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Transmission Loss Allocation in Deregulated Power Systems Comprising Renewable Distributed Generation

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Abstract— Since renewable resources have different characteristics and mandatory output unlike conventional sources, the existence of renewable distributed generation as a part of the network represents a new challenge that needs different handling of loss allocation techniques. In this paper, a new methodology is introduced for handling transmission power loss allocation techniques for loop networks comprising renewable distributed generation. This necessitates an investigation of the effect of integrating renewable distributed generation on loss allocation among individual generators and loads of the network using different loss allocation techniques. Also, the effects of separate and simultaneous time variation of both loading and renewables generation are analyzed. The paper implements two different techniques for loss allocation, which are based on circuit laws and power flow solution. The techniques are applied on IEEE 14-bus system, where Photovoltaics and wind sources are optimally allocated. The results prove the considerable effect of different levels of loading and renewables output power on loss allocation. The proposed methodology maintains the accuracy of loss allocation with considering the time variations of loading and renewable generation. Also, it overcomes the problem of huge calculations for large systems and thus, reduces time consumption.

Keywords— Loss allocation; Deregulated power systems; Distributed generation; Power tracing; Renewable energy sources.

1. INTRODUCTION

During the nineties, deregulation of the electricity market was introduced in many countries over the world [1, 2]. The main purpose of restructuring electricity market was to overcome monopoly of power industry and encourage competition among different utilities in favor of consumers. This led to the emergence of many challenges related to planning and operation of restructured power system such as, transmission pricing and transmission loss allocation [3, 4]. It is found that the amount of power loss in transmission systems can represent about 5–10% of the total active power generation [5, 6], which causes a cost of million dollars yearly. In deregulated market, where there are different utilities and competitors, it is a challenging task to identify who would incur this cost. From this point of view, the definition of “transmission power loss allocation” has appeared [6, 7]. The purpose of transmission loss allocation is to determine the amount of losses that is caused/ provided by each generator /load to specify its share in the total losses cost [8].

Since the transmission power loss has a non-linear nature, there is no straightforward method for its allocation among network participants. Therefore, different methods were proposed to provide solutions for the problem of power loss allocation. However, no method proved high reliability and accuracy for all systems under different conditions. Nevertheless, great efforts have been exerted to solve this problem from different points of view using various techniques. Examples of these techniques are pro-rata method [6, 9], incremental

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technique [10], substitution technique [11], proportional sharing-based techniques [7, 12, 13] and circuit theory-based techniques [3, 14 -16].

A concept for dealing with transmission losses is proposed in [14, 15] where transmission loss is decomposed into three components. These components are load loss caused by the current feeding loads, circulating current loss caused by the circulating currents between generators and network loss. The authors examined also the characteristics of these loss components and their dependence on the network parameters.

The authors of [3] proposed an analytical method for loss allocation, which divides the current in each branch into only two components: one component for feeding the loads and the other due to circulating currents between generators. The paper analyzed a system containing a wind resource.

A formula for allocating transmission loss to load buses is implemented in [16] depending on proportional sharing method. Also, relative electrical distance (RED) concept is utilized for comparison reasons. For determining complex power loss allocation, i.e., real and reactive power, the author of [17] proposed a method that uses current adjustment factors. The method is used for bilateral transaction and it assumes that each transaction has two effects on the system: i) its own effect and ii) its interactive effect with other transactions. Power flow tracing based on proportional sharing principle is performed using particle swarm optimization (PSO) algorithm in [18], which introduced a method to determine the real power loss using generator tracing through applying maximum value of generation and load tracing when maximum load demand is applied.

In [19], an algorithm for loss allocation of systems including distributed generation (DG) units is introduced depending on power injected into distribution lines. The algorithm obtains the contribution of loads and DGs separately and uses normalization factors to obtain loss allocated to both loads and DGs simultaneously. Another approach to solve loss allocation problem is proposed in [20]. The approach determines the contribution of each individual generator into the network loads and, then, network losses are determined and allocated to loads in accordance to the Generation to Load Allocation Coefficient matrix based on the Inherent Structural Characteristics Theory.

The authors in [21] proposed routing algorithm for transmission loss allocation between generators and loads of a network utilizing the shortest path with minimum loss criterion. Also, this research shows the effect of changing location of generators and loads on power loss reduction. Hota and Mishra [22] employed a bus identification scheme for faster load flow and loss calculation. They proposed a technique for power loss allocation among network participants considering their load demands and geographical locations. The technique eliminates the effect of cross-term from the loss formulation without justifications. Also, the results are compared with quadratic method with and without DGs before and after network reconfiguration.

Although the previous works proposed different techniques for solving the problem of power loss allocation, most of these techniques are applied for maximum or average load condition on systems that contain only conventional sources. Renewable resources are usually non-dispatchable and have different characteristics and mandatory output unlike conventional sources. The existence of renewable DG as a part of the network represents a new challenge that needs different handling of loss allocation techniques. Some researchers used renewable generation sources with a single operating condition, where the effect of time variation of loading and renewable generation was not presented. Even in [3], the authors dealt with the time variation of load and wind generation for each hour as separate calculation and the allocation of losses is obtained as the average of all results for each network participant. This procedure is time consuming and requires huge calculations for large systems.

This paper aims to propose a methodology for handling the application of loss allocation techniques for loop networks comprising renewable DG, i.e., photovoltaics (PV) and wind sources, in a manner that maintains accuracy and reduces calculation time. This necessitates investigating the effect of distributed renewable generation on transmission power loss allocation among individual generators and loads in the network. This paper performs two different techniques for loss allocation, which are based on circuit theory and power flow solution. A comparison between the cases of presence and absence of renewables is performed to evaluate the influence of their integration to the network. Also, the effect of time variation of loading and renewables generation conditions is analyzed.

2. PROBLEM STATEMENT AND PROPOSED METHODOLOGY

An overview of existing power loss allocation techniques and the proposed methodology are highlighted in this section.

2.1. Overview of Existing Power Loss Allocation Techniques

As mentioned earlier, there are different techniques used for solving the problem of transmission power loss allocation. Each technique has its pros and cons. In this paper, two different techniques are applied for power loss allocation. These two techniques are chosen due to their concept simplicity, ease of implementation and dependency on power flow solution. Also, they have different merits such as their dependency on network configuration, which means that they reflect the actual usage of network. In addition, there is no pre-defined sharing ratio to allocate the losses between generators and loads. Also, they are different in implementation, where one is based on proportional sharing concept and the other deals with circuit laws. One of them allocates losses to both loads and generators simultaneously and the other allocates losses to loads and generators separately. In the following subsections, an overview about these two techniques will be introduced.

2.1.1. Power Flow Tracing Technique (Bialek's Method)

Power flow tracing technique is a mechanism for determining the contribution of each network participant to the transmission system to identify the charges that should be incurred by each one [12, 13]. Power flow tracing methods depend on the network topology and power flow solution unlike other methods such as pro-rata method [6, 9]. These methods are based on Kirchhoff's current law and proportional sharing principle [13]. Bialek's method is one of power flow tracing methods that can allocate transmission losses to individual generators or loads separately. It is implemented through two algorithms:

a) Upstream looking algorithm: It allocates the losses to individual loads only, while charges of transmission usage are allocated to individual generators. It uses the term "gross demand" which is defined as the sum of the actual demand and its allocated part of losses. The algorithm depends on the following equations.

$$P_i^{gross} = \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk} \tag{1}$$

$$P_{Li}^{gross} = \frac{|P_{Li}^{gross}|}{P_i^{gross}} P_i^{gross} \approx \frac{P_{Li}}{P_i} \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk} \tag{2}$$

where A_u is the upstream distribution matrix; P_i is the actual total flow through node i; P_G is the vector of nodal; P_i^{gross} is the unknown gross nodal flow in node i; P_{Li}^{gross} is the load gross demand as a sum of components supplied from individual generators and P_L is the vector of nodal load demands.

b) Downstream looking algorithm: It allocates charges of transmission usage to individual loads, while allocating the power loss to generators. The algorithm uses the term "net generation" to represent the difference between actual generation and allocated part of total transmission loss. The algorithm uses the following main equations:

$$P_i^{net} = \sum_{k=1}^{n} [A_d^{-1}]_{ik} P_{Lk} \tag{3}$$

$$P_{Gi}^{net} = \frac{|P_{Gi}^{net}|}{P_i^{net}} P_i^{net} \approx \frac{P_{Gi}}{P_i} \sum_{k=1}^{n} [A_d^{-1}]_{ik} P_{Lk} \tag{4}$$

where A_d is the downstream distribution matrix; P_{Gi}^{net} is the net i-th generation distributed among all loads in the network and P_i^{net} is an unknown net nodal power flow through node i.

2.1.2. Circuit Theory-Based Technique

It is based on circuit laws and superposition principle. The technique allocates the transmission power loss to generators and loads simultaneously. In this method [3], current flows in each transmission line are split into two components:

- The first one is due to the power transfer from generators to loads. It is obtained by setting all voltage sources at generation buses to zero and modelling the load currents as current sources.
- The second component is due to the voltage differences between generator buses. This circulating current is obtained by setting load currents to zero.

The technique is based on applying Kirchhoff's law at each node of network. The allocation of losses to generators and loads depends on the two components of currents explained above. These losses can be obtained through the following equations:

$$[I_{Bus}] = [Y_{Bus}][U_{Bus}] \tag{5}$$

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} U_G \\ U_L \end{bmatrix} \tag{6}$$

where U_{Bus} is a vector of buses voltages; U_G is the voltage vector of generation nodes; U_L is the voltage vector of loads nodes; ; I_{Bus} is a vector of bus current injections in the system; I_G is the vector of current injection in generation nodes; I_L is the vector of current consumption at loads nodes; Y_{Bus} is the bus admittance matrix; 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 and Y_{LL} is the self-admittance matrix of load nodes.

a) Losses caused by loads:

Setting all voltages sources at generation buses to zero:

$$VD_{Br} = A^T U_{Bus} = A_L^T U_L = A_L^T Z_{LL} I_L \quad (7)$$

$$I_{Br.LT} = Y_{Br} VD_{Br} = Y_{Br} A^T \begin{bmatrix} Zeros[N_G \times N_L] \\ Z_{LL} \end{bmatrix} I_L \quad (8)$$

$$I_{Br,L} = Y_{Br} A^T \begin{bmatrix} Zeros[N_G \times N_L] \\ Z_{LL} \end{bmatrix}, diag\ (I_L) \quad (9)$$

$$\Delta P_{Br,LT} = \frac{I_{Br,LT} \bullet I_{Br}}{|I_{Br}|^2} \times \Delta P_{Br} \quad (10)$$

$$\Delta P_{Br,L} = \frac{I_{Br.L} \bullet I_{Br,LT}}{|I_{Br,LT}|^2} \times \Delta P_{Br,LT} \quad (11)$$

where A^T is the transpose of bus incidence matrix of the system; I_{Br} is the total branch current; $I_{Br,L}$ is the contribution of each load current in total branch current; $I_{Br.LT}$ is the total loads-produced current in each branch; n is the number of system nodes; N_G is the number of generator buses; N_L is the number of load buses; VD_{Br} is the voltage drop across branches due to load currents; Z_{LL}, is the inverse of self-admittance matrix of loads nodes; ΔP_{Br} is the total loss in each branch; $\Delta P_{Br,L}$ is the branch loss allocated to each load and $\Delta P_{Br,LT}$ is the total loads-produced power loss in a branch.

b) Losses caused by generators:
   Setting load currents to zero:

$$\Delta P_{Br,GT} = \frac{I_{Br,GT} \bullet I_{Br}}{|I_{Br}|^2} \times \Delta P_{Br} \quad (12)$$

$$\Delta P_{Br,G} = \frac{I_{Br.G} \bullet I_{Br,GT}}{|I_{Br,GT}|^2} \times \Delta P_{Br,GT} \quad (13)$$

where $I_{Br,G}$ is the contribution of each generator in total branch current; $I_{Br.GT}$ is the branch current due to generators circulating currents; $\Delta P_{Br,G}$ is the branch loss allocated to each generator and $\Delta P_{Br,GT}$ is the total generators-produced power loss in a branch.

2.2. The Proposed Methodology

Usually, in transmission power systems, the overall variations in the demand of load centers over a period of time are close to each other. The corresponding variations of output power from conventional generators have the same trend. Therefore, the power loss allocation among network participants according to different techniques can be performed depending on the average load or maximum load condition.

On another side, in the presence of renewable generators in transmission systems, it is known that the output of renewables - PV and wind sources - depends on local weather and climate conditions. The intermittent and stochastic characteristics of renewable energy require variations of the output generated power from conventional sources even for the same loading condition. This can cause a considerable difference in the results of power loss allocation. Also, variations of load over the day accompanied with variations of renewables output could make significant changes in power loss allocation results. This means that integration of renewables into a network may require different handling of loss allocation techniques.

In this paper, a new methodology is proposed for handling the application of loss allocation techniques for networks comprising renewable distributed generation.

As a preliminary step, an evaluation is made to prove the effect of time variation of loading and renewable generation on results of loss allocation. The analysis is performed through four categories of investigation as follows:

- Investigating the effect of presence and absence of renewables with constant loading
- Investigating the effect of renewables output variation with constant loading
- Investigating the effect of loading variation with the absence of renewables
- Investigating the effect of simultaneous variation of loading and renewables generation.

The proposed methodology is implemented in steps which can be presented in a flowchart as shown in Fig. 1. The main idea is to take the variations of load and renewable power into account, while reducing the computation time when performing a point-by-point calculation.

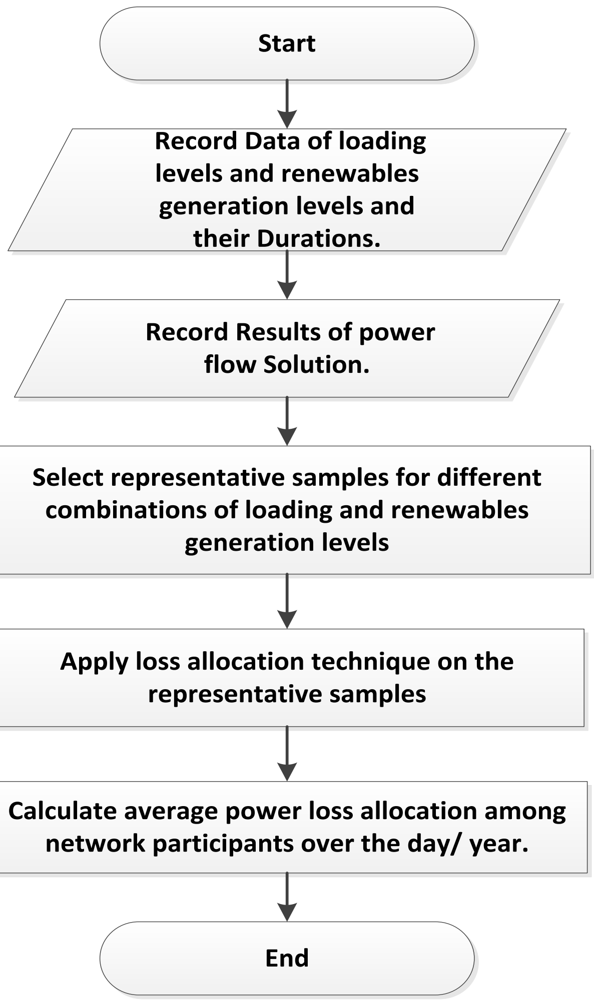

Fig. 1. Flowchart for implementing the proposed methodology.

According to the proposed methodology, the operating states will be classified in groups according to the load demand and the output power from renewables. These steps can be explained as follows:

- The variations of loading and renewables output power are recorded over the day. The levels of loading, and also renewables output power, are classified - according to the maximum demand of loading and the rating of renewables - to high, medium, and low.

- Representative samples, denoting different cases, are selected to cover all possible combinations of different levels of loading and renewables output power.
- The duration of each case is determined over the day.
- A selected loss allocation technique is applied on the representative samples.
- The average power loss allocation among network participants over the day is calculated depending on the percentage results of applying loss allocation technique on the representative samples considering the total power loss at each case and its duration. The duration of each case is used as a weight for allocated loss of this case.
- The procedure can also be applied over the whole year using representative samples denoting the possible different cases considering different seasons of the year.

The proposed methodology maintains the accuracy of loss allocation by considering the time variations of loading and renewable generation. Also, it overcomes the problem of huge calculations for large systems and, so, reduces the consumed time.

3. SYSTEM DESCRIPTION

The IEEE 14-bus system, shown in Fig. 2 [5], is used as a case study for power loss allocation. The system consists of 14 buses and 20 lines. Bus (1) is a slack bus, buses (2), (3), (6) and (8) are voltage-controlled buses and the remaining are load buses. It contains only two generators and 11 load centers. Some modifications are made on IEEE 14-bus system for practical considerations. Renewable distributed sources are inserted into the network through optimal sizing and siting.

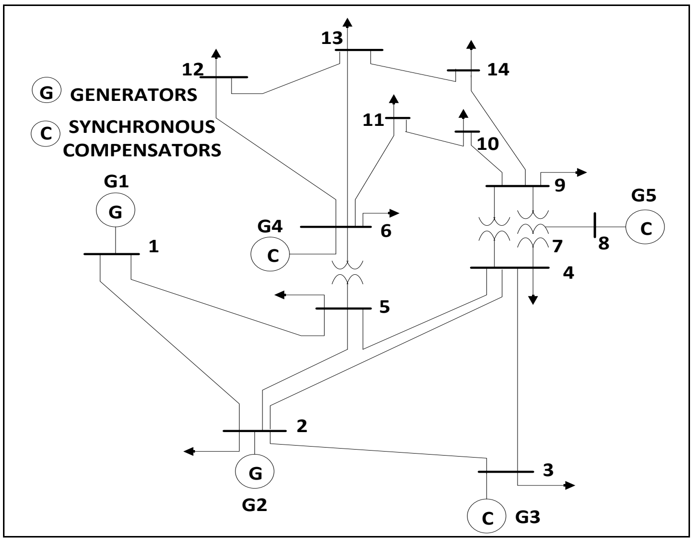

Fig. 2. IEEE 14-bus system.

Hybrid optimization model for multiple energy resources (HOMER) is an optimization tool developed by National Renewable Energy Laboratory in the USA. It is used for designing micro-grids with different components and ranges. In this paper, HOMER is used to determine the optimal size of the renewable distributed resources, namely PV and wind to achieve cost efficiency.

Usually, the allocation of renewable resources through a network is subjected to many different criteria such as power loss reduction [23], voltage improvement [24], and improvement of voltage stability index [25]. In this paper, the siting of the renewable resources is implemented through a heuristic method that depends on measuring the network sensitivity to integrating the renewables, with optimal sizes, at different buses in terms of power loss reduction. Candidate buses, which cause lower power loss, are chosen for further investigation of integrating renewables with different distributions considering optimal capacities that are chosen by the HOMER package.

4. RESULTS AND DISCUSSION

The power flow solution of the system is implemented using power system analysis toolbox (PSAT) integrated to MATLAB library. The case of the network without renewables and with a maximum load is used as a base case.

The two loss allocation techniques discussed above are applied to the base case of the system and the results are shown in Tables 1 through 3. Table 1 presents the allocation of power loss to individual loads according to Bialek's upstream-looking algorithm while Table 2 presents the allocation of power loss to individual generators according to Bialek's downstream-looking algorithm. In Table 3, the allocation of power loss to both loads and generators is presented according to the circuit theory-based technique.

Three cases are studied in Table 3, where column (3) shows the results of loss allocation of IEEE 14-bus system in the absence of synchronous condensers. Column (4) presents the results of loss allocation in case of integrating contribution of condensers of voltage-controlled buses to the contribution of loads located at the same buses. Column (5) shows the results of loss allocation in case of separating the contribution of condensers from that of loads connected at the same buses. It should also be noted that all power loss results in this paper are given in per-unit with a base power of 100 MW.

Table 1. Allocation of power loss to individual loads using Bialek's upstream-looking algorithm.

Load bus No.	Generators		Total gross demand	Actual gross demand	Losses allocated to each load
	G1	G2			
1	0	0	0	0	0
2	0.1765	0.0453	0.2218	0.217	0.0048
3	0.8113	0.1858	0.9971	0.942	0.0551
4	0.4347	0.0677	0.5024	0.478	0.0244
5	0.0733	0.0058	0.0791	0.076	0.0031
6	0.1080	0.0085	0.1166	0.112	0.0046
9	0.2683	0.0418	0.3101	0.295	0.0151
10	0.0855	0.0101	0.0956	0.09	0.0056
11	0.0343	0.0027	0.037	0.035	0.0020
12	0.0594	0.0047	0.0641	0.061	0.0031
13	0.1321	0.0104	0.1425	0.135	0.0075
14	0.1417	0.0174	0.159	0.149	0.0100
Total losses					0.1353

As shown from the results depicted on Tables 2 and 3, the location of generators has a great effect on transmission loss allocation such that:

- Some generators can cause reduction of losses, according to circuit theory-based technique, due to their locations and amount of power generated within the network, such as G2 and, hence, they could be rewarded.
- There is no direct relation between percentages of generators' output power and the associated losses allocated to them.

Table 2. Allocation of power loss to individual generators using Bialek's downstream-looking algorithm.

	Bus No.	Generators	
		G1	G2
Net generation due to each load	1	0	0
	2	0.1717	0.0453
	3	0.7626	0.1795
	4	0.4123	0.0657
	5	0.0704	0.0056
	6	0.1037	0.0083
	9	0.2545	0.0405
	10	0.0803	0.0097
	11	0.0324	0.0026
	12	0.0565	0.0045
	13	0.1250	0.0100
	14	0.1324	0.0166
Total net generation		2.2017	0.3883
Actual generation		2.3253	0.4
Losses allocated to each generator		0.1236	0.0117
Total losses		0.1353	

Table 3. Allocation of power loss to both loads and generators according to the circuit theory-based technique.

Allocation to	Bus No.	Allocated losses		
		Without Compensators	Compensators' contribution integrated to loads' contribution	Compensators' contribution separated from loads' contribution
Generators	1	0.0615	0.0585	0.0585
	2	-0.0133	-0.0105	-0.0106
Loads	2	0	0	0.0004
	3	0.0436	0.0379	0.0381
	4	0.0157	0.0150	0.0154
	5	0.0022	0.0018	0.0022
	6	0.0038	0.0070	0.0034
	8	0	0.0005	0
	9	0.0125	0.0088	0.0092
	10	0.0042	0.0028	0.0033
	11	0.0015	0.0010	0.0015
	12	0.0026	0.0018	0.0022
	13	0.0066	0.0043	0.0047
	14	0.0089	0.0065	0.0068
Total losses		0.1498	0.1353	0.1353

From Table 3, it is obvious that the network compensators contribute to power losses as in the case of bus (8). Although condensers decrease the total power loss of the system, some losses are allocated to them due to current flows they cause in transmission lines. In contrast, Bialek's algorithm does not allocate losses to condensers as shown in Tables 1 and 2 because the algorithm depends on active power flow tracing.

The results in the fourth column of Table 3 illustrate integration of contributions of both condensers and loads at buses (3) and (6) to be allocated to the loads at these buses. On another side, condensers at buses (3), (6) and (8) are connected to keep the voltage level through the system. This means that they benefit all load centers connected to system buses. From this point of view, it is seen that dividing the power losses allocated to condensers among all system's load centers is fair for allocation. The proposed loss allocation method is performed and the results are presented in the fifth column of Table 3 . The proposed method is used for transmission power loss allocation in the following analysis which depend on the circuit theory-based technique.

Integrating renewable sources to the system is performed in two steps. The first step is optimizing the size of the resources according to the system nature and loading conditions. This step is accomplished through HOMER program concerning economic efficiency. The system built in HOMER consists of an AC electrical load with a peak demand of 259 MW, a conventional power source and renewable resource (with 15% renewable penetration) comprised of 15 MW wind resource and 36 MW PV resource. The second step is to allocate the renewable resources through the network such that minimum total power loss is achieved. The allocation is accomplished by a heuristic method, where the wind resource is allocated at bus (14) and the PV resource is allocated at bus (3). For analyzing the effect of time variation of loading and renewable generation, a representative daily power generation and demand curves are used. Two days are used as representative samples of daily variations, one in winter and the other in summer. The curves shown in Fig. 3 present the time variation of load and renewable generated power of a representative summer day, while Fig. 4 presents the variations for a winter day.

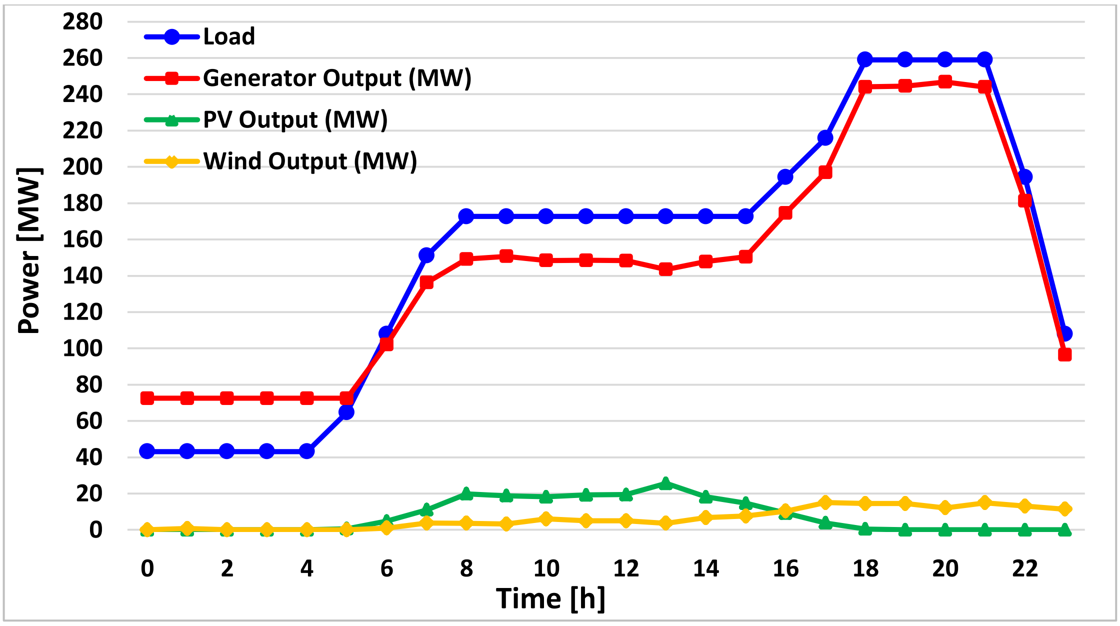

Fig. 3. Representative daily power generation and demand in summer.

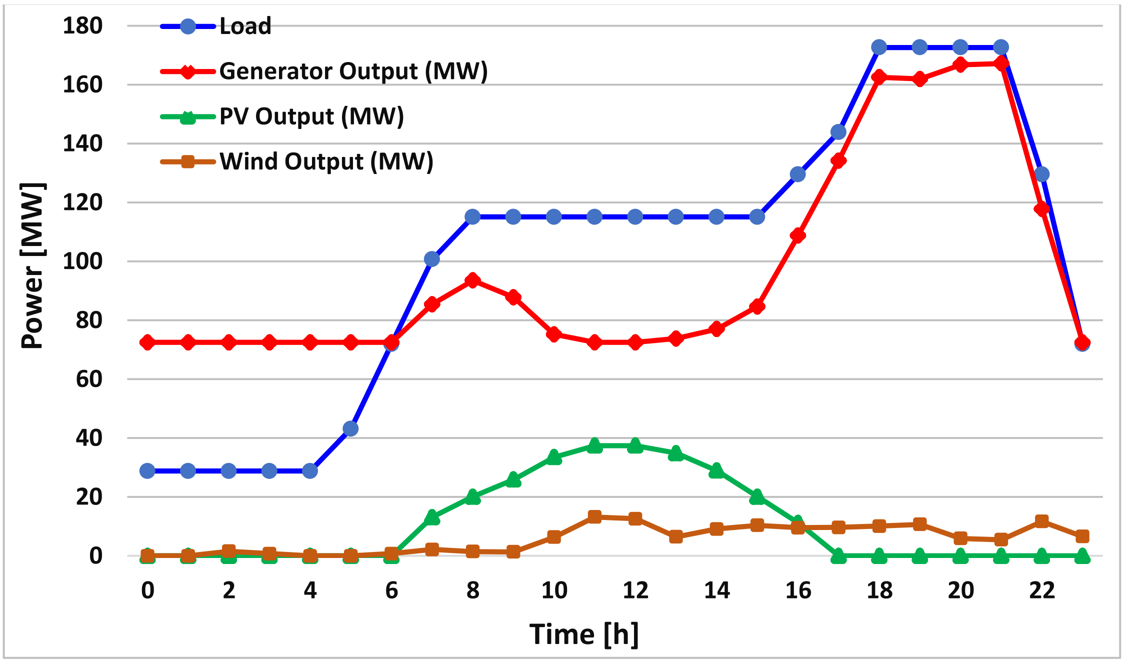

Fig. 4. Representative daily power generation and demand in winter.

Tables 4 and 5 present different cases – that cover the possible combinations of high (H), medium (M) and low (L) levels of load demand, wind output power and PV output power - through the summer and winter days, respectively. The levels of load are according to their maximum value and those of renewables are according to their ratings. A certain code is identified for each case which corresponds to an hour of the day, for example: case 0 represents hour 0 of the summer day and case 1 represents hour 1 of this day. There are two cases in Table 4, which represent cases without any renewable sources. The first one is the base case with a load demand of 259 MW and the second is case 00 with a load demand of 151.08 MW. There are four cases of the same code but with different conditions for summer and winter days, i.e., cases 11, 13, 15 and 23.

Table 4. Investigated cases of load demand and renewable resources output in summer.

Case	Level			load demand	Renewables output [MW]		Total losses
No.	Load	PV	Wind	[MW]	PV	Wind	[p.u.]
Base case	H	-	-	259	0	0	0.1353
00	M	-	-	151.08	0	0	0.0413
0	L	-	-	43.17	0	0	0.008
1	L	-	L	43.17	0	0.7303	0.0079
5	L	L	-	64.75	0.6776	0	0.0101
7	M	L	L	151.08	11.08016	3.7183	0.0324
11	M	M	M	172.67	19.20722	4.947	0.0383
12	M	M	M	172.67	19.39421	4.9768	0.0382
13	M	H	L	172.67	25.56253	3.601	0.03568
15	M	M	M	172.67	14.62924	7.5939	0.0394
16	H	L	H	194.25	9.21504	10.3861	0.0548
21	H	-	H	259	0	14.9549	0.1174
23	L	-	M	107.92	0	8.27749	0.0173

Table 5. Investigated cases of load demand and renewable resources output in winter.

Case	Level			Load demand	Renewables output [MW]		Total losses
No.	Load	PV	Wind	[MW]	PV	Wind	[p.u.]
8	M	M	L	115.11	20.10392	1.46544	0.0163
11	M	H	H	115.11	37.41525	13.18133	0.0111
13	M	H	M	115.11	34.86136	6.46821	0.0123
15	M	M	H	115.11	20.07852	10.37839	0.0137
19	M	-	H	172.67	0	10.70995	0.0475
20	M	-	M	172.67	0	5.90348	0.0505
23	L	-	M	71.94	0	6.56319	0.0101

As expected, Tables 4 and 5 show that the presence of renewables results in considerable reduction of total network losses. The reduction of losses is attributed to the location of distributed renewable generation near load centers that reduces the power flow in the lines connecting the loads with substations. Consequently, power loss is reduced in the network. The conventional centralized power plants cannot provide this advantage due to their locations that are restricted by many factors and generally they are located far from load centers. It is also noticed that, for the same load, the higher the level of renewables generation is, the lower total network losses are.

As aforesaid, the two previously discussed loss allocation techniques are applied on the selected cases. The results are shown in Figs. 5 to 10. Figs. 5 and 6 present loss allocation to individual generators using Bialek's downstream-looking algorithm for summer and winter days, respectively. Figs. 7 and 8 present power loss allocation to individual loads using Bialek's upstream-looking algorithm for summer and winter days, respectively and Figs. 9 and 10 show power loss allocation to both generators and loads using the circuit theory technique for summer and winter days, respectively

The presented results of power loss allocation are used to cover four categories of investigation as follows:

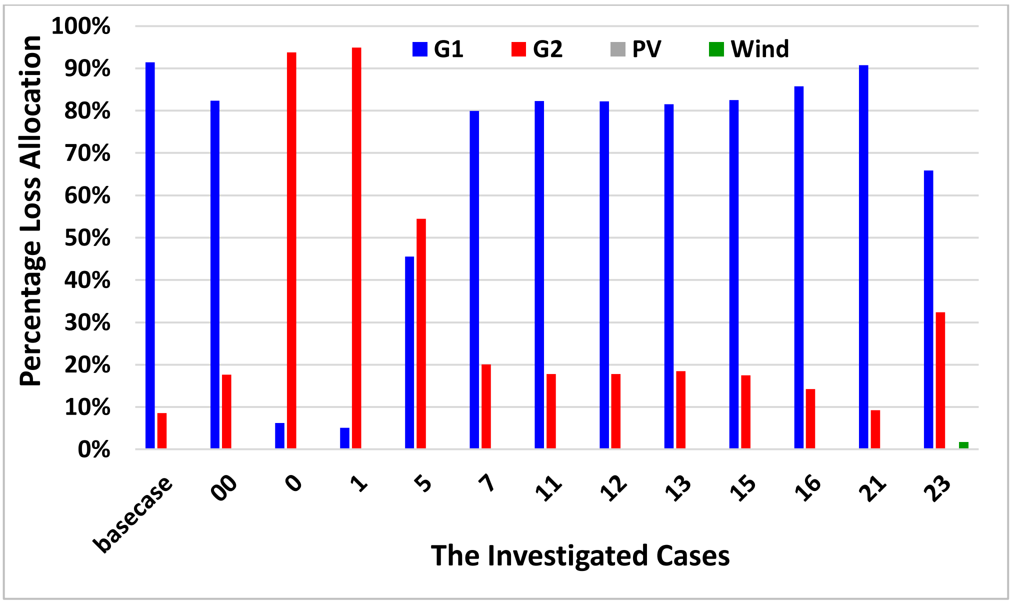

Fig. 5. Percentage allocation of power loss to individual generators by Bialek's downstream-looking algorithm for summer days.

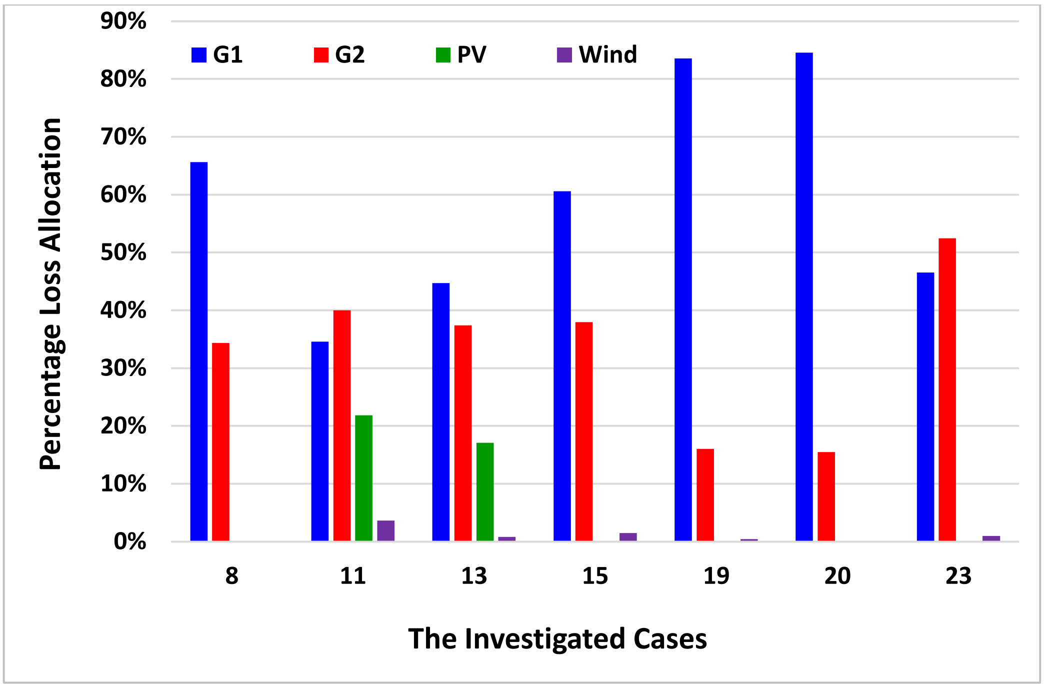

Fig. 6. Percentage allocation of power loss to individual generators by Bialek's downstream-looking algorithm for winter days.

4.1. Effect of Renewables with Constant Loading

Cases of same load demand are selected from Table 4. Each two cases are compared in terms of loss allocation such that one of the two cases represents a case without renewables and the other represents a case with renewables. Two groups of cases are used, where group one is for base case and case 21 with a load demand of 259 MW and group two is for cases 00 and 7 with a load demand of 151.08 MW. The results are shown in Figs. 5, 7 and 9.

Fig. 5 shows that renewables have no effect on losses allocated to generators, i.e., their allocated power losses are zeros except for the case 23 where power loss allocated to wind resource is not zero. This could be attributed to the low level of renewables output in these cases. Although wind resource has a high level of output according to its rating in case 21, its output is still small compared to load level. However, this result does not mean that the penetration of renewables is an ineffective factor because higher level of renewables with respect to load level can affect loss allocation considerably as can be noticed in case 23, where load is low and wind output is medium.

As depicted in Fig. 7, for group one, although the load demand is the same in both cases, the loss allocated to L14 decreased significantly. This reduction reflects the effect of wind resource on the local load connected at the same bus. The same effect is noticed in group two such that PV source reduced the losses portion of L3, and wind source reduced that of L14. It can be said that the integration of renewables not only reduces the total power loss of the network, but also reduces the loss allocated to the loads connected at the same buses with renewable DGs. The higher the renewable generated power is, the lower loss allocated to loads at the same buses is.

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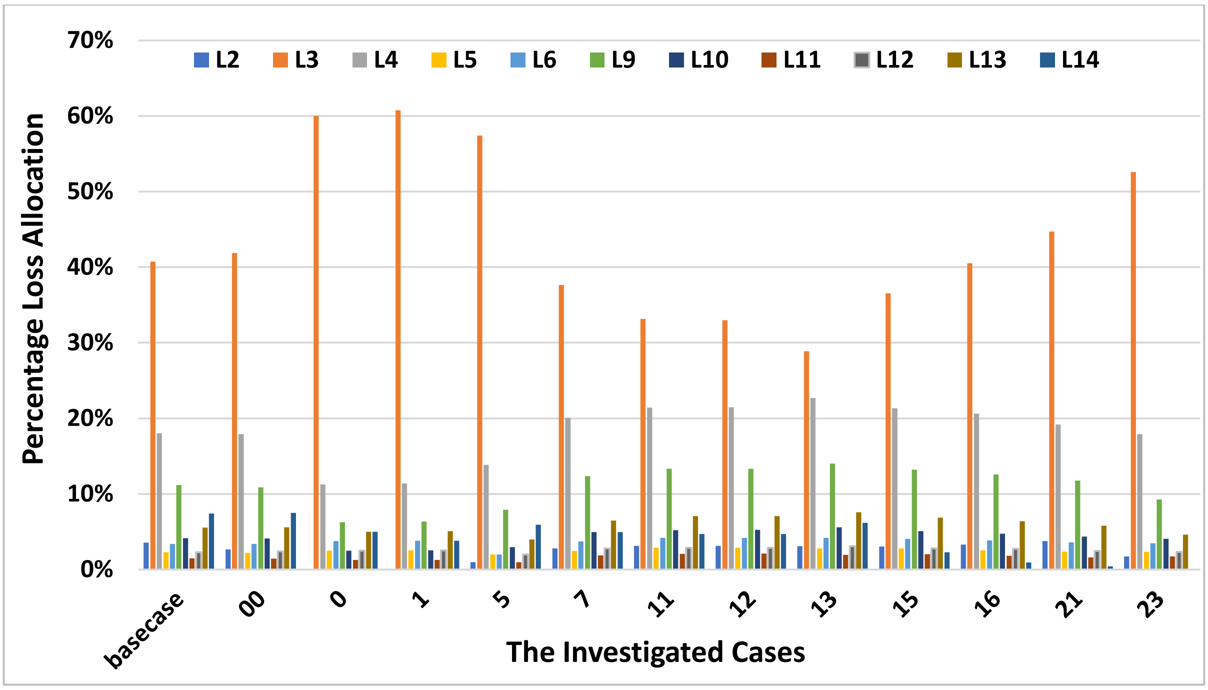

Fig. 7. Percentage allocation of power loss to individual loads by Bialek's upstream-looking algorithm in summer.

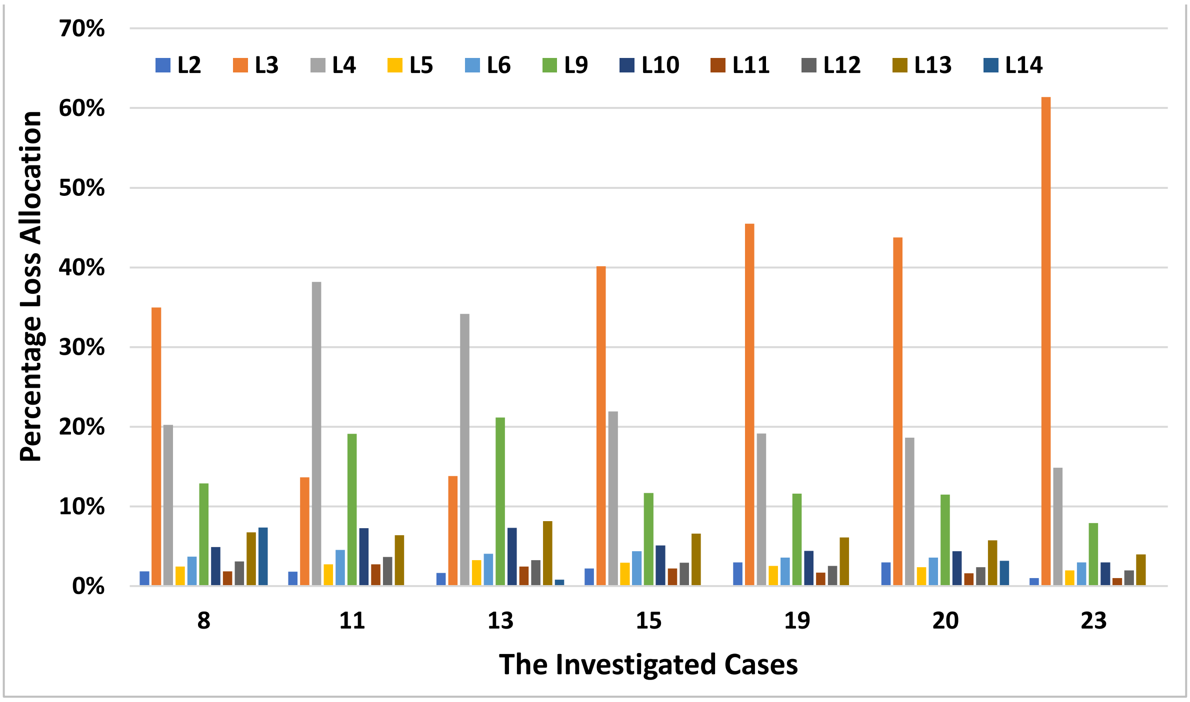

Fig. 8. Percentage allocation of power loss to individual loads by Bialek's upstream-looking algorithm in winter.

Unlike the results of Bialek's algorithms, results of circuit theory-based technique, exhibited in Fig. 9, show the considerable effect of renewables presence through network. Renewables nearly cancelled the allocated portion of losses for loads connected to their buses, i.e., L3 and L14. For example, for group two, renewables generation is at low level in case 7. Nevertheless, loss allocated to L3 and L14 are significantly reduced. Also, losses allocated to loads at buses connected directly to renewables buses are also reduced. In contrast, the losses allocated to generators increased and there is loss allocation for renewables.

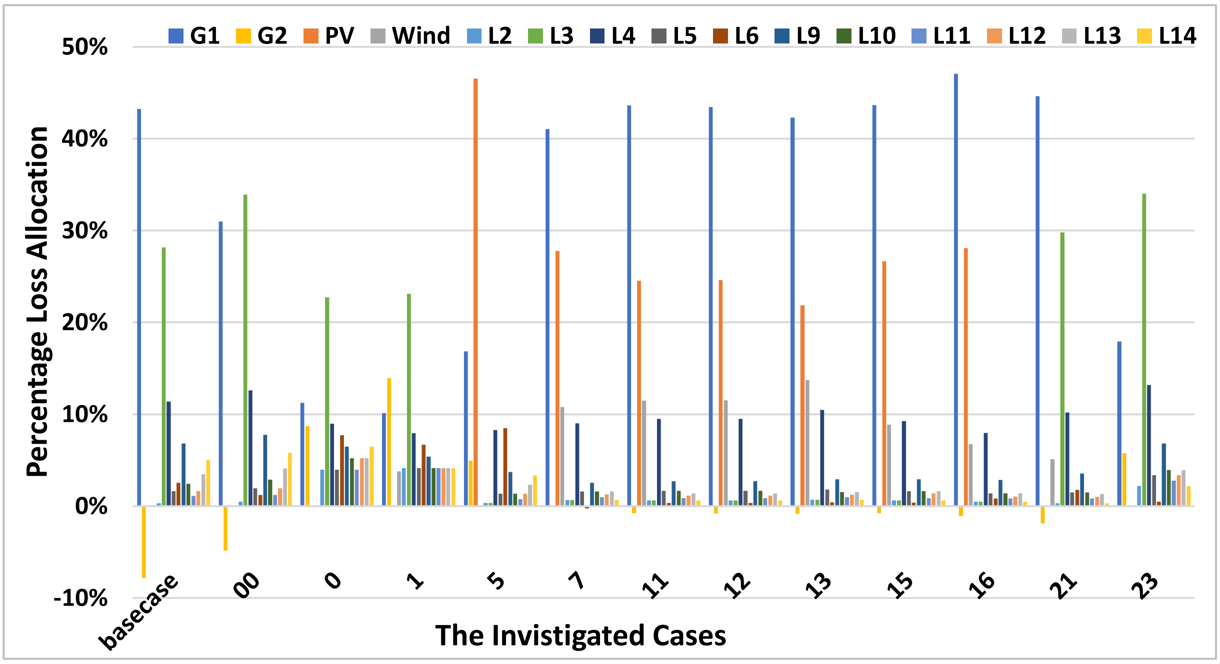

Fig. 9. Percentage allocation of power loss to individual loads and generators using circuit theory-based technique for summer days.

4.2. Effect of Renewables Output Variation with Constant Loading

Cases of same load demand are selected from Tables 4 and 5. Two groups are formed: group one for demand of 172.67 MW and group two for demand of 115.11 MW. The two groups represent loads of medium level. Group one contains cases 11, 13 and 15 from the summer day and cases 19 and 20 from the winter day. Group two contains cases 8, 11, 13 and 15 from the winter day. A comparison, in terms of loss allocation, is made among cases and the results are shown in Figs. 5 to 10.

From Figs. 5 and 6, the loss allocation among individual generators is not affected by the change in renewables outputs in group one. This could be attributed to that in most cases of group one, levels of renewables output vary between medium and low.

In contrast, change of renewables output has a considerable effect on loss allocation for group two, despite of medium level of load for the two groups. The effect is more obvious in case 11 from group two, in Fig. 6, where PV generates its maximum power and wind resource has high level of generation close to its maximum. It can be said that high renewables output affect loss allocation considerably. Therefore, a higher penetration of renewables may cause more changes in loss allocation between individual power sources.

For group one, it can be noticed from Fig. 7 that the main variation of losses allocated to loads occurs for L3 and L14, connected at buses to which PV and wind resources are, respectively, also connected. As shown in Table 5, group two presents cases with medium and high levels of renewables output power. In Fig. 8, a considerable variation of allocated losses to loads is obvious, especially for loads connected with renewables at the same bus. The level of renewable generated power is an important influencing factor. For example, cases 11 and 13 has high level of PV causing lower loss allocated to L3 than that of cases 8 and 15, where PV level is medium.

From Figs. 9 and 10, it can be noticed that the main effect of renewables is on losses allocated to their local loads L3 and L14. Also, it can be said that there is no direct relation between conventional generators' output power and the associated losses allocated to them since a generator with lower output power may contribute to losses with higher portion as in cases 11 and 13 from group two. In these two cases, the output power from G1 is lower than that of G2, but allocated losses to G1 is higher than that of G2.

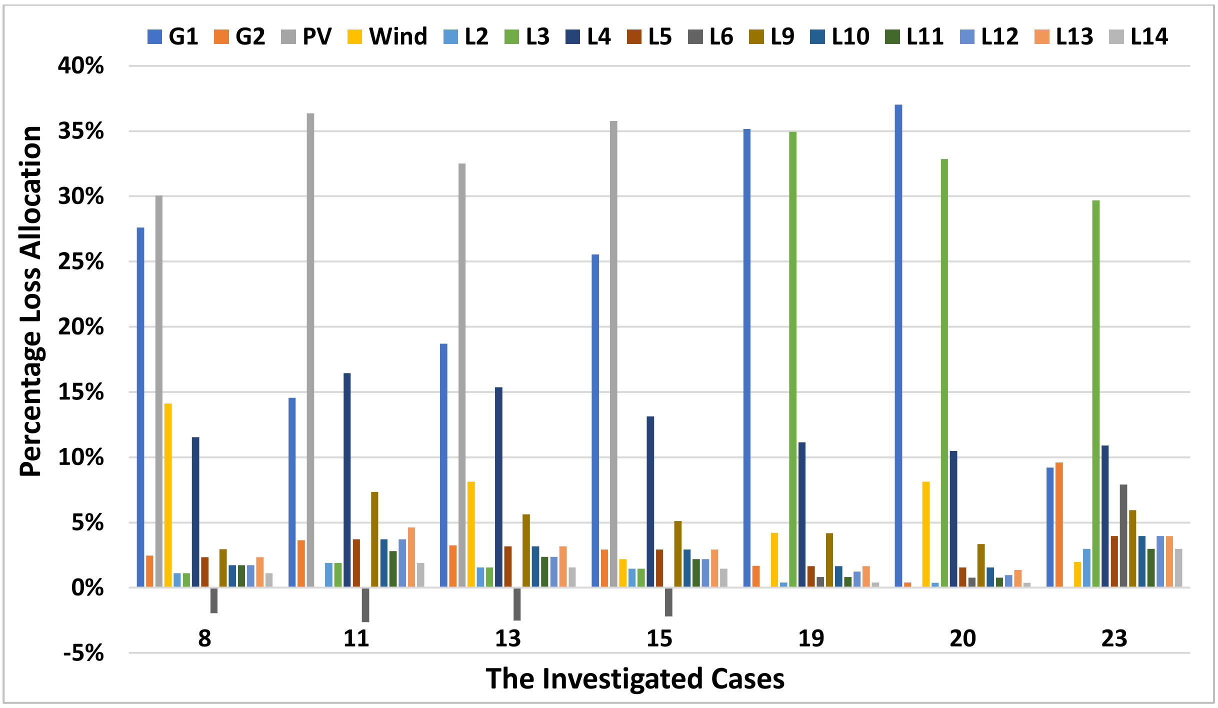

Fig. 10. Percentage allocation of power loss to individual loads and generators using circuit theory-based technique for winter days.

4.3. Effect of Loading Variation in the Absence of Renewables

Three cases of variable load demand are used from Table 4. These cases are: base case, case 00 and case 0. They represent the condition of power generation from conventional sources only in the absence of renewable resources in the network. The cases cover all levels of load demand: high, medium, and low. The loss allocation techniques are applied for these cases to investigate the effect of loading variation only.

According to Bialek's downstream-looking algorithm, Fig. 5 shows that loss allocation among generators depends on domination of generators in terms of output power for each time interval. At low level of load, G2 is the dominant but variation of load from low to high level changes the loss allocation significantly.

Fig. 7 shows that loading variation affects the loss allocated to the load centers with higher demand more than other load centers. This is obvious for L3, where its portion of losses increases considerably with the decrease of load level.

It can be noticed from Fig. 9 that loading variation considerably affects the loss allocated to both loads and generators. Unlike results of Bialek's downstream-looking algorithm, variation of load level from high to low makes the losses allocated to conventional generator converge. At low level of loading, allocated losses to conventional generators are close and no certain generator is dominant or has a negative effect. The total contribution of system's condensers increases obviously at low level of loading. This is noticed clearly in case 0, where the contributions of both loads and generators are close.

4.4. Effect of Simultaneous Variation of Loading and Renewables Generation

Cases of different load demands, and variable renewable output power are selected from Tables 4 and 5. The cases cover different combinations of low, medium and high levels of load demand and renewables generation. Two groups are created to investigate the simultaneous time variation of loading and renewables generation. One group represents a day in summer, which includes cases 1, 5, 7, 11, 16, 21 and 23. The other group represents a day in winter, which includes cases 11, 19 and 23.

For loss allocation among generators, high renewables output and load level affect loss allocation considerably. For example, as shown in Fig. 6, medium load in case 11 with high renewable generation causes the loss portions of generators to be close to each other. For case 23, PV has no generation, wind has medium level of generation and load has low level. These conditions cause losses allocated to conventional generators to be close to each other in contrast to case 1, shown in Fig. 5, that has almost the same conditions. The only exception in case 1 is that the level of wind generation is low causing the loss portion of G2 to be the dominant.

As shown in Figs. 7 and 8, the simultaneous time variation of loading and intermittent nature of renewables affects the loss allocation among loads such that the generation level of PV and wind resources affect their local loads inversely.

Figs. 9 and 10 show that time variation of load and renewables generation significantly affects the losses allocated to loads and conventional generators. At low level of loading, as in cases 1 and 23 shown in Figs. 9 and 10, conventional generators' allocated losses are close and positive. In addition, the contribution of total condensers in system's losses increases.

From the results of category (4), it can be said that simultaneous variation of loading and renewables generation integrates the effects noticed from investigated categories (2) and (3). It can be also noticed from Figs. 5, 7 and 9 and Table 4 that cases 11 and 12 have the same attitude of loss allocation since they have the same conditions, i.e., represent the same case.

Tables 6 through 8 show loss allocation results of the implemented two techniques over a summer day. In each table, column two shows the loss allocation at the time interval of maximum demand. Column three shows the average loss allocation, where calculations are performed at each hour over the day and, then, the average is allocated to each element. Column four represents the average loss allocation using the proposed methodology.

Table 6. Allocation of power loss to individual generators using Bialek's downstream-looking algorithm over a summer day.

Generator No.	Losses allocated to each generator using Max. demand (with renewables)	Average losses allocated to each generator using:	
		calculations at each hour over the day	proposed methodology
G1	0.1065	0.0375	0.0371
G2	0.0109	0.0067	0.0076
G3 (PV)	0	0.0000	0.0000
G4 (wind)	0	0.00004	0.0000
Total losses	0.1174	0.04424	0.0447

As seen from results in Tables 6 through 8, the loss allocation at maximum demand intervals are inaccurate compared to results based on hourly calculations. This means that it is not fair to allocate losses depending on just one condition of load, maximum load demand, as performed in techniques or applications of other previous works such as in [19]. This can be explained as follows:

- In absence of renewable sources, the overall variations in the demand of load centers - in transmission power systems - over a period of time are close to each other. Also, the corresponding variations of output power from conventional generators have the same trend. Therefore, the power loss allocation can be performed depending on average load or maximum load condition.
- In contrast, the presence of renewable resources with their intermittent and stochastic characteristics requires variations of the output generated power from conventional sources even for the same loading condition. This can cause a considerable difference in the results of power loss allocation. Also, variations of load over the day accompanied with variations of renewables output could make significant changes in power loss allocation results. This means that integration of renewables into a network requires taking all variations of loading and power generation over the day into consideration.

On another side, dealing with time variation of loading and wind generation for each hour as separate calculation and obtaining the loss allocation for each network participant from the average of all results, as in [3], is time consuming and requires huge calculations for large systems. Alternatively, the use of specified categories representing all conditions taking their weights into account could give high accuracy with simplified calculations.

Therefore, the results based on the proposed methodology maintain the accuracy by considering the time variations of loading and renewable generation. Also, it overcomes the problem of huge calculations and time consumption, which are required for accurate allocation based on hourly calculations for large systems.

Table 7. Allocation of power loss to individual loads using Bialek's upstream-looking algorithm over a Summer day.

Load No.	Losses allocated to each load using max. demand (with renewables)	Average losses allocated to each load using	
		calculations at each hour over the day	proposed methodology
L2	0.0044	0.0015	0.0014
L3	0.0525	0.0183	0.0185
L4	0.0225	0.0088	0.0088
L5	0.0028	0.0011	0.0011
L6	0.0042	0.0017	0.0017
L9	0.0138	0.0053	0.0054
L10	0.0051	0.0020	0.0021
L11	0.0019	0.0008	0.0008
L12	0.0029	0.0012	0.0012
L13	0.0068	0.0027	0.0028
L14	0.0005	0.0009	0.0009
Total losses	0.1174	0.0442	0.0447

Table 8. Allocation of power loss to individual loads and generators using circuit theory-based technique over a Summer day.

Allocation to	Losses allocated to each element using max. demand (with renewables)	Average loss allocation using:	
		Calculations at each hour over the day	Proposed methodology
G1	0.0524	0.0193	0.0190
G2	-0.0022	-0.0004	-0.0003
G3 (PV)	0	0.0069	0.0061
G4 (wind)	0.006	0.0032	0.0031
L2	0.0004	0.0002	0.0003
L3	0.0350	0.0058	0.0066
L4	0.0120	0.0041	0.0043
L5	0.0018	0.0007	0.0007
L6	0.0021	0.0005	0.0006
L9	0.0042	0.0014	0.0015
L10	0.0018	0.0007	0.0008
L11	0.0010	0.0004	0.0005
L12	0.0012	0.0005	0.0006
L13	0.0016	0.0006	0.0007
L14	0.0004	0.0003	0.0003
Total losses	0.1174	0.0442	0.0447

5. CONCLUSIONS

This paper proposed a methodology for handling transmission power loss allocation techniques for networks comprising renewable distributed generation. An analysis was introduced for the effect of integrating renewable distributed generation on loss allocation among individual generators and/or loads of the network. Two different loss allocation techniques were applied to a loop system, where one of them depends on power flow tracing and the other one is a circuit theory-based technique. The proposed methodology used representative samples, which were selected to cover all possible combinations of different levels of loading and renewables output power. The results show that integrating renewables causes reduction of total network losses.

Also, different levels of load demand and renewables output power considerably affect loss allocation, especially for higher penetration of renewables. In addition, it was shown that time variation of loading and/or renewables output power has different effects and different results according to the applied loss allocation technique. This means that allocating losses according to maximum or average load demand only - without considering the variations of loading and renewable generation -results in inaccurate results. Also, performing analysis for each time interval is time consuming and needs huge calculations for large systems. The proposed methodology maintained the accuracy of loss allocation by considering time variations of loading and renewable generation. Also, it overcame the problem of huge calculations for large systems and, so, reduced time consumption.

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