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Dynamic Network Reconfiguration for Unbalanced Power Distribution Systems

Dr J.Sridevi,
Professor
Department of Electrical and Electronics Engineering
Gokaraju Rangaraju Institute of Engineering and Technology,
Bachupally, Hyderabad

drjamisridevi@gmail.com

***Abstract*— This paper presents a network reconfiguration methodology for three-phase unbalanced distribution systems, addressing both normal operating and post-fault conditions. Under normal operating conditions, network reconfiguration is carried out to minimize real power losses. In post-fault conditions, the reconfiguration focuses on isolating faulty lines while ensuring maximum demand is met. A graph theory-based method is employed to achieve maximum service restoration, and a power flow algorithm is developed to calculate power losses in unbalanced distribution systems. The proposed algorithm is tested on IEEE 34-bus unbalanced radial distribution system under both normal and faulty conditions. The results demonstrate the effectiveness of the methodology in achieving the desired objectives.**

Keywords*— Maximum service restoration, network reconfiguration, power loss minimization, three-phase load flow, unbalanced distribution systems.

I. INTRODUCTION

The rapid increase in electricity demand often surpasses the generation and transmission capacity, causing the transmission and distribution systems to operate under heavily loaded conditions. Distribution systems serve various types of loads, such as commercial, residential, and industrial, each with unique daily load curves. Consequently, peak loads on feeders occur at different times. Network reconfiguration can mitigate this load imbalance by transferring loads from heavily loaded feeders to underutilized ones. This reduction in load imbalance not only provides economic benefits but also decreases power losses [1].

Network configuration refers to the process of changing the topological structure of a system by altering the open/closed states of sectionalizing and tie switches [2]. When the operating conditions of the system change, network reconfiguration is performed while adhering to limitations such as feeder thermal capacity, voltage drop, transformer capacity, and the radial nature of the network. The reconfiguration problem is often treated as a multi-objective optimization problem, which includes objectives such as minimizing power losses, maximizing reliability, reducing voltage deviation along the lines, and minimizing load imbalance within the system.

Significant research has been conducted in the area of loss minimization and maximum service restoration. Network reconfiguration in distribution systems for loss minimization was first proposed by Merlin and Back. Merlin [3] introduced a branch-and-bound optimization technique for minimizing losses, treating the distribution system as a meshed network by initially closing all switches and then successively opening switches to maintain the system's radial structure. In [4], a modified simplex method is discussed for network reconfiguration. To reduce computational burden and execution time, linear programming is employed. A Binary Particle Swarm Optimization (BPSO)-based technique for power loss minimization and reliability maximization is proposed in [5]. Dynamic programming is used to identify the minimal cut set for each load point, and possible switch combinations are generated. Power loss and reliability are then calculated for each switch combination, and a tradeoff function is used to determine the optimal solution.

In [6], a hypercube ant colony optimization method is proposed for minimizing power losses. The aforementioned research assumes a balanced distribution system, but in reality, distribution systems are rarely perfectly balanced. Therefore, it is essential to consider this imbalance when evaluating the system. The focus on unbalanced systems is limited in the previous research, and this area requires further development. In [7], a spanning tree-based network reconfiguration approach is proposed for unbalanced distribution systems, with an emphasis on power loss minimization and load balancing. The process begins with all switches closed, forming a closed loop, and switches are then opened one by one based on a switching index. Only constant impedance-type loads are considered in this approach. In [8], a heuristic method for loss minimization in three-phase unbalanced systems is introduced. This approach considers weakly meshed systems, and a Z-loop matrix is calculated for each loop. The branch with the highest order is prioritized for reconfiguration.

All the reconfiguration techniques discussed in the literature primarily focus on balanced distribution systems, or in the case of unbalanced systems, they operate under normal conditions. However, the execution time of many of these algorithms is quite high. The main contribution of this paper is the development of a reconfiguration algorithm specifically designed for unbalanced distribution systems that can operate under both normal and fault conditions.

In healthy conditions, the objective of the algorithm is to minimize power losses, while in fault conditions, the algorithm focuses on isolating faulty lines and maximizing service restoration. Additionally, the execution time of this algorithm is significantly lower compared to other existing methods, making it suitable for real-time applications. A

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three-phase load flow algorithm is developed to accurately calculate power losses in unbalanced distribution systems.

II. Power Loss in Unbalanced Three Phase Distribution System

Distribution lines are rarely transposed, and the loadings can often be heavily unbalanced. As a result, three-phase load flow methods are essential for accurately modeling unbalanced distribution systems. In this paper, a three-phase load flow algorithm is developed using the forward-backward sweep method [9]. The developed algorithm accounts for the unbalanced loading of the three phases, mutual coupling between the lines, the ZIP model of the load, and the presence of capacitor banks, if applicable. The steps of the algorithm are briefly outlined below:

- Read the input data, viz., line data, load data, capacitor data, and transformer data.
- Set convergence, ∈= 0.0001, i.e, 4Vmax = 0.0001.
- Calculate charging current in the system as

$$\begin{bmatrix} \bar{I}^a_{SH,i} \\ \bar{I}^b_{SH,i} \\ \bar{I}^c_{SH,i} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \bar{B}_{aa} & \bar{B}_{ab} & \bar{B}_{ac} \\ \bar{B}_{ba} & \bar{B}_{bb} & \bar{B}_{bc} \\ \bar{B}_{ca} & \bar{B}_{cb} & \bar{B}_{cc} \end{bmatrix} \begin{bmatrix} \bar{V}^a_i \\ \bar{V}^b_i \\ \bar{V}^c_i \end{bmatrix} \quad (1)$$

Where $I^{-a}_{SH,i}$, $I^b_{SH,i}$, and $I^c_{SH,i}$ are the components of the three-phase injected charging current vector, and $Vi=[V^a_i,V^b_i,V^c_i]^T$ is the vector of phase voltages at the i-th bus. B_{aa} and B_{ab} represent the self-susceptance of phase a and the mutual susceptance between phases a and b, respectively.

- The load current is calculated according to the given load model. If the loads are star-connected and of constant power type, the load current is given by:

$$\begin{bmatrix} \bar{I}^a_{p,i} \\ \bar{I}^b_{p,i} \\ \bar{I}^c_{p,i} \end{bmatrix} = \begin{bmatrix} \left(\frac{PL^a_i + j \times QL^a_i}{V^a_i}\right)^\star \\ \left(\frac{PL^b_i + j \times QL^b_i}{V^b_i}\right)^\star \\ \left(\frac{PL^c_i + j \times QL^c_i}{V^c_i}\right)^\star \end{bmatrix} \quad (2)$$

Where $I^a_{p,i}$, $I^b_{p,i}$, and $I^c_{p,i}$ represent the load current at phases a,b, and c corresponding to constant-power type loads, and $(PL^a_i+jQL^a_i)$ is the load at phase a of the i-th bus.

For constant power type loads, the load remains constant in every iteration, but the voltage at each phase is updated in each iteration. In contrast, for constant impedance type loads, the load is a quadratic function of voltage magnitude.

For a constant impedance type, star-connected load, the current can be calculated as:

$$\bar{I}^a_{Z,i} = \frac{\bar{V}^a_i}{\bar{Z}^a_i}, \quad \bar{I}^b_{Z,i} = \frac{\bar{V}^b_i}{\bar{Z}^b_i}, \quad \bar{I}^c_{Z,i} = \frac{\bar{V}^c_i}{\bar{Z}^c_i} \quad (3)$$

Where Z^a_i, Z^b_i, and Z^c_i are the load impedances for phases a, b, and c at the i-th bus, respectively. These impedances can be calculated as:

$$\bar{Z}^a_i = \frac{|\bar{V}^a_i|^2}{(PL^a_i + j \times QL^a_i)^\star} \quad (4)$$

$$\bar{Z}^b_i = \frac{|\bar{V}^b_i|^2}{(PL^b_i + j \times QL^b_i)^\star} \quad (5)$$

$$\bar{Z}^c_i = \frac{|\bar{V}^c_i|^2}{(PL^c_i + j \times QL^c_i)^\star} \quad (6)$$

Where$[I^a_{Z,i},I^b_{Z,i}$, and $I^c_{Z,i}]^T$ are the components of the vector representing the three-phase load current corresponding to constant impedance type loads. For constant impedance type loads, the impedance of each phase remains constant, and the node voltages must be updated in each iteration.

For constant current type loads, the load current is a linear function of the voltage magnitude. The load current for constant current type loads can be calculated as follows:

$$\bar{I}^a_{I,i} = |I^a_i| \angle (\delta^a_i - \theta^a_i) \quad (7)$$

$$\bar{I}^b_{I,i} = |I^b_i| \angle (\delta^b_i - \theta^b_i) \quad (8)$$

$$\bar{I}^c_{I,i} = |I^c_i| \angle (\delta^c_i - \theta^c_i) \quad (9)$$

Where θ^a_i is the power factor of the load and δ^a_i is the voltage angle at the i-th bus. The vector $I^a_{I,i}$, $I^b_{I,i}$, $I^c_{I,i}$ represents the three-phase load current at the i-th bus for a constant-current type load.

For constant-current type loads, only the voltage angle is updated in each iteration, while the current magnitude remains constant. The total load current can be calculated as follows:

$$\begin{bmatrix} \bar{I}^a_{L,i} \\ \bar{I}^b_{L,i} \\ \bar{I}^c_{L,i} \end{bmatrix} = \begin{bmatrix} \bar{I}^a_{p,i} \\ \bar{I}^b_{p,i} \\ \bar{I}^c_{p,i} \end{bmatrix} + \begin{bmatrix} \bar{I}^a_{Z,i} \\ \bar{I}^b_{Z,i} \\ \bar{I}^c_{Z,i} \end{bmatrix} + \begin{bmatrix} \bar{I}^a_{I,i} \\ \bar{I}^b_{I,i} \\ \bar{I}^c_{I,i} \end{bmatrix} \quad (10)$$

Where $[I^a_{L,i}, I^b_{L,i}, I^c_{L,i}]$ are the components of the vector representing the three-phase injected load current at the i-th bus.

- Backward Sweep: After calculating the load current for all the loads, the branch current is determined by starting from the farthest node at the load end and moving towards the slack bus. The branch current is given by:

$$\bar{I}^a_{ji} = \bar{I}^a_{L,i} + \bar{I}^a_{SH,i} + \sum_{m \epsilon A_i} \bar{I}^a_{im} \quad (11)$$

Where I^a_{ji} is the phase a current between buses j and i, and A_i is the set of nodes adjacent to bus i.$I^a_{L,i}$ and $I^a_{SH,i}$ represent the phase a load current and charging current at the i-th bus, respectively.

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- Forward Sweep: In the forward sweep, the voltage at each bus is calculated using the branch currents obtained during the backward sweep. The calculation starts from the source end and moves towards the load end.

$$\begin{bmatrix} \bar{V}_i^a \\ \bar{V}_i^b \\ \bar{V}_i^c \end{bmatrix} = \begin{bmatrix} \bar{V}_j^a \\ \bar{V}_j^b \\ \bar{V}_j^c \end{bmatrix} - \begin{bmatrix} \bar{Z}_{ij}^{aa} & \bar{Z}_{ij}^{ab} & \bar{Z}_{ij}^{ac} \\ \bar{Z}_{ij}^{ba} & \bar{Z}_{ij}^{bb} & \bar{Z}_{ij}^{bc} \\ \bar{Z}_{ij}^{ca} & \bar{Z}_{ij}^{cb} & \bar{Z}_{ij}^{cc} \end{bmatrix} \begin{bmatrix} \bar{I}_{ij}^a \\ \bar{I}_{ij}^b \\ \bar{I}_{ij}^c \end{bmatrix} \quad (12)$$

Where $[V^a{}_i, V^b{}_i, V^c{}_i]^T$are the components of the three-phase voltage vector at the receiving end bus, and $[V^a{}_j, V^b{}_j, V^c{}_j]^T$ are the components of the three-phase voltage vector at the sending end bus, respectively.

$Z^{aa}{}_{ij}$ and $Z^{ab}{}_{ij}$ represent the self-impedance of phase a and the mutual impedance between phases a and b, respectively.

The power loss of each branch can be calculated as:

$$P_{L_{ij}} = Re\left(\bar{V}_i \bar{I}_{ij}^{\star} - \bar{V}_j \bar{I}_{ij}^{\star}\right) \quad (13)$$

The loss of each branch of each phase is added to calculate the overall loss in the system.

III. PROPOSED METHODOLOGY

This paper proposes a network reconfiguration technique for unbalanced three-phase distribution systems. While most previously proposed techniques are limited to normal operating conditions or focus on balanced distribution systems, the method presented here operates under both normal conditions and post-fault situations in unbalanced systems.

A. Reconfiguration when the System is in Healthy Condition

In normal operating conditions, a distribution system can be reconfigured for various objectives, such as loss minimization, reliability maximization, maximizing the penetration of renewable energy, and load balancing, among others. In this paper, the reconfiguration is performed specifically for loss minimization when the system is in a healthy condition.

To perform the reconfiguration, three-phase switches are considered in the system, where a value of 0 represents the closed status of a switch and 1 represents the open status. The process begins by determining the total number of switches in the system, followed by finding all possible switch combinations that satisfy certain conditions, which are listed below:

- No switch combination should form a loop in the system, ensuring the network always remains radial in nature.
- Maximum load demand should be met.
- In a three-phase system, the phase sequence from the sending end bus to the receiving end bus must be correct.

The three-phase power loss is calculated for each valid switch combination that satisfies the above conditions. To calculate the three-phase power loss, a forward-backward sweep method-based algorithm for unbalanced distribution systems is developed, as discussed in Section II.

Mathematically, the reconfiguration problem for power loss minimization is formulated as follows:

$$\text{Minimize} \quad J = \sum_{i=j,i<j} P_{L_{ij}} \quad (14)$$

$$\text{Such that} \quad 0.95 \le V_i \le 1.05 \quad (15)$$

$$I_{ij} \le I_{max} \quad (16)$$

Where P_{Lij} is the real power loss in the line connecting bus i and bus j, and I_{ij} is the current in the branch between buses i and j. When the switch status changes, the system topology also changes accordingly. Therefore, to perform network reconfiguration, an adjacent node vector, an adjacent branch vector, and a dynamic connectivity matrix are created. These structures allow the system topology to automatically adjust according to the switch status, enabling the reconfiguration process to take place seamlessly.

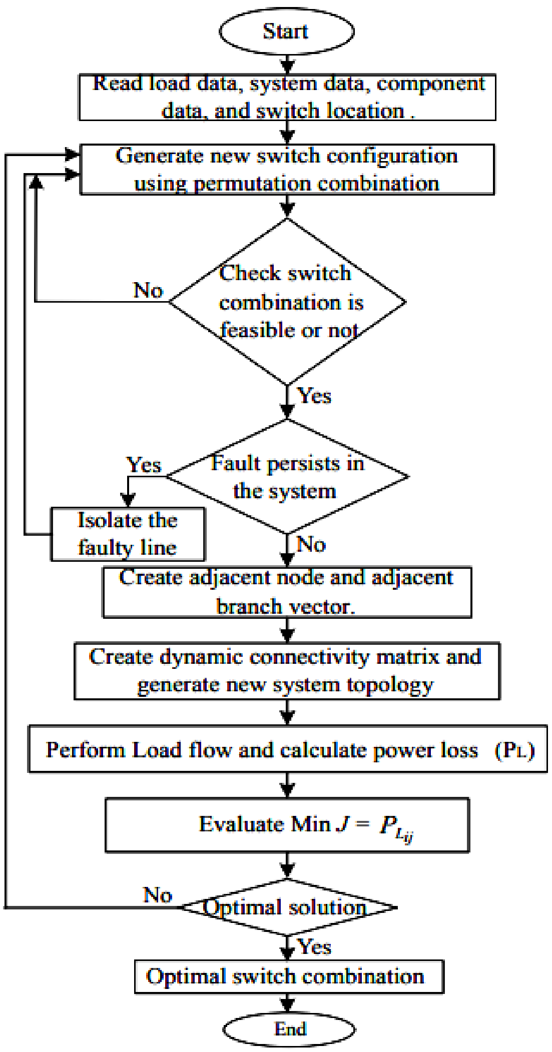

Fig. 1. Flow chart for Reconfiguration algorithm of three-phase unbalanced system

B. *Reconfiguration When Fault Persists in the System*

When a fault persists in the system, the proposed method isolates the faulty line and performs reconfiguration for maximum service restoration, while minimizing losses. This algorithm is capable of handling faults on multiple lines. It is assumed that the location of the fault is known, with a value of 1 indicating the faulty line.

When a fault occurs, the algorithm isolates the faulty line, forms the dynamic connectivity matrix, and identifies the valid switch combinations. The switch combinations must satisfy the following conditions:

- Isolate the faulty line from the system.
- Restore maximum service, ensuring that the maximum demand is met after isolating the faulty line.
- Maintain the radial nature of the system.
- Ensure that the phase sequence from the sending end bus to the receiving end bus remains correct after isolating the faulty line.

Power loss is calculated for each valid switch combination. The optimal solution is the switch combination that restores the maximum service while minimizing power losses. The overall methodology is illustrated in the flowchart shown in Fig. 1.

IV. Results and Discussions

The IEEE 34-bus distribution system is used as the test case and is described in [10]. It is a 24.9 kV, 34-bus unbalanced distribution system, with both lumped and distributed loads considered. The proposed technique does not depend on the initial position or status of the switches. A total of nine switches are considered for the reconfiguration process. Except for the substation bus, all other buses are treated as load buses. Fig. 2 illustrates the single-line diagram of the test system.

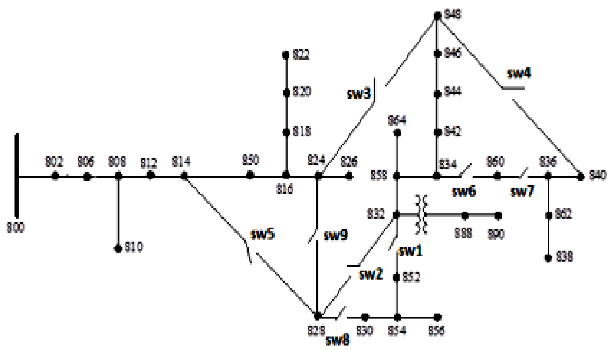

Fig. 2. IEEE 34-bus system

The proposed algorithm is implemented in MATLAB. When the system is in normal condition, reconfiguration is performed to minimize losses. The reconfiguration is tested under different loading conditions: light, nominal, and heavy. In the light loading condition, the system load is reduced to half of the nominal load. In the heavy loading condition, the load is increased up to 1.5 times the nominal load.

Under each loading condition, the voltage profile of the system is improved, and the power losses are significantly reduced. The results are presented in Table I below.

TABLE I. OPTIMAL SOLUTION FOR IEEE 34-BUS SYSTEM

Case		Load Level		
		Light	Nominal	Heavy
Base Case	Switches Closed	9,8,6,7,1	9,8,6,7,1	9,8,6,7,1
	Power Loss (kw)	146.929	247.6149	512.5927
	Minimum Voltage (p.u)	0.97	0.92	0.87
After Reconfiguration	Switches Closed	8,6,3,4,5	8,7,3,4,5	8,6,7,2,5
	Power Loss (kw)	93.4646	184.1713	395.1963
	Minimum Voltage (p.u)	0.99	0.94	0.91

In the post-fault situation, suppose a fault occurs between buses 852 and 854. Reconfiguration is performed to isolate the faulty line and restore maximum service. Table II shows that after reconfiguration, all the loads are successfully restored. Under nominal loading conditions, the losses are reduced by 27%, and the minimum voltage profile of the system is improved, even after isolating the faulty line. The

CPU runtime of this algorithm for the system is approximately 6 seconds.

TABLE II. OPTIMAL SOLUTION FOR IEEE 34-BUS SYSTEM WHEN FAULT PERSISTS IN THE SYSTEM

Case		Load Level		
		Light	Nominal	Heavy
Base Case	Switches Closed	9,8,6,7,1	9,8,6,7,1	9,8,6,7,1
	Power Loss (kw)	146.929	247.6149	512.5927
	Minimum Voltage (p.u)	0.97	0.92	0.87
After Reconfiguration (After Faulty Line Isolation)	Switches Closed	8,6,1,3,4,5	8,7,1,3,4,5	8,6,7,1,2,5
	Power Loss (kw)	89.7152	182.5722	395.3986
	Minimum Voltage (p.u)	0.98	0.94	0.91
	Maximum No. Of Restored Load	34	34	34

V. CONCLUSION

A significant contribution of this study is the development of a reconfiguration technique for unbalanced distribution systems that operates effectively under both normal operating conditions and post-fault situations. In normal conditions, the objective of this method is to minimize power losses. When a fault occurs, the reconfiguration isolates the faulty line and restores maximum service. In this paper, reconfiguration is performed under three different loading conditions: light, nominal, and heavy. Additionally, a three-phase load flow algorithm is developed to accurately calculate power losses in unbalanced distribution systems. The runtime of this method is notably lower compared to other existing methods, making it suitable for real-time applications.

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