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RESEARCH ARTICLE

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An alternative algorithm for solving generation-to-load matching and loss allocation problems

Akintunde S. Alayande[1] | **Adisa A. Jimoh**[1] | **Adedayo A. Yusuff**[2]

[1] Department of Electrical Engineering, Faculty of Engineering and the Built Environment, Tshwane University of Technology, Private Bag X680, Pretoria 0001, Staatsartillerie Road, Pretoria West, South Africa

[2] Department of Electrical and Mining Engineering, University of South Africa, Florida Campus, Pretoria, South Africa

Correspondence
Akintunde S. Alayande, Department of Electrical Engineering, Faculty of Engineering and the Built Environment, Tshwane University of Technology, Private Bag X680, Pretoria 0001, Staatsartillerie Road, Pretoria West, South Africa.
Email: aalayande@unilag.edu.ng

Summary

This paper presents an alternative approach of Inherent Structural Characteristics Theory (ISCT), for solving loss allocation to network participants as well as generation-to-load matching problems in a deregulated environment. The mathematical formulations of ISCT, based on the fundamental circuit theory laws, are revisited. A Generation-to-Load Allocation Coefficient (GLAC) matrix for solving generation-to-load allocation and network loss allocation to load problems, for efficient transmission pricing, is formulated. The allocation of real and reactive power contributions, by individual generator, required to serve the network demands is also determined on the basis of the GLAC matrix. Total network losses are determined and allocated to individual network loads based on GLAC matrix. The approach is demonstrated using the standard IEEE 30 bus network. The results obtained are compared with that obtained using graph theory approach based on the solved power flow. The comparison of the results shows that the ISCT approach is reasonable and it is a good signal, which could be useful for pricing of electricity by the market regulators.

KEYWORDS

circuit theory, generation-to-load matching, GLAC matrix, graph theory, Inherent Structural Characteristics Theory, transmission loss allocation

1 | INTRODUCTION

Electric power industry is being restructured globally, in recent times, with transmission open access being an essential part of the restructuring.[1,2] This transformation has brought up new challenges, which threatens, to a greater extent, the reliability of power system operations.[3,4] Such challenges include loss allocation issues, power-flow tracing problem, transmission pricing problem, network congestion management problem, ancillary services,[5] and decisions on the scheduling of generators to meet the network demands.[6,7] For the operation of the new restructured power networks to be efficient, in real-time power system operations, the existing generating resources need to be fairly traced[8] and the associated transmission costs transparently allocated to the network participants.[9,10] In solving a realistic scenario of allocation problems, there is the need to establish the amount of both real power and reactive power that each individual network

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LIST OF SYMBOLS AND ABBREVIATIONS: $P_{j \to k}$, Active power loss on the line connecting buses j and k; $P_{loss\,,\,i-j}$, Active transmission loss in the line $i-j$; D, Allocation factor matrix; Z, Bus impedance matrix of the network; I, Bus injected current; V, Complex bus voltage; V_i, Complex node voltages at bus i; V_j, Complex node voltages at bus j; $[S_{loss}]$, Complex power loss by the generators to meet the network power demands; $[S_{load}]$, Complex power received by the load; $[S_{gen}]$, Complex power supplied by the generators; $d^{-}(v_i)$, In-degree of bus i; ISCT, Inherent Structural Characteristics Theory; a_{ij}, $(i,j)^{th}$ entry in the adjacency; GLAC, Generation-to-Load Allocation Coefficient; Y_{ij}, Mutual branch admittance between buses i and j; NIM, network incidence matrix; Y, Network bus admittance matrix; n, Number of buses within the network

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generator is delivering to the loads within the network and the losses across each branch of the transmission network. Availability of this information helps in solving transmission pricing problems in a deregulated environment. The reactive power injection at some of the network buses also has greater influence on the allocation of the losses. This injection of reactive power to the network is often made possible by the network ancillary services and tends to minimize the network losses by maintaining an acceptable voltage limits.[5] These services can be provided either by the network generating units or through the use of transmission network components, which could be static VAR compensators or shunt capacitors located at few buses within the network.[11] Furthermore, the contribution of the individual generating company to consumers within the network, which is an important issue in the transmission service pricing, will be easily determined.[4] Moreover, in practical power systems, a substantial amount, which could be up to millions of dollars, is associated with the system losses. The main challenge here is the allocation of the costs, associated with these losses, to the market participants in a fair and transparent manner. Although actions caused by one participant may have an influence on the other participants since all the participants are in the same power network, the allocation of losses to the participants suppliers (generators) and consumers (loads) within the network may be treated separately on the basis of the network structural characteristics as dictated by Ohm's law.

Significant contributions have been made by power system engineers and researchers in finding an efficient approach to generator-to-load matching and loss allocation problems in recent times.[12–14] The pro rata approach, which is mainly dependent on the injected power at the buses, is discussed in previous studies.[13,15] However, it does not take into account the physical distribution of the network buses or topology of the system. This, therefore, limits its suitability for a transparent and more efficient allocation in practical power networks. Marginal approach has also been proposed.[16,17] It is based on a well-known incremental transmission loss coefficient, which depends on the influence of small change in the power injection to the network loss, and it is solely dependent on the slack bus within the network. However, several repetitive power-flow analyses need to be performed. Proportional sharing method with graph-theoretical approach and its application is demonstrated in the literature.[18,19] This approach assumes that power at nodal inflows is shared proportionally between the nodal outflows.[20] Previous studies have also proposed an approach called "Z-bus" and modified Z-bus allocation methods for loss allocation.[20–22] The formulation of the approach is based on complex network impedance and the nodal injections.[23] Although this method takes into consideration the locations of the buses within the network, it is not capable of providing the indication to individual market participants as regards the overall operational efficiency of the network usage. In addition, this method involves matrix inversion, which may require lots of computational effort in real-time power networks. Narimani et al,[24] proposed a game-theoretical approach is proposed. The approach is an acceptable and an independent solution tool that satisfies the individual network players. However, it is computationally demanding, as it requires handling a large amount of data for the solution of a single case in practical power systems. In another study,[25] optimization approach is considered with loading conditions of the system. Since the solutions to power system problems are not influenced by the network loading conditions,[26] the time required to obtain the results presented in this study[25] may be of significant value. This may take longer time in large practical networks. Other approaches to solving these problems have been reviewed in the work of Kazemi et al.[27] Ghofrani-Jahromi et al[28] proposed a circuit-based approach, which could be applied for loss allocation in real-time power network. However, this approach is based on the solved power flow, which may experience divergence of solution in most radial power networks.

Although different methods have been explored for solving allocation problems in the open literature, achievement of an efficient method of allocating the losses to the network participants still remains a greater challenge. This is why, in practice, it is often advisable for each restructuring model to choose a pricing scheme that best suits its market models on the basis of network structural characteristics. Unfortunately, this network characteristic inherent in the topological structure of power networks has not been holistically considered in the problem formulation. In this paper, a new computational algorithm, for quick solution to generation-to-load allocation and loss allocation problems, based on the network structural interconnections between the buses and their impedance values is suggested.

The contributions of the approach presented in this paper, to the active streams of research, are three folds. Firstly, it determines the contribution of individual generator to the network loads. It worth noting that the network generations required to supply the network loads and losses are not known beforehand but are determined through the approach of Inherent Structural Characteristics Theory (ISCT) based on the given network loads. This could be of utmost importance during transmission network expansion planning and operation stages. Secondly, the network losses are determined and allocated to loads in accordance to the GLAC matrix based on the ISCT. The merits of this information, if available, are two folds. Structurally, it could serve as a good locational signal, during the system design stage to know the strength of the load nodes and during critical network operations such as rerouting of power during critical outages. It could also be of help to the system operators in proper allocation of network losses to individual load node, which could be of great assistance in determining the charges for other utilities. Thirdly, the approach is simple, as it does not involve power-flow analysis but strictly follows the fundamental circuit laws on which power-flow formulation is based. Consequently, unnecessary repetitive iterations are avoided. This therefore makes this approach to have a significant amount of computational time saving, which significantly reduces the space required for storage in computer memory.

The remaining sections of the paper are structured as follows: Section 2 presents the theory of inherent structural characteristics from the first principle. Section 3 presents transmission loss formulations based on both the ISCT of power networks and conventional power-flow algorithm. In section 4, the mathematical derivations for the graph theory approach based on the solved power-flow are presented. Section 5 gives the results and their discussions while the concluding remark is presented in section 6.

2 | THE ISCT APPROACH

In this section, the inherent structural characteristics indices of power system networks, as given by the authors of reference,[29] are retraced and presented. This theory argues that it is possible to assess the inherent behaviour of any given electric power network based on the structural relationship between the voltages at the network nodes and the currents flowing through the links of the network. This inherent structural properties of power system network can be easily captured by the Y-bus matrix of the network as stated by Ohm's law

$$I = YV \tag{1}$$

where $Y = Z^{-1}$ is highly sparse as most of the buses within the network are not connected.

By considering the electrical distances between the generator and load nodes with proper partitioning based on the relative location of the generators with respect to load nodes, Equation 1 can be rewritten as

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{2}$$

where all the subvectors and submatrices given in Equation 2 have their usual meanings.

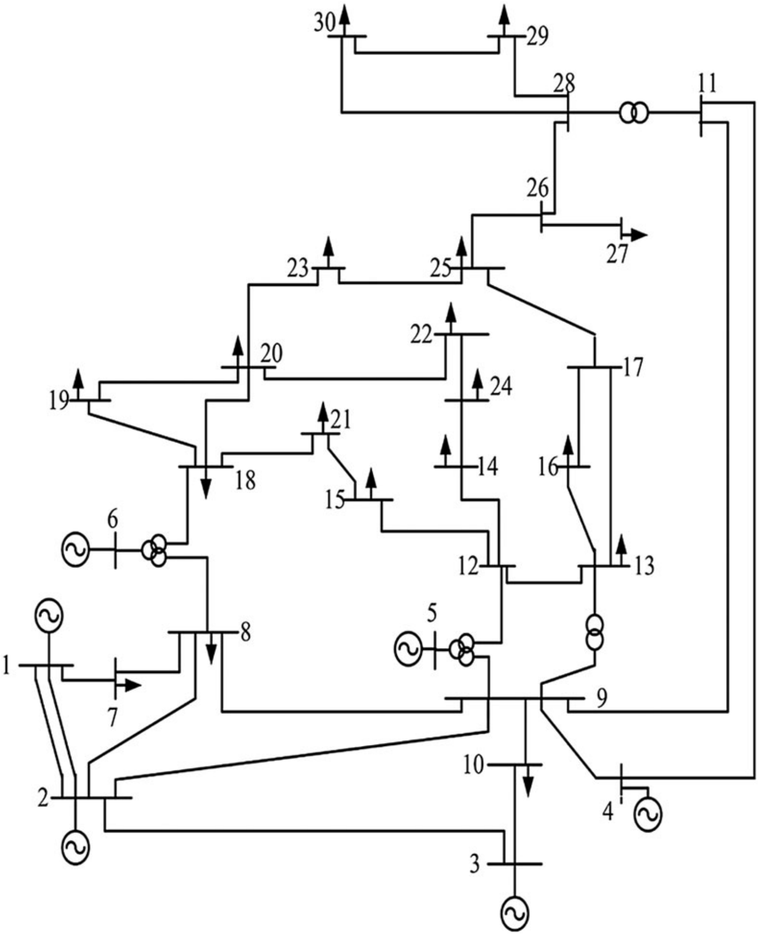

FIGURE 1 One-line diagram of the standard IEEE 30 bus network

The vectors of load voltage and the generator current can be written as a function of load current and generator voltage vectors by mathematical manipulations of Equation 2 respectively as

$$[V_L] = [Z_{LL}]\,[I_L] + [F_{LG}]\,[V_G] \tag{3}$$

where

$$[Z_{LL}] = [Y_{LL}]^{-1} \tag{4}$$

$$[F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}] \tag{5a}$$

$$Load = diag[L_1, L_2, \ ...L_n] \tag{5b}$$

where L_1 , L_2, ...L_n represent the network demands connected at buses 1, 2, …, n. The absolute value of Equation 5a gives the ideal contribution factor from each generator that is required to satisfy the network demands[30] termed Generation-to-Load Allocation Coefficient (GLAC) matrix. It is referred to as an ideal generator contribution index by the authors of previous study.[29] This coefficient matrix not only serves as the starting point for the generation-to-load matching but also serves as the basis for the solution to loss allocation problems within the network. Each element of this matrix represents the contribution factor of individual generator required to serve the network demands in a fair and economical manner for a secure power system operation, taking into consideration the network topology. The benefits of ISCT as captured in GLAC matrix will be explored to allocate individual generation and transmission loss to loads. In solving allocation problems, the network demands as given by Equation 5b are used in conjunction with the GLAC matrix to obtain the required generation-to-load allocation from which the loss allocation could also be

TABLE 1 GLAC matrix for the standard IEEE 30 bus network

Load Bus No.	Generator Contribution Coefficient					
	G1	G2	G3	G4	G5	G6
7	0.3716	0.3068	0.0846	0.3850	0.0224	0.0780
8	0.2110	0.3479	0.0959	0.4365	0.0254	0.0885
9	0.0847	0.2350	0.1313	0.5972	0.0327	0.0150
10	0.0554	0.1537	0.5370	0.3907	0.0214	0.0098
11	0.0830	0.2289	0.1273	0.6273	0.0219	0.0108
12	0.0245	0.0615	0.0358	0.1596	0.2464	0.2049
13	0.0523	0.1153	0.0625	0.2861	0.3319	0.4756
14	0.0691	0.1239	0.0413	0.1842	0.1007	0.5344
15	0.0326	0.0776	0.0386	0.1718	0.2204	0.1223
16	0.0674	0.1450	0.0735	0.3388	0.3642	0.5481
17	0.0695	0.1493	0.0747	0.3446	0.3620	0.5462
18	0.0574	0.0751	0.0110	0.0477	0.1378	0.6684
19	0.0597	0.0767	0.0303	0.1363	0.2659	0.7940
20	0.0422	0.0738	0.0424	0.1925	0.2739	0.5614
21	0.0490	0.0878	0.0310	0.1372	0.1150	0.4013
22	0.0709	0.1359	0.0559	0.2515	0.2007	0.5656
23	0.0549	0.1363	0.0725	0.3325	0.3466	0.3016
24	0.0764	0.1402	0.0500	0.2241	0.1248	0.5845
25	0.0709	0.1605	0.0758	0.3510	0.2822	0.3175
26	0.0385	0.0943	0.0494	0.2185	0.1693	0.1852
27	0.0574	0.1407	0.0737	0.3261	0.2526	0.2764
28	0.0070	0.0181	0.0114	0.0660	0.0711	0.0782
29	0.0122	0.0317	0.0199	0.1155	0.1246	0.1369
30	0.0140	0.0364	0.0229	0.1326	0.1430	0.1571

Abbreviations: GLAC, Generation-to-Load Allocation Coefficient; IEEE, Institute of Electrical and Electronics Engineers.

determined as will be presented in subsection 3.1. More details regarding Equations 4 and 5a are provided in 1 study.[29]

3 | TRANSMISSON LOSS CALCULATIONS

The challenge facing every power system operator in the allocation of transmission loss is how to distribute the network transmission loss among the pool market participants based on the network usage. Although no ideal approach to loss allocation exists, several power-flow–based methods have been published in the literature. The challenges associated with these methods are numerous and therefore necessitated further researches in finding faster and efficient methods of tackling the problem. This section considers transmission loss calculations as formulated based on the new approach of ISCT and the conventional power-flow approach.

3.1 | Loss formulation based on ISCT approach

From the inherent structural characteristics point of view, recall from Equation 3 that

$$[V_L] = [Z_{LL}]\,[I_L] + [F_{LG}]\,[V_G]$$

It can easily be shown that

$$[S_{load}] = [-S_{loss}] + \left[S_{gen}\right] \tag{6}$$

where $[S_{load}] = [I_L]^*\,[V_L]$, $[S_{loss}] = [I_L]^* \times [Z_{LL}] \times [I_L]$, and $\left[S_{gen}\right] = [I_L]^* \times [F_{\mathrm{LG}}] \times V_G$

TABLE 2 Real power contribution to load based on GLAC matrix for the standard IEEE 30 bus network

Load Bus Number	Generator Contribution, MW					
	G1	G2	G 3	G4	G5	G6
7	0.8919	0.7364	0.2031	0.9241	0.0538	0.1872
8	1.6033	2.6438	0.7292	3.3176	0.1932	0.6723
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10	1.2630	3.5052	12.2430	8.9072	0.4879	0.2242
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13	0.3031	0.6687	0.3628	1.6596	1.9253	2.7587
14	0.7741	1.3878	0.4625	2.0625	1.1274	5.9858
15	0.2021	0.4811	0.2391	1.0652	1.3662	0.7581
16	0.5529	1.1893	0.6027	2.7783	2.9863	4.4941
17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
18	0.2008	0.2630	0.0387	0.1670	0.4823	2.3393
19	0.5377	0.6906	0.2728	1.2264	2.3930	7.1461
20	0.1350	0.2362	0.1358	0.6162	0.8765	1.7966
21	0.4653	0.8345	0.2944	1.3033	1.0928	3.8128
22	0.1559	0.2989	0.1230	0.5533	0.4416	1.2444
23	0.9616	2.3858	1.2696	5.8181	6.0649	5.2786
24	0.2445	0.4487	0.1601	0.7170	0.3992	1.8704
25	0.6169	1.3963	0.6595	3.0541	2.4551	2.7620
26	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
27	0.2010	0.4923	0.2579	1.1413	0.8842	0.9673
28	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
29	0.0293	0.0761	0.0479	0.2772	0.2990	0.3284
30	0.1486	0.3861	0.2426	1.4058	1.5159	1.6654
Total	9.2867	18.1208	18.3447	36.9941	25.0445	44.2918

Abbreviations: GLAC, Generation-to-Load Allocation Coefficient.

3.2 | Formulation based on conventional power-flow approach

The total network real losses can be expressed as

$$P_{Loss} = \sum_{\substack{i-j \\ over\, all \\ the \quad lines}} P_{loss,i-j} \tag{7}$$

where Ploss, $i-j$ in equation 7 is the power loss in a branch connecting any two buses i and j which can easily be shown to be

$$P_{loss,i-j} = \left(V_i^* V_i + V_j^* V_j\right) Y_{ii} + \left(V_i^* V_j + V_j^* V_i\right) Y_{ij} \tag{8}$$

where V_i and V_j are the complex node voltages at buses i and j, respectively, which can be obtained from power-flow solution.

4 | GRAPH THEORY–BASED APPROACH FOR LOSS ALLOCATION TO LOADS

The allocation of transmission loss using graph theory approach is mainly based on the solved power-flow analysis.[18,19] The main bottleneck of this approach is that it is computationally intensive as it involves power-flow solution of the network. In this approach, the participation of each load bus to the line flows is determined. This approach is revisited for the sake of comparison with the approach presented in this paper.

The Kirchoff matrix for any given network can be defined by

$$K(G) = \begin{cases} d^{-}(v_i) & for\, i = j \\ \\ -a_{ij} & for \;\; i \neq j \end{cases} \tag{9}$$

where $d^{-}(v_i)$ is the indegree at any given node i.

a_{ij} is the $(i,j)^{th}$ element, associated with row i and column j, in the adjacency matrix.

The adjacency matrix of the network is defined as

$$A = \begin{cases} 1 & if\, buses\, i\, and\, j\, are\, connected\, and\, bus\, i \\ & is\, directed\, towards\, bus\, j \\ 0 & otherwise \end{cases}$$

A Network Incidence Matrix (NIM), based on Equation 9, is expressed as

$$NIM(G) = \begin{cases} -P_{ij} & for\, i \neq j\, and\, P_{ij} > 0 \\ P_{Ti} & for \;\; i = j \\ 0 & otherwise \end{cases} \tag{10}$$

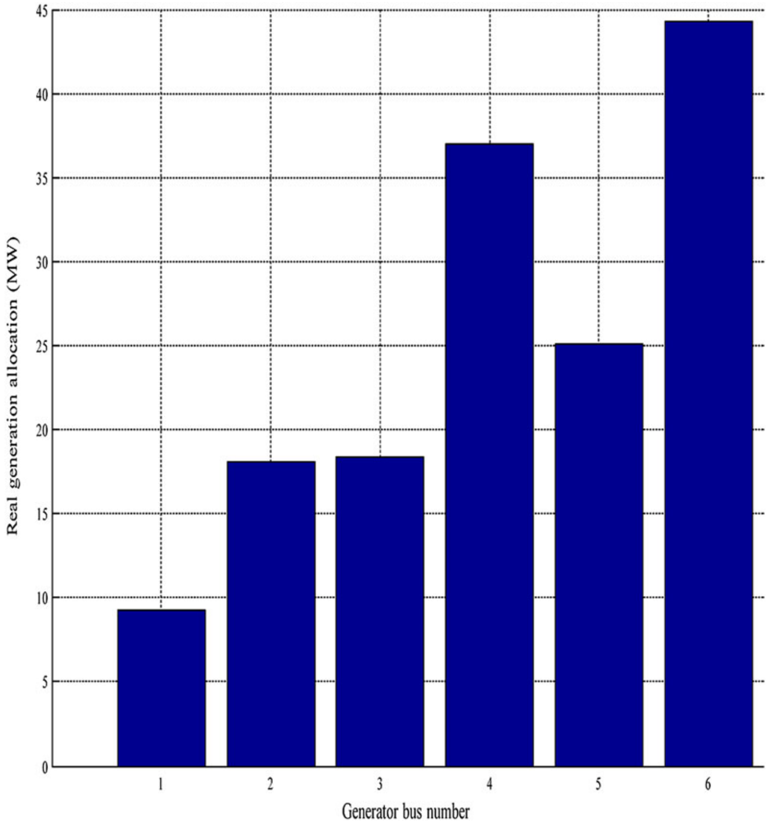

FIGURE 2 Real power generation contribution based on Generation-to-Load Allocation Coefficient matrix

$$P_{Ti} = P_{gi} + \sum_{k=1}^{n} P_{ki}, \text{for}, \quad P_{ij} > 0, \quad j = 1, 2, \ldots, n \tag{11}$$

The properties of NIM matrix on which its mathematical formulations are based include the following[18,31]:

1. Matrix NIM is a $n \times n$ square and invertible matrix. Hence, its inverse A^{-1} exists.
2. The algebraic sum of all the elements in the *k*th column of NIM matrix equals the total real power generated at bus *k*.
3. The algebraic sum of all the elements in the *k*th row of NIM matrix equals the total real power demanded at bus *k*.

Based on these properties of NIM, it can easily be shown that the share of the load, located at any bus *i*, received from the transmission line loss connecting any two buses *j* and *k* is given by

$$P_{Li \to j-k} = D_{ij} \times P_{j \to k} \tag{12}$$

where

D gives the participation of each load by different transmission lines given by

$$D = P_{LL}(NIM)^{-1} \tag{13}$$

and

$$P_{LL} = diag(P_{L1}, P_{L2}, P_{L3}, \ldots, P_{Ln}) \tag{14}$$

5 | RESULTS AND DISCUSSIONS

This section presents a numerical example to illustrate the effectiveness of the ISCT approach and the graph theory–

TABLE 3 Reactive power allocation based on GLAC matrix for the standard IEEE 30 bus network

Load Bus Number	Generator Contribution					
	G1	G2	G3	G4	G5	G6
7	0.4459	0.3682	0.1015	0.4620	0.0269	0.0936
8	0.3375	0.5566	0.1535	0.6984	0.0407	0.1415
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
10	0.6038	1.6757	5.8530	4.2583	0.2333	0.1072
11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
13	0.1045	0.2306	0.1251	0.5723	0.6639	0.9513
14	0.5184	0.9294	0.3097	1.3812	0.7550	4.0084
15	0.0521	0.1242	0.0617	0.2749	0.3526	0.1956
16	0.1686	0.3626	0.1838	0.8471	0.9104	1.3701
17	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
18	0.1033	0.1352	0.0199	0.0859	0.2480	1.2031
19	0.3465	0.4451	0.1758	0.7903	1.5422	4.6053
20	0.0380	0.0664	0.0382	0.1733	0.2465	0.5053
21	0.1665	0.2987	0.1054	0.4664	0.3911	1.3646
22	0.0496	0.0951	0.0391	0.1761	0.1405	0.3959
23	0.6154	1.5269	0.8126	3.7236	3.8815	3.3783
24	0.1222	0.2244	0.0801	0.3585	0.1996	0.9352
25	0.4751	1.0753	0.5079	2.3520	1.8907	2.1271
26	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
27	0.1321	0.3235	0.1694	0.7500	0.5810	0.6356
28	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
29	0.0110	0.0286	0.0179	0.1040	0.1121	0.1232
30	0.0266	0.0692	0.0435	0.2520	0.2717	0.2985
Total	4.3171	8.5355	8.7981	17.7261	12.4878	22.4398

Abbreviations: GLAC, Generation-to-Load Allocation Coefficient.

based approach presented in this paper. The study uses the Institute of Electrical and Electronics Engineers (IEEE) 30 bus network to illustrate the method. A MATLAB code is developed using MATLAB 2013a as the simulation tool.

Figure 1 shows a single-line diagram of the IEEE-30 bus network. The system has 6 generator buses, 41 transmission lines, and 24 load buses.

5.1 | Generation-to-load allocation

The numerical results obtained, for the GLAC matrix when the approach is tested on a standard IEEE-30 bus network, are presented in Table 1, which has six columns and twenty-four rows. The columns represent generator nodes while the rows denote the load nodes within the network. The elements of the matrix GLAC as presented in Table 1 are the contribution coefficients from the generator buses to the load buses.

With the given network demands, the real and reactive power generation are determined on the basis of the GLAC matrix. The results obtained for the real power allocation to network loads are presented in Table 2. Six of the 30 buses in the network are zero injection buses since no load is connected at these buses. These include buses 9, 11, 12, 17, 26, and 28. This is clearly revealed in Table 2 with zero contribution from the generators to those zero injection buses. In this work, the focus is not on the current injection buses whose contributions from all the generators are zeros but rather on the load buses whose generation contributions from the generators are nonzeros. It can be seen from Table 2 that the sum of all the elements in rows that corresponds to a particular generator gives the total contribution of that generator to the network loads. From the results of each total generator contribution to loads, it can be seen that generator 1 gives the least real power contribution of 9.2867 MW to the loads of which the largest amount of 1.6033 MW is allocated to bus 8 while the smallest percentage of 0.0293 MW is allocated to the load at bus 29. Also, generator 6 contributes the highest real power of 44.2918 MW into the network of which 7.1461 MW is allocated to bus 19 while it allocates 0.1872 MW to bus 7.

It can therefore be concluded that bus 6 has the highest capacity and contributes more than any other generator while generator 1 has the lowest capacity and has the least contribution to meet up with the network demands and losses. The total estimated real power contributed, from Table 2, by all the generators, as determined, based on the GLAC matrix to meet the load demands of 137.50 MW and the real power loss within the network is 152.0826 MW. Figure 2 shows the

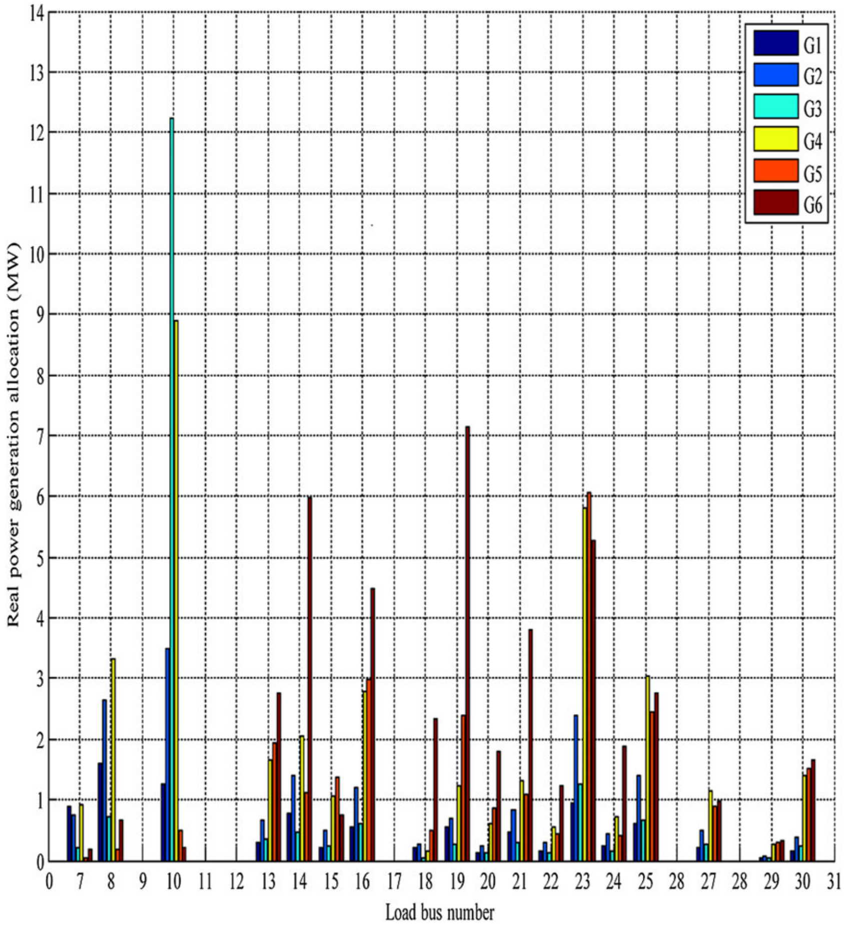

FIGURE 3 Total power generation to loads based on Generation-to-Load Allocation Coefficient matrix for the standard IEEE 30 bus network

graphical illustration for the total estimated contributions from the 6 generators to meet the loads and losses on the network.

The results obtained for the associated reactive power contributed by the generators to meet the loads according to the GLAC matrix are presented in Table 3. It can be seen that while generator at bus 1 is contributing, the least amount of reactive power of 4.3171 MVAR of which 0.6154 MVAR (the highest) is contributed to the load connected at bus 23 and 0.0266 MVAR (the least) at bus 30. In a similar manner, the most contribution to the network is provided by bus 6 (22.4398 MVAR) of which load bus 14 takes 4.0084 MVAR and load bus 7 takes 0.0936 MVAR.

From Table 3, it can be seen that the total reactive power contributions required to satisfy the network demand amounts to 74.3044 MVAR. Based on the developed GLAC matrix, the total estimated reactive power contributed by all the generators to meet up with the network reactive demand of 64.50 MVAR and reactive loss is 74.3044 MVAR.

Figure 3 illustrates the total generation to individual load point within the network. The load connected at bus 10 receives the highest contribution of 26.6305 MW from all the generators followed by the load at bus 23 with a contribution of 21.7787 MW while the lowest contribution of 1.0579 MW from all the generators is received by the load at bus 29.

5.2 | Network loss allocation

The transmission loss across each branch of the network and total transmission loss are determined on the basis of the power-flow solutions using Newton-Raphson iterative method. The total network loss is then allocated to the network loads using the graph theory approach. The results obtained for the load bus voltage magnitudes and their associated load losses as determined from the graph theory–based approach are presented in Table 4. It can be seen that the highest loss of 2.2429 MW is allocated to load bus 10 while the least loss value of 0.6179 MW is allocated to load bus 13. The results obtained for the network loss allocation to loads, using ISCT, as compared with that obtained using graph theory–based are presented in Table 5. It is worth noting that the results obtained by ISCT are determined using the GLAC matrix without running the power-flow analysis. It can be observed that the largest percentage of real power loss, which amounts to 5.2357 MW, is allocated to bus 30 while bus 18 has the smallest, which amounts to 0.0090 MW, allocated to it.

Furthermore, it can be seen from the results presented in Table 5 that negative loss allocation is experienced by some of the buses. This negative loss allocation by the ISCT shows the occurrence of cross subsidy as opposed to the graph theoretical approach, which relies on power-flow for its solution. This indicates that the current contribution by such buses plays the role of reducing the overall transmission network loss by contributing a counter flow against the net transmission loss of that bus. With reference to the results presented in Table 5, it can be seen that buses 15, 18, 21, 29, and 30 have negative loss allocation values. This negative loss allocation experienced at these buses implies that more power can be injected into or withdrawn from such buses for maintaining the integrity of the network. Although buses 29 and 30 are located close to each other geodesically within the network, they are electrically far apart with an electrical distance of 0.5128. Furthermore, the electrical distance between buses 15 and 21 (0.21) is in the neighborhood of that found between buses 18 and 21 (0.22). This, therefore, further explains how the location of a bus within a network could affect the values of the loss allocation as well as its influence on the other buses within a network.

TABLE 4 Loss allocation using graph theory–based approach

Load Bus Number	Voltage Magnitude, PU	Loss Allocation, MW,
7	1.0380	1.9609
8	1.0329	1.4889
9	1.0326	0.0000
10	1.0313	2.2429
11	1.0528	0.0000
12	1.0368	0.0000
13	1.0608	0.6179
14	1.0442	0.6939
15	1.0383	0.8429
16	1.0436	0.6679
17	1.0336	0.0000
18	1.0256	0.6549
19	1.0213	0.6409
20	1.0244	0.7039
21	1.0246	0.7359
22	1.0246	1.6729
23	1.0245	0.6529
24	1.0144	1.2039
25	1.0213	0.6329
26	1.0037	0.0000
27	1.0341	0.6629
28	1.0298	0.0000
29	1.0145	0.7049
30	1.0032	0.8129

TABLE 5 Comparison of loss allocation methods

Load Bus Number	ISCT Approach, MW	Graph Theory Approach, MW
7	0.5964	1.9609
8	1.5593	1.4889
9	0.0000	0.0000
10	3.8305	2.2429
11	0.0000	0.0000
12	0.0000	0.0000
13	1.8781	0.6179
14	0.6002	0.6939
15	−2.0881	0.8429
16	4.4037	0.6679
17	0.0000	0.0000
18	−0.0090	0.6549
19	3.2666	0.6409
20	0.5963	0.7039
21	−1.6970	0.7359
22	0.6171	1.6729
23	4.2787	0.6529
24	0.6399	1.2039
25	2.2439	0.6329
26	0.0000	0.0000
27	0.4439	0.6629
28	0.0000	0.0000
29	−1.3421	0.7049
30	−5.2357	0.8129

Abbreviation: ISCT, Inherent Structural Characteristics Theory.

This signal could be useful for congestion management within power network, which is one of the active research areas in recent times. Such a condition of negative allocation of losses arises if a given contract has the net tendency to send power through the network along paths opposite to the flow from generators to loads. This clearly reveals the network participants, which could have been overcharged to subsidize lower prices for other network participants. More so, the influence of reducing the transmission network loss can be identified from the negative loss allocation point of view, which could serve as an important signal to the market participants.

TABLE 6 Comparison of approaches

Total simulation time, s	ISCT approach Power-flow approach	3.1840 6.0800
Transmission loss, MW	ISCT approach Power-flow approach	14.5827 17.594

Abbreviation: ISCT, Inherent Structural Characteristics Theory.

5.3 | Comparison of the loss calculation methods

The results obtained for the computation of the total network losses using the traditional power-flow and the ISCT-based methods as well as their respective simulation time are presented in Table 6. The simulations are performed on a machine having an AMD E2-1800 APU processor of 1.70 GHz, 32-bit operating system, and an installed memory capacity of 4 GB. It can be inferred that, for the IEEE 30 bus network in consideration, there is a significant reduction in both the losses obtained and simulation times using the ISCT-based approach compared with that obtained through the repetitive and time-consuming power-flow approach.

From Table 6, it can be observed that the total losses obtained when power-flow approach is applied are 17.594 MW while that obtained through the ISCT-based method is 14.5827 MW. This implies that the total transmission loss obtained using ISCT approach is minimal as compared to the power-flow approach as seen from Table 6. The implication of this is that by using ISCT approach, minimum loss is obtained, which results to substantial savings in total transmission costs. It can also be seen that there is a significant reduction in the simulation time that is 3.1840 seconds when the ISCT approach is applied as compared to the simulation time of 6.080 seconds obtained when power flow based is used.

Based on the foregoing, it can be seen that ISCT approach determines the transmission loss for the network in a straightforward and economic manner and also allocates the network losses to loads faster than the existing graph theory method. Hence, the application of ISCT in solving loss allocation problems within power networks could result in faster allocation and greater savings in total transmission costs.

6 | CONCLUSION

A new approach to the solution of generation-to-load allocation and network loss allocation problems, in power networks, is presented in this paper. A detailed mathematical formulation of the method based on the structural interconnections of the network components and their impedance values is presented. The mathematical derivations of graph theory approach whose results solely depend on the power-flow solution are also presented. The influence of the inherent topological characteristics of power system networks in solving generation-to-load matching and loss allocation to load problems is investigated. The effectiveness of the two methods in solving generation-to-load and loss allocation problems is tested on a standard IEEE 30 bus power network. The results obtained from the two approaches are compared, which show that the alternative approach of ISCT suggested in this paper is faster, it gives minimal network loss and consequently reduces the transmission costs. It is worth noting that the approach does not involve power-flow analysis and hence, the problem of slack bus identification as well as its influence on the results obtained is avoided. The approach mainly integrates power network structural characteristics and circuit theory for solving the problems in a natural way. Hence, the structural interconnections of power networks play a prominent role in solving generation-to-load matching and loss allocation to load problems without the need for performing the repetitive and time-consuming power-flow analysis.

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