HiJASE
Himalayan Journal of Applied Science and Engineering (A peer-reviewed Journal)

ISSN 2738-9898 (Print) ISSN 2738-9901 (Online)

Review of Various Transmission Loss Allocation Methods: A Case Study of Integrated Nepal Power System using Best Method

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Received on: 26th Oct., 2022

Accepted for publication: 24th Nov., 2022

Abstract

This paper presents a review of the most relevant and practical methods for allocating transmission loss in a deregulated market. They are the pro-rata (PR) method, the marginal allocation (ITL) method, the proportional sharing (PS) method, and the Z-Bus method. This study has also performed a qualitative comparison of four methods using the IEEE 14 bus system. Finally, the Z-Bus method is selected as the best option for implementation in the Integrated Nepalese Power System Network (INPS). As of 2022, the loss allocation is determined at all 132 and 220 kV substations of INPS. The study of transmission loss allocation for INPS is carried out for six different cases, considering the variation in patterns of energy generation and demand, i.e., system full generation, summer peak, winter peak, average peak, dry peak, and contingency condition. The result shows the load, like Kathmandu Valley, which is in the region of generation, and the generator, like in the eastern region, which is in the region of demand, are mostly compensated with negative losses. Loads in the western region and generators like the Upper Tamakhoshi, which are far from the generator or load, are assigned the highest positive loss. Loss allocation to load and generator can vary depending on the loading conditions that INPS is operating under. The generation is comparably distributed in the full generation, summer, and contingency instances; as a result, the loss allocation to both loads and generators is significant. However, the bulk of losses are only attributed to the generator side in the three other scenarios with less generation, when the majority of the generation is only aggregated in a specific location. This is a result of the remote generator's long-distance power flow, which raises system loss. As a result, the Z-Bus method assigned the generator side the majority of the losses. Additionally, the majority of INPS's generation is determined to be remotely located, which increases their risk of transmission loss. Because of this, INPS is best served by the Z-Bus approach, which takes into account the locations of buses within the network. In order to minimize system loss, this encourages big demand or generation to be positioned close to the center of generation or demand.

Keywords: ITL, INPS, pro-rata, proportional sharing, Transmission loss allocation (TLA), Z-bus method

1. Introduction:

The transmission loss in electric power system is a natural phenomenon. Most of these losses are due to the electrical current flowing through them and causes heating of power lines. Transmission loss represents about 4-6% of total generation [1]. This quantity of power loss is worth millions of dollars per year in a system. In a deregulated market system transmission loss has to be shared among the market participants due to the financial independence and competition. Loss allocation just adjusts the revenue distribution at the network buses among generators and loads. Power systems inevitably lose power, hence the units contributing the loss in the system must be compensated at the system marginal price. As a result, the loss allocation procedure decides how the extra cost might be equally split among all generators and loads.

In context of Nepal power system, the government has planned and proposed the complete unbundling of the Nepal Electricity Authority, NEA (the sole government-based utility that transmits & distributes the electricity). The government has already established Rastriya Prasaran Grid Co Ltd. (RPGCL) on July 2015 and Vidyut Utpadan Company Limited (VUCL) on November 2016. The generation part has been deregulated with number of IPPs generating electricity and selling it to the NEA. Now the distribution sector is planned to be unbundled. With complete unbundling, the Nepalese power system has to enter in the electricity market. Even now NEA is participating in Indian spot markets, purchasing almost 20-25% of total energy from it in order to manage the deficit energy demands and also selling excess energy during the wet season. With the realization of the electricity spot market in near future, the transmission loss allocation and the appropriate method to implement will be a major concern.

In [1], transmission losses are characterized into three components: load loss due to current flow from generator to load, generators circulating current loss and network loss. The paper [1] proposed a method for loss allocation based on the proposed loss decomposition. In the study [2], a loss allocation method called "Z-bus allocation" was proposed. Based on the complex impedance matrix and complex nodal injections, which specify the network equations precisely. The sparse admittance matrix is the foundation for all calculations. Instead of power flow, it concentrates on intricate current flows. Research paper [3] has discussed about incremental methods where two vectors: the loss supply and the load distribution parameters are specified. Unique, non-arbitrary incremental loss allocations have performed initially in small increments and finally extended to large variations. In the paper [4], a thorough comparison of four real-world strategies was covered. These strategies were the PR method, marginal allocation, unsubsidized marginal allocation, and proportional sharing. Research paper [5] has also presented the comparison of three important methods: PR, incremental and Z-bus methods that are used in transmission networks. The paper [5] shows that PR method does not depend on the network which represents a drawback. The Incremental technique based on the incremental loss factor and Z-bus methods presented both positive and negative allocation which is considered as an advantage. The improved Z-bus approach for loss allocation was covered in paper [6]. The connection between the bus current injections and the generation/load currents is initially established using a power invariant matrix. The Z-bus is then updated by representing the network's actual power loss in terms of the currents flowing through generators or loads. Unlike the Z-bus approach, which merely distributes losses to each bus in accordance with equivalent injected current, this method allocates the total losses to both generators and loads independently.

In [7] & [8], the paper presented a loss allocation method based on the physical power flow in the system. The method determined the shares of individual loads in the total line loss based on the contributions of the individual load currents. In the loss allocation process, the suggested solution took into account both the active and reactive power of loads. Research paper [9] has proposed an efficient method for solving the reactive power tracing problem based on the ac power flow computation. The paper presented two new matrix named Outflow-line and inflow line matrix which are used to calculate the contribution of each source or load to the reactive power flow and loss of each line, and determine the share of each source in the reactive power consumed by each load. In the paper [10], a routing method is provided that uses an algorithm of least loss path to trace the power flow path from generator to load. This method evaluated zero loss to the loads having a generator on the same bus and used a probabilistic approach to routing current flow with the criterion of minimum loss path. The idea of lowering losses by reducing the pathways of current flow with the placement of generators of minor capacities at various locations was also proposed in the study, in addition to loss allocation. Research paper [11] has presented a combined ANN and game theoretic approach for loss allocation. Using Shapley values, the artificial neural network-based approach calculates the losses on game theory solutions and uses those results to train the neural network.

In the paper [12], a scheme based on the set-theoretic principle is presented for allocating active power loss in the context of the smart grid to load nodes. The above principle identifies nodes using certain segments of a network. The identified nodes are then allocated with active loss in line with active power demands. In [13], a methodology was proposed 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 paper employs two distinct loss allocation techniques based on circuit theory and power flow solutions. A comparison of cases with and without renewables is performed to assess the impact of renewables integration into the network. The effect of time variation on loading and renewable energy generation conditions is also investigated.

Many techniques, as mentioned above, have been practiced and researched in the literature, but a unique and accurate method has not yet been found. Different methods are implemented by different countries as per their market structure (bilateral or pool market), network topology, types of energy resources used, and demands of market participants. Nepal also had to quickly implement one technique in the electricity market. The Nepalese power system has a very sparse network topology and mostly hydroelectric energy. Thus, it is necessary to find out the best option for Nepal's INPS.

2. Transmission Loss Allocation Methods:

Four relevant and practical loss allocation techniques are taken in this study. These four techniques are compared qualitatively with six parameters.

1. Network Topology Dependent
2. Power/Current Dependent
3. Non Volatile
4. Cross Subsidies (Negative Loss Allocation)
5. Easy to understand, and
6. Simple to implement

We know that the sum of all generations is equal to the sum of all demands plus the losses. That is

$$P_G = P_D + L,\ P_G = \sum_{i=1}^{N_G} P_{Gi},\ P_D = \sum_{j=1}^{N_D} P_{Dj} \tag{1}$$

where

P_G Total active power generated;

P_{Gi} Power output of generators of bus i;

P_D Total active power demand;

P_{Dj} Active power demanded by consumers of bus j;

L Transmission power losses;

N_G Number of generating buses;

N_D Number of demand buses;

It is assumed that there is only one generator and one demand in each bus for the sake of simplicity and generality. As a result, there will be no longer be any differentiation between generator i, load i, and bus i.

The four subsections below provide descriptions of the transmission loss allocation techniques under consideration.

2.1. Pro Rata (PR) Method:

In this case, the losses are proportionally distributed between generators and consumers, with 50% of losses going to each group. A proportional allocation rule is then implemented. The losses assigned to a generator or consumer are inversely correlated with their respective rates of energy production or consumption. In the energy market of mainland Spain, where 100% of losses are given to consumers, a PR technique is now in use [4].

According to the PR technique, 50% of losses go to requests and 50% go to generators, so

$$L_{Gi} = \frac{L}{2}\frac{P_{Gi}}{P_G} \text{ and } L_{Dj} = \frac{L}{2}\frac{P_{Dj}}{P_D} \quad (2)$$

where L_{Gi} are the losses allocated to the generator i, and L_{Dj} are the losses allocated to the demand j.

Generation and demand loss allocation factors are computed, respectively, as

$$L_{Gi} = \frac{L}{2}\frac{P_{Gi}}{P_G} = K_G P_{Gi}, K_G = \frac{1}{2}\frac{L}{P_G} \quad (3)$$

$$L_{Dj} = \frac{L}{2}\frac{P_{Dj}}{P_D} = K_D P_{Dj}, K_D = \frac{1}{2}\frac{L}{P_D} \quad (4)$$

It should be remembered that all buses have the same generating loss allocation factors K_G and demand loss allocation factors K_D. Losses attributed to generators and demands in this case are always positive.

2.2. Marginal Allocation (ITL) Method:

In order to allocate losses to generators and demands appropriately, this method uses ITL coefficients. Using a convergent power flow, ITL may be easily obtained [4]. An incremental change in the power pumped into a bus results in a change in total losses, which is represented by the ITL of that bus.

Therefore

$$K_i = \frac{\partial L}{\partial (P_{Gi} - P_{Di})} \quad (5)$$

where K_i is the ITL corresponding to bus i. It should be noted that the ITL of the slack bus is zero by definition.

First computations of the losses allocated to generator i, and demand j are respectively,

$$L_{Gi} = P_{Gi}\frac{\partial L}{\partial P_{Gi}} = P_{Gi}K_i \quad (6)$$

$$L_{Dj} = P_{Dj}\frac{\partial L}{\partial P_{Dj}} = -P_{Dj}K_j \quad (7)$$

The aggregate of all allocated losses (L'), however, does not equal the total real (measured) losses L, which is due to nonlinearities.

$$L \neq \sum_{i=1}^{N_G} L_{Gi} + \sum_{j=1}^{N_D} L_{Dj}$$
$$= \sum_{i=1}^{N_G} P_{Gi}K_i - \sum_{j=1}^{N_D} P_{Dj}K_j = L' \quad (8)$$

Therefore, to apportion the precise amount of losses L, a normalizing process is employed.

$$L = L'\frac{L}{L'} = \left(\sum_{i=1}^{N_G} P_{Gi}K_i - \sum_{j=1}^{N_D} P_{Dj}K_j\right)\frac{L}{L'}$$
$$= \sum_{i=1}^{N_G} P_{Gi}K'_i - \sum_{j=1}^{N_D} P_{Dj}K'_j \quad (9)$$

where $K'_i = K_i\left(\frac{L}{L'}\right)$ is the normalized ITL coefficient for bus i.

Finally, losses allocated to every generator and demand are, respectively,

$$L'_{Gi} = P_{Gi}K'_i \text{ , \& } L'_{Dj} = P_{Dj}K'_j \quad (10)$$

This marginal procedure may allocate negative losses to either generators or demands, and these negative losses can be seen as cross-subsidies. This marginal procedure can be modified by modifying the ITL coefficients to avoid subsidies and this modified method can be referred as unsubsidized marginal (U-ITL) method. In this research, only normal ITL method is considered for comparison.

2.3. Proportional Sharing Allocation (PS) Method:

The distribution of losses among generators and consumers is made possible by using the output of a convergent power flow in combination with a linear proportional sharing concept [4]. This theory, which is neither demonstrable nor disputable [4], claims that "the power flow reaching a bus from any power line splits among the lines expelling electricity from the bus proportionally to their corresponding power flows."

With this methodology, generators are assigned losses after demands. In respect to demands, a total gross demand including losses P_D^G is defined as

$$P_D^G = P_D + L \text{ and } P_D^G = \sum_{j=1}^{N_D} P_{Dj}^G \quad (11)$$

where P_{Dj}^G is the gross demand of bus j.

In order for $P_G = P_D^G$., the total gross demand must equal the total generation. The power balance in each bus of an equivalent lossless network can be calculated using the proportionate sharing principle.

$$P_i^G = P_{Gi} + \sum_{j\in\alpha_i} c_{ji}P_j^G, \forall i = 1, \dots, N \quad (12)$$

With $c_{ji} = \frac{P_{ji}^G}{P_j^G} \approx \frac{P_{ji}}{P_j}$ (13)

where

P_i^G	gross power injected in bus i;
P_{Gi}	generation in bus i;`
$\sum_{j \in \alpha_i} c_{ji} P_j^G$	power flow reaching bus i from lines connected to it;
α_i	set of buses from which power flows toward bus i;
P_{ji}^G	gross power flow from j to i;
P_{ji}	actual power flow from j to i (measured in j);
P_j	actual power injection in bus j.

Equation (12) constitutes a system of linear equations that is solved easily for P_i^G, $i = 1, \dots, N$. Gross demands and losses are then computed, respectively, as

$$P_{Dj}^G = \frac{P_j^G}{P_j} P_{Dj} \text{ and } L_{Dj} = P_{Dj}^G - P_{Dj} \quad (14)$$

Analogously, losses are assigned to generators. Total gross generation including losses P_G^G is defined as

$$P_G^G = P_G + L \text{ and } P_G^G = \sum_{i=1}^{N_G} P_{Gi}^G \quad (15)$$

where P_{Gi}^G is the gross generation of bus i (including losses).

This gross generation must equal total demand, so that $P_G^G = P_D$. Using the proportional sharing principle, the power balance in bus i, of an equivalent lossless network becomes

$$P_i^G = P_{Di} + \sum_{j \in \gamma_i} c_{ji} P_j^G, \ \forall i = 1, \dots, N \quad (16)$$

where

P_i^G	gross power injected in bus i;
P_{Di}	demand in bus i;
$\sum_{j \in \gamma_i} c_{ji} P_j^G$	power flow leaving bus i;
γ_i	set of buses drawing power from bus i;

Equation (16) constitutes a system of linear equations that can be solved easily for P_i^G, $i = 1, \dots \dots, N$. New generations and losses are then computed, respectively, as

$$P_{Gi}^G = \frac{P_i^G}{P_i} P_{Gi} \text{ and } L_{Gi} = P_{Gi} - P_{Gi}^G \quad (17)$$

In order to assign 50% of losses to the generation and 50% to the demand, the generation and demand per bus are computed as

$$P'_{Gi} = \frac{P_{Gi}^G + P_{Gi}}{2} \text{ and } P'_{Dj} = \frac{P_{Dj}^G + P_{Dj}}{2} \quad (18)$$

Final losses assigned to every generator and demand are, respectively,

$$L'_{Gi} = P_{Gi} - P'_{Gi} \text{ and } L'_{Dj} = P'_{Dj} - P_{Dj} \quad (19)$$

Finally, generation and demand loss allocation factors are calculated as

$$K_{Gi} = 1 - \frac{P'_{Gi}}{P_{Gi}} \text{ and } K_{Dj} = \frac{P'_{Dj}}{P_{Dj}} - 1 \quad (20)$$

2.4. Z-Bus Allocation (Z-Bus) Method:

The Z-bus allocation method's objective is to take a solved power flow and evenly distribute the system transmission losses, P_{loss}, among the n network buses in accordance with

$$P_{loss} = \sum_{k=1}^{n} L_k \quad (21)$$

where,

P_{loss}	Total power loss
L_k	Real loss allocation to bus k

In order to calculate L_k according to Z-bus allocation method, let us consider the network admittance matrix,

$$Y = G + jB \quad (22)$$

The system real losses can be expressed either in terms of Y and V or through Z and I, where,

$$Z = Y^{-1} = R + jX \quad (23)$$

Since the total system loss is the sum of power injections at all buses, P_{loss} can be found as:

$$P_{loss} + jQ_{loss} = \sum_{k=1}^{n} V_k I_k^* \quad (24)$$

where Q_{loss}= reactive component of the system loss

Therefore, the real part of the system loss is,

$$P_{loss} = R\{\sum_{k=1}^{n} V_k I_k^*\}$$

or, $P_{loss} = R\{\sum_{k=1}^{n} I_k^* \left(\sum_{j=1}^{n} Z_{kj} I_j\right)\}$

Thus,

$$P_{loss} = R\{\sum_{k=1}^{n} I_k^* \left(\sum_{j=1}^{n} R_{kj} I_j\right)\} + R\{\sum_{k=1}^{n} I_k^* \left(\sum_{j=1}^{n} jX_{kj} I_j\right)\} \quad (25)$$

Since matrix X is symmetric, the 2nd term of above equation (25) becomes zero [2], so that the system losses can be expressed uniquely in terms of the complex currents and the resistance matrix, R. Thus,

$$P_{loss} = R\{ \sum_{k=1}^{n} I_k^* \left(\sum_{j=1}^{n} R_{kj}\, I_j \right) \} \qquad (26)$$

Therefore, the loss components associated with bus k can be expressed as,

$$L_k = R\{ I_k^* \left(\sum_{j=1}^{n} R_{kj}\, I_j \right) \} \qquad (27)$$

As seen in equation (27), the loss component, L_k, encompasses n terms representing the coupling actions between current injections at all n buses with the current injection at bus k. One characteristic of this natural separation of the system losses is that the loss terms depend primarily on the complex bus current injections.

If demand, P_{dk} and the generation, P_{gk} exist in the same bus k, then the loss component L_k is further divided among the two using pro-rata technique.

Let, $$\gamma_k = \frac{P_{gk}}{P_{gk} + P_{dk}} \qquad (28)$$

Generator's share of loss component is $\gamma_k L_k$ and load's share is$(1 - \gamma_k)L_k$.

3. System Under Study:

The objective of this research is to review and compare different transmission loss allocation methods and apply one best method to the existing INPS model for analysis. The IEEE-14 bus system is used as a test system for comparing four different loss allocation techniques. The IEEE 14 bus system consists of one Slack bus, four PV buses, and eight PQ buses. It consists of twenty branches, five generators, and eleven load points. The IEEE14 bus system and modified IEEE 14 bus system are used in this study to initially calculate the loss allocation and compare them with each other.

INPS network (as of July, 2022) [14], is taken for detail study. The transmission model of INPS has considered only 220 kV and 132 kV voltage level buses, and all other lower voltage level loads and generation are lumped into these buses for proper calculation. INPS is an electrical network of a combination of all generation, transmission, and distribution systems of Nepal. NEA is responsible for its operation and acts as the system operator. With an installed generation capacity of 2081.788 MW of hydro, 53.41 MW of Thermal, and 54.72 MW of Solar Power Plant, a total of 2,185.382 MW installed generation capacity is connected to the INPS [14]. Since most of the generation is hydro-based, the generation mostly depends upon the flow of rivers. The national peak demand of wet season occurred on July 12, 2022 A.D. was 1747.53 MW [14]. And the annual system peak demand (with export) noted on July 6, 2022 A.D. was 1963.98 MW [14]. To meet the demands of INPS, power is imported from India through a number of import points. INPS operates at different voltage levels from 0.23 kV to 220 kV. The major transmission line network runs parallel to the East-West Highway and major river corridors. INPS is made up of 5,329 circuit kilometers of transmission lines ranging from 66 kV to 400 kV and 137 substation nodes with a total capacity of 7148.60 MVA (11 kV to 220 kV) [14]. For the last nine years, the INPS network's transmission loss has been in the 4-6 % range. The generations connected to 33/11 kV distribution substations are not considered, and their respective generations are deducted from the total load of the system. A total of 69 buses and 75 branch systems are considered.

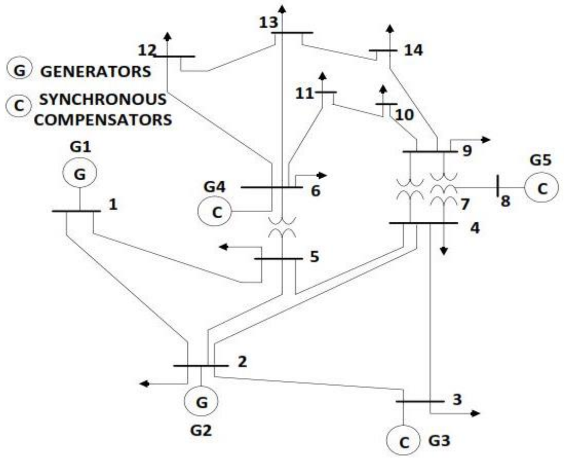

Figure 1: IEEE 14 Bus Test System

Some data related to INPS has been assumed to be the closest possible approximation and reactive power is calculated using the formula. The transmission line data such as connecting substations, type of circuit (single/double), length of circuit, and conductor type are taken from NEA Transmission Report 2022. Using the standard values of R & X per unit length, the R & X parameters of each transmission line are calculated. For bus data, different seasons' loading conditions of INPS are considered for analysis. Summer peak, winter peak, dry peak, annual average peak, system full generation condition, and one heavy line contingency condition are taken into consideration.

The AC power flow result is found using MATPOWER toolbox of MATLAB software. The AC power flow is calculated in MATPOWER to determine line loss and system loss.

4. Simulation and Results:

4.1. IEEE 14 Bus System:

The Loss allocation of different methods on the IEEE 14 bus system is shown in Table I. The units of Loss Allocation can be in per unit [pu] of a total loss, percentage loss per unit, and the loss cost in NRs/h. Here, the evaluation of each method is based on the values of the percentage of system loss.

In Table I, Generator 1 with about 85% of the total generation, has the highest loss/cost allocation in all methods except ITL where it is chosen as a slack bus and has no allocation. Similarly, load bus 3 which comprises about 36% of the total load has the next highest loss allocation. The remaining buses have received varying allocations with differences but a relatively similar trend in all four methods. The Z-bus method prioritizes current injections, which explains why bus 1 has the highest allocation (56.7%). Whereas due to low current injection, bus 2 where both load & generation is placed has received a low allocation (i.e. 0.8%). If a bus contains both a load and a generator, the loss allocated to the bus is divided again using the simple pro-rata method in the Z-Bus method. Thus in bus 2, the generator part receives 0.52% and the load part 0.28% loss.

Table 1: Loss Allocation Of IEEE 14 Bus System

Bus No.	Active Power Gen. Pg [pu]	Active Load Dem. Pd [pu]	Bus Current Injection |I|pu	Distribution of Active Power losses, P_{loss}=13.393 MW			
				PR L% [pu]	ITL L% [pu]	PS L% [pu]	Z-Bus L% [pu]
1	2.324	0	2.176	0.464	0.000	0.382	0.568
2	0.4	0.217	0.222	0.036	0.031	0.118	0.008
3	0	0.942	0.954	0.198	0.434	0.197	0.213
4	0	0.478	0.775	0.101	0.176	0.101	0.091
5	0	0.076	0.530	0.016	0.023	0.020	0.020
6	0	0.112	0.615	0.024	0.035	0.023	0.016
7	0	0	0.112	0.000	0.000	0.000	-0.007
8	0	0	0.159	0.000	0.000	0.000	-0.010
9	0	0.295	0.411	0.062	0.109	0.061	0.034
10	0	0.09	0.103	0.019	0.034	0.019	0.011
11	0	0.035	0.037	0.007	0.013	0.007	0.003
12	0	0.061	0.068	0.013	0.023	0.013	0.008
13	0	0.135	0.140	0.028	0.053	0.028	0.015
14	0	0.149	0.149	0.031	0.069	0.031	0.029
Total	2.724	2.59	6.450	1	1	1	1

Table II describes the results of the modified IEEE 14 bus system where a generation of 100 MW is added at bus 8. The other loads and network parameters remain same as in Table I. Here, the motive is to examine the result after placing generation at central. As from Table II, one of the major notices found is that the result shows system losses reduction by 56.6% and relatively loss percentage allocation has decreased significantly. For example, Bus 1 is now generating 47% of the total generation and is allocated 38.91% of the total loss. On the other hand, load bus 3 constituting 36% of the total load is now allocated 42.73% of the system losses. Here it can be explained as load bus 3 is now not as close to the "Centre of Gravity" of the generation as it was in the first case and also here the current injection has relatively increased by 12%.

Table 2: Loss Allocation Of Modified 14 Bus System

Bus No.	Active Power Gen. Pg [pu]	Active Load Dem. Pd [pu]	Bus Current Injection |I|pu	Distribution of Active Power losses, System loss=5.816 MW; PR L% [pu]	ITL L% [pu]	PS L% [pu]	Z-Bus L% [pu]
1	1.248	0	1.149	0.257	0.000	0.217	0.389
2	0.4	0.217	0.136	0.038	0.084	0.112	0.011
3	0	0.942	0.952	0.198	0.648	0.196	0.427
4	0	0.478	0.558	0.101	0.173	0.100	0.053
5	0	0.076	0.443	0.016	0.025	0.017	0.013
6	0	0.112	0.462	0.024	0.049	0.023	0.037
7	0	0	0.113	0.000	0.000	0.000	-0.003
8	1	0	0.941	0.206	-0.303	0.171	-0.020
9	0	0.295	0.512	0.062	0.085	0.061	-0.011
10	0	0.09	0.092	0.019	0.031	0.019	0.007
11	0	0.035	0.034	0.007	0.014	0.007	0.003
12	0	0.061	0.071	0.013	0.034	0.002	0.018
13	0	0.135	0.129	0.028	0.076	0.044	0.030
14	0	0.149	0.151	0.031	0.084	0.031	0.046
	2.648	2.59	5.743	1	1	1	1

In both cases, it can be noticed that ITL and Z-bus method has one common characteristic of negative loss allocations. The fact that negative allocation is provided can be viewed as a benefit. As it informs which buses (generators and loads) are well positioned in the network, and this can help to indicate the bus for increasing the generation or the demand, in certain areas. Thus, this negative loss allocation can be used as a monetary incentive to those generators which is well positioned in the network. Alternatively, generators or loads which are poorly positioned receive proportionally higher loss allocations.

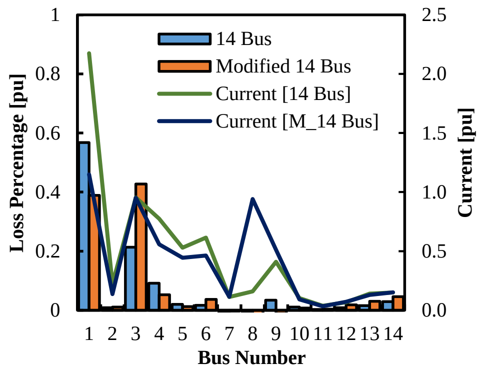

Figure 2: Comparison of LA between two Cases (Z-Bus method)

In the latter case, for the ITL method bus 8 receives -30.32% loss allocation and similarly in the Z-bus method also, the relocation has resulted in negative loss allocation to bus 9 with the change of percentage loss allocation from 3.4% to -1.13% only because of relocation of generation. This generator relocation has resulted in a reduction in the line flow path for bus 9, contributing less to the total loss. This generation relocation has resulted in a more evenly distributed generation and load distribution.

In both cases, it can be noticed that the Z-bus method differs significantly from other methods in buses no. 2, 7, 8, and 9. It can be explained by two factors: the increased sensitivity of network location and current injections, which have a significant impact on network losses.

After applying four LA methods to the IEEE 14 bus system, it is discovered that PR and PS are quite similar in that they share losses proportionally, whereas ITL and Z-Bus appear to be quite similar in that they also have negative loss allocation provisions. Z-Bus methods strongly focus on bus current injection for losses and consider network topology for loss allocation.

Table III shows that the Z-Bus method fulfills all the required parameters. Hence, the Z-Bus method is selected as the best option for the Nepalese power system, where generation and demand are generally sparse. As a result, the Z-Bus allocation method is chosen as a suitable method for analyzing the INPS network.

Table 3: Qualitative comparison of four loss allocation methods

Parameters	PR	ITL	PS	Z-Bus
Network Topology Dependent	No	Yes	Yes	Yes
Power/Current Dependent	Yes	Yes	Yes	Yes
Non Volatile	Yes	No	Yes	Yes
Cross Subsidies(Negative Loss Allocation)	No	Yes	No	Yes
Easy to understand	Yes	Yes	Yes	Yes
Simple to implement	Yes	Yes	Yes	Yes

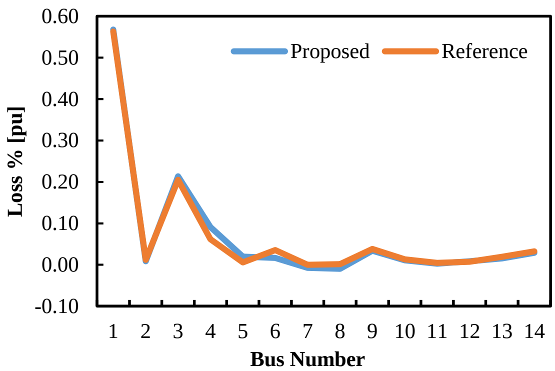

Figure 3: Comparison of proposed Z-bus Algorithm results with Reference [2]

In Fig. 3, a graph between the proposed and reference results has been plotted to test the validity of our Z-Bus method. As the system loss obtained in reference [2] is 13.5 MW, whereas we obtained a total system loss of 13.39 MW. This indicates that there are few differences in the branch data collected, or that there may be some approximate error in those data. Otherwise, it can be seen that the curve follows a similar trend.

4.2. Case Study of INPS:

Bus no. 11 (Dhalkebar) is a substation with a capacity of 950 MVA and is also the point of import and export between India and Nepal. Thus, bus 11 is considered the slack bus of this INPS model. Table III shows the loading data for the INPS model. System loss is found within the range. The Z-bus method's loss allocation is examined in the generator and load buses. The generators are mostly located in remote hill regions, and large loads are located in the Kathmandu valley and Terai region. Terai has a main power import point as the source of generation.

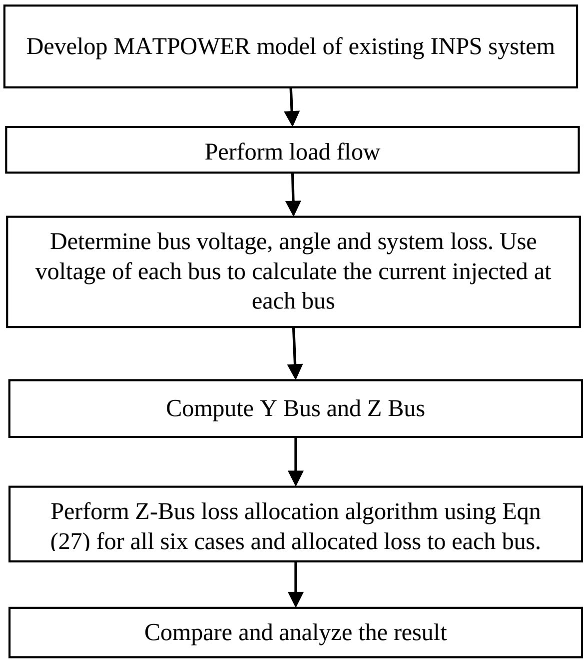

Figure 4: Flowchart of Z-Bus Method in INPS

Table IV shows the data [14], which are taken from the NEA's annual report of 2021/2022. Case 1 (Full Generation) and Case 5 (Contingency) are performed under summer peak data.

Table 4: Data for different cases of INPS [14]

Cases	Generation [MW]	Demand [MW]	System Losses [MW]
Full Generation	2210.78	1658.54	92.72
Summer Peak	1750.89	1658.54	92.12
Winter Peak	1614.61	1530.49	84.03
Annual Average Peak	1479.36	1407.57	71.73
Contingency (Upper Tamakhoshi Line)	1721.23	1658.54	62.79
Dry Peak	1481.46	1426.01	55.43

Table V shows the loss allocation at generator bus and Table VI shows the loss allocation at load bus of INPS at different loading condition.

In the eastern region, generation accounts for approximately 39.8% of the total installed capacity. There are many hydropower-based generations situated in remote places. As a result, Buses 1, 2, and 3 have the highest generation and the lowest load on the same bus, and they are assigned a positive loss. Despite the fact that bus

5 has less generation capacity and maximum loads on the same bus, it is assigned a negative loss except in dry cases. The reason for this is its proximity to large generations. During the dry season, there is no generation at all. As a result, these buses incur a net loss. Buses 7 and 11, which use imported power from India, are also assigned a positive loss. Generator buses 15, 16, and 17 are assigned a positive loss due to their remote location from the load center. The generator with the highest generation capacity is bus 17 (Upper Tamakoshi), which is also 150 km away from slack bus 11. It is allocated with a maximum loss of 13%–65% in all five cases except contingency. Power from buses 16 and 17 are directly exported to India during the system's full generation. As a result, they contribute very little system loss. During contingencies, buses 16 and 17 are cut off from the network. The load demand is about 27.8 % of the total maximum demand in the eastern region. Load buses are typically assigned a negative loss. The reason for this is that its location is closer to the center of the generation region.

Table 5: Loss allocation at generator buses of INPS

	Loss Allocation [% pu] at Different Loading Cases					
Load Bus No.	**Full Gen.**	**Summer Peak**	**Winter Peak**	**Avg. Peak**	**Continge ncy**	**Dry Peak**
1	0.020	0.019	0.004	0.008	0.030	0.002
2	0.023	0.022	0.005	0.010	0.035	0.003
3	0.037	0.030	0.009	0.018	0.055	0.006
5	-0.006	-0.007	-0.006	-0.008	-0.009	0.002
7	0.014	0.002	0.017	0.007	0.023	0.012
11	0.211	0.014	0.332	0.125	0.038	0.326
14	0.031	0.006	-0.028	-0.028	0.044	-0.027
15	-0.005	0.009	0.006	0.007	-0.007	0.005
16	-0.009	0.087	0.083	0.103	0.000	0.048
17	0.137	0.466	0.539	0.651	0.000	0.482
19	0.027	0.005	-0.005	-0.007	0.039	-0.009
20	-0.007	0.001	0.007	0.007	-0.010	0.008
22	-0.001	0.002	0.000	0.006	-0.001	0.002
23	0.001	0.000	0.005	-0.001	0.000	0.006
24	0.000	0.000	0.008	0.000	-0.001	0.010
25	0.000	0.000	0.003	0.001	0.001	0.002
27	0.003	0.011	0.009	0.015	0.006	0.015
31	0.028	0.015	-0.001	0.006	0.042	-0.001
32	-0.003	-0.001	0.015	0.000	-0.006	0.018
35	0.015	-0.004	0.001	-0.002	0.023	0.001
37	0.035	0.027	-0.001	0.008	0.052	-0.001
38	0.072	0.068	0.006	0.020	0.107	0.008
39	-0.001	0.001	0.004	0.002	-0.002	0.002
41	0.026	0.015	0.000	0.002	0.039	0.000
43	0.016	0.019	0.005	0.015	0.024	0.012
44	0.016	0.018	0.002	0.007	0.024	0.004
45	0.120	0.070	0.001	0.021	0.178	0.006
46	0.000	0.000	0.001	0.001	0.000	0.001
47	0.020	-0.020	-0.038	-0.031	0.031	-0.032
50	0.002	0.020	-0.002	0.007	0.003	-0.004
55	0.002	0.000	0.003	0.002	0.003	0.004
58	0.024	0.051	0.055	0.060	0.034	0.060
64	0.026	0.003	0.002	-0.010	0.039	0.010
65	0.014	-0.015	-0.016	-0.014	0.021	-0.012
Total	0.886	0.931	1.027	1.008	0.856	0.968

Table 6: Loss allocation at load buses of INPS

Load Bus No.	Loss Allocation [% pu] at Different Loading Cases					
	Full Gen.	**Summer Peak**	**Winter Peak**	**Avg. Peak**	**Contingency**	**Dry Peak**
4	-0.005	-0.006	-0.007	-0.007	-0.008	-0.003
6	0.010	-0.005	-0.042	-0.032	0.013	-0.017
8	0.003	-0.004	-0.012	-0.010	0.004	-0.010
9	0.005	-0.007	-0.019	-0.014	0.007	-0.017
10	0.005	-0.006	-0.014	-0.012	0.006	-0.014
12	0.017	-0.011	-0.029	-0.024	0.024	-0.031
13	0.003	0.001	0.003	0.001	0.005	0.001
18	0.015	-0.002	-0.014	-0.012	0.021	-0.013
21	0.009	0.006	0.005	0.001	0.013	0.005
26	0.000	0.001	0.001	0.001	0.001	0.001
28	0.000	-0.001	0.000	-0.001	0.000	-0.001
29	0.007	0.002	-0.001	-0.002	0.010	-0.001
30	0.003	-0.003	-0.008	-0.006	0.004	-0.008
33	0.002	0.004	0.005	0.005	0.003	0.005
34	0.003	0.005	0.005	0.006	0.004	0.006
36	0.002	0.001	-0.001	-0.001	0.002	-0.001
40	-0.022	-0.016	0.001	-0.007	-0.033	-0.002
42	-0.002	-0.004	-0.002	-0.004	-0.003	-0.002
48	0.018	0.051	0.057	0.054	0.025	0.059
49	0.001	0.002	0.002	0.002	0.001	0.002
51	0.013	0.023	0.024	0.025	0.019	0.028
52	0.010	0.017	0.018	0.019	0.014	0.021
53	0.002	0.002	0.003	0.003	0.002	0.003
54	0.006	0.009	0.008	0.007	0.008	0.009
56	0.001	0.001	0.001	0.001	0.001	0.002
57	0.005	0.009	0.009	0.011	0.007	0.011
59	0.000	0.001	0.001	0.001	0.001	0.001
60	0.001	0.006	0.006	0.009	0.001	0.006
61	0.000	0.002	0.002	0.003	-0.001	0.002
62	-0.003	0.006	0.005	0.010	-0.004	0.005
63	-0.003	0.001	0.001	0.003	-0.004	0.000
66	0.004	0.010	0.011	0.010	0.006	0.011
67	0.010	-0.026	-0.044	-0.047	0.001	-0.025
68	0.000	-0.001	-0.001	-0.001	0.000	-0.001
69	0.000	0.000	0.000	-0.001	0.000	0.000
Total	0.116	0.071	-0.025	-0.007	0.148	0.033

Hydropower from the hilly region and import power from the Indian border. Only in the case of full generation and contingency, these load buses are allocated with minimum +ve loss. In these cases, the power from a nearby generator supplying the demand is insufficient and extra power from a far generator is required to match the demand.

The Terai section of the central region has generally maximum loads, such as buses 14 (New Parwanipur), 19 (Hetauda), and 21 (Bharatpur), which account for about 20% of total system demand. This Terai has few generators and large load demands. Bus 21 has a load demand of 87.6 MVA, and hence it is allocated with a positive loss. Buses 14 and 19, on the other hand, have both generation and demand on the same bus, resulting in both positive and negative loss allocation depending on the loading cases. In the case of Kathmandu Valley, the buses no. 23 (Balaju), 24 (Chapali), 25 (Suichatar), and 32 (Bhaktapur) form a 132 kV ring network and represent the substation inside the valley, serving maximum loads as well as receiving more generation from nearby hydropower. These buses are receiving enough power to fulfill their demand, and in such cases, they are allocated with a negative loss. When it is not possible to meet the demand of Kathmandu Valley, such as during the winter and dry season, other distant generators must fill the void, resulting in a net loss of allocation.

In the mid-western region, the Terai part has load buses with maximum loading like bus no. 48 (Butwal), 51 (Shivpur), and 52 (Lamahi). This terai part doesn't have any generations nearby. The nearest generator is bus 47 (Kaligandaki HEP), located in the hilly region. Thus, load buses 48, 51, and 52 are always allocated with positive losses, whereas generator bus 47 is mostly compensated with negative losses. In the hill part, there are large sources of generation, which are about 489.2 MW, and only a demand of about 149.4 MVA. Here, the load is compensated for being in the center of generators, and all generators are allocated with a positive loss accountable for system loss. Bus 40 (Pokhara) and 42 (Markichowk) are the load buses. Buses 39 (Damauli), 41 (Lekhnath), 43 (Mid Marshyangdi), 44 (Upper Marshyangdi), 45 (New Modi), and 46 (Syangja) are the generator buses, which are always allocated with a positive loss.

In the far western region of INPS, most of the buses are load buses, and very few generations are available; only buses 58 (Kohalpur), 64 (Chameliya), and 65 (Mahendranagar import) are generator buses. The load on buses like nos. 53–63 is all positively allocated. Bus 58 (Kohalpur) has only a 6 MW import capacity and 54.2 MVA demands. Bus 58 is quite similar to bus 5, both having less generation and high demands. However, because bus 58 is in a high-demand area and lacks generation, it is always assigned a positive loss. where bus 5 was in the region of large generators and thus compensated with a negative loss. Bus 64 (Chameliya) has a 38 MW generation capacity but is about 260 km away. Thus, it is also assigned a negative loss due to its remote location. Likewise, bus 65 (Mahendranagar) has an 80 MW import capacity and 23.3 MVA demand. This bus is also more convenient for loading buses 62, 61, and 60. As a result of being in the load center region, bus no. 65 suffers a negative loss.

With the observations on the loss allocation results for all six loading conditions, the general trend shows that the generator bus located in the center of gravity of demand and the load bus located in the center of generation are mainly compensated with negative losses. The generator or load that is located far from the center of the INPS network is essentially assigned positive losses.

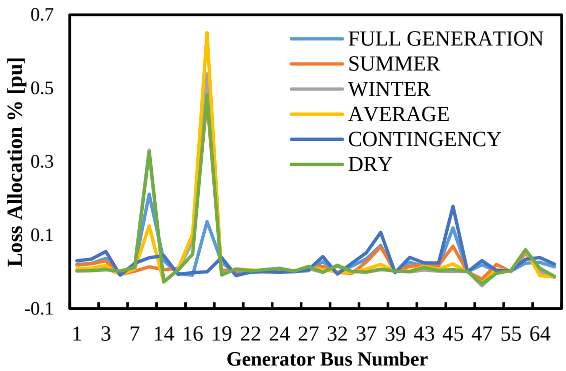

Figure 5: Loss Allocation at Generator buses at different cases

The Z-bus method also reflects the magnitude of bus current injection, which can be justified by observing Fig. 5 with Fig. 6 and Fig. 7 with Fig. 8. The bus injecting high current into the INPS network is basically allocated with high loss. However, the positive or negative sign of a loss allocation is determined by its location in the network topology. In general, generator buses 11 and 17 have a high current injection, and they are allocated with maximum positive losses of up to 33% and 65%, respectively.

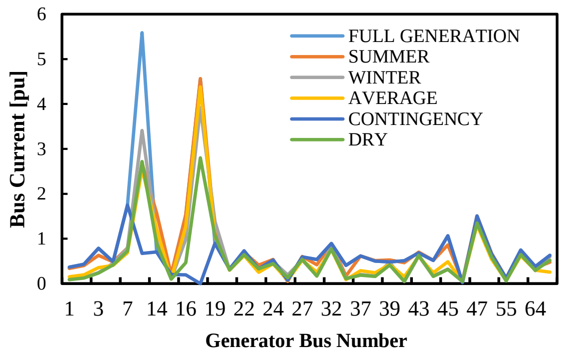

Figure 6: Bus Current Injection at Generator buses at different cases

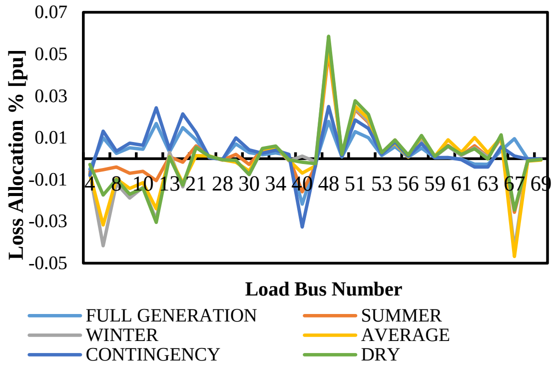

Figure 7: Loss Allocation at Load buses at different cases

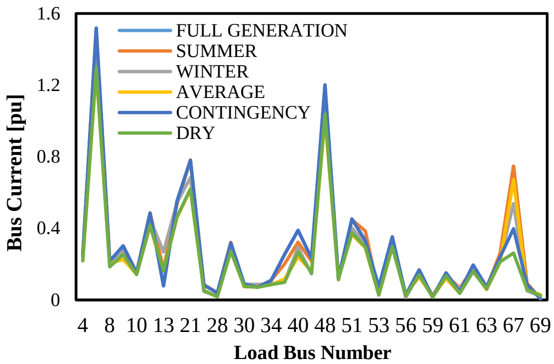

Figure 8: Bus Current Injection at Load buses at different cases

Similarly, in case of load buses from Fig. 7 & 8, bus 6 and bus 67 have high current injection and compensated with negative loss due to its well position in network. Whereas bus 48 also has high current magnitude but it is allocated with high positive loss also due to its poor location. Load bus 21 has also high current magnitude but allocated with less positive loss. It can be explained as Z-bus method is more sensitive to network location.

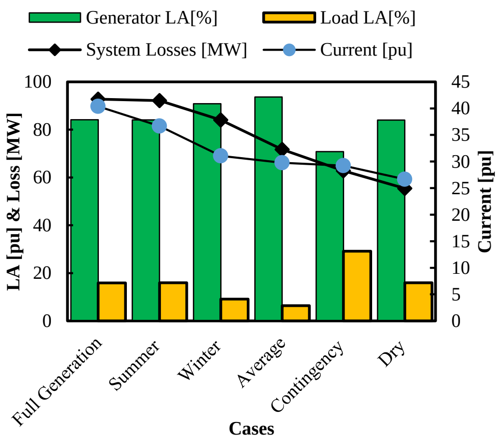

Figure 9: Loss Allocation of Generator & Load at different cases

The total loss allocation to loads and generator at different cases is shown in Fig. 9. For the buses with both load and generator on same node, the pro-rata method is applied after Z-bus loss allocation. Therefore, the Z-bus loss allocation method in average has allocated majority of loss to generator side with 84.6% and only 15.4% has been allocated to the load side.

5. Conclusion:

After the qualitative comparison of four Loss Allocation methods on the IEEE 14 bus system, the Z-Bus method was found to satisfy our all parameters. As Z-Bus method strongly focuses on bus current injection and also an emphasis on network topology. There is also a provision for negative loss which is an advantage. Also, it is non-volatile, easy, and simple.

Therefore, the Z-bus method was implemented on the INPS network. Considering the location of buses in the network with the help of line impedance and magnitude of bus current injection, the Z-Bus method has allocated total system losses among all the buses in the INPS network. According to the findings, Bus 17 (Upper Tamakoshi) has the highest loss allocation under all loading conditions since it generates bulk electricity and is 150 kilometers away from the major load center, represented by Bus 11. (Dhalkebar). In Kathmandu Valley, buses 23, 24, 25, and 32 have both load and generation. Because they typically have enough electricity to meet demand on the same bus during the wet season, they are typically allotted with negative loss or almost nil allocation. If the buses run out of electricity, they must be supplied with more power by other generator buses that are located distant from Kathmandu. Due to the line loss caused by the extended line flow at that time, they are allotted with some positive losses. Similar to this, the load buses in the western portion of INPS are assigned with positive losses due to the lack of sufficient generation in that area, and the generation/import bus nearby is compensated with a negative loss or minimum loss. In conclusion, the load that is near the generator and the generator that is near the demand are typically compensated with negative loss. While the load and generator, which are separated by a great distance, are given a positive loss.. The different loading cases undertaken in INPS show the variation in generation in different areas. Since the generation is rather fairly distributed in the cases of full generation, summer, and contingency, the loss allocation to loads and generators is obviously noticeable. However, in the other three instances where generation is spread very unevenly, the load side is primarily compensated while the generating side bears the majority of the losses. This is due to the limited distribution of generation in INPS, which causes long-distance power flow.

Thus Z-Bus method allocates a major portion of the losses to the generator side. And it can be found that most of the generation in INPS is remotely located and they are more liable for the transmission loss. Thus, this Z-Bus method which considers the location of buses in the network is best suited for INPS. To reduce system loss, this encourages planning to locate larger industrial demand or generation near the center of gravity.

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