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Multi-attribute based optimal location and sizing of solar power plant in radial distribution system

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ABSTRACT

Advancements in renewable energy sources (RES) have significantly increased power generation and reduced emissions. Optimally integrating RES into distribution systems can minimize power losses, emissions, and enhance voltage profile and stability. Therefore, determining the optimal location and size of RES is crucial for their effective integration. This paper presents a novel approach for identifying the optimal location and size of a solar power plant (SPP) in a distribution system, considering system power losses, voltage profile, voltage stability, and emissions simultaneously. A simple yet effective methodology combining repeated load flow and fuzzy systems is proposed. Repeated load flow is used to calculate the relevant attributes, while fuzzy decision-making is employed to determine the optimal solution. The effectiveness of the proposed method is demonstrated through its application to the IEEE-33 bus system. The results illustrate that integrating a SPP at the optimal location and size can significantly reduce power losses and emissions while improving voltage profile and stability.

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1. INTRODUCTION

To meet the load demand imposed on power generation sector without investment in existing infrastructure, injection of reactive power to control voltage; addition of generation near load centers that does not require much alteration in existing infrastructure can be done. This can also lead to reduction in system power losses, voltage profile and voltage stability improvement. If renewable energy sources (RESs) are used for generation, it can additionally lead to reduction in emission. Due to worsening environmental conditions and depleting fossil fuel reserves focus has shifted to increasing share of RESs in power generation. RESs are perennial and a clean source of energy which if used effectively and efficiently can mitigate power shortage problem faced by many developing nations [1], [2]. Integration of generation in distribution system is on the rise and they are gradually being converted to active systems from current passive systems. Impact of this integration can vary widely depending on size and location [3]. R/X ratio of a distribution system is high and high currents flow in primary as well as secondary feeders thus large power losses occur in distribution systems. Inappropriate allocation might even increase operation cost and system losses [3]–[5].

Several techniques such as particle swarm optimisation [6], [7] analytical method [3], [8] genetic algorithms [9], [10] have been used to find optimal location and size. Several objectives such as PL, VS, and VP have been considered and the optimal solution is found using a novel chaotic symbiotic organisms search algorithm considering constant load models [3], [11]. Bat algorithm has been used considering PL and VS in [12], overall real power losses have been taken performance index. Improved harmony search method has been used considering PL and VD to determine impact of placement of distributed generation at optimal location having optimal size [13]. Anbuchandran *et al*. [14], power loss, cost, and voltage deviation were considered. Nematollahi *et al*. [15] formulated a multi-objective function incorporating power loss indices, voltage deviation index, reliability index, and shift factor indices. Genetic algorithms and particle swarm optimization techniques were utilized to find the optimal solution. The process of identifying the optimal type, location, and size of DG units is known as 'DG allocation'. Existing research on DG allocation problems has been reviewed in [3], focusing on optimization algorithms, objectives, decision variables, DG types, applied constraints, and uncertainty modeling. Pesaran *et al*. [7] loadability, PL, cost have been considered and different cost functions have been used for different type of RESs. Mixed integer non-linear programming has been employed to solve these functions and then analytical hierarchy process has been used to find optimal location.

Literature related to this topic consists of research work where just two or three of the attributes have been considered for solving the optimization problem. While each of the aforementioned methods offers valuable insights for determining the optimal location of RES in power systems, none have comprehensively considered power loss, voltage deviation, voltage stability, and emissions simultaneously to identify the optimal solution. A novel approach is needed to integrate these factors. This paper proposes a combined approach using real-time load flow (RLF) and fuzzy decision-making to determine the optimal location and size of a static synchronous compensator (STATCOM) while considering power loss, emission reduction, voltage profile, and voltage stability improvement. Load flow analysis is crucial for power system operation, planning, and modification. The backward-forward sweep method was employed for load flow analysis, as traditional techniques like Newton-Raphson and Gauss-Seidel often fail in distribution systems due to their ill-conditioned nature. Here, RLF has been used to calculate the values of considered attributes by performing load flow repeatedly for various combinations of solar power plant (SPP) location and size. This provides values of considered attributes. These values are then adjusted according to the requirement of fuzzy inference system (FIS) and fed into FIS. FIS is then used to determine optimal location and size of SPP.

STATCOMs in distribution systems can effectively address power shortages while enhancing system efficiency and voltage profile. This approach can defer substantial investments and modifications to the existing infrastructure that would otherwise be necessary if additional power were sourced from the central grid. The advantages of optimally locating STATCOMs include reducing the burden on central generation, improving the utilization of transmission and distribution networks, and minimizing power losses.

2. PROPOSED METHOD

A combination of repeated load flow and fuzzy system based decision making is used to find the optimal solution.

a. Considered attributes

Following attributes have been considered to find the optimal solution:

- Power loss: RESs integration in distribution system has vast potential for minimising power losses due to its close proximity to the load centres. Power loss has been calculated by using (1) [3]. Total power loss can be calculated by summation of individual power losses as given by (2). Minimum value of power loss is desired to improve the efficiency of system.

$$P_i = I_i^2 R_i \quad (1)$$

$$P_l = \sum_{i=1}^{nb} I_i^2 R_i \quad (2)$$

Where Pi, Ri, and Ii are power loss, current and resistance of branch i, Pl is total power loss, nb is total number of branches.

- Voltage deviation: the per unit voltage at each node can be determined during the load flow analysis. The maximum voltage deviation (VDm) from the nominal value of 1 p.u. was considered. A lower VDm value is preferable, as it indicates a better voltage profile. VDm was calculated using (4).

$$VD_j = \left|V_j - 1\right| \quad (3)$$

$$VD_m = max(VD_j) \quad (4)$$

Where VDj and Vj are voltage deviation and voltage at j bus.

– Voltage stability: voltage stability index (VSI) at each node was calculated using (5) [16]. The overall voltage stability index (OVSI) was determined by summing the VSIs of all nodes. A higher OVSI value indicates better voltage stability.

$$VSI_{j+1} = |V_j|^4 - 4(P_{j+1}X_{j+1} - Q_{j+1}R_{j+1})^2 - 4(P_{j+1}R_{j+1} + Q_{j+1}X_{j+1})|V_j|^2 \quad (5)$$

$$OVSI = \sum_{j=2}^{NB} VSI_j \quad (6)$$

VSI must be greater than or equal to 0 for stable operation of radial distribution system.
Where VSIj is VSI of bus j and NB is total number of buses.

– Emission: CO_2 emissions were calculated based on the average emission rate per megawatt-hour in India, which is 1030 kg [17]. Emissions were considered as a reduction in CO_2 emissions for a given size of RES plant, as calculated using (7):

$$Emission = 1030 * SPP_s \quad (7)$$

Where SPPs is size of SPP.

b. Load flow

Backward forward sweep load flow technique [18] has been used to carry out load flow solution. It is an iterative method in which computation is done in two stages for each iteration. Current through each branch has been determined in the backward direction starting from end node using (8):

$$I_j = \left(\frac{S_{j+1}}{V_{j+1}}\right)^* \quad (8)$$

Voltage at each node has been determined in the forward direction using (9):

$$V_{j+1} = V_j - I_j Z_j \quad (9)$$

Where Vj+1 and Sj+1 are the voltage and power injection at node j. Ij and Zj are current and impedance of branch j. Some assumptions are made before starting load flow is given:

– A balanced three phase distribution network is considered which can be represented by single line diagram.
– Loads are modelled as constant power.
– Starting node voltages are taken as 1 p.u.

c. FIS

FIS consists of a set of rules which are formed according to qualitative description. Here it has been used to find out suitability index of each node for placing SPP. Mamdani multiple input single outputs (MISO) has been used. Basic block diagram of fuzzy system is shown in Figure 1.

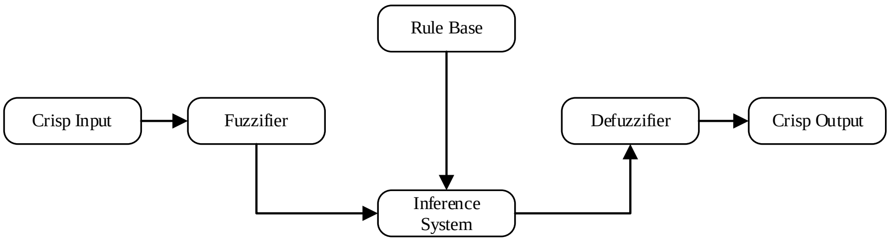
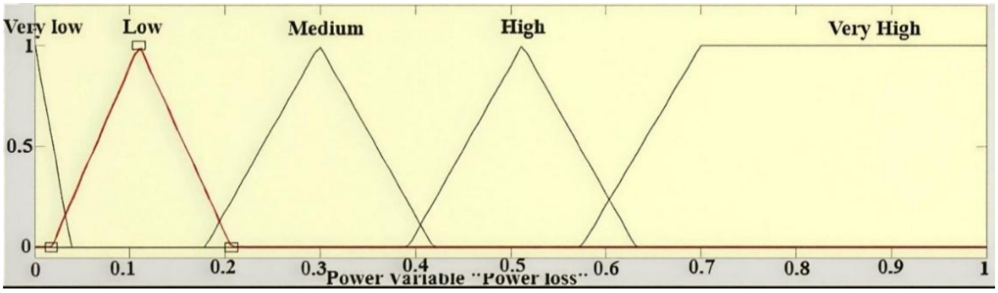


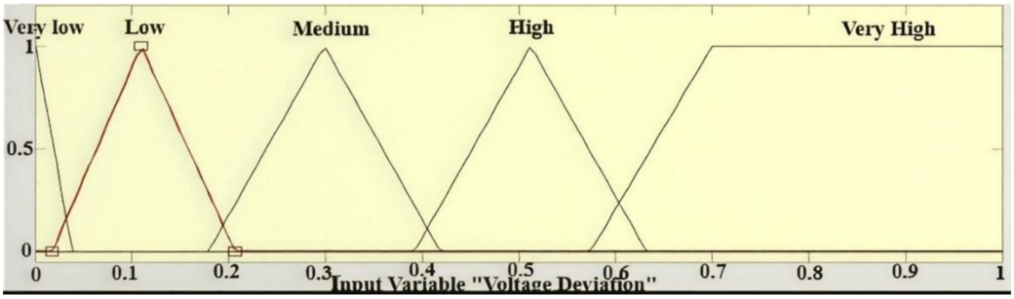
Figure 1. Block diagram of fuzzy system

Membership functions for input such as PL and VD, overall VSI and emission reduction as shows in Figure 2. The membership functions for the input variables such as the power losses, voltage deviation, OVSI, and emission reduction, which is in Figures 2(a)-(d) respectively. These sub-figures depict the linguistic terms (e.g., VL, L, M, H, and VH for power losses and voltage deviation; L, M, H for OVSI) using triangular membership functions, chosen for their computational efficiency and realistic representation.

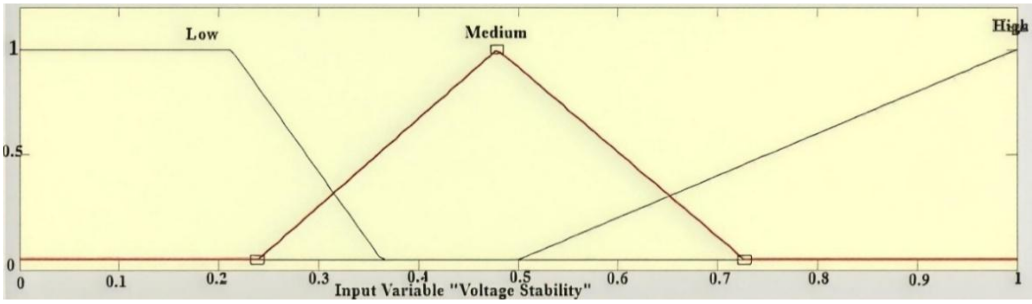
Similarly, the output variable, SPP suitability index, is defined by analogous linguistic terms, as shown in Figure 3. The FIS processes these inputs to derive the suitability index, with defuzzification performed via the centroid method in (10) to determine the optimal SPP configuration.



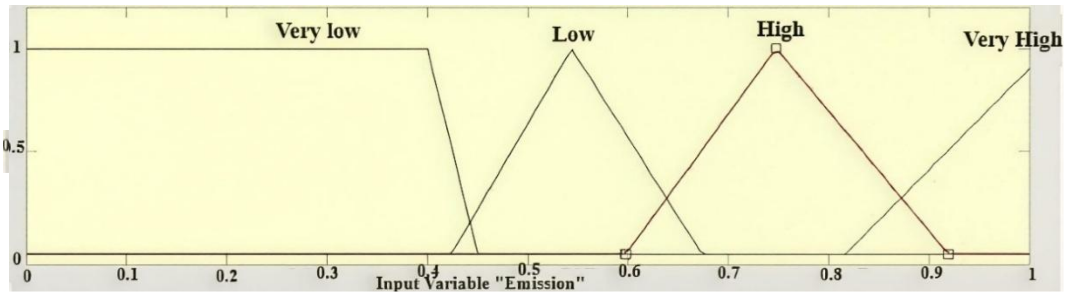
(a)



(b)



(c)



(d)

Figure 2. Membership functions for input such as PL and VD, overall VSI and emission reduction; (a) power losses membership functions for input, (b) voltage deviation membership functions for input, (c) overall VSI membership functions for input, and (d) emission reduction membership functions for input

The initial step involves fuzzyfication of the input variables. Power loss, voltage deviation, and emissions are characterized by linguistic terms: very low (VL), low (L), medium (M), high (H), and very high (VH). The OVSI is categorized as L, M, or H. These linguistic terms are illustrated in Figure 2. The output of the FIS, the STATCOM suitability index, is also defined by the same linguistic terms, as shown in Figure 3.

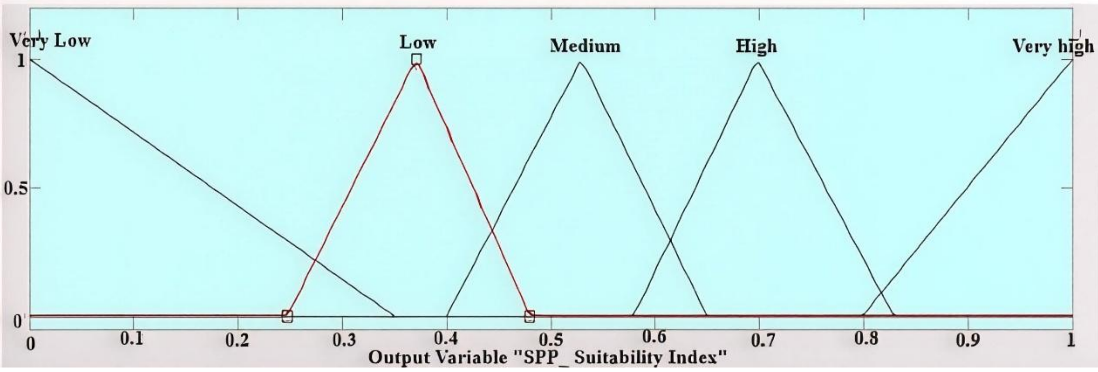


Figure 3. Membership functions for output i.e., SPP suitability index

The initial step involves fuzzyfication of the input variables. PL, VD, and emissions are characterized by linguistic terms: VL, L, M, H, and VH. The OVSI is categorized as low L, M, or high H. These linguistic terms are illustrated in Figure 2. The output of the FIS, the STATCOM suitability index, is also defined by the same linguistic terms, as shown in Figure 3.

Membership function of triangular type is used as they are more realistic in nature and provide faster computation. Value of power loss and voltage deviation should be minimum where as values of emission and OVSI should be maximum. Once membership function of SPP suitability index for each node has been determined, it must be defuzzified. To carry out the defuzzification process centroid method has been used [19]–[22]. This method finds the centre of area of membership function and returns it as defuzzified value.

$$S = \frac{\int \mu_S(A)AdA}{\int \mu_S(A)dA} \tag{10}$$

Where μs(A) is membership function of fuzzy set A.

3. OPTIMAL LOCATION AND SIZING OF REG

To find optimal location and sizing of SPP value of nodal voltages and branch current is found using load flow. These values are then used to calculate system power losses, voltage deviation, OVSI, reduction in emission [23]. Load flow is run for every possible combination of bus location and SPP size [24], [25]. A FIS is developed having suitable membership functions for input and output. FIS based decision making is used to determine optimal solution. The proposed methodology is outlined in the flowchart depicted in Figure 4 (in Appendix). The step-by-step algorithm is as: i) perform a base case load flow analysis without a STATCOM; ii) iteratively place a STATCOM on each bus, varying its size from 0 to 4 MW in increments of 0.1 MW; iii) calculate power loss using (2); iv) determine voltage deviation using (4); v) calculate VSI using 6; vi) calculate emissions using (7); vii) store the calculated values in a matrix; viii) normalize these values to a scale of 0 to 1; ix) convert each attribute's values into a separate single-column matrix; x) create a fuzzy input matrix where each column represents a single input attribute and each row represents a set of inputs to be fed into the FIS sequentially; xi) process these input sets through the FIS to obtain a suitability index for each STATCOM placement; xii) identify the maximum suitability index, which corresponds to the optimal STATCOM location and size; xiii) calculate the optimal bus location and STATCOM size based on the maximum suitability index, and; xiv) determine the values of the considered attributes using the optimal bus location and size.

4. RESULTS AND DISCUSSION

In this proposed methodology, the optimal location for a STATCOM in the IEEE 33-bus radial distribution system was determined to be bus 6. To identify the optimal size, STATCOMs of various capacities were sequentially placed at each bus, and the resulting data were processed by a fuzzy system. After analyzing 1353 input sets, the optimal solution was determined to be a 3.6 MW STATCOM at bus 6. This solution led to a significant reduction in total power loss (from 202.68 kW to 118.06 kW), maximum voltage deviation (from 0.08691 p.u. to 0.03478 p.u.), and CO_2 emissions (by 3708 kg compared to a coal-based power plant). The overall system reliability improved, as indicated by an increase in the OVSI from 26.33 to 30.427. These results are summarized in Table 1.

Table 1. Comparison of system attributes with and without SPP

	Without solar	With solar	Changes %
OVSI	26.333	30.427	15.56
Total power loss	202.68 KW	118.06 KW	-41.75
Emission reduction	0 kg	3708 kg	--
Voltage deviation	0.08691 (p.u.)	0.03478 (p.u.)	-59.98

Figure 5 illustrates the change in voltage deviation at each bus before and after the installation of an optimally sized SPP at its ideal location. The maximum voltage deviation decreased significantly from 0.08691 to 0.03478. Figure 6 compares the VSI at each bus under two scenarios: without SPP and with an optimally sized SPP connected at the most advantageous location. The results demonstrate a significant improvement in VSI at all nodes, leading to an overall enhancement in system reliability.

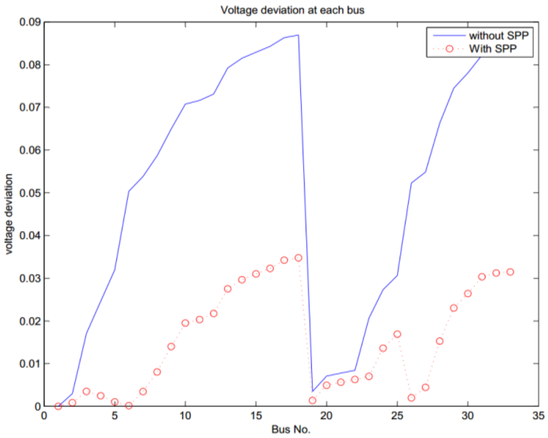


Figure 5. Voltage deviation at each bus

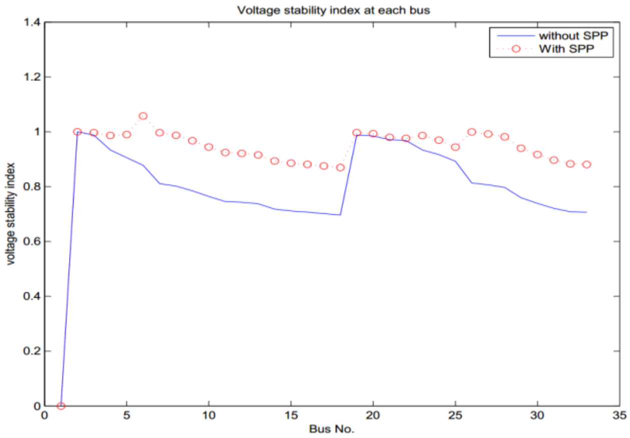


Figure 6. VSI at each bus

Figure 7 illustrates a comparison of real power losses across different branches of the network under two conditions: with and without the presence of SPP. It was observed that power losses were particularly significant between nodes 1 and 5, but the introduction of SPP effectively mitigated these losses.

Since power loss, VD, VSI, and emission reduction has been considered simultaneously in the paper to determine optimal location and size of SPP. At present literature is not available to perform comparative analysis, so comparative analysis has not been carried out. Also shown the Table 2 of a simple comparision of optimization with benchmark funsction.

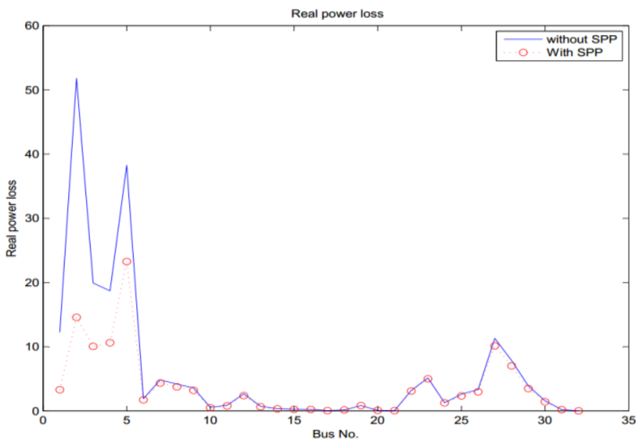


Figure 7. Real power loss variation in each branch

Table 2. Comparison of system attributes optimization and benchmark

Metric	Without SPP (base case)	With optimized SPP	Improvement %	Single-objective methods	Superiority of proposed approach
OVSI	26.33	30.43	+15.56	+8.2% (VS only)	Holistic improvement (VS+PL+VP+emissions)
Power loss (kW)	202.68	118.06	-41.75	-32.1% (PL only)	Lower losses due to multi-attribute optimization
Voltage deviation	0.0869	0.0348	-59.98	-45.3% (VD only)	Better voltage profile via combined FIS-RLF
Emission reduction	0	3,708	100	Not considered	Unique inclusion of emissions

5. CONCLUSION

This study introduces an integrated approach combining repeated load flow analysis and fuzzy logic to determine the optimal placement and capacity of SPPs in radial distribution networks. The proposed methodology simultaneously addresses four key objectives: minimizing real power losses and voltage deviations while maximizing voltage stability and reducing emissions. When applied to the IEEE-33 bus system, the approach demonstrated significant improvements in grid performance, successfully reducing power losses, stabilizing voltage profiles, and lowering emissions. The power loss minimization decreases feeder line stress, extends equipment lifetime, and increases capacity for future load growth.

Despite these contributions, the study has certain limitations that should be acknowledged. The analysis assumes balanced three-phase systems and constant power loads, which may not fully capture real-world grid complexities. Future research should expand this work by applying the methodology to unbalanced systems and dynamic load models to better reflect practical operating conditions. Additionally, comparative studies with metaheuristic optimization techniques such as PSO and genetic algorithms would help validate the effectiveness and computational efficiency of the proposed approach. Further investigations could also explore the integration of energy storage systems to enhance renewable energy utilization and grid flexibility.

The findings of this study provide a valuable framework for integrating SPPs into distribution networks while balancing technical, economic, and environmental objectives. Grid operators and policymakers can leverage these insights to support renewable energy adoption while maintaining system stability. Future efforts should focus on real-world implementation, adaptive control strategies, and large-scale validation to maximize the practical impact of this methodology. By addressing the identified limitations and exploring new applications, this research can contribute to more efficient, sustainable, and resilient power distribution systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Digambar Singh		✓				✓		✓	✓	✓	✓	✓		
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Manish Kumar Singla	✓	✓			✓		✓		✓	✓	✓		✓	
Shashank Tripathi	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available at http://doi.org/10.32604/ee.2025.060658 (ref [4]).

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APPENDIX

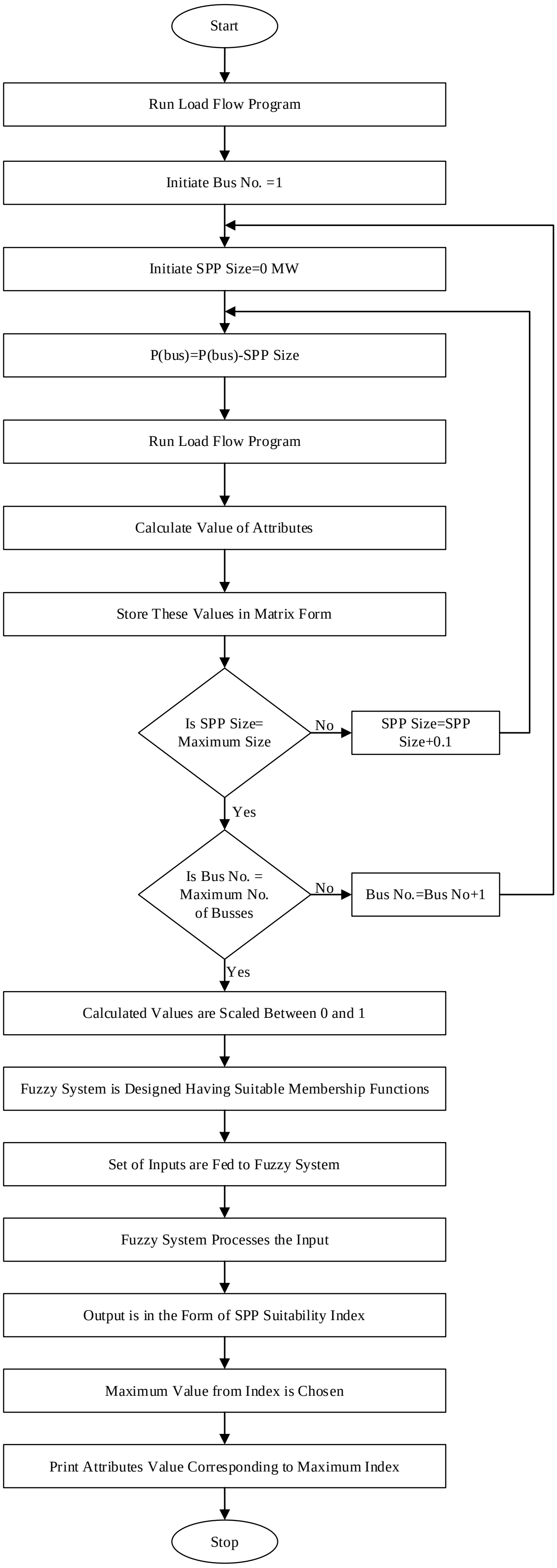

Figure 4. Flowchart of proposed method

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