ISSN 2250-3153

Methods for Load Flow Analysis of Weakly Meshed Distribution System

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Abstract- The distribution system provides the link between bulk power system and consumer. The various classical power flow methods are required modification in algorithm for solving large distribution system network having ill condition and weakly meshed structure. This paper gives a review of the various computational methods suited for the analysis of weakly meshed distribution networks. The analytical bases, computational requirements and comparative numerical performance of the methods are discussed.

Index Terms- power flow, weakly meshed network, distribution network

I. Introduction

The power flow is an important tool used by power system analysts. For proper planning of expansion and operation of distribution networks, the maximum currents carried by the distribution feeders and associated voltage drops, annual energy loss, and the reliability of supplying consumer demands are to be analyzed. The efficiency of such power flow algorithm is utmost importance as each optimization study requires numerous power flow runs. Unfortunately, many of the inputs forming the basis for these studies such as load forecast, load model coefficients, network parameters, and bus shunts forming are often assessed with some uncertainty. This uncertainty is usually of non statistical type due to practical difficulties in data acquisition in large and complex distribution systems [2].

The Newton Raphson and the fast decoupled power flow solution techniques and a host of their derivatives have efficiently solved 'well behaved' power systems. However the shortcomings have been encountered when there algorithms are generally implemented and applied to ill-conditioned and poorly initialized power system. The Gauss Siedel power flow technique, another classical power flow method, although very robust, has shown to be extremely inefficient in solving large power systems. This paper represents a fast and efficient method for obtaining load flow solutions of weakly meshed power systems or distribution systems [2, 4].

II. Compensation Based Method

It gives the three new features.

- First, by using powers *(P,Q)* as variables in the solution process instead of complex currents, it handles the *PV* buses in a direct manner as simple loop breakpoints, thereby reducing the related computational effort to half.
- Second, by applying the tree labeling technique of network flow programming to labeling the radial network. The sensitivity matrix (equivalent to the breakpoint impedance matrix) can be constructed using the network graph which minimizes the effort.
- Third, based on the finding that in each iteration the CPU time required for obtaining the breakpoint voltage mismatches is dominant, savings are achieved by using single sweeps instead of converged sets to calculate the mismatches [1].

In this method for the solution of weakly meshed networks, first break the interconnected grid at the number of breakpoints in order to convert it into one radial network. Each breakpoint will open one single loop. The radial network is solved efficiently by direct application of Kirchhoff's voltage and current law. Then account for the flows at the breakpoints by injecting currents at their two end nodes. The breakpoint currents are calculated using the multi-port compensation method. In presence of constant P, Q loads, the network is nonlinear causing the compensation process to become iterative. The solution of the radial network with the additional breakpoint current injections completes the solution of the weakly meshed network.

The mathematical formulation steps of compensation based method are given by using the figure shown below.

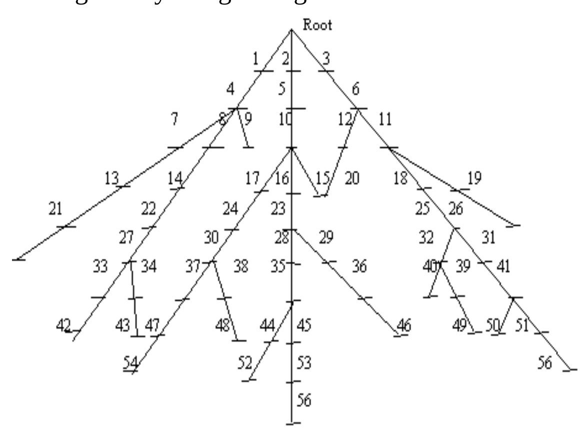

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Fig.1: Radial distribution network with branchnumbering

A. Nodal current calculation

At iteration k, the nodal current injection, *I(k)*, at network node i is calculated as,

$$I_i^{(k)} = (S_i / V_i^{(k-1)})^* - Y_i V_i^{(k-1)} \quad (1)$$

Where i=1,2,………..n and $V_i^{(k-1)}$ is the voltage at voltage node i calculated during the $(k-1)^{th}$ iteration and S_i is the specified power injection at node i. Y_i is the sum of all the shunt elements at the node i.

B. Backward sweep

At iteration k, starting from the branches in the last branches connected to the root node the current in branch L, J_L is calculated as:

$$J_L^{(k)} = -I_{L2}^{(k)} + \sum(I) \tag{2}$$

Where L=b, b-1……….1 and $I_{L2}^{(k)}$ is the current injection at node L2 and I is the current in branches emanating from node L2. This is the direct application of the KCL.

C. Forward sweep

Nodal voltages are updated in a forward sweep starting from branches in the first layer toward those in the last. For each branch, L, the voltage at node L2 is calculated using the updated voltage at node L1 and the branch current calculated in the preceding backward sweep:

$$V_{L2}^{(k)} = V_{L1}^{(k)} - Z_L J_L^{(k)} \tag{3}$$

Where L=1, 2…….,b and Z_L is the series impedance of branch L. This is the direct application of the KVL. Step *A*, *B*, and *C* is represented until convergence is achieved.

III. LOOP BASED METHOD

The limitation of the compensation based method is that n node in the network is a injection of more three brances, i.e, one coming and two outgoing branches. In this method multi port compensation technique is used for computation of break point current injections. The special topological characteristics of distribution networks have been fully exploited to make the solution possible. A branch injection to branch current matrix is formed (BIBC) [5].

For bus-i, the complex load S_i is expressed as

$$S_i = P_i + Q_i \tag{4}$$

Where i=1.2.3……,n

And the corresponding equivalent current injection at the k^{th} iteration of solution is

$$I_i^k = ((P_i + Q_i)/V_i^k)_k^* \tag{5}$$

Where V_i^k and I_i^k are the bus voltage and equivalent current of bus-i the k^{th} iteration respectively. Form equation (5), obtained current injections and current can be obtained by applying Kirchoff's current law (KCL) to the distribution network. The branch injection branch current (BIBC) calculate by the following method. A simple distribution system shown in the figure 1 is used as example.

Branch currents can then be formulated as functions of equivalent current injections. For example, the branch currents B_1, B_3 and B_5 can be expressed as

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6$$
$$B_3 = I_4 + I_5$$
$$B_6 = I_6 \tag{6}$$

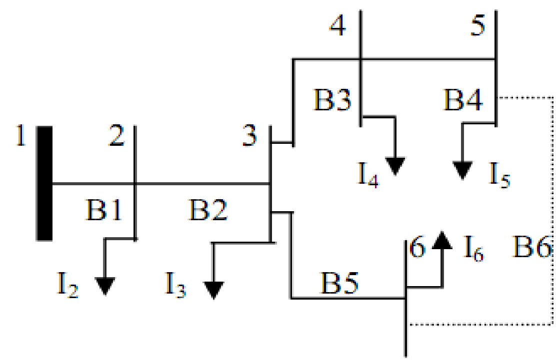

Fig. 2: Simple distribution system

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 11111 \\ 01111 \\ 00110 \\ 00010 \\ 00001 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \end{bmatrix} \tag{7}$$

Equation (7) can be expressed as

$$[B] = [BIBC][I] \tag{8}$$

Where BIBC is bus i on to branch current injection matrix, the BIBC matrix is a upper triangular matrix and contains values of 0 and +1 only. The receiving end bus voltages are found by a forward sweep through the ladder network using the generalized equation (3).

IV. NOVEL BASED METHOD

One of the main disadvantages of the compensation based methods is that in addition to the conventional bus-branch oriented data format, new data bases have to be built and maintained for these methods. Since the feeder-lateral based model is adopted, the "layer-lateral" based data format is required. In addition, the relationship between the system status and control variables cannot be expressed as a mathematical expression, which makes the applications of the compensation based algorithm difficult [14].

The proposed method is classic since its input data is the same as the conventional bus branch oriented data used by most utilities. The proposed method is also novel since it takes advantage of the topological characteristics of distribution systems and solves the distribution load flow efficiently [15]. The proposed method is based on the Newton Raphson formulation and utilizes the branch voltage as state variables. By using those ideas, a constant Jacobian matrix can be developed, and the traditional Newton Raphson technique can be utilized to find the solution.

The novel technique developed is suitable for unbalanced 3-phase radial distribution systems. The analysis proceeds from one branch to another in a systematic way until all the branches in the feeder have been traced. First, the voltages at all the buses, except the source bus, are assumed to be 1 p.u., with zero angle at phase a, +120 on phase b, and -120 on phase c. Based on these voltages and Specified active and reactive power, simultaneously, the branch currents, starting from the end buses to the source, are calculated and saved. This, of course, requires a logical procedure to ensure that the branches of the system are correctly traced. Then, branch currents, including the return-conductor current, are computed in order to find the active and reactive power losses in the system. The current at the source end is now calculated as follows:

$$I_a = \frac{(\sum_a P + \sum_a P_{LOSS}) + j(\sum_a Q + \sum_a Q_{LOSS})}{V^*_{Sa}}$$

$$I_b = \frac{(\sum_b P + \sum_b P_{LOSS}) + j(\sum_b Q + \sum_b Q_{LOSS})}{V^*_{Sb}} \quad (9)$$

$$I_c = \frac{(\sum_c P + \sum_c P_{LOSS}) + j(\sum_c Q + \sum_c Q_{LOSS})}{V^*_{Sc}}$$

$$I_d = -I_a - I_b - I_c$$

Where $\sum_m P$ and $\sum_m Q$ are the sum of load of phase m, $\sum_m P_{LOSS}$ and $\sum_m Q_{LOSS}$ are the total losses in phase *m* and V^*_{sm} is the conjugate of source voltage on phase m. The computation then proceeds from the source to the end of the feeder to find the voltage drop, current, and loss in each branch in each phase of the feeder, including the return conductor, in a systematic manner. The branch incidence table is again used to facilitate proper retracting of the network branches. Once this process is completed, the total losses are calculated and compared to the values initially obtained by assuming one per unit voltage at all the buses. If the difference kth is outside the specified tolerance limits, the source current is re-computed using eq. (9), in terms of the newly obtained values for losses, and the path retracting operation is repeated. The process is repeated until the difference in losses between 2 successive values of the source current is within the specified tolerance limits. The feeder is represented by its unbalanced 4-line representation [14] shown in the i-th branch in Figure 3.

The voltage drop in each branch is then calculated as

$$\begin{bmatrix} V_a - V_a^* \\ V_b - V_b^* \\ V_c - V_c^* \\ V_d - V_d^* \end{bmatrix} = \begin{bmatrix} Z_{aa} Z_{ab} Z_{ac} Z_{ad} \\ Z_{ba} Z_{bb} Z_{bc} Z_{bd} \\ Z_{ca} Z_{cb} Z_{cc} Z_{cd} \\ Z_{da} Z_{db} Z_{dc} Z_{dd} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \end{bmatrix} \quad (10)$$

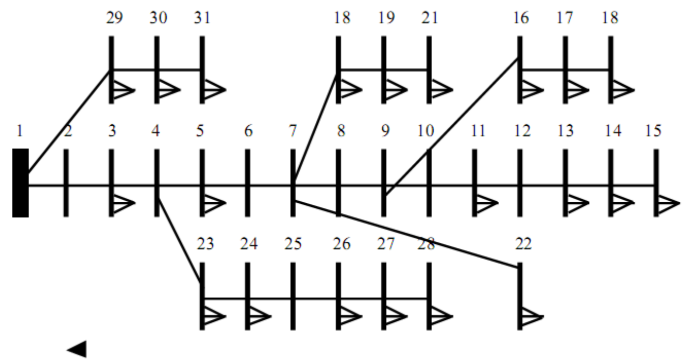

Fig. 3: Four line representation of each branch in an unbalanced distribution feeder.

And the losses in each branch are calculated by

$$\begin{bmatrix} (S_{LOSS})_a \\ (S_{LOSS})_b \\ (S_{LOSS})_c \\ (S_{LOSS})_d \end{bmatrix} = \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \end{bmatrix}^t \begin{bmatrix} Z_{aa} Z_{ab} Z_{ac} Z_{ad} \\ Z_{ba} Z_{bb} Z_{bc} Z_{bd} \\ Z_{ca} Z_{cb} Z_{cc} Z_{cd} \\ Z_{da} Z_{db} Z_{dc} Z_{dd} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \end{bmatrix}^* \quad (11)$$

From this method calculation of the unbalance distribution system is easier.

V. OBJECT ORIENTED METHOD

Object oriented load flow method based on the Newton Raphson technique. In the object oriented formulation, Jacobian matrix are introduced, a detailed study of the convergence characteristics. The Newton Raphson based methods use the distribution load flow equations to derive voltage drop and power propagation along a radial distribution system. The values of the active and reactive powers that are injected into the main section and into the laterals are corrected using the Jacobian matrix and the power errors at the terminal nodes. In the convergence characteristics of the Newton Rapson-based method have been studied in the case of radial networks. The method has improved the computational efficiency of the solving algorithm [12]. The Newton Raphson based method is applied to a radial network which is obtained by breaking the loops and applying the equivalent current injection method to the break points. This method presents a high convergence rate but each iteration requires matrix computations.

Classes are the key concept in the Object Oriented modeling of a system. There are set of objects that share the same attributes, properties, and behavior.. It has ports and it represents some relations between port variables. Each port is characterized by four variables, which represent the active and reactive powers and the real and imaginary components of the voltage at the port. A connection port is referred to be incoming or outgoing according to whether the conventional direction of powers is assumed to be inwards or outwards oriented.

From the connection class, all of the concrete classes needed to load flow problem modeling are derived:

- *Branch* is a connection with a single incoming port and a single outgoing port and it models a physical line or a transformer.
- *Root* is a connection with a single outgoing port and it models the supplying system at higher voltage level.
- *Fork* is a connection with a single incoming port and multiple outgoing ports and it models a zero-impedance busbar.
- *Terminal* is a connection with a single incoming port and it models the "dead" end of the distribution system.
- *Switch* is a connection with two incoming ports and it models a looping switch.

Specific distribution system is modeled by an oriented graph of object instances. The association of instances is obtained by connecting outgoing ports to incoming ports. The graph is built according to the following constraints:

- An outgoing port can be connected to only one incoming port.
- An incoming port can be connected to only one outgoing port.
- No port can be left unconnected.

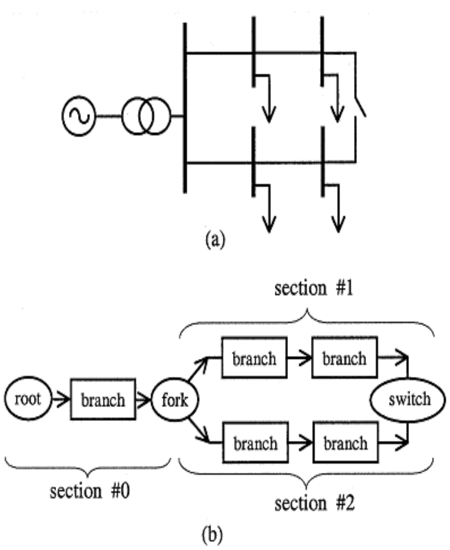

Fig. 3: Simple distribution system: (a) one-line diagram; (b) oriented graph of instances in the Object Oriented modeling

The oriented graph of object instances is divided into sections. A *section* is defined as a sequence of connections, starting with either a root or a fork, ending with either a fork, or a terminal or a switch, and with only branches in between. Let us assume that the network has $mf \pm 1$ sections and kth the section is composed of a starting connection, branches and an ending connection. Notation A_j^k stands for quantity referred to the jth connection to the kth of the section.

For example, Fig. 3(a) shows the one-line diagram and the related oriented graph of instances [Fig. 2(b)] for a simple distribution system. The graphics composed of a main section (section #0) which starts with the root and ends with a fork. Two subsequent sections (sections #1 and #2) start with the fork and end start with the switch.

VI. FUZZY LOGIC BASED METHOD

In distribution system planning study, the operating condition (loads at various buses) is obtained from a load forecast. Such a forecast is always subject to some error, which may not be of statistical type. Moreover, the voltage dependent load model parameters can never be specified with complete certainty due to well-known difficulties. Uncertainty in network parameter values can arise due to imprecise data used in modeling inductance and capacitance calculation and ageing of system components. Resistance parameters can also undergo variation due to temperature changes.

In the fuzzy logic based method, a matrix similar to Jacobian inverse is directly evaluated, in an efficient manner. The method can handle simultaneous presence of several uncertainties in input variables such as network parameters, load model coefficients, load forecast, and bus shunts. This uncertainty is usually of non statistical type due to practical difficulties in data acquisition in large and complex distribution systems. Although it is difficult to provide exact values of these variables, it is relatively much easier to provide a possibility distribution of these variables. As these input data substantially affect the results of the network analysis, it is important to have some idea as to how uncertain the results are if some inputs can be only roughly assessed. Fuzzy algebra can be used to model the uncertainties in output variables in the presence of uncertainties in the input variables [13].

The network performance variables considered for distribution system, voltage magnitude of buses, branch currents and system real power loss are treated as the output variables of the fuzzy distribution power flow solution. The algorithm for fuzzy distribution load flow is as follows:

1. Perform crisp power flow solution with central values of input variables and identify the output variables of concern.
2. Select a variable of concern out of the list prepared in step 1.
3. Select the breakpoint of interest for the variable selected in step 2.
4. Select the input vectors for the breakpoint selected in step 3 using the signs of the row elements (corresponding to the output variable) in the matrices.
5. Using the selected input variables, evaluate updates and update state variables.
6. Check for convergence of bus power mismatch vector.
7. If converged, go to step 9.
8. Evaluate matrices and bus powers using latest state variables, and then, go to step 4.

9. Evaluate the breakpoint value, and check whether all the breakpoints of the present variable under consideration are evaluated.
10. If not, go to step 3. Check whether all the variables of concern are evaluated.
11. If completed, stop; otherwise, go to step 2.

VII. CONCLUSION

The various classical methods are not having sufficient convergence criterion for solving the large distribution system. The modification in the algorithm of this method has been discussed. This paper gives an overview of the various load flow techniques of the weakly meshed distribution system which are very efficient.

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