contributes towards the competitive electricity markets. In all the methods discussed in this paper, pro rata allocates losses only to consumers proportionally with the level of energy consumption but not to producers, P.S method looks simple andtransparent to implement it does not take the network in to consideration and allocates the fixed real power losses to the participants irrespective of distancebetween the generators and loads, and Current Adjustment Factors (CAFs) method, allocate losses to each network user's. From the comparison of the results on IEEE 14 bus system,it has been recognised that former two methods have a crucial problem in allocating a fair transmission price in deregulated power system. The later method can fairly allocate losses to network users. Though it has been discussed about real power allocation,it can also allocate both real and reactive power simultaneously without any additional calculations except the substitution of reactance's instead of resistances.

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