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Restructured Power System: Transmission Loss Allocation between Generators and Loads Using Innovative Mathematical Approach

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Abstract: *The former epoch has seen a melodramatic transformation in the way in which the electrical power industry is organized. In a restructured atmosphere, loss separation in the transmission lines is one of the most significant issues, so a Transmission Loss Allocation (TLA) scheme for generator and load nodes is presented by allowing mathematical formulation by using power flow at node and line. The proposed loss separation technique is also one of useful approach to evaluate grid use cost for separate transaction member in the deregulated electrical market. The main target of this paper is transmission loss allocation procedures for active power transmission network losses and provides a comparison. Algorithms have been developed and implemented for proposed loss separation method. Also proposed power flow method used to discover the network usage by every participant so as to separate the transmission charges and losses. Additionally, in this paper, using the load flow calculations, the part of every bus in the power losses is found by the N-R method. This proposed methodology is illustrated on sample IEEE 14-bus system and IEEE- 57 bus system. The simulation results obtained from the MATLAB program are analyzed.*

Key words: *Restructuring or Reform or Deregulation, Loss Separation, Circulating Current, load loss, Power Flow*

I. INTRODUCTION

The restructuring of electric power systems has resulted in market-based competition by creating an open market environment [1]. Such changes in the electric power industry have created a movement from a government-based market toward a private and competitive market which, in turn, leads to lower price and more services [1-2]. In a restructured power system, the generation and distribution parts which are the sellers and buyers of the generated power respectively should have a fair access to the transmission system for maintaining an effective operation [2-3]. Transmitting the electric power through the power lines imposes the costs of voltage and frequency regulations, maintaining the power system stability and so on. Besides, a significant percent of the power losses are pertained to the transmission systems which should be carefully calculated and allocated to the agents in the power market [12].

The free access of the all agencies to the transmission system and repaying the network costs by them, it is necessary to determine the portion of each generators or consumers from the power losses in the network [13]. Usually 4% to 8% of the generated active power by the power plants is lost in the transmission system which is highly depended on the level and the distance between the generation and consumption areas and is economically consequential [4]. In electricity market money flow is based on agreements among consumers and producers. But the power flow is based on Kirchhoff's laws. It is complicated task to identify the supplier for a particular customer because all transactions have to share on same transmission network simultaneously [4-5]. So the problem is that 'which generators are supplying this load? Which generator or load is producing loss of this transmission line? And also who should pay for their individual losses? [6]. In open access transmission grid it is required to follow the network flows and losses in order to remunerate the network owners in a transparent and fair way.

Based on different methodologies, some of technique has been announced for transmission line loss separation [8]. Established on a solved power flow, a technique uses Z-bus to find the loss components linked with different buses [10], whereas in [11], a modified Y-bus is used to find the association among the branch currents and the load/generator current injections permitting the power loss of respective line to be expressed in terms of current injection.

This paper proposed a method to separate losses for restructured power system based on circulating current method with the help and some modification in N-R method. This method also helps for the ideal location and rating of compensation devices so that we obtain very good performance of the line with minimum losses [4, 9]. For that, basic concepts can be used to solve particular problem means this paper gives the solution of loss separation of each line, which is produced by each generators and each loads. Test results demonstrate the main contribution of the proposed method [14].

II. BASIC CONCEPTS OF NEW APPROACH

After two or more generator sets are run in parallel, a current may mingle between the generators. This current will exist when the internal voltage generated by apiece generator is slightly different; current will flow out the line leads of one generator, through the paralleling bus and into the second generator. It does not flow into the load, this current, called "circulating current". A loss produce due to circulating current is called circulating current loss. When circulating currents pass through the generator coils, these currents heat the coils the same way as does the load current, and

circulating currents are superimposed on the load current passing through the circuit breaker, circulating currents can cause a breaker to trip as the breaker could notice an actual ampere overload. So the circulating current is also important for consideration for loss allocation method [15].
Transmission loss is decomposed into three modules. The first is due to current flow from generators to loads. Next is due to the circulating current between generators. Last is due to network structure.

Consider the AC simple system of Fig. 1. It is similar to the DC system except that line impedances, voltages and currents are all complex quantities. Also, the difference between the voltages of the source nodes 1 and 2, V_1-V_2, is a complex quantity with a magnitude of ΔV and angle δ, i.e. $V_1 - V_2 = \Delta V \angle\delta$

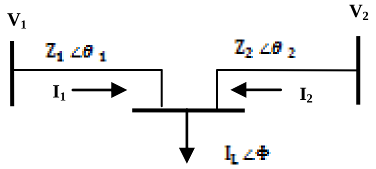

Fig. 1: Simple 3 bus AC system

The same steps follow as in the case of DC system, the total power loss in the transmission lines of the AC system can be proved to be as follows.

$$P_t^{Loss} = \frac{|I_L|^2(Z_1^2.Z_2 .\cos(\theta_2)+Z_1 Z_2^2.\cos(\theta_1))}{|Z_1+Z_2|^2} + \frac{|\Delta V|^2.(r_1+r_2)}{|Z_1+Z_2|^2} + \frac{2|\Delta V||I_L||z_1.z_2|}{|Z_1+Z_2|^2}. \sin(\emptyset - \delta). \sin(\theta_1 - \theta_2) \quad (1)$$

The first term of equation (1) is the load loss, and the second term is show the circulating current loss. The third term is due to the difference of X/R ratio of the two lines and can be considered as a sort of impedance mismatch loss. Also, the presence of transformers which have X/R ratio larger than that of the lines gives rise to this term, if the two lines have the same X/R ratio, i.e. θ1 = θ2 = θ, the total loss becomes closely like the case of a DC system.

$$P_t^{Loss} = \frac{|I_L|^2|Z_1.Z_2|.\cos(\theta)}{|Z_1+Z_2|} + \frac{|V_1-V_2|^2.(r_1+r_2)}{|Z_1+Z_2|^2}$$

(2)

The first term of equation (2) determines the load loss and load loss can be determined by short-circuiting the all the sources and letting the load currents alone flow through the network and the second term determines the circulating current loss. It can be calculated by simply letting the load current equal to zero.

III. MATHEMATICAL MODEL

Transmissions losses are divided in two parts are following:

3.1 Load Loss:

Loss due to load currents are obtained by assuming that all generators act as ideal voltage sources with no circulating currents between them. In such a case, generation nodes are short circuited and the load nodes are considered as current sources [4]. Considering the node equations of the power system, and by proper partitioning of Y_{BUS}, the power system equations can be written as:

$$I = Y\,V \quad (3)$$

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (4)$$

I_G, V_G, I_L and V_L are the current and voltage vectors for generation and load nodes, respectively. Y_{GG} is the self-admittance matrix of generator nodes, Y_{GL} is the mutual admittance matrix between generation and load nodes, Y_{LG} is the mutual admittance matrix between load and generation nodes, Y_{LL} and is the self-admittance matrix of load nodes.

$$I_G = Y_{GG} V_G + Y_{GL} V_L \quad (5)$$

$$I_L = Y_{LG} V_G + Y_{LL} V_L \quad (6)$$

To determine the current flow through branches due to loads are determined while the voltages at generation nodes are set to zero in (6). In this condition, the load node voltages will be

$V_L = Z_{LL} I_L$

(7) With N_G the number of generation nodes and N_L the number of load nodes, generation node voltages can also be expressed as

$$V_G = 0_{NG \times NL}\, I_L \quad (8)$$

The branch currents I_b can be calculated as follows:

$$I_b = [Y_{br}]\ [A^T]\, V_{bus} \quad (9)$$

Where Y_b is the branch admittance matrix, which is a diagonal matrix with its main diagonal elements are the branch admittances. A^T is transpose of the branch to node incidence matrix. To decompose the branch current into its components caused by individual load currents, the current column is replaced by diag (I_L), which is a diagonal matrix having load currents as its main diagonal elements

$$[I_{br}^{L}] = K.\,\mathrm{diag}[I_L] \quad (10)$$

Where, $K = [Y_{br}]\ [A^T] \begin{bmatrix} 0_{N_G \times N_{Load}} \\ Y_{LL}^{-1} \end{bmatrix}$

K is the load current distribution factors matrix, where k_{br}^{L} is the fraction of the current of load L that flows through branch b, that is, $I_{br}^{L} = k_{br}^{L} . I_i$

$[I_{br}^{L}]$ is $N_{br} \times N_{Load}$ matrix with its ij^{th} element equals the current flowing in the i^{th} branch due to the current injection of the j^{th} load. The summation of each row gives the total branch current due to all loads. Using this total branch current and the resistance of the line, the power loss through this line can be determined.

Using the partial currents, elements of the row, the loss due each load through this line can be determined using the equation of loss allocation [5].

$$\Delta P_{ij} = r_i\ [I_{br_{ij}}^{L}] \bullet [I_i] \quad (11)$$

Where,

ΔP_{ij} =Power loss in branch i due to load at node j,

$I_{br\,ij}^{L}$ = Current through branch i due load at node j,

I_i = Current through branch i due to all loads,

$\bullet$ = the dot product of a vector defined as follows:

$$I_{br}^{L} \bullet I_i = \Re(I_{br}^{L})\Re(I_i) + \Im(I_{br}^{L})\Im(I_i)$$

$\Re$ = real part of an expression

$\Im$ = imaginary part of an expression

3.2 Loss Due To Difference In Voltage at Generation Point:

Another loss can be obtained by voltage difference at generator node during operating condition which is known as circulating current loss. The generator circulating current is obtained by setting the load currents to zero, and the generator voltage as obtained the from power flow solution. The generator circulating current is calculated as follows.

$$[I_G^{cir}] = [[Y_{GG}]-[Y_{GL}].\,[Y_{LL}]^{-1}.\,[Y_{LG}]][V_G] \quad (12)$$

The voltage vector of load nodes is determined as,

$$[V_L] = -\,[Y_{LL}]^{-1}.\,[Y_{LG}].\,[V_G] \quad (13)$$

The node voltage vector in this case can be written in terms of the generator circulating current as,

$$\begin{bmatrix} V_G \\ V_L \end{bmatrix} = \begin{bmatrix} Z_{GG} \\ -Y_{LL}^{-1}.Y_{LG}.Z_{GG} \end{bmatrix} [I_G^{cir}] \quad (14)$$

So,

$$[Z_{GG}] = [[Y_{GG}]-[Y_{GL}]\,[Y_{LL}]^{-1}.[Y_{LG}]]^{-1} \quad (15)$$

The branch current due to the generators' circulating current can thus be obtained as follows.

$$[I_{br}^{cir}] = [Y_{br}][A^T] \begin{bmatrix} Z_{GG} \\ -Y_{LL}^{-1}.Y_{LG}.Z_{GG} \end{bmatrix} .\mathrm{diag}[I_G^{cir}] \quad (16)$$

$[I_{br}^{cir}]$ is $N_{br} \times N_G$ matrix with its ij^{th} element equals the current flowing in the i^{th} branch due to the circulating current of j^{th} generator. The summation of each row equals the total current flowing in the branch due to the circulating current of the generators.

The circulating current losses in each branch due to each generator can be calculated the same way as for the load losses using (11).

$$\Delta P_{ij} = r_i\ [I_{br}^{cir}] \bullet [I_i] \quad (17)$$

Where,

ΔP_{ij} = Power loss in branch i due to load at node j,

I_{br}^{cir} = Branch current due to the generators' circulating current,

I_i = Current through branch i due to all loads,

$\bullet$ = Dot product of a vector defined as follows:

$$I_{br}^{cir} \bullet I_i = \Re(I_{br}^{cir})\Re(I_i) + \Im(I_{br}^{cir})\Im(I_i)$$

$\Re$ = real part of an expression

$\Im$ = imaginary part of an expression

IV. CASE STUDY

Figure 2 shows the single line diagram of IEEE 14-bus System. The systems have loads on 13 buses, generations on 2 buses and synchronous condenser on 3 buses. Bus number 3, 6, 8 has both load and synchronous condenser.

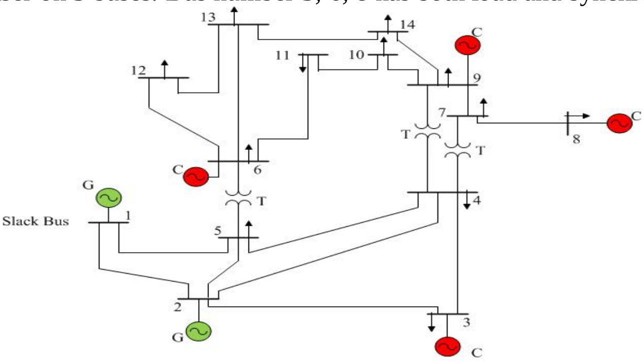

Figure 2: IEEE 14 Bus Systems Single Line Diagram

After simulation by using proposed approach with MATLAB programming, the total loss according to N-R method is 34.227MW. On the other by using new technique for transmission loss allocation first calculated load loss; it is 23.628 MW and circulating current loss 10.5998 MW. This two loss gives total system loss is 34.227 MW shown in below Table: 1.The total losses obtain from this method is same as total loss obtain by N-R method, which proofs the accuracy of this method.

Bus	**Load (MW)**	**Total Loss (MW)**
Load 3	5.7696	23.6288
Load 4	3.2298	
Load 5	1.8767	
Load 6	3.3091	
Load 7	1.3082	
Load 8	1.3387	
Load 9	1.8414	
Load 10	1.0909	
Load 11	0.6670	
Load 12	1.2105	
Load 13	0.9428	
Load 14	1.0442	
Generator 1	5.4269	10.5732
Generator 2	5.1463	
Total Loss		**34.2020**

Table 1: Loss Separated by Each Load and Generator

P_{G2}	Total Loss (MW) According to N-R Load Flow Method	Load loss (MW) P_L	Cir. Current Loss (MW) P_C	Total Loss (MW) P_L+P_C	Circulating Power $G_1 \rightarrow G_2$ (MW)	Circulating Power $G_2 \rightarrow G_1$ (MW)
80	38.212	25.3101	12.8573	38.167	226.0724	226.0724
85	37.467	25.2705	12.2095	37.480	220.0911	-207.9081
90	34.202	23.628	10.5998	34.227	204.4693	-193.8961
95	37.362	26.5380	11.0815	37.619	209.2316	-209.2316

Table 2: Different Losses for Different Outputs of Generator 2

In the table 2 shows the different loss for different output of generator 2, at that time load keep constant. In the first set of cases the generation at bus 2 is changed while load is kept constant. The change in bus 2 generation is made according to the calculated load loss, circulating current loss and circulating power between two generators. From table 2 it is clear that the load loss is constant and virtually independent of the generator outputs, which approve the validity of this method.

The variation of circulating current loss and circulating power both with changes with generation. The first row of table 2, when P_{G2} is 80 MW the load loss is 25.3101 MW and circulating current loss is 12.8573 MW and circulating power is 226.0724 from generator G_1 to G_2. P_{G2} is increase up to 90 MW, at that time circulating power is 204.4693 circulate from bus 1 to 2. When P_{G2} is 90 MW at that time minimum load loss which is 23.628 MW and circulating current loss will be occurs is 10.5998 MW. Total losses obtain from this method is same as the N-R method, which again proofs the accuracy of this method. Table 1 show the loss allocated by each load and generator separately.

Here, on IEEE 14 bus system provide compensation on bus no. 3, 6, 8 and 9 with the value of 24, 19, 15 and 60 MVAR respectively, and again simulate we clearly observe that from table total active power loss is 46.069 MW which mean system is poor but when with compensated system the active power loss 34.202 MW shown in above table 3, means active power loss is reduce as compare with without compensated line and also reduce generator, load loss, improve voltage profile and system is more stable as well in compensated line.

	Without Compensation	**With Compensation**
Generator Loss (MW)	11.213	10.5732
Load Loss (MW)	34.856	23.6288
Total Active Power Loss (MW)	46.069	34.202

Table 3: IEEE 14- Bus System Generator and Load Loss

Without Compensation				**With Compensation**			
Bus No.	Voltage Profile	Bus No.	Voltage Profile	Bus No.	Voltage Profile	Bus No.	Voltage Profile
1	1.000	8	0.713	1	1.000	8	0.982
2	0.995	9	0.738	2	0.995	9	1.002
3	0.863	10	0.729	3	0.935	10	0.995
4	0.833	11	0.732	4	0.929	11	0.979
5	0.854	12	0.722	5	0.939	12	0.956
6	0.745	13	0.730	6	0.968	13	0.965
7	0.743	14	0.720	7	0.975	14	0.979

Table 4: IEEE 14-Bus System With and Without Compensation

Figure 3 shows the single line diagram of IEEE 57-bus System. The systems have loads on 13 buses, generations on 4 buses and synchronous condenser on 3 buses. Bus number 3, 6, 8 has both load and synchronous condenser.

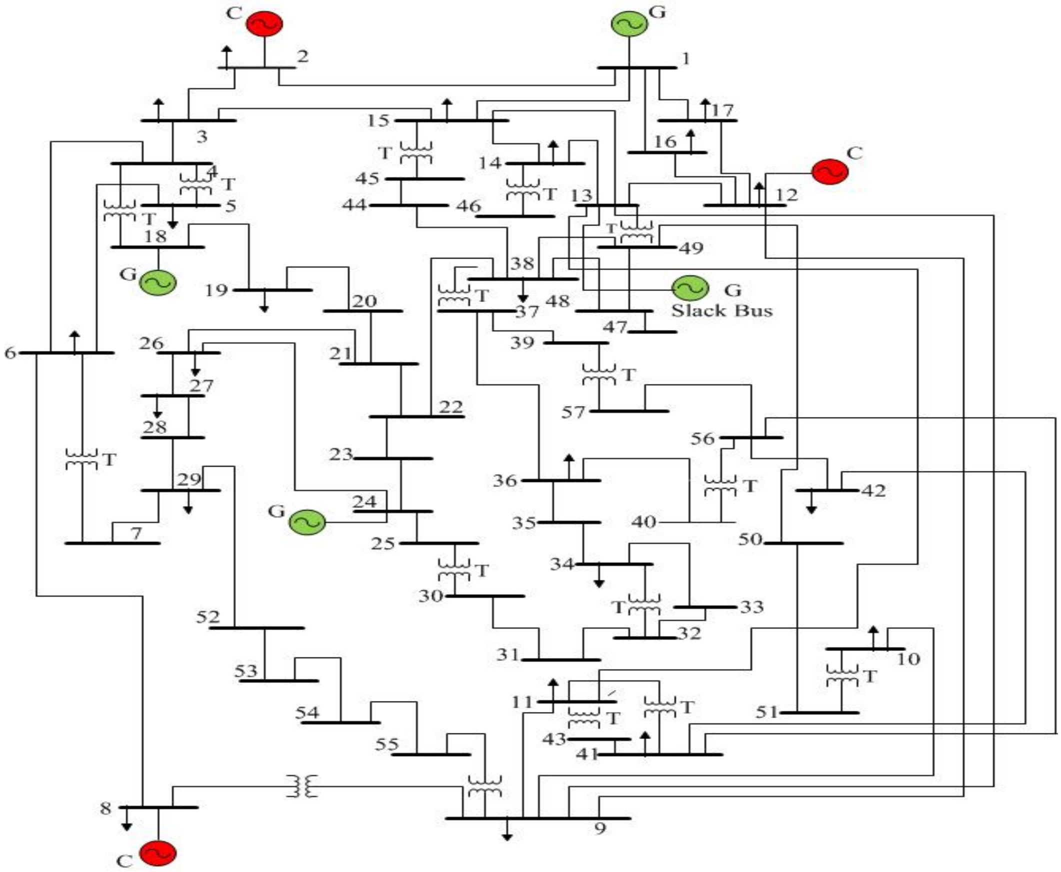

Figure 3: IEEE 57 Bus Systems Single Line Diagram

For find out the strength of MATLAB programming of new approach again first determine total loss according to N-R method, it is active power loss is 82.0155 MW and reactive power loss is 127.003 MW. The loss separated by each load and generator loss separately which are 59.8108 MW and 22.2052 MW respectively and its total loss is 82.0155 MW. The total loss obtain from this method is same as total loss obtain by N-R method, which again proofs the accuracy of this method with more complex power system. By using this method also find out the economic operation of power station same as find out in IEEE 14 bus system.

Now, compare IEEE 57 bus system results with and without compensation and observes the load loss, generator loss, voltage profile and line losses through proposed method, which results shown in below table 5. Compensation provide on bus no. 2, 8 and 12 with the value of 50, 50 and 45 MVAR respectively.

Without Compensation				**With Compensation**			
Bus No.	Voltage Profile	Bus No.	Voltage Profile	Bus No.	Voltage Profile	Bus No.	Voltage Profile
1	1.000	29	1.205	1	1.000	29	1.052
2	1.217	30	1.209	2	1.076	30	1.010
3	1.294	31	1.129	3	1.073	31	1.030
4	1.279	32	1.136	4	1.035	32	1.041
5	1.154	33	1.136	5	1.081	33	1.042
6	1.119	34	0.935	6	1.050	34	0.948
7	1.204	35	0.919	7	1.060	35	0.931
8	1.219	36	0.908	8	1.090	36	0.920
9	0.943	37	0.920	9	0.997	37	0.931
10	0.964	38	0.992	10	1.017	38	1.002
11	0.918	39	0.921	11	0.943	39	0.932
12	0.975	40	0.911	12	1.030	40	0.922
13	1.000	41	0.957	13	1.000	41	0.981
14	1.030	42	0.955	14	1.038	42	0.977
15	1.014	43	0.959	15	1.023	43	0.984
16	0.966	44	0.987	16	1.009	44	0.998
17	0.985	45	1.045	17	1.035	45	1.055
18	1.000	46	1.017	18	1.000	46	1.026
19	1.087	47	1.006	19	1.091	47	1.015
20	1.092	48	1.007	20	1.098	48	1.017
21	1.011	49	1.014	21	1.019	49	1.024
22	1.000	50	1.001	22	1.009	50	1.016
23	1.001	51	0.997	23	1.007	51	1.020
24	0.987	52	1.154	24	0.987	52	1.285
25	1.252	53	1.103	25	1.054	53	1.224
26	0.985	54	1.055	26	1.050	54	1.150
27	1.079	55	1.014	27	1.199	55	1.083
28	1.155	56	0.952	28	1.091	56	0.973
		57	0.947			57	0.967

Table 5: IEEE 57-Bus System With and Without Compensation

	Without Compensation	**With Compensation**
Generator Loss (MW)	25.5155	22.2052
Load Loss (MW)	69.3858	59.8108
Total Active Power Loss (MW)	94.9013	82.0155

Table 6: IEEE 57 Buses - System With and Without Compensation

During this time voltage profile of the system are also improved means increasing power quality, individual bus voltage profile given in table 5. In without compensated line from the table 6 total active power loss is 94.9013 MW which means system is poor but when provide the compensation on line the system active power loss in table 6 is 82.0125 MW, means active power loss is diminish as compare with without compensated line and also reduce generator loss, load loss, and system is more stable as well in compensated line.

V. CONCLUSION

In this paper proposed methodology tested on IEEE 14 and 57 bus system and result compared with N-R method. The advantages of this approach are finding the load losses and circulating current losses separately, and separated loss in between particular loads and generators as well as determine the proper location of compensating device on the system. This proposed method is more reliable, more accurate, unpretentious, sensitive and more flexible, which is based on solves load flow and network parameter. This method is also used for calculate circulating power between all generators. This methodology provides better reliability and no negative loss allocation for generators or loads.

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