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A Review of Load Flow Methods in Analysis of Power Distribution Systems

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***Abstract*—** Power systems consist of four important segments namely, generation, transmission, distribution and utilization. Each of these segments require to be planned and operated securely in order to maintain a given frequency and voltage level. In order to carry out effective planning, operation, optimization and control, load flows are important for determining the state variables of these networks. With proper method of load flow, the planner would be able to determine network problems such as voltage stability, network power loss and transient stability therefore operating the network securely and economically. In this paper, a review of methods of load flows used in analysis of distribution network has been carried out. The review seeks to highlight strengths and weaknesses of different load flow methods while studying distribution networks.

***Keywords*—** Distribution Network, Load Flow methods.

I. Introduction

POWER distribution networks form the link between transmission network and the consumer. Distribution networks have unique characteristics that differentiate them from transmission network. These characteristics include unbalanced distributed loads, multiphase unbalanced operation, large number of nodes, high resistance-to-reactance (R/X ratios) of the feeders and distributed generation [1].

A. Distribution Network components

Distribution networks consists of distributed feeders, distributor and service mains. Distributed feeders are conductors that connect a substation to the point where power is to be distributed. There are no tapping made on the distributed feeder and therefore the current in a feeder remains constant. A distributor is a conductor where tapping are made to the consumer. Current in a distributor varies due to tapping. A service main forms the link between the consumer terminal and the distributor.

B. Types of Distribution System Configurations

Depending on the feeder configuration, distribution networks can be classified into four categories namely radial distribution system, parallel feeders, ring main and meshed systems.

1) Radial Distribution systems

Radial Distribution Networks are the most common form of distribution system. This is because they are easy to construct, have a relatively simple protection scheme and are not expensive. The configuration of radial distribution system is as shown in fig. 1.

The disadvantage of these systems is that when a fault occurs on a feeder, the consumers connected on that feeder are disconnected during the entire period of the fault. They therefore are less reliable.

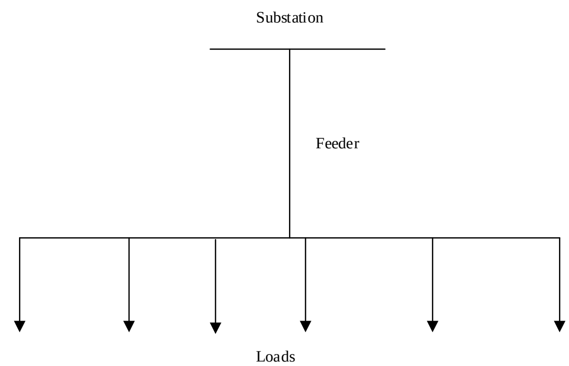

Fig. 1: Line diagram of a radial distribution system

2) Parallel Feeders

In this system, two parallel feeders run to the distributor through different routes. The aim is to increase reliability of the network in that when there is a fault in one feeder, the supply is maintained using the other feeder. This network however is more expensive than the radial distribution network. Fig. 2 shows a line diagram of a parallel feeder system.

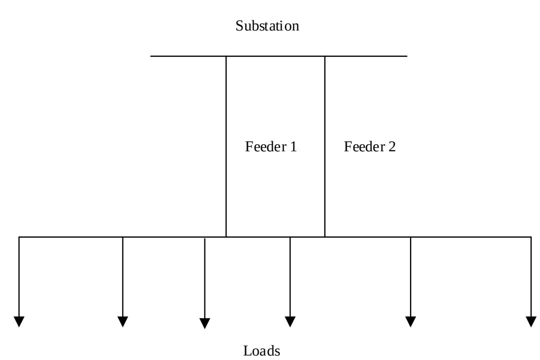

Fig. 2: Line diagram of a parallel feeder system

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3) Ring main Feeders

In this configuration, the start and end of a feeder are at the same location. This increases liability because if there is fault on one end of the feeder, the supply is maintained through the other end. The configuration of this network is as shown in fig.3.

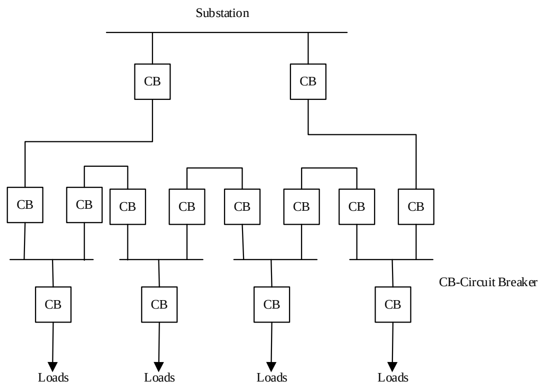

Fig. 3: Ring main feeder configuration

4) Meshed distribution systems

In meshed networks multiple paths are available between multiple points in the network. Power flow is split along several paths between any two points in the network. If a fault occurs at a point in the network, power flow reroutes to another path.

This type of network is the most reliable but also most complex and therefore difficult to analyze. This network is also the most expensive owing to its complexity and use of more conductors. Fig. 4 shows the configuration of a meshed network.

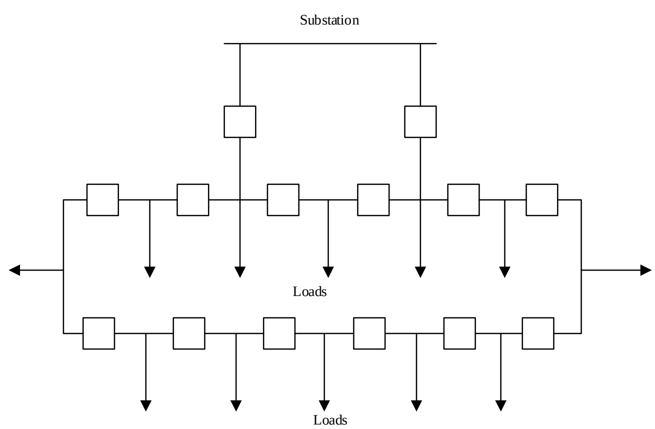

Fig. 4: Meshed distribution network

II. METHODS OF LOAD FLOW IN DISTRIBUTION NETWORKS

The choice of method of power flow is determined by the value of ratio of R/X of the network, presence of distributed generation, multiphase power flow and unbalanced loads [2].

Distribution networks have high R/X ratio and operate in unbalanced conditions. In addition, distribution networks are increasingly becoming active due to presence of distributed generation and as such new techniques of load flows are being adopted.

This section gives a review of various techniques that researchers have applied to solve load flows in distribution networks.

A. Forward and Backward Sweep Method

This method has been used in [3] to solve load flow for IEEE-33 bus radial distribution system. The method involved two steps, which are done iteratively, namely forward sweep and backward sweep.

In the forward sweep, voltage drop calculation is done. In addition, power flow and nodal voltages are updated in a forward direction starting from branches in the first layer towards those in the last layer. The effective power in each branch is held constant to the value obtained in the backward sweep during this step.

The backward sweep starts with branches in the last layer moving towards the branches connected to the root node. Effective power flows in each branch are obtained by considering the node voltages of previous iteration. The voltages obtained during the forward sweep are held constant during this step and updated power flows in each branch are transmitted backwards along the feeder using backward path.

The forward and backward sweep method has three variants determined by the quantity calculated during the backward sweep of each iteration. These include:

i) The current summation method where the branch currents are evaluated according to the equation (1).

$$J_L(k) = -I_{L2}(k) + \sum \begin{matrix} \textit{currents in branches emanating} \\ \textit{from node } L2 \end{matrix} \quad . \qquad (1)$$

where, $J_L(k)$ is the current in branch L at iteration k,

$I_{L2}(k)$ is current injection at node L and

$L = b, b-1, b-2, \ldots, 1$

This is the direct application of the Kirchhoff's Current Law.

ii) The power summation method where the power flows in the branches are evaluated.

iii) The admittance summation method where, node by node, the driving point admittances are evaluated.

The advantage of this method is that the Jacobian Matrix is not required. In addition, this method is suitable for radial and weakly meshed networks with a high R/X ratio. It also has a fast convergence [4].

B. Direct method(BIBC/BCBV matrix Method)

This method has been applied in [5] to solve load flow for a radial distribution system. It uses three steps namely, equivalent current injection, formulation of BIBC matrix and formulation of BCBV matrix.

1) Equivalent current injection

During this step, the current injection at bus i during the kth iteration is computed as shown in equation (2).

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k} \right). \qquad (2)$$

where,

I_i^k -is equivalent current injection at the kth iteration for ith bus

P_i - is the real power at ith bus

Q_i - is the reactive power at ith bus

V_i^k - is the bus voltage at the kth iteration for ith bus

2) Formulation of BIBC matrix

This step involves forming current injection equations using the Kircchoff's Current Law for the radial distribution network and then writing the branch current as a function of the equivalent current injections. The relationship is given by equation (3).

$$[B]=[BIBC][I] \tag{3}$$

where,

$[B]$-Branch Current Matrix

$[BIBC]$-Bus injection-Branch Current Matrix

$[I]$-Bus Injection Matrix

3) Formulation of BCBV matrix

The BCBV matrix is represents the relationship between the branch currents and the bus voltages. Using the BCBV matrix, the respective variation of the bus voltages which is generated by the variation of the branch currents is established directly. This relationship is represented by equation (4).

$$[\Delta V]=[BCBV][B] \tag{4}$$

where,

$[\Delta V]$-Variation of bus voltage matrix

$[BCBV]$-Branch Current-Branch Voltage matrix which consist of line impedance parameters

$[B]$-Branch Current matrix

This method eliminates formation of Jacobian matrix and therefore its implementation is less time consuming. It is effective for analysis of radial networks.

C. Implicit Z_{BUS} Gauss Method

This method has been used in [6] to solve load flow flow for a three phase unbalanced radial distribution network. This method works on the principle of superposition. The voltage at each bus arises from the contribution of source bus voltage and the equivalent current injections.

When using the superposition principle, only one type of source is considered at a time while determining the bus voltages. That is to mean that when the slack bus is connected, all current injections are disconnected and vice versa.

The current injection at bus i at kth iteration is given by equation (2). The branch current vector and bus voltage vector at iteration k are given by equation (5) and equation (6) respectively.

$$I^{(k)}=Y\Delta V^{(k)}=LU\Delta V^{(k)} \tag{5}$$

$$V^{(k+1)}=V_{NL}+\Delta V^{k} \tag{6}$$

where,

Y - is the admittance matrix

$\Delta V^{(k)}$ -is the vector of voltage deviation of the kth iteration

LU -is the triangular factorization of the admittance matrix

V_{NL} -is the no load node vector matrix taken as equal to source node

The Z_{BUS} method is solved by equations (2), (5) and (6) iteratively.

Patil and Kurkani [6] concluded that the Z_{BUS} method performed better in execution time and rate of convergence than the conventional Newton Raphson method because it does not require computation of the elements of Jacobian. From this paper, the authors demonstrated the effectiveness of this method in solving load flow for unbalanced radial distribution systems.

D. Loop impedance method

The concept of loop impedance matrix has been used in [7] to solve power flow of three phase unbalanced radial distribution system. This method is based on graph theory where basic loop incidence matrix **C** and branch-path incidence matrix **K** of a connected graph are used to describe the system.

1) Basic Loop Incidence matrix

A distribution network is described by n nodes, e elements, b branches and l links. The number of branches is given by:

$$b=n-1 \tag{7}$$

The number of elements is given by:

$$e=b+l \tag{8}$$

A basic loop incidence matrix **C** of a directed graph is an e x l matrix with elements of different dimensions according to number of phases of elements. The number of links and number of basic loops is the same.

Matrix **C(*i,j*)= +U** if element *i* is incident to and directed in the same direction as the j^{th} basic loop. Matrix **C(*i,j*)= -U** if element *i* is incident to and directed in the opposite direction as the j^{th} basic loop. **U** is a unit matrix whose dimensions correspond to the number of phases of element ***i***.

2) Branch path incidence matrix

The branch path incidence matrix represents the incidence of branches to paths in a tree, where a path is directed from a bus to the reference bus. The elements of branch path incidence matrix **K**(*i,j*)= **+U** if the branch *i* is in the path from bus *j* to the reference node and directed in the same direction. **K**(*i,j*)= **-U** if the branch *i* is in the path from bus *j* to the reference node and directed in the opposite direction.

Once the incidence matrices are formed, they are combined with the primitive network matrices to completely describe the system. In [7], loop impedance matrix $\mathbf{Z}_{loop}$ is obtained by combining the primitive impedance matrix |**Z**| and loop incidence matrix as shown in equation (9).

$$\mathbf{Z}_{\mathbf{Loop}}=\mathbf{C}^{t}|\mathbf{Z}|\mathbf{C} \tag{9}$$

The network equation are obtained by equation (10).

$$\bar{V}_{Loop}=\mathbf{Z}_{\mathbf{Loop}}\bar{I}_{Loop} \tag{10}$$

where $\bar{V}_{Loop}$ is the basic loop voltage vector, $\bar{I}_{Loop}$ is the vector of basic loop currents and $\mathbf{Z}_{\mathbf{Loop}}$ is the loop impedance matrix.

This method has a fast convergence for large unbalanced radial distribution networks. In addition, it does not require formation of admittance matrix and therefore offers less computation time.

E. Newton Based Methods

Newton based methods are modified forms of the conventional Newton Raphson power flow solution. The modification is necessary because of the unique characteristics of distribution networks which affect the convergence of conventional Newton Raphson power flow method.

In [8], Polar Current Mismatch Version has been used to solve a three phase power flow problem in distribution network. This version is obtained using the current mismatch functions in polar co-ordinates.

Other versions include Cartesian current mismatch, complex current mismatch, Cartesian power mismatch and complex power mismatch which are detailed in [9]. Newton Based Methods have the disadvantage of using Jacobian Matrix which increases the computation time especially for large distribution networks.

III. CONCLUSION

This paper has reviewed methods used for load flow solution in distribution systems. These methods include forward and backward sweep method, implicit Z_{bus} Gauss Method, BIBC/BCBV matrix method, Newton Based Methods and Loop impedance method.

Newton Based methods use Jacobian matrix which requires modification in order to adapt it to the unique characteristics of a distribution system which include high R/X ratio and unbalanced loads. The other methods exploit the topological structure of the distribution system and therefore reduce the number of equations. This therefore means that the computational burden is reduced.

It can therefore be concluded that in solving load flow in distribution system, methods that exploit topological structure of the distribution network are more suited than the conventional load flow solution methods such as Newton Raphson.

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