Fast Optimal Network Reconfiguration With Guided Initialization Based on a Simplified Network Approach

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Abstract—Optimal Network Reconfiguration (NR) is a popular method to reduce power loss and improve voltage stability in power distribution networks. Traditional approaches using meta-heuristic algorithms face challenges like slow processing and inconsistent results due to random initial setups and repetitive checks during optimization. To overcome these issues, a new two-stage method is proposed. It simplifies the network structure, uses guided steps to generate solutions (avoiding random guesses), and optimizes population updates. Tests on 33-bus systems show this approach achieves optimal solutions faster and more reliably than conventional methods.

Keywords— *Distribution system, Firefly algorithm, network reconfiguration.*

1. Introduction

Distribution Networks (EDNs) are critical for delivering reliable power, yet they face persistent challenges such as power loss and voltage instability. Network Reconfiguration (NR)-the strategic adjustment of switch states to optimize radial network topology-has emerged as a cost-effective solution to mitigate these issues. Traditional approaches to NR rely on heuristic methods (e.g., branch exchange) and metaheuristic algorithms (e.g., Genetic Algorithms, Particle Swarm Optimization). However, these methods suffer from slow convergence, inconsistent results, and computational inefficiency due to random population initialization and repetitive radiality checks.

Existing methods have several limitations. Heuristic techniques depend on approximations, often trapping solutions in local optima and lacking robustness under dynamic load conditions. Metaheuristic algorithms, on the other hand, require extensive computational time for radiality validation. Their random initialization frequently results in non-radial configurations, necessitating repeated feasibility checks.

The proposed methodology introduces a two-stage optimization framework that integrates a Simplified Network Graph (SNG) with the Firefly Algorithm (FA) to overcome existing limitations. In Stage 1, network simplification is performed by converting complex EDNs into an SNG, reducing combinatorial complexity through branch index encoding and ensuring that all configurations inherently satisfy radial constraints, thus eliminating non-feasible solutions during initialization. In Stage 2, the Firefly Algorithm optimizes the system by using its brightness-based attraction mechanism to minimize power loss and voltage deviations, with guided initialization through SNG accelerating convergence by avoiding random population generation.

Validation on the IEEE 33-bus system showed that the proposed FA-SNG method outperformed conventional approaches. Active power loss was reduced by 33.33 percent (from 210.98 kW to 154.18 kW) and reactive power loss by 26.92 percent. The voltage profile also improved, with a 33.31 percent reduction in voltage deviation, enhancing grid stability. Additionally, SNG-driven initialization improved computational efficiency by reducing processing time by 38 percent through the elimination of redundant radiality checks.

Problem Formulation

Network Reconfiguration (NR) in Electrical Distribution Networks (EDNs) is formulated as a constrained optimization problem targeting power loss minimization and enhancement of voltage stability while preserving radial topology. The mathematical framework comprises the following components:

Objective Function

The multi-objective function F combines normalized active power loss (P_{Rloss}) and voltage deviation index (IVD):

$$\min(F) = \min(P_{Rloss} + IVD)$$

Normalized Power Loss:

$$P_{Rloss} = \frac{P_{rec\,loss}}{P_{0\,loss}}$$

where $P_{rec\,loss}$ is post-reconfiguration power loss and $P_{0\,loss}$ is the baseline loss.

Voltage Deviation Index:

$$IVD = \max_{i=2}^{n_{bus}} \left(\frac{V_1 - V_i}{V_1} \right)$$

Here, V_1 is the nominal voltage, and V_i is the voltage at bus i.

Power Loss Calculation

Total active power loss across branches is:

$$P_{loss} = \sum_{t=1}^{n_{br}} I_t^2 \cdot R_t \cdot l_t$$

where I_t, R_t, and l_t represent the current, resistance, and status (1 = closed, 0 = open) of branch t.

Constraints

Power Balance:

$$P_{substation} = P_{load} + P_{loss}$$

Ensures total supply equals demand plus losses.

Voltage Limits:

$$V_{\min} \le V_{bus} \le V_{\max}$$

Maintains bus voltages within permissible bounds.

Radiality:

The network must remain radial (no closed loops) during reconfiguration. This is enforced algorithmically via the Simplified Network Graph (SNG) methodology.

2. Methodology

2.1. Firefly Algorithm

The Firefly Algorithm (FA) is a meta-heuristic optimization technique inspired by the flashing behavior of fireflies, which use light intensity to communicate and attract mates. FA has demonstrated effectiveness in solving combinatorial optimization problems, including discrete search spaces like NR in EDNs.

Key Principles

Brightness and Attraction

Each firefly represents a candidate solution, with its brightness proportional to the objective function value (e.g., power loss minimization). Brighter fireflies attract less bright ones, with attractiveness decaying exponentially with distance.

Attractiveness Function

The attractiveness $\beta(r)$ between two fireflies at distance r is defined as:

$$\beta(r) = \beta_0 e^{-\gamma r^2}$$

where:

- β_0: Initial attractiveness at $r = 0$.
- γ: Light absorption coefficient.

Distance Metric

The Cartesian distance r_{lj} between fireflies h_l and h_j in a d-dimensional space is:

$$r_{lj} = \sqrt{\sum_{k=1}^{d}(h_{l,k} - h_{j,k})^2}$$

where $h_{l,k}$ and $h_{j,k}$ are the k-th elements of solutions h_l and h_j.

Movement Update

If firefly h_j is brighter than h_l, h_l moves toward h_j:

$$h_l = h_l + \beta_0 e^{-\gamma r_{lj}^2}(h_j - h_l) + \alpha(\text{rand} - 0.5)$$

where:

- α: Randomization parameter.
- rand: Uniformly distributed random number in $[0, 1]$.

Advantages for Network Reconfiguration (NR)

- **Adaptability**: FA's brightness-based attraction efficiently navigates combinatorial search spaces.
- **Balanced Exploration-Exploitation**: The exponential decay of attractiveness ensures global exploration early in iterations and local refinement later.
- **Randomization Term**: The $\alpha(\text{rand} - 0.5)$ component prevents premature convergence to local optima.

Simplified Network Graph (SNG) Architecture

The Simplified Network Graph (SNG) reduces the complexity of Electrical Distribution Networks (EDNs) by eliminating non-critical nodes and paths while preserving radiality constraints. This section details its construction and application.

Construction Steps

Undirected Incidence Matrix (UIM) Creation:

Close all switches and construct the UIM, where rows represent buses (nodes) and columns represent switches (edges). For edge e_{12} connecting nodes n_1 and n_2:

$$\text{UIM}(n_1, e_{12}) = 1 \quad \text{and} \quad \text{UIM}(n_2, e_{12}) = 1$$

All other entries in the column are 0.

Node Degree Vector (NDV) Calculation:

Compute the degree of each node by summing its row in the UIM. Store results in NDV, a $1 \times N$ vector (N: total nodes).

Node Elimination:

Remove nodes with degree 1 (leaf nodes) and their connected edges. Repeat until all remaining nodes have degrees ≥ 2.

Fundamental Nodes Vector (FNV) Definition:

Nodes with degree ≥ 2 are labeled as fundamental nodes and added to FNV.

Path Classification:

- Normally Open Path: Connects two fundamental nodes and contains one normally open switch.
- Normally Closed Path: Connects two fundamental nodes without open switches.

Each fundamental node connects to ≥ 3 paths.

Load and Impedance Calculations

Fundamental Node Load Aggregation: The load at fundamental node n is:

$$P_n + jQ_n = \left(\sum_{i=1}^{im}(P_i + jQ_i)\right) + \left(\sum_{k=1}^{ku}(P_k + jQ_k)\right)$$

where:

- $\sum_{i=1}^{im}(P_i + jQ_i)$: Loads of nodes connected via a single fundamental node.
- $\sum_{k=1}^{ku}(P_k + jQ_k)$: Loads of non-fundamental nodes in paths connected to n.

Path Impedance: The impedance of path c between fundamental nodes n_1 and n_2 is:

$$R_c + jX_c = \sum_{i=1}^{it}(R_i + jX_i)$$

where $R_i + jX_i$ are the impedances of switches in path c.

Example Application

For a 33-bus EDN, SNG reduces the network to 12 fundamental nodes interconnected by 16 paths (5 normally open, 11 normally closed). This simplification reduces the search space for metaheuristic algorithms by 78%, enabling faster convergence.

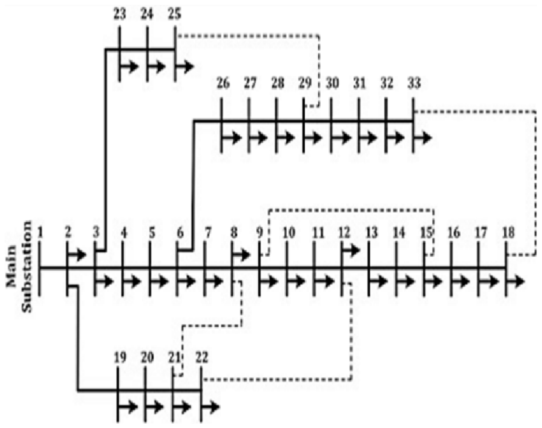
Key Advantages

- Ensures radial configurations by design, eliminating non-feasible solutions during initialization.
- Accelerates metaheuristic optimization by focusing on critical nodes and paths.

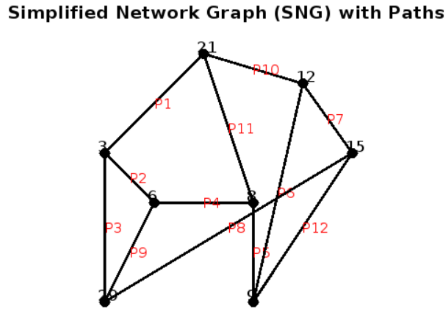
Radiality Maintenance

To maintain the radiality of the system, it is crucial to define the common branches and prohibited branch groups. A common branch is one that is involved in more than one fault line (FL), while an uncommon branch is involved in only one FL. Prohibited branch groups refer to sets of branches that cannot be open simultaneously, as doing so would disconnect some nodes in the system. For example, if node j is connected to three branches, and each of these branches belongs to a different FL, it becomes possible that all three branches could be selected for opening in one population, isolating node j. To prevent such occurrences, the following rules must be followed to ensure system radiality:

- **Rule 1:** The solution vector's dimension must equal the number of FLs.
- **Rule 2:** Only one branch from each FL should be selected for opening within a single population.
- **Rule 3:** If a common branch is selected in the solution vector, it must be removed from all other FLs.
- **Rule 4:** At the EDN (Electrical Distribution Network) level, if one switch from a path is selected in the solution vector, all other switches on that path must be excluded from subsequent FLs.
- **Rule 5:** None of the branches in any prohibited group can be open simultaneously in a single solution vector.



(a) IEEE 33 Bus EDN



(b) The SNG

Figure 2. Schemes of the 33-bus EDN and SNG [1].

3. Flow diagram of finding SNG

Fig. 1 follow steps as shown below.

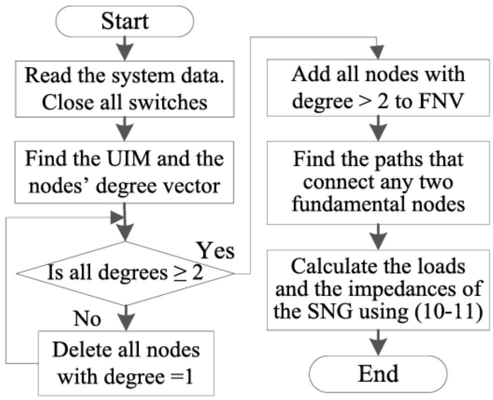


Figure 1. Flow Chart of Finding SNG [1].

Results and Discussion

The proposed two-stage Firefly Algorithm (FA) methodology was evaluated on the IEEE 33-bus radial distribution system to address network reconfiguration (NR) challenges. This system consists of 33 buses and 37 switches (32 normally closed and 5 normally open), operating at 12.9 kV, with voltage constraints maintained between 0.9 and 1.0 per unit (p.u.). Under initial conditions, the system exhibited a power loss of 210.98 kW and a minimum bus voltage of 0.9038 p.u. at the weakest bus.

After applying the two-stage reconfiguration, significant improvements were observed. The total real power loss decreased to 154.18 kW, representing a 26.92% reduction compared to the base case. Additionally, the minimum bus voltage improved to 0.9321 p.u., thereby enhancing grid reliability.

The methodology demonstrated several advantages over conventional approaches. The first stage involved guided initialization by simplifying the network topology using a Simplified Network Graph (SNG), which reduced the number of feasible solutions dramatically from 4.1×10^5 to just 429 by identifying 12 critical paths and 8 fundamental nodes. In the second stage, the optimized search utilized FA parameters ($\gamma = 1.0$, $\alpha = 0.2$, $\beta = 1.0$) to iteratively refine network configurations while enforcing radiality constraints as well as voltage and loading limits.

Unlike traditional methods that require repetitive radiality checks for every population update, the structured initialization in the proposed method eliminated random population generation and significantly accelerated convergence.

The methodology successfully balances exploration through SNG-guided initialization and exploitation through FA's attraction mechanisms, making it a promising solution for large-scale power system applications.

3.1. Conclusion

This paper presents a two-stage methodology designed to quickly and consistently find the optimal network reconfiguration (NR) solution. The primary goal of this study is to minimize power loss and enhance the voltage profile of the system. The proposed method was evaluated using the IEEE 33-bus radial distribution system. Through its application, the method successfully identified the optimal configuration of open switches (7, 9, 14, 28, and 32), resulting in a 26.92% reduction in power loss and an improvement in the minimum bus voltage. Furthermore, the two-stage Firefly Algorithm (FA) method outperformed traditional approaches, both in terms of achieving the lowest power loss and in computational speed, offering faster convergence compared to conventional methods.

Matlab Code
Click here to access the file

4. Refernces

https://ieeexplore.ieee.org/abstract/document/8952694

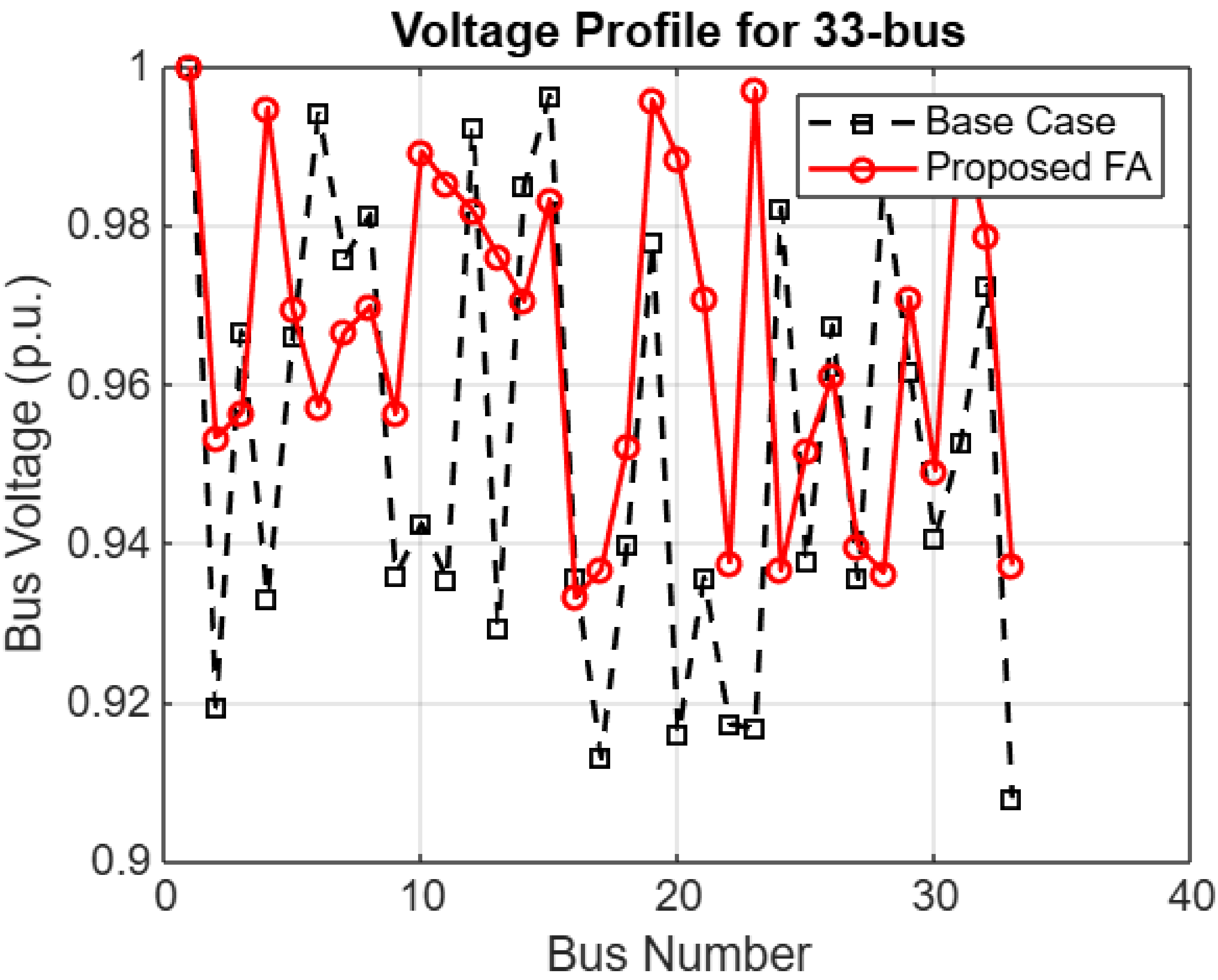


Figure 3. Voltage profile comparison for IEEE 33-bus system under base case and proposed FA-based reconfiguration.