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Optimal Allocation and Sizing of Distributed Generators for Multi-Objective Function in Distribution Network Using Intelligent Water Drop Algorithm

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Abstract

There is need to optimize the operation of a distribution system for power losses minimization, voltage profile improvement and network efficiency. The researchers in this work have deployed novel concept in order to achieve the above aim. The main purpose of this research is to minimize total active power losses and improve the voltage profile in IEEE 33 bus and Irrua Distribution Network (IDN). Stability Index (SI) is used to optimally allocate Distributed Generators (DGs), while the Intelligent Water Drop Algorithm (IWD) is deployed for computing the size of DGs. IWD is an algorithm which is inspired by nature were water drops or river find easy path to flow from source to its destination when the entire possible path from source to its destination are available. The proposed method is demonstrated on IEEE 33 bus and IDN. From the simulation results obtained, it was observed that the proposed method optimally placed DGs on two (2) buses for IEEE 33 Bus network and IDN, the power loss were minimized by 66.3% and 60% respectively, also there was great improvement on the voltage profile and Stability index for both networks. The proposed method was compared with other existing methods and it proves to perform better in terms of power losses.

1. Introduction

Electric power system is divided into three segments which are; Generation, Transmission and Distribution. Distribution network is the segment which links the transmission network at high voltage to the final consumers at low voltage. It is a very important segment in electric power systems because it should supply stable and reliable electric power since the end users of electricity depends on its efficiency [1]. The electric load demand is rising extensively which in turns leads to increase in power losses and poor voltage regulation [2]. Line losses and voltage drops are more significant to a distribution network since it has low reactance to resistance (X/R) ratio compare to a transmission network [3]. About 70% of the losses in electric power systems occur at the distribution segment while the remaining 30% occur at the transmission segment, that is why more attention have been shifted to the distribution segment.

A good distribution network should be able to supply constant electric power with good voltage profile and should be reliable [4]. To improve the efficiency of a distribution network, the following approach can be deployed on the network; network reconfiguration, installing reactive power compensation, placing distributed generators (DGs), and hybrid approach [5]. Distributed generators are small-scale power generating unit, which can provide both active and reactive power that can be integrated into a distribution network. However, uncontrolled DG penetration can cause some operational challenges such as voltage fluctuation, overloading challenges, poor power quality and protection problems [6]. Placing and sizing of DGs in the appropriate position have both technical and economic benefit on the network, the technical benefits are minimizing power losses, improve the voltage profile, power factor, loadability, system security, and voltage stability while the economic benefits are low maintenance and operational cost, reduced capital cost, and reduced cost for enhancement and expansion of the network. Therefore, it is important to note that the maximum DG injected into the network should not exceed the operating capacity of the network.

Researchers from literature have deployed several methods to simultaneously determine DGs allocation and sizing in order to reduce power losses, improve voltage profile, stability index and so on. Furthermore, some of the approaches that have been deployed for allocation and sizing of DGs in a distribution network are conventional approach, meta-heuristic optimization approach, and hybrid approach. These approaches have demonstrated their strength in terms of power losses reduction, improved voltage profile, and strengthen the performance of the whole system. The conventional approach involves the mathematical modeling of power system resulting in a set of numerical equations which can be used to obtain the objective functions, the objective function can be singular or multiple. The authors in [7] have optimally allocated DGs for a real power losses minimization as a singular objective function; while Authors in Article [8] uses the same approach to optimally place and size DGs for multi-objective functions. A meta-heuristic optimization technique is an iteration based techniques that manipulate the candidate solution, in order to control a subservient heuristic where different concepts have to function together. However, for their effective performance in the area of optimality, reliability and efficiency, it depends on the tuning of optimization parameters. They have the capacity to solve power system problem with multiple or single objection functions. In [9], Stud Krill Herd Algorithm (SKHA) was used to achieve power losses reduction in IEEE 33 and 69 bus systems, as well as in 94 bus Portuguese distribution network considering some constraints like power balancing, limiting DG power generation, voltage limitation and DG placement. Dragonfly Optimization Algorithm (DOA) was implemented in IEEE 15, 33, and 69 bus networks for optimal allocation of DGs for reducing line losses in [10]. In [11], Water, Energy and Food Algorithm (WEFA) was proposed for optimally placing and sizing of DGs in a radial distribution network. Bacterial Foraging Algorithm (BFA) was deployed for optimal allocation and sizing of multiple DG units in IEEE 33 and 69 bus radial networks in [12]. Grey Wolf Optimization (GWO) was used to determine the optimal allocation and sizing of multi-DG units in a distribution network and to perform multi-objective functions like kVAr losses reduction and voltage profile improvement in [13]. The author in [14], proposed a Shuffled Bat Optimization (SBO) Algorithm for multi-DGs units placement and sizing for different load model, the algorithm was tested in IEEE 33 and 69 bus radial networks. In [3], Artificial Bee Colony (ABC) Algorithm was proposed to solve multi-objective function by optimally placing and sizing of DG units and it was demonstrated in IEEE 33 and 69 bus radial networks. Meta-heuristic optimization techniques were modified by various researchers for optimally placing and sizing of DG units in order to improve the general performance of a radial distribution network. In [15], the authors modified a Bacterial Foraging Algorithm (MBFA) which was demonstrated on IEEE 12, 34 and 69 bus systems, the proposed method was able to reduce the total power losses and improve the voltage profile. A Modified Grey Wolf Optimization (MGWO) was proposed in [16] which was deployed to optimally allocate multi DG units in IEEE 33 bus system.

Researcher have employed Hybrid Optimization Technique (HOT) in optimally allocating and sizing of DG unit and it is the combination of two or more optimization techniques. The author in [17] proposed an Improved Reinitialized Social Structure Particle Swarm Optimization Algorithm (IRS-PSOA) for optimally placing multiple DG units in a Microgrid System. In [18], the author proposed an hybrid approach which comprises of Mixed Integer Nonlinear Programming (MINLP) used for loadablilty, power losses and costing while Analytic Hierarchy Process (AHP) was used for optimal location of Renewable Energy Sources (RESs).

In recent time, researchers have deployed bio-inspired meta-heuristic algorithms for allocating and sizing of DGs in distribution network for effective network performance. In [6], Coronavirus Herd Immunity Algorithm (CHIA) was used to minimize power losses and improve the voltage profile for a IEEE 69 bus system. Symbiotic Organism Search optimization method (SOS) was used to allocate and size DGs which resulted in power losses reduction, as well as improve the voltage profile in the network in [19] and [20]. The authors in [21] deployed Quasi-oppositional Chaotic Symbiotic Organism Search Algorithm (QCSOA) for placing and sizing of DGs.
The aim of this research work is to initiate intelligent water drop optimization for optimal sizing while stability index is deployed for optimal allocation of multi-DG unit in IDN and IEEE 33 bus system in order to minimize power losses and improve the voltage profile.

2. Methodology

2.1 Problem Formulation
The problem comprises of optimal placement of DG units and its sizes in kW to minimize line losses, improve voltage profile and the whole network performance.

2.2 Objective Functions
The objective function (OF) consist of kW and kVAr losses, voltage profile, and voltage stability while finding the best location and sizing for DGs that can be injected into the distribution network.

2.2.1 Total Real Power Losses
There are more losses in a distribution network compared to a transmission system due to $X/_R$ ratio, while copper losses are considered to be more. In a radial distribution system with M number of buses, the total kW and kVAr losses is the summation of line losses in all the buses on the network [22]. The total kW power loss is given as;

$$P_{Tloss} = \sum_{i,k=1}^{M} i_k^2 \ R_{ik} \tag{1}$$

$$i_k^2 = \frac{P_k^2 + Q_k^2}{|V|^2} \tag{2}$$

where P_k and Q_k represent the kW and kVAr power flowing on the network, R_{ik} is the resistance between i^{th} and k^{th} lines and V is the bus voltage.

Similarly, the total kVAr loss is given as;

$$Q_{Tloss} = \sum_{i,k=1}^{M} \frac{P_k^2 + Q_k^2}{|V|^2} \ X_{ik} \tag{3}$$

where X_{ik} is the reactance between i^{th} and k^{th} lines. When DGs are incorporated into the distributed network, the total kW loss can be expressed in eq.(4) [12]

$$P_{Tloss+DG} = \sum_{i,k=1}^{M} \frac{\left(P_k - \beta_p P_{DG}\right)^2 + \left(Q_k - \beta_q Q_{DG}\right)^2}{|V|^2} \ R_{ik} \tag{4}$$

where β_p and β_q are the multiplier for real and reactive DG power respectively.
The real power losses reduction for the network is given as:
$$P_{Tloss}^{reduced} = P_{Tloss} - P_{Tloss+DG} \quad (5)$$

2.2.2 Voltage Stability Index

A distribution network performance can be assessed by using voltage stability index (VSI). The functions of VSI on distribution network are that it gives the present operating state of the network, it helps to predict the future changes, and it helps for network expansion within predefined circumstances [23]. There are different types of VSI assessment tool used by researchers, but in this research work Stability Index (SI) were employed. Any bus with the smallest magnitude of SI value indicates the most sensitive bus to voltage collapse, the equation is given as [24]:

$$SI = 2V_i^2V_k^2 - V_k^4 - 2V_k^2(P_kR_{ik} + Q_kX_{ik}) - Z_{ik}^2(P_k^2 + Q_k^2) \quad (6)$$

where; V_i and V_k represent the sending and receiving end voltages, R_{ik} and X_{ik} are the line resistance and reactance, and Z_{ik} is the line impedance.

2.2.3 System Operational Constraints

The optimization technique used for this research work subjects the system to two constraints which are equality and inequality constraints.

2.2.3.1 Equality Constraints

Its involve the power balancing on the system, that is, the summation of power injected to the network including DG unit plus the total load connected to the network and the total power losses must be equal to zero, as given by eq.(7).

$$\sum_{k=1}^{m} P_{g+DG} + P_{Tload} + P_{Tloss+DG} = 0 \quad (7)$$

where; P_{g+DG} is the power injected including DG units, P_{Tload} is the total power connected and $P_{Tloss+DG}$ is the total network losses when DG units are incorporated.

2.2.3.2 Inequality Constraints

The inequality constraints considered are as follows:

i. The power injected or absorbed by the DG units should not exceed its maximum and minimum capacity.

$$\left.\begin{aligned} P_{DG}^{min} \le P_{DG} \le P_{DG}^{max} \\ Q_{DG}^{min} \le Q_{DG} \le Q_{DG}^{max} \end{aligned}\right\} \quad (8)$$

ii. Bus voltage should be within the range of $\pm 5\%\ of\ 1pu$, that is,

$$0.95pu \le 1pu \le 1.05pu \quad (9)$$

iii. Node currents limit, which is given as:

$$i_k \le i_k^{rated} \quad (10)$$

where i_k and i_k^{rated} are the current at node k and maximum or rated current at node *k.*

2.3 Intelligent Water Drop Optimization (IWD)

It is a naturally inspired algorithm derived from water drop that flows from rivers or streams to find optimum path to its destination and there are barriers that need to be overcome from the environment before getting to its final destination. Water drop flows with a unique velocity which is influenced by the environmental factor. They flow with some amount of soil taking from the river bed. The easiest path is the path with the least soil [25]. The intelligent water drop optimization (IWD) has two properties, which are:

i. The velocity at which water drops is moving.
ii. The amount of soil carried by the water drop.

IWD can be used to solve optimization problem with many paths and there are two scenarios to be consider. Firstly, if the destination of the water drops is known, the target is to find the best possible path. Secondly, if the destination is unknown, the target is to optimize the best possible path to the destination.

IWD algorithm is described as constructive-based method where water drops flows in discrete step from one node to another until it reaches its final destination [22]. The changes in velocity of the IWD are non-linear and inversely proportional to the amount of soil on the path. Water drops from source start with an initial velocity and zero amount of soil, the amount of soil increases with changes in the velocity as the IWD moves from one location to another. The time taken for IWD to move between two nodes obeys the law of linear motion in physics, which states that the time taken for IWD to move between two nodes is directly proportional to the distance between the two nodes and inversely proportional to the velocity

2.3.1 Intelligent Water Drops (IWD) Algorithm

IWD is an algorithm that is based on constructive population in which water drops flow from its source by flowing through the easiest path to its destination. The amount of soil increases and there are changes in the velocity as water drops move from one location to another. IWD algorithm is divided into four phases as shown in the flowchart in figure 1 below.

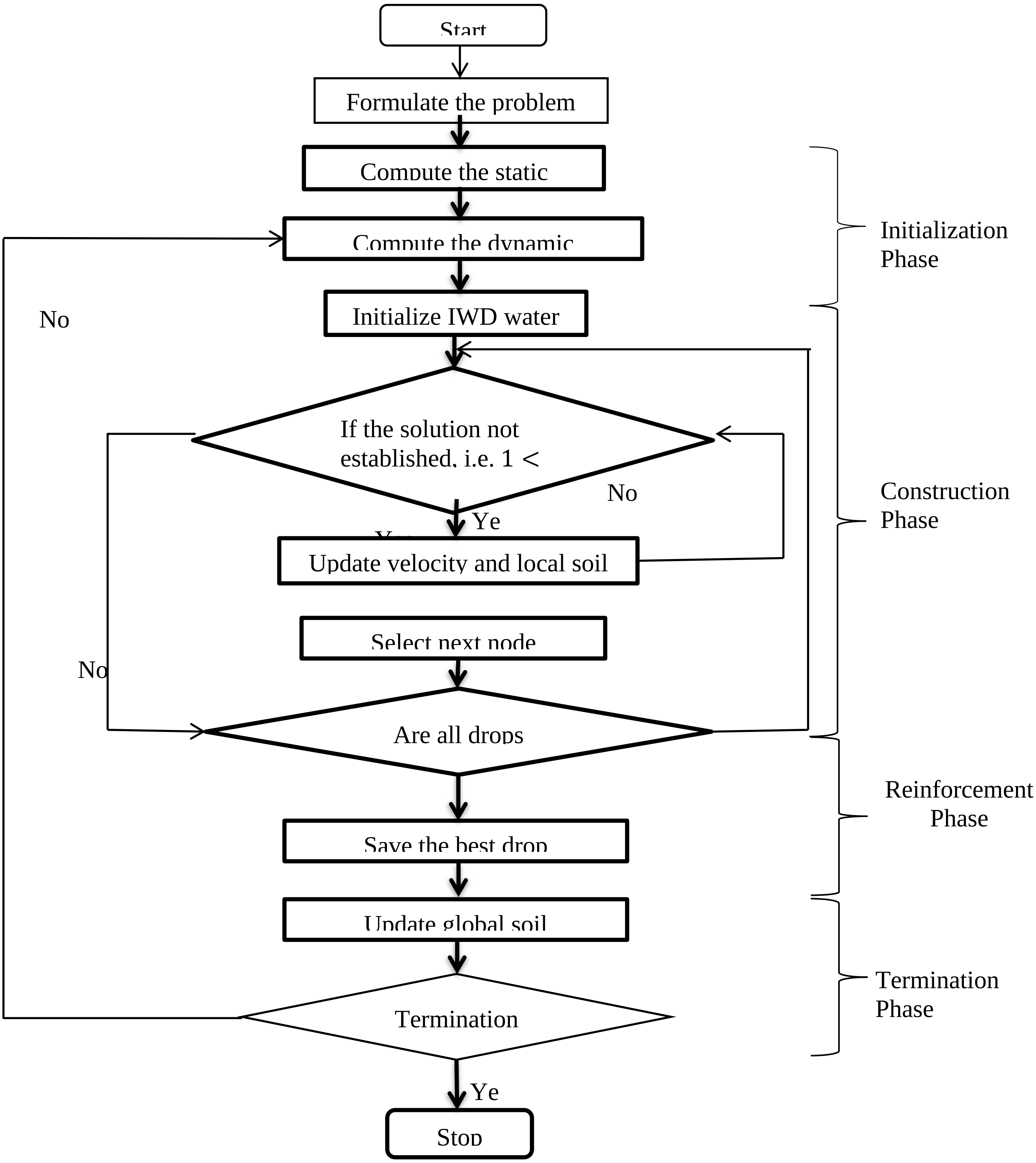


Figure 1: Flowchart for the different phases of IWD algorithm

2.3.2 Step by Step IWD Algorithm

The steps involve are as follows:

Step 1: formulate the Problem by using constructive-based graphic approach, where the optimization problem is represented as G(V,E) where; V is the set of vertices in the graph and E is the set of edges.

Step2: there are two parameters to be considered; which are static and dynamic parameters. The static parameters remain unchanged throughout the duration of the iteration while dynamic parameters are reinitialized for each period of iteration.

Step 3: the list of visited nodes of each IWD and initial $soil_{(IWD)}$ were set to zero.

Step 4: obtain the water drops optimum path, when the water drops were spread randomly on the nodes of the system.

Step 5: update the nodes as a visiting node for that particular IWD.

Step 6: for the water drops in node i, the next node to be visited will be selected with minimum soil that will not violate any constraints. The probability of choosing the next node is given as;

$$\rho_i^m (j) = \frac{f(soil(i,j))}{\sum_{k \neq v_c} f(soil(i,k))} \quad (11)$$

where $f(soil(i,j))$ represents the amount of soil from node i to node j.

It can be defined as;

$$f(soil(i,j)) = \frac{1}{\in + h(soil(i,j))} \quad (12)$$

where ∈ is a small positive integer.

$$h(soil(i,j)) = \begin{Bmatrix} soil(i,j) & if\ k \neq v_c^{min}(soil(i,k) \geq 0 \\ soil(i,j) - & k \neq v_c^{min}(soil(i,k)\ \ otherwise \end{Bmatrix} \quad (13)$$

The node with the maximum probability will be selected as the next visiting node.

Step 7: the IWD velocity and soil parameters will be updated for both nodes, if the IWD moves from one node to another.

Step 8: the IWD velocity can be updated using eq. (14).

$$V_{IWD}^1 = V_{IWD}^0 + \frac{a_v}{b_v + c_v * [soil(i,j)]^2} \quad (14)$$

where; a_v, b_v, c_v represent the static parameters used for non-linear relationship between velocity and water drops, V_{IWD}^0 is the initial IWD velocity and $V_{IWD}^1$is the updated IWD velocity.

Step 9: the soil of the IWD is increased using eq. (15).

$$\Delta soil\ (i,j) = \frac{a_s}{b_s + c_s * [time(i,j)]^2} \quad (15)$$

$time(i,j)$ is defined as follows

$$time(i,j) = \frac{HUD(i.j)}{V_{IWD}^1} \quad (16)$$

Where; a_s, b_s, c_s represent the static parameter for the non-linearity between soils from node i to j, $time(i,j)$ is the time needed for the water drops to move from node i to j, $HUD(i.j)$ is a heuristic desirability function that measure IWD when moving from one location to another.

Step 10: the $soil\ (i,j)$ in the path through which IWD moves through is updated by using eq.(17).

$$soil(i,j)^1 = (1 - \rho_m) * soil(i,j) - \rho_m * \Delta soil\ (i,j) \quad (17)$$

where ρ_m is a positive constant.

Step 11: the soil update of the water drop is calculated by;

$$soil_{IWD}^{1} = soil_{IWD} + \Delta soil\ (i,j) \tag{18}$$

Step 12: follow steps (1-11) for all iterations in the IWD system.

Step 13: obtain the best iteration solution.

$$T_{\alpha} = \min(soil) \tag{19}$$

Step 14: obtain the soil global update of all the paths using the best iteration solution to form the current best iteration solution.

$$soil(i,j)^{1} = (1 + \rho_m) * soil(i,j) - \rho_m * soil_{IB}^{k} * \frac{1}{q(T^{IB})} \tag{20}$$

where T^{IB} is the iteration best solution and can be defined as

$$T^{IB} = \frac{Arg_{min}}{max_{x \in T^{iwb}} q(x)} \tag{21}$$

where; T^{iwb} is the population of the complete solution and $q(x)$ is the fitness function.

Step 15: obtain the global best solution if the current best solution is better than the previous best solution as shown in eq. (22).

$$T^{GB} = \begin{Bmatrix} T^{IB}\ if\ current\ T^{IB} < previous\ T^{IB} \\ T^{GB} \quad else \end{Bmatrix} \tag{22}$$

Step 16: follow steps (1-15) for each process and increase the iteration count if the iteration count is less than the maximum iteration.

2.4 The Proposed IWD Algorithm for Optimal Placement and Sizing of DGs

Figure 2 depict the flowchart when IWD Algorithm is used to optimally placed and size DGs in a distribution network.

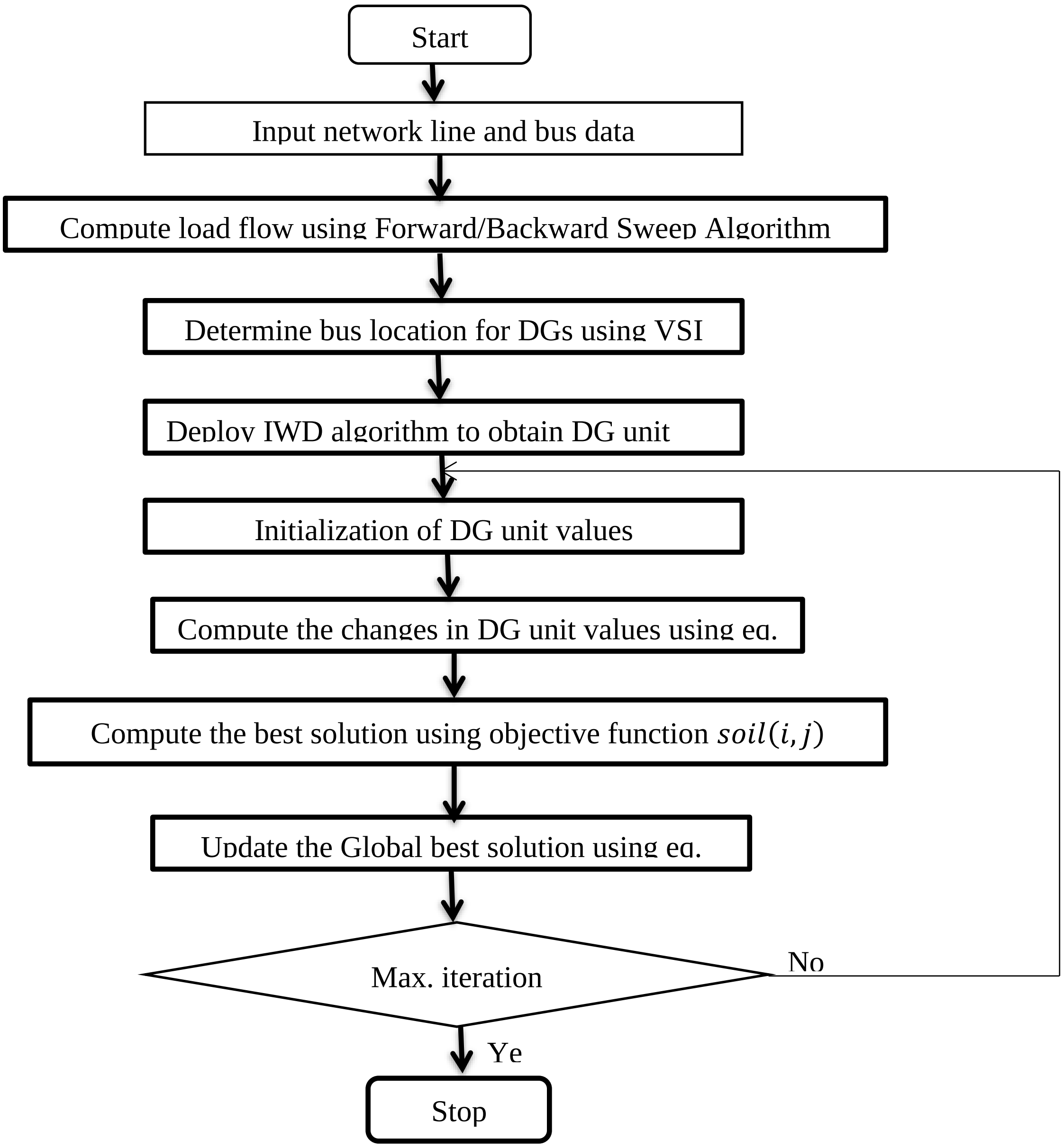


Figure 2: Flowchart for the proposed algorithm.

3. **Simulation Results and Discussion**

In order to demonstrate the effectiveness of the proposed algorithm, the algorithm was demonstrated in IEEE 33 bus radial distribution network before deploying in IDN as shown in figure 3 and 4 respectively. The proposed algorithm parameters used are similar for both networks and the simulation was carried out using MATLAB R2020a.

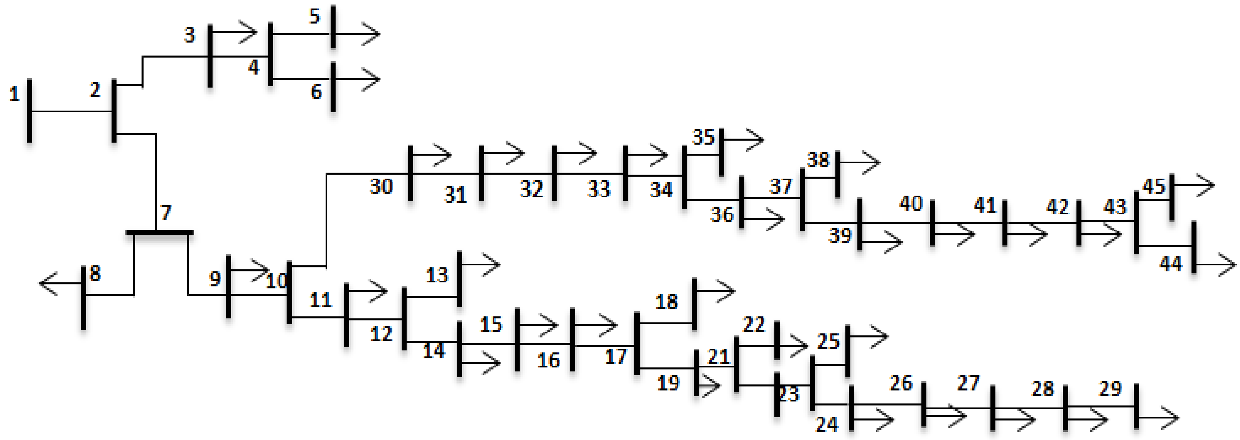


Figure 3: Irrua distribution network single line diagram (45-buses)

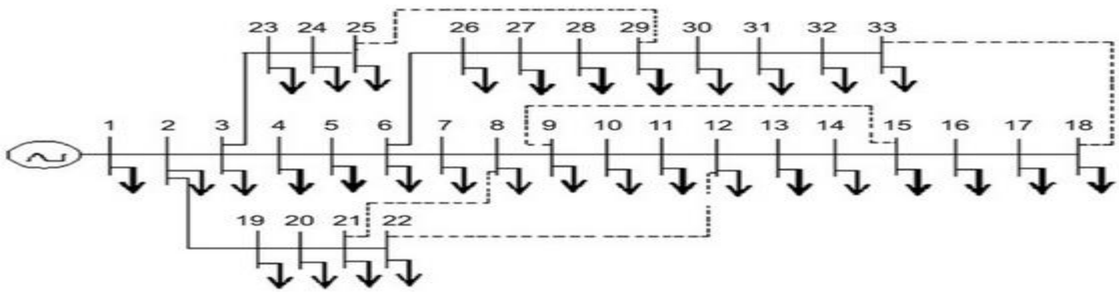


Figure 4: IEEE 33-bus radial distribution Network

3.1 Simulation Results for IEEE 33 Bus Network

The network consists of 33 buses, 32 lines with a total kW and kVAr load of 3715 and 2295 respectively. The network input powers are 3996.59kW and 2487.96kVAr. Load flow analysis and stability index (SI) technique is used for allocating the DG units; any bus with the lowest SI value is classified as a weak bus which can cause voltage instability in the network. The buses selected by SI are 6 and 15. From table 1, it was observed that the total power losses reduced by 66.3% after installing DG units. Likewise, figure 5a shows SI values for all the buses with and without DG units; while figure 5b shows the voltage profile improvement after installing DG units.

Table 1: Location of DGs for IEEE-33bus network using the proposed Algorithm

	Without DG	With DG
DG bus location		6 & 15
Active power loss (kW)	273	92
Min. voltage (p.u)	0.8693	0.9481
Min. stability index (p.u)	0.5734	0.7769
Total DG size (MW)/Bus no		3.0396(6)/0.3697(15)
Loss reduction in %		66.3

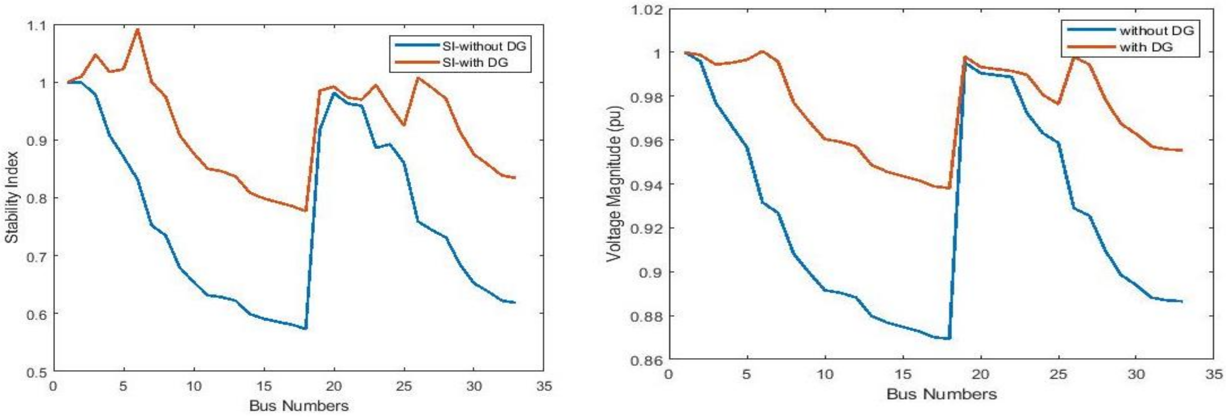


Figure 5: With and without DG in IEEE-33 bus network (a) Stability index. (b) Voltage profile.

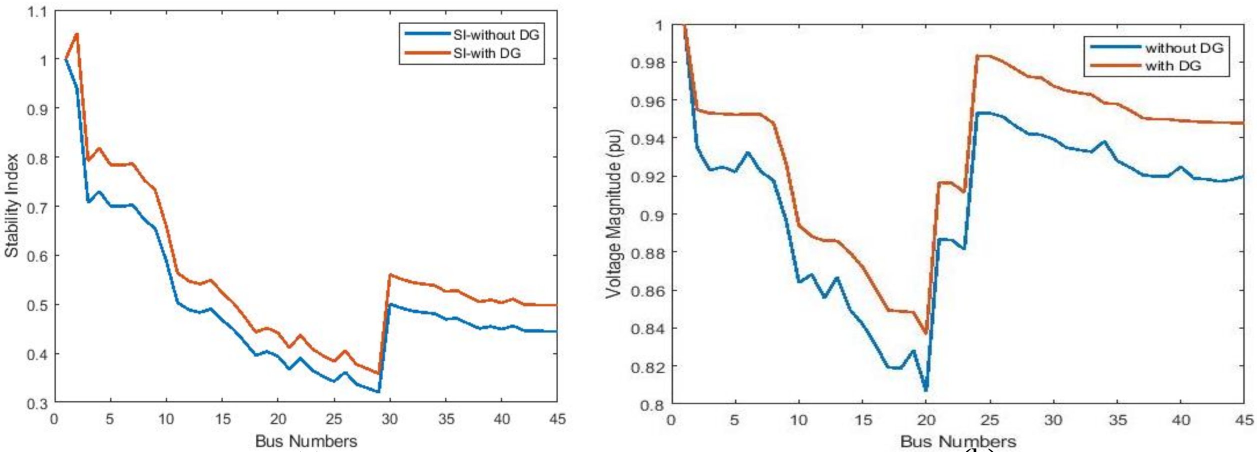
3.2 Irrua Distribution Network (45-bus) Simulation Results

(b)

The network consists of 45 buses, 44 lines with a total load of 8817 kW and 5596 kVAr respectively. Load flow analysis and stability index (SI) technique is used for allocating DG units; any bus with the lowest SI value is capable of causing voltage instability in the network and classified as a weak bus. The buses selected by SI are 1 and 27. From table 2, it was observed that total power losses without DG units are 1528.56 kW. After installing DG units, the total power losses reduced to 611.34 kW. Likewise figure 6a shows the SI values with and without DG units and figure 6b shows the voltage profile improvement after installing DG units.

Table 2: Location of DGs for Irrua Distribution Network using the Proposed Algorithm

	Without DG	With DG
DG bus location		1 & 27
Active power loss (kW)	1528.56	611.34
Min. voltage (p.u)	0.8066	0.8366
Min. stability index (p.u)	0.3203	0.3586
Total DG size (MW)/Bus no		11.907(1) / 0.882(27)
Loss reduction in %		60



(a) (b)

Figure 6: With and without DG on Irrua distribution network (a) Stability index. (b) Voltage profile.

3.3 Comparison of Proposed Method with Existing Method for IEEE-33 Bus Network

The results from the proposed method were compared with other existing standard algorithms using IEEE-33 bus network is as presented in Table 3. It is observed that the proposed algorithm allocated DG units on bus 6 and 15 with high power loss reduction compared to other Algorithms. It was observed in [26] that as the number of buses allocated with DG unit increases, the power losses will be reducing accordingly.

Table 3: Comparison of proposed algorithm with existing algorithms for IEEE 33 bus network

Method	Year	Minimum voltage (V_{min}) p.u	DG bus location	P_{TLoss} Without DG (kW)	DG size in (WM)	P_{TLoss} With DG (kW)	Loss Reduction in %
CSCA[27]	2020	0.9690	13, 24, 30	202.68	2.9166	71.94	64.51
WCA[28]	2018	0.9730	14, 24, 29	203.05	3.1373	71.052	65
HGWO[29]	2017	0.9715	13, 30	210.98	2.010	87.164	58.69
MOTA[30]	2017	0.9986	7, 14, 30	202.67	3.2800	106.12	52.4
SKHA[9]	2016	0.9687	13, 24, 30	210.99	4.4955	72.79	65.5
ACO-ABC[26]	2015	0.9735	14, 24, 30	202.70	2.9260	71.40	62.80
BFOA[12]	2014	0.964	14, 18, 32	210.98	2.2153	89.90	51.5
Proposed (IWD)		**0.9481**	**6, 15**	**273**	**3.4093**	**92.00**	**66.3**

4.0 Conclusion

In recent times, researchers have used novel methods to optimally place and size DGs on a radial distribution network so as to minimize power losses, improve the voltage profile and the network efficiency. In this research paper, IWD Algorithm was deployed for the task where VSI was used to optimally place DGs and IWD was used for the sizing of the DGs. The effectiveness of the proposed method was demonstrated on IEEE-33 bus network and IDN. The proposed method proved to have high power loss reduction and improve the voltage profile simultaneously when compared to other standard methods. IWD is a fast and appropriate technique for a distribution Network. The results obtained from the research work shows that the proposed method is a good option for optimally placing and sizing of DGs on a distribution network. The main benefit of the proposed method is the high reduction in active power loss, placement of DGs in less number of buses and its accuracy.

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