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Graph Theoretic Loss Allocation Method for Microgrids having Variable Generation

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ABSTRACT

With some assumptions and limitations, various methods have been developed in literature mainly for loss allocation in transmission network and afterwards extended for radial distribution network and some methods are specifically developed for radial distribution network. But, these methods are not suitable for microgrids which are integrated with conventional grid at sub-transmission and distribution levels depending on their geographical location. This paper presents a loss allocation method based on power flow results and relative position of buses for interconnected microgrid which is very effective in case of frequent change of generations due to intermittent nature of renewable resources. The implementation of the proposed method is very simple in microgrid with both meshed as well as radial topology without any computational complexity and requires only power flow solution and network data. The results are illustrated for different generating conditions of renewable sources in microgrid to demonstrate the efficiency of proposed loss allocation method.

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1. INTRODUCTION

Microgrid is an integration of various distributed generation (DG) especially renewable energy sources such as photovoltaic and wind which operates autonomously or in synchronous with conventional electrical grid. The incorporation of microgrids into distribution system has also transformed the structure of grid from radial to weakly meshed network. Energy insecurity, climate change and pollution are major concerns addressing significant changes in energy infrastructure by integrating renewable energy generation [1]. In modern power system structure, several renewable generations are integrated to conventional grid at sub-transmission level and several may be connected at distribution level. Hydro plant and wind farm are always far away from populated area and need to be connected to long-distance transmission [1]. Some of solar generations are present at low voltage distribution level. Due to independent ownership of DGs present in microgrid, it is essential to have a robust loss allocation (LA) method for attaining transparency. LA method should be applicable to both radial and meshed structured microgrid because depending on type of integration, some of the microgrids are of radial topology and some are of meshed topology.

1. 1. Literature Review

In microgrids, conventional power generations are required to avoid power interruption as electricity generation by renewable energy resources are intermittent [1]; the output from a wind farm or a photovoltaic array depends on the climatic conditions. In interconnected mode, microgrid is connected with distribution network and works in co-ordination with the distribution management system. The power flow pattern varies very frequent in microgrids due to integration of non-conventional generation units. The presence of multiple source changes the distance between sources and loads which also alters network usages. Any LA method intended to be used for microgrid operation must be equally applicable to both radial as well as meshed network topology since the microgrid can be of either configuration. This makes LA problem very significant in microgrids. A robust LA method is required to differentiate between the contributions of individual participants i.e. the generators and loads connected in the

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microgrid and it should also consider amount of network usage of any participant as well as distance from source while making allocations to it.

There exist various LA methods in literature for transmission systems [2]. With some assumptions and modifications, transmission LA methods can also be used for distribution systems. Table 1 summarized discussion about different allocation methods proposed earlier.

An improved average LA method for distribution network is proposed by Zhang et al. [3]; which is especially suitable for harmonic loss. Moret et al. [4] presented an analysis of LA policies for avoiding market outcomes which categorizes agents for geographical location. It also suggests inclusion of system operator in both transmission and distribtion level.

1. 2. Contribution of Proposed Work A fair and satisfactory LA method should reflect both the network topology and the magnitude of power injected or consumed at a bus. The present work proposes a LA strategy for interconnected microgrid with meshed as well as radial structure which works on power flow result of the system and relative distance between buses in network. Proposed method requires only power flow results and electrical closeness centrality indices, which is a measure of the degree to which an individual is near all other individuals in a network. The proposed LA method is straightforward without any intricate computational applications.

1. 3. Organization of Paper The next section confers electrical closeness centrality measures and their

TABLE 1. Different existing LA methods

Ref.	Method	Merits	Demerits
[2]	Pro-rata method	Allocation of loss is characterized by loss proportionally to the power delivered by generators and loads.	Neglects relative location of generators and loads within the network.
[5]	MW-mile methods	Considers the relative position of each participant from slack bus	Neglects the amount of power flowing through network.
[6]	ITL (incremental transmission loss) methods	Suitable for networks with high X/R ratio and dependent on choice of slack bus	Due to dependency on slack bus, ITL method results in over recovery of network loss.
[7]	DLC (direct loss coefficient) method	Allocates loss directly by establishing relation between real/reactive power of a bus and network loss	Application of Hessian included in procedure of DLC is computationally exhaustive for handling larger system
[8]	Proportional sharing principle based methods	Allocate total network loss to either generators/DGs or loads as it involves application of linear principle	Proportional sharing principle is an assumption.
[9]	Z-bus/Y-bus methods	Easy to implement in larger networks	Not applicable to microgrid with radial topology when shunt admittance of the lines are negligible
[10, 11]	Circuit theory based methods	Suitable for system with high value of X/R ratio	Not justified in microgrids connected at distribution level where X/R ratio is low
[12]	Branch current decomposition method	Suitable for radial distribution configuration with DGs	Requires an additional forward sweep power flow on modified network
[13]	Power summation method	Tracing based approach	Suitable for radial distribution system
[14]	Energy summation method	Based on disintegration of energy	Suitable for radial distribution system
[15]	Exact formulation method	Suitable for allocating branch loss to the nodes	Applicable to radial system
[16]	Branch oriented method	Loss are allocated to loads and DGs	Results into over-recovery of loss
[17]	Current/Power summation method	Easy to implement	Suitable for radial distribution system
[18]	Branch oriented methods	Employ backward sweep reduction technique	Applicable only for microgrid with radial topology
[19]	Game theory based methods	Overcomes the limitations of conventional Shapley value method	Considers DGs as negative loads
Proposed method	Pro-rata method	Allocates loss directly by establishing relation between real power of a bus and network loss. Considers relative position of each participants, Suitable for microgrid with radial & meshed topology, easy to implement	Applies normalization process for distributing loss to generators and loads.

use in proposed LA method. Section 2 discusses relevance of electrical closeness centrality measure in LA in brief and describes the steps of calculating closeness centrality and proposed method with an example. Section 3 demonstrates the application of proposed method in different scenario of microgrid and presents the comparison of proposed method with existing methods. The results of proposed method for larger microgrid are given in section 4. Finally, section 5 concludes the work.

2. CENTRALITY MEASURES AND LOSS ALLOCATION

Distributed energy resources (DERs) of microgrids are owned by different entity which necessitates implementation of a robust LA method by distribution system operator (DSO). In microgrids, generations are sporadic subject to climatic changes which lead to change in power flow results. With changing generation pattern the power flow through different paths of the network changes, resulting into change in network usage. Electrical closeness centrality is the measure of relative position of a bus in the network and dependent on system data and power flow results. To change the loss contribution according to relative position and network usage by individual participant, electrical closeness centrality is used for allocating loss to generators and loads.

Electrical closeness centrality measures are calculated by using bus dependency matrix [20], which exhibits dependability of buses on each other present in network. The method discussed by Bharti and De [20] for finding bus dependency matrix is applicable to both meshed and radial electrical network. A fair LA method needs to take care of the relative location and importance of any bus in the network and this aspect can be included by incorporating centrality index in the allocation method. The following section discusses the method of determining centrality measure of a network.

3. 1. Calculation of Electrical Closeness Centrality Measures

The electrical closeness centrality measure is calculated from the bus dependency matrix which is of order (bus*bus). The bus dependency matrix of any $'n'$-bus system is calculated as Equation (1) then:

$$D_{bus\_dep_n} = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1n} \\ d_{21} & d_{22} & \dots & d_{2n} \\ \vdots & \dots & \dots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{nn} \end{bmatrix} \quad (1)$$

The computation of bus dependency matrix depends on shortest path between pair of buses and active power flowing it. In shortest path between pair of bus of power system network, there will be intermediate buses if selected buses are not adjacent buses. There may be either single bus or multiple intermediate buses in shortest path. So, the elements of bus dependency matrix can be calculated as:

Step I: Run power flow of the system.
Step II: Determine the shortest path for each bus pair by assigning impedance as weights.
Step III: Find the maximum active power in each shortest path, P_{st}. (see Figures 1 and 2).
Step IV: Ascertain the maximum of inflow and outflow at intermediate bus within each shortest electrical path, $P_{st}(i)$. (see Figures 1 and 2).
Step V: The dependency of bus $'s'$ upon bus $'i'$ to transmit power to other buses of the network can be given by,

$$d_{si} = \sum_{\substack{t=1 \\ s\neq t\neq i\in V}}^{n} \frac{P_{st}(i)}{P_{st}}$$

For example, in a 5-bus system, element d_{14} and d_{35} are calculated as:

$$d_{14} = \sum_{t\in\{2,3,5\}} \frac{P_{1t}(4)}{P_{1t}} = \frac{P_{12}(4)}{P_{12}} + \frac{P_{13}(4)}{P_{13}} + \frac{P_{15}(4)}{P_{15}} \quad (2)$$

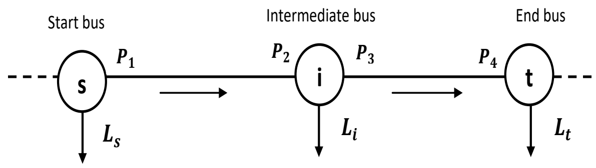
$$d_{35} = \sum_{t\in\{1,2,4\}} \frac{P_{3t}(5)}{P_{3t}} = \frac{P_{31}(5)}{P_{31}} + \frac{P_{32}(5)}{P_{32}} + \frac{P_{34}(5)}{P_{34}} \quad (3)$$

The diagonal elements of bus dependency matrix will be zero and its row summation gives electrical closeness centrality.

Electrical closeness centrality of each can be calculated by row sum of matrix. For example, closeness centrality of n^{th} bus will be calculated as:

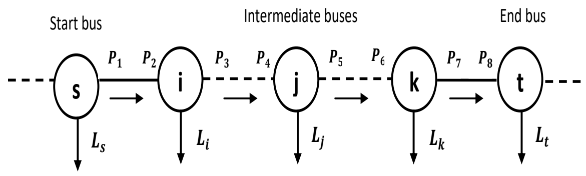
$$C_n = d_{n1} + d_{n2} + \cdots \dots \dots \dots + d_{nn} \quad (4)$$

The closeness centrality computes the extent of connectivity to which a bus is in close proximity to all other buses of the network. Electrical closeness centrality measures are calculated by using bus dependency matrix which is dependent on system impedance and power flow results. A fair LA method should incorporate the relative location and importance of any bus in the network and



$P_{st} = \max of\ (P_1, P_2, P_3, P_4)$
$P_{st}(i) = \max of\ (P_2, P_3)$

Figure 1. Description of $P_{st}(i)$ and P_{st} in shortest path with single intermediate bus



$P_{st} = max\ of\ (P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8)$
$P_{st}(x) = max\ of\ [max(P_2, P_3), max(P_4, P_5), max(P_6, P_7)]$
x is the intermediate bus depending upon amount of active power inflow/outflow.

Figure 2. Description of $P_{st}(i)$ and P_{st} in shortest path with multiple intermediate buses

this aspect can be included by integrating centrality index in the allocation method.

3. 2. Loss Allocation using Electrical Closeness Centrality Measures The algorithm used for allocating loss to each node of the network is given as follows:

Step I: Calculate total loss (P_{loss}) of the system using power flow results.

Step II: Calculate electrical closeness centrality indices (C_i) for each bus present in the network by using bus dependency matrix as discussed in section 2.1.

Step III: Calculate total outgoing power (P_i) at each bus present in the system.

Step IV: Calculate proportional indices (a_i) for each bus by using Equation (5).

$$a_i = \frac{P_i}{\sum_{i=1}^{n} P_i C_i} \tag{5}$$

Where, $'n'$ is the number of buses present in network.

Step V: Loss allocated to each bus can be given by

$$p_i = P_{loss}.\, a_i.\, C_i \tag{6}$$

Step VI: Normalize loss at various buses to calculate loss contribution of individual loads and generators.

The formula given as Equation (6) allocates loss to individual bus as:

$$p_i = P_{loss}.\, a_i.\, C_i$$

Here, a_i is proportional index of bus 'i' and C_i is electrical closeness centrality index of bus 'i'. p_i is loss allocated to bus 'i'. The proportional index of bus 'i', (a_i) depends upon outgoing power and closeness centrality of bus 'i' as represented in Equation (5). For calculating electrical closeness centrality by bus dependency matrix, shortest path between pair of buses and active power flowing in them will be determined (as detailed in section 2.1).

$$Where,\ a_i = \frac{P_i}{\sum_{i=1}^{n} P_i C_i}$$

And, $C_i = d_{i1} + d_{i2} + \cdots \ldots \ldots \ldots + d_{in}$

$$\Rightarrow C_i = \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq 1\in V}} \frac{P_{it}(1)}{P_{it}} + \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq 2\in V}} \frac{P_{it}(2)}{P_{it}} + \ldots + \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq n\in V}} \frac{P_{it}(n)}{P_{it}}$$

So, allocation of loss to bus can also be written as:

$$p_i = P_{loss}.\left(\frac{P_i}{\sum_{i=1}^{n} P_i\left(\sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq 1\in V}} \frac{P_{it}(1)}{P_{it}} + \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq 2\in V}} \frac{P_{it}(2)}{P_{it}} + \ldots + \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq n\in V}} \frac{P_{it}(n)}{P_{it}}\right)}\right). \left(\sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq 1\in V}} \frac{P_{it}(1)}{P_{it}} + \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq 2\in V}} \frac{P_{it}(2)}{P_{it}} + \cdots \ldots + \sum\nolimits^{n}{}_{\substack{t=1\\ i\neq t\neq n\in V}} \frac{P_{it}(n)}{P_{it}}\right) \tag{7}$$

In above expression,

P_{loss}: Total loss of the system using power flow results

P_i: Total outgoing power at each bus 'i' present in the system

n: Total number of bus in the system

P_{it}: Maximum active power in each shortest path

$P_{it}(k)$: Maximum of inflow and outflow at intermediate bus within each shortest electrical path

$P_{it}(k)$ will be 'zero' if shortest path is trough directly connected buses and 'non-zero' if there exists intermediate bus in shortest path.

3. 3. Validation of Proposed Loss Allocation Method A test system with 5-bus and 7 links is considered as microgrid with meshed topology to demonstrate the applicability of proposed method. Microgrid is integrated with conventional grid at bus 1 and there are two nonconventional energy resources: solar plant and wind farm with installed capacity of $40MW$ and $30MW$ respectively, connected at bus 2 and bus 3. Figure 3 represents 5-bus test system with system impedance, outflow power and inflow power at each node. The bus dependency matrix (given below in Equation (8)) is calculated which depends on shortest path and power flow result. Total loss of the system (P_{loss}) is $12.6806MW$.

$$D_{bus\_dep} = \begin{bmatrix} 0.0000 & 4.8650 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.9803 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 10.7646 & 0.0000 \\ 0.0000 & 1.9730 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 4.9730 & 0.0000 & 0.0000 & 0.0000 \end{bmatrix} \tag{8}$$

As described above, the row sum of bus dependency matrix can be used as electrical closeness centrality measures which are $C_1 = 4.8650$, $C_2 = 0.9803$, $C_3 = 10.7646$, $C_4 = 1.9730$ and $C_5 = 4.9730$ and outgoing power are $P_1 = 142.6805$, $P_2 = 149.3261$, $P_3 = 64.7077$, $P_4 = 111.1685$ and $P_5 = 60.0000$ for buses 1, 2, 3, 4 and 5 respectively.

By using Equation (6), loss allocated to buses 1, 2, 3, 4 and 5 can be calculated as $p_1 = 4.2837$, $p_2 = 0.9034$, $p_3 = 4.2985$, $p_4 = 1.3536$ and $p_5 = 1.8414$ respectively. The fairness of the LA method can be verified that $p_1 + p_2 + p_3 + p_4 + p_5 = 12.6806$ MW.

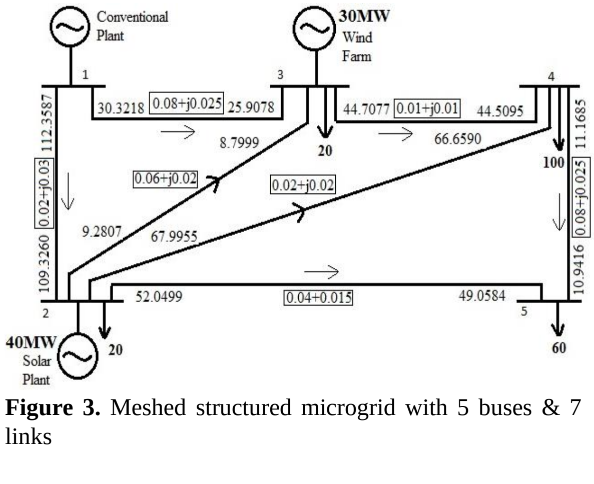


Figure 3. Meshed structured microgrid with 5 buses & 7 links

The proposed LA technique can be easily applied to the microgrids where change in generations is very frequent as it requires very less computational time and is a very fast and efficient technique. Electrical closeness centrality measures based LA method is efficiently applicable to both meshed structured microgrid and radial topology based microgrid.

4. APPLICATION OF PROPOSED METHOD

To illustrate applicability of proposed method with variable sources modified IEEE 14-bus test system is considered as an interconnected microgrid with meshed topology. Two different cases with altered renewable generation are considered to validate the applicability of proposed method in microgrids where alteration in power flow pattern is very frequent. The following scenarios are considered as microgrid for analysis of proposed LA method:

4. 1. Application of Proposed Loss Allocation Method With Variable Sources

Case 1: Interconnected microgrid with one solar plant and one wind farm

A modified IEEE 14-bus system is considered in which node 2 is assumed to be connected with a wind farm of 40MW rated capacity and node 3 has a concentrated solar plant of 60MW rated capacity. A new branch is added between buses 1 and 3 in this modified system and conventional grid is interconnected at bus1. Single line diagram of the modified test system is shown in Figure 4 with direction of power flow through the lines. Branch data for modified system are listed in Table 2.

After power flow, total loss of the system (P_{loss}) is calculated as 4.4700 MW. After power flow, by using LA technique proposed in section 2.2, loss allocated to each bus present in the network is given in Table 3.

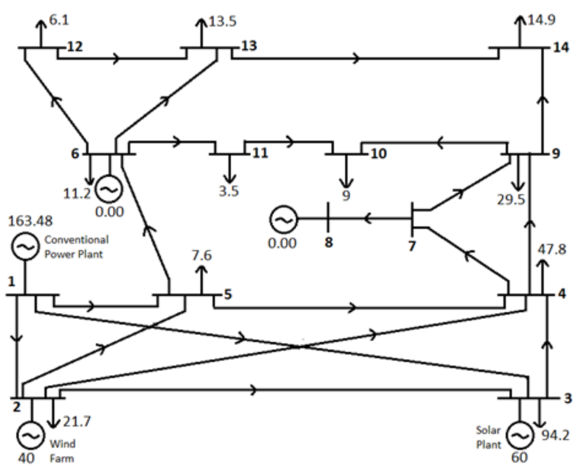


Figure 4. Modified IEEE 14-bus test system as meshed structured microgrid

TABLE 2. Branch data of modified IEEE 14-bus system

From Bus	To Bus	Resistance (in Ω)	Reactance (in Ω)
1	2	0.01938	0.05917
1	5	0.05403	0.22304
1	**3**	**0.00000**	**0.04211***
2	3	0.04699	0.19797
2	4	0.05811	0.17632
2	5	0.05695	0.17388
3	4	0.06701	0.17103
4	5	0.01335	0.04211
4	7	0.00000	0.20912
4	9	0.00000	0.55618
5	6	0.00000	0.25202
6	11	0.09498	0.19890
6	12	0.12291	0.25581
6	13	0.06615	0.13027
7	8	0.00000	0.17165
7	9	0.00000	0.11001
9	10	0.03181	0.08450
9	14	0.12711	0.27038
10	11	0.08205	0.19207
12	13	0.22092	0.19988
13	14	0.17093	0.34802

* Newly Added line

TABLE 3. Results of loss allocation of modified IEEE 14-bus system (with 2 DERs) considered as microgrid

Bus	Electrical Closeness Centrality	Outgoing Power (in MW)	Loss allocated (in MW)
1	9.9971	163.4800	1.0149
2	9.8958	96.4100	0.5924
3	10.8397	127.1300	0.8557
4	9.0000	94.3700	0.5274
5	8.9733	73.5900	0.4101
6	8.9777	41.6400	0.2321
7	9.9524	29.6100	0.1830
8	11.9524	0.0000	0.0000
9	9.9465	46.5700	0.2876
10	10.9456	9.0000	0.0612
11	10.9963	5.8200	0.0397
12	10.9993	7.5300	0.0514
13	9.9993	18.2100	0.1131
14	10.9407	14.9000	0.1012
	Total		4.4700

In Table 3, electrical closeness centrality, outgoing power and loss allocated to each bus is listed. In Table 3, loss allocated to bus 8 is zero as neither generator nor load is connected at bus 8 shown in (Figure 4). From Figure 4, it can also be observed that generator connected at bus 6 is not delivering any power but load is obtaining power. So, the loss is being allocated to bus 6. From results presented in Table 3, it can be concluded that total loss allocated to generators and loads are 2.463 MW and 2.0068 MW respectively. So, the proposed method is not dividing total loss to generators in equal proportional unlike pro-rata method and this is realized by including electrical closeness centrality indices which is representation of relative electrical distance of buses present in network.

Case II: Interconnected microgrid with two solar plants and two wind farms

Again, modified IEEE 14-bus system is considered as microgrid in which both node 2 and 6 are assumed to be connected with a wind farms of 40MW rated capacity and node 3 and 8 has a concentrated solar plant of 60MW and 50MW rated capacity respectively. After power flow, total loss of the system (P_{loss}) is calculated as 2.8777 MW. Proposed LA method is applied to IEEE-14 bus system considered as microgrid and results are listed in Table 4.

From results of Table 4, it can be concluded that total loss allocated to generators is 1.6671 MW while total loss allocated to loads is 1.2106 MW which indicates that total loss is not being shared by generators and loads in equal fraction which was drawback of LA methods related to pro-rata techniques. From Tables 3 and 4, it is clear that depending on power flow results, electrical closeness centrality changes. Loss allocated to buses changes depending on power flow results and electrical closeness centrality but sum of loss allocated to buses is exactly equal to the total loss of the system.

TABLE 4. Results of loss allocation of modified IEEE 14-bus system (with 4 DERs) considered as microgrid

Bus	Electrical Closeness Centrality	Outgoing Power (in MW)	Loss allocated (in MW)
1	10.8214	71.8779	0.3613
2	8.9686	86.0742	0.3586
3	10.9765	94.2000	0.4803
4	8.9801	58.9536	0.2459
5	8.9929	39.8391	0.1664
6	8.9440	45.3010	0.1882
7	9.9765	66.0341	0.3060
8	12.0000	50.0000	0.2787
9	9.9684	43.0276	0.1992
10	10.9715	9.0000	0.0459
11	10.9717	8.0126	0.0408
12	10.9748	7.7963	0.0397
13	9.9852	19.5840	0.0908
14	10.9666	14.9000	0.0759
Total			2.8777

4. 2. Application of Proposed Loss Allocation Method in Microgrid with Radial Topology A microgrid with radial topology is considered in Figure 5. It represents a modified 12-bus radial system integrated with conventional power plant at bus 1 and a solar plant and wind farm are connected at bus 5 and 9 respectively. It is assumed to be connected with a wind farm of 60MW rated capacity at bus 9 and node 5 has a concentrated solar plant of 90MW rated capacity. Bus 1 is not connected to any load; only conventional power plant is integrated into the network at bus 1. All the connected loads (shown in Figure 5) are in MW. Direction of power flow is shown in Figure 5.

After power flow, it has been found that the total loss of the system is 6.8429 MW. The loss allocated by the proposed method is listed in Table 5.

From results of Table 5, also it can be concluded that proposed method overcomes the drawback of LA methods based on pro-rata by sharing 2.9135 MW to generators and 3.9295 MW to loads.

It has been also observed from Tables 3, 4 and 5 that LA by proposed method has not given negative loss contribution to any generators or loads.

4. 3. Comparison of Proposed Loss Allocation Method For comparison of proposed method, two different test systems are considered: one with meshed and another with radial configurations. A 6-bus meshed topology with/without DGs connection can be found in literature [9] and 17-bus radial network with DGs can be perceived from [14].

4. 3. 1. 6-bus System with Meshed Topology A 6-bus test system with meshed topology, shown in Figure 6, is considered whose power flow results and system data can be found in literature [9]. Results obtained by proposed method for active power LA in 6-bus test

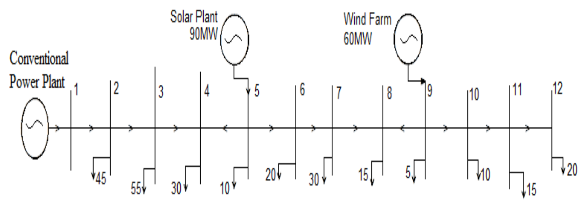


Figure 5. 12-bus radial system modified as microgrid

system is compared with the results of few other established and popular LA methods found in literature.

A modified 6-bus test system with meshed topology is considered where active power loss is 12.5561 MW. The proposed method for LA is applied to allocate loss contribution to each bus and then to loss contribution of individual generator and load. The comparison of LA to generators and loads with other methods for this 6-bus test system shown in Figure 6 is provided in Table 6.

From results listed in Table 6, it can be concluded that proposed method allocates 6.236 MW loss to generators connected at buses 1 and 2 while total loss allocated to loads is 6.3202 MW. In case of pro-rata method, total loss allocated to generators is 6.278 MW which is equal to total loss allocated to loads (6.278 MW). In cases of 6-bus system, method proposed in [9] gives negative loss contribution to bus 1 while proposed method does not allocate negative power loss contribution is any participants.

It can be observed from Table 6 that loss allocated to generators is 6.27811MW, 10.4771MW and 6.4231MW by pro-rata method [2], Z-bus method [7] and game theory method respectively. The proposed method allocates 6.236MW loss to generators, which seems similar as by pro-rata method [2]. Total loss allocated to loads are 6.278MW, 1.989MW and 6.106MW by pro-rata method [2], Z-bus method [7] and game theory method respectively. However, loss allocated to loads is 6.3202MW by proposed method.

TABLE 5. Results of loss allocation of 12-bus radial system considered as microgrid

Bus	Electrical Closeness Centrality	Outgoing Power (in MW)	Loss allocated (in MW)
1	15.8263	111.8429	1.6618
2	10.8454	110.6288	1.1264
3	8.9293	64.7067	0.5424
4	8.9751	30.0000	0.2528
5	8.8759	90.0000	0.7500
6	8.9586	56.6397	0.4764
7	8.9201	36.3377	0.3043
8	8.9603	15.0000	0.1262
9	8.9071	60.0000	0.5017
10	8.9676	45.0362	0.3792
11	12.3343	35.0049	0.4054
12	16.8483	20.0000	0.3164
Total			6.8429

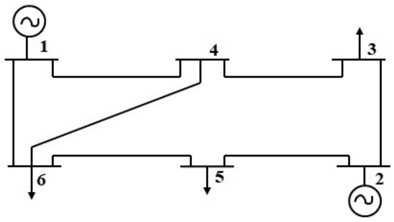


Figure 6. Six bus test system

TABLE 6. Loss allocation for 6-bus system at given load without wind generator

Bus No.	Pro-rata[2]	Z-bus [7]	Game theory	Abdelkader [8]	Elmitwally [9]	Proposed
Generators						
Bus 1	3.7252	3.4677	1.4325	0.0596	-0.1679	3.8489
Bus 2	2.5528	7.0994	4.9906	0.0498	0.4013	2.3871
Loads						
Bus 3	2.5577	0.9756	2.7365	4.8611	4.8611	2.5172
Bus 4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bus 5	1.3951	0.2769	2.6436	3.2991	3.2991	1.5048
Bus 6	2.3252	0.7365	0.7259	4.1624	4.1624	2.2982
Network loss	0.0000	0.0000	0.0000	0.1240	0.0000	0.0000
Total	12.5561	12.5561	12.5561	12.5561	12.5561	12.5561

4. 3. 2. 17-bus System with Radial Topology

A 17-bus radial distribution network with DGs is considered as microgrid and is shown in Figure 7. The power flow results with system data is listed in Table 7 for 17-bus system. Total active power loss of the system is 6.627kW.

Proposed method is applied to 17-bus radial topology network for comparing results with some existing methods. The system data and power flow results of 17-bus radial network is similar to that of [14] and presented in Table 7. The results of comparison with few existing methods for loss contribution by loads and generators in 17-bus radial system are presented in Table 8.

From Table 8, it is clear that total loss allocated to generators is 6.627 kW while total loss allocated to loads is 3.4272 kW in 17-bus radial network. It can be seen from Table 8 that total loss allocated to loads and generators is -0.41 kW and 7.04 kW respectively by marginal method. Total loss allocated to loads is greater

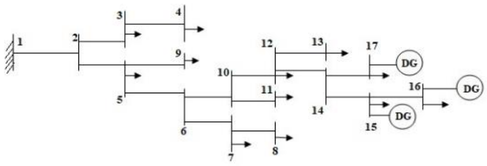


Figure 7. 17-bus radial distribution network

than that of generators by methods of [14], Z-bus and succinct. Proposed method does not allocate negative loss contributions to any participant like marginal, Z- bus or succinct methods in case of 17-bus radial network also.

From the results listed in Tables 3-8, we can see that higher amount of loss is allocated to buses having higher load or generation as expected. From the results it can be observed that, loss allocated to each bus is positive

TABLE 7. 17-bus system data [14]

Branch No.	From node	To node	r (pu)*10^{-3}	x (pu)*10^{-3}	b (pu)	From node injection (kW)	From node injection (kVAR)	To node injection (kW)	To node injection (kVAR)
1	1	2	2.5	2.6	0.03	1100.62	561.059	-1096.7	-586.919
2	2	5	0.7	0.7	0.02	896.716	493.692	-895.960	-512.750
3	2	3	0.8	0.8	0.02	200.050	93.2270	-200.010	-113.010
4	3	4	0.7	0.7	0.00	111.010	63.0120	-111.000	-63.0000
5	5	9	2.1	2.2	0.02	89.0200	30.2350	-89.0000	-50.0000
6	5	6	2.0	2.1	0.02	666.949	402.521	-665.706	-420.960
7	6	10	0.1	0.1	0.00	186.170	168.100	-186.170	-168.100
8	6	7	0.9	0.9	0.00	479.529	252.855	-479.258	-262.429
9	7	8	1.7	1.7	0.00	338.258	182.429	-338.000	-192.000
10	10	11	0.6	0.6	0.00	152.019	86.0190	-152.000	-86.0000
11	10	12	1.8	1.8	0.00	34.1520	82.0840	-34.1370	-82.0690
12	12	13	0.3	0.3	0.00	10.0000	5.0000	-10.0000	-5.0000
13	12	14	1.1	1.1	0.00	-241.860	-73.9310	241.930	74.0020
14	14	15	1.1	1.1	0.00	-222.930	-85.0840	222.990	85.1480
15	14	17	0.7	0.7	0.00	-19.0000	11.0820	19.0000	-11.0820
16	15	16	0.1	0.1	0.00	-127.998	-55.8580	128.000	55.8600

TABLE 8. Loss allocation results with load and DG data for 17-bus radial system

Bus No.	P (kW)	Q (kVAR)	Loss Allocation in kW					
			Pro rata	Marginal	Z-bus	Succinct	Jahromi [14]	Proposed
Loads								
3	89.000	50.0000	0.1600	0.3400	0.220	0.2200	0.0900	0.1995
4	111.00	63.0000	0.2000	0.4900	0.290	0.2900	0.1800	0.1186
5	140.00	80.0000	0.2500	0.5600	0.430	0.4400	0.2600	0.8285
7	141.00	80.0000	0.2500	0.5200	0.780	0.7900	0.8600	0.4778
8	338.00	192.000	0.6000	2.0800	2.120	2.1500	3.3900	0.6311
9	89.000	50.0000	0.1600	0.4900	0.300	0.3000	0.1600	0.0951
11	152.00	86.0000	0.2700	0.3700	0.770	0.7900	1.2300	0.1624
12	266.00	151.000	0.4800	-0.3000	1.360	1.4200	0.3900	0.2555
13	10.000	5.0000	0.0200	-0.0300	0.050	0.0500	0.0100	0.0107
15	205.00	116.000	0.3700	-1.9800	-0.250	-0.1500	0.0000	0.4267
16	72.000	41.0000	0.1300	-0.8000	-0.090	-0.0600	0.0000	0.2137
17	241.00	137.000	0.4300	-2.1400	-0.510	-0.1800	0.0000	0.2777
Subtotal			3.3100	-0.4100	5.470	6.0500	6.5700	3.4272
Generators								
15	300.00	145.290	1.3100	2.7900	0.360	0.2200	0.0300	1.2631
16	200.00	96.8600	0.8700	2.1000	0.240	0.1700	0.0200	0.8421
17	260.00	125.920	1.1300	2.1500	0.550	0.1900	0.0000	1.0947
Subtotal			3.3100	7.0400	1.150	0.5800	0.0500	3.1998
Total			6.6200	6.6300	6.620	6.6300	6.6200	6.6270

always which indicates that the proposed method does not allocate negative loss contribution to renewable energy resources which are DGs connected in a microgrid.

From Table 8, it can be observed that loss allocated to loads is 3.31 kW, 5.47 kW and 6.05 kW by pro-rata, Z-bus and succinct method respectively while marginal method allocates negative loss (-0.41 kW) to loads. Loss allocated to generators is 3.31 kW, 1.15 kW and 0.58kW by pro-rata, Z-bus and succinct method respectively while marginal method while marginal method makes over recovery by allocating 7.04kW loss to generators.

5. APPLICATION OF PROPOSED LOSS ALLOCATION METHOD IN LARGER MICROGRID

Consider a modified 30-bus system as interconnected microgrid with meshed topology in which distributed energy resources (DERs) are connected at five buses. Bus 13, bus 23 and bus 27 have solar plants of 30 MW, 20 MW and 30 MW rated capacity respectively. Bus 2 and bus 22 are connected with a wind farm of 60 MW and 20 MW rated capacity respectively. After power flow analysis, total system loss is 5.6436 MW. Results of LA to various buses of 30-bus microgrid system by proposed method are listed in Table 9.

TABLE 9. Results of loss allocation of 30-bus system with 5 DERs considered as microgrid

Bus	Electrical Closeness Centrality (C_i)	Outgoing Power at bus (P_i), (in MW)	Proportional Index ($a_i = \frac{P_i}{\sum_{i=1}^{n} P_i C_i}$)	Loss Allocated (in MW)
1	26.6132	93.8436	0.0047	0.7008
2	24.4788	115.9418	0.0058	0.7964
3	26.9713	36.4975	0.0018	0.2762
4	24.8902	62.6927	0.0031	0.4379
5	26.9121	26.6015	0.0013	0.2009
6	22.9696	82.7536	0.0041	0.5334
7	26.9586	22.8000	0.0011	0.1725
8	27.9586	30.0000	0.0015	0.2354
9	25.9417	20.9345	0.0010	0.1524
10	24.9225	12.5812	0.0006	0.0880
11	27.9530	10.0000	0.0005	0.0784
12	23.8812	39.1963	0.0019	0.2627
13	27.9776	30.0000	0.0015	0.2355
14	26.9403	6.2000	0.0003	0.0469
15	24.9361	18.6747	0.0009	0.1307
16	26.9189	10.8659	0.0005	0.0821
17	26.9384	9.0000	0.0004	0.0680
18	26.9236	9.9101	0.0005	0.0749
19	26.9171	9.5000	0.0005	0.0718
20	26.9218	5.0267	0.0002	0.0380
21	26.9371	18.2619	0.0009	0.1380
22	26.8745	18.3642	0.0009	0.1385
23	26.8853	20.0000	0.0010	0.1509
24	25.9338	10.0965	0.0005	0.0735
25	25.9366	14.6109	0.0007	0.1063
26	27.9202	3.5000	0.0002	0.0274
27	24.8803	15.1454	0.0008	0.1057
28	26.9485	12.4682	0.0006	0.0943
29	26.9459	6.0838	0.0003	0.0460
30	26.9459	10.6000	0.0005	0.0802
Total				5.6436

In modified 30-bus microgrid system, DGs are connected at buses 2, 13, 22, 23 and 27. From the results listed in Table 9, it can be calculated that total loss allocated to generators and loads is 1.8955 MW and 3.7482 MW respectively. It is clear that distribution of system loss among generators and loads is not like pro-rata method. The proposed method segregates loss on the basis of electrical closeness centrality which includes the relative position for sustaining transparency.

6. CONCLUSION

This paper proposes a simple and robust method for LA in interconnected microgrid with meshed topology as well as radial topology where generations are considered to be variable. Due to various non-conventional energy sources in microgrid, power flow changes very frequently and presence of multiple sources modifies network usages. Proposed method easily determines loss allocated to each bus for every scenario. While allocating loss to different buses, the proposed method considers relative position of buses in the network and requires only power flow solution with network data. Electrical closeness centrality measure is used to identify the relative location of buses present in the network and can be calculated by using power flow results. The results obtained by proposed method shows that electrical closeness centrality changes according to power flow results and corresponding to that amount of loss allocated to different buses changes. LA by proposed method includes position of each load and generators in the network and loss contribution to generators and loads depend on the amount of power produced or consumed by them. The proposed procedure is simple to understand and its execution is undemanding because it does not require intricate computational application.

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Persian Abstract

چکیده

با برخی فرض ها و محدودیت ها ، روش های مختلفی در ادبیات به طور عمده برای تخصیص تلفات در شبکه انتقال و پس از آن برای شبکه توزیع شعاعی گسترش یافته و برخی از روش ها به طور خاص برای شبکه توزیع شعاعی توسعه یافته است. اما این روش ها برای میکرو شبکه هایی که با شبکه های معمولی در سطح انتقال و توزیع فرعی بسته به موقعیت جغرافیایی یکپارچه هستند ، مناسب نیستند. در این مقاله یک روش تخصیص تلفات بر اساس نتایج جریان برق و موقعیت نسبی اتوبوس ها برای میکرو شبکه بهم پیوسته ارائه می شود که در صورت تغییر مکرر نسل ها به دلیل تناوب منابع تجدید پذیر بسیار موثر است. اجرای روش پیشنهادی در ریز شبکه با توپولوژی مشبک و شعاعی بدون هیچ گونه پیچیدگی محاسباتی بسیار ساده است و فقط به راه حل جریان برق و داده های شبکه نیاز دارد. نتایج برای شرایط مختلف تولید منابع تجدید پذیر در ریز شبکه نشان داده شده است تا کارآیی روش تخصیص تلفات پیشنهادی را نشان دهد.