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Three-Phase Unbalanced Radial Distribution Load Flow Method

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Abstract: *This paper deals with a new, efficient power flow method for unbalanced radial distribution systems based on improved backward/forward sweep (BFS) algorithm. This proposed method utilizes simple and flexible numbering scheme and takes full advantage of the radial structure of distribution systems. This method is tested on an 8-bus Three-phase unbalanced distribution system. The numerical test proves this method is very robust and has excellent convergence characteristics.*
Key Words: *Backward/Forward Sweep, Radial Distribution Systems (RDS)*

I. INTRODUCTION

In power engineering, the power flow study also known as load-flow study is an important tool involving numerical analysis applied to a power system. Load flow studies are used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economic. Load flow calculations provide power flows and voltages for a specified power system subject to the regulating capability of generators, condensers and tap changing under load transformers as well as specified net interchange between individual operating systems. There exist a number of software implementations of power flow studies. The efficiency of such power flow algorithm is of utmost importance as each optimization study requires numerous power flow runs. Backward/Forward sweep (BFS) methods take the advantage of the radial nature and have become the preferred method for by many distribution systems developed by C.S. Cheng and D. Shirmohammadi [1].

The ladder network theory given by W. H. Kersting [2], in which the optimal ordering of nodes is done first. Both BFS and ladder network theories are derivative free approaches, instead, they employ the simple circuit laws. However the ladder solution uses many sub iterations on laterals, which is not required. Thukaram [3] utilized the backward/forward sweep technique, in which the bus numbering procedure was based on a sophisticated “parent node” and “child node” arrangement.

G.W. Chang, et al. [4] suggested an improved BFS load flow algorithm for three phase power flow analysis of radial distribution systems using linear proportional principle, but the data preparation will be cumbersome for a practical RDS.

In this paper, the unique structure of the RDS is exploited in order to build up a fast and flexible radial power technique. Firstly the radial network is restructured by giving the numbers to buses and sections using flexible numbering scheme [5]. Now assume the flat voltage profile at all other buses except slack bus. We then account for the flows at the nodes by injecting currents. The section currents are calculated from the last node to the substation bus by the direct application of Kirchhoff's current law (KCL). This step is also known as backward sweep. The bus voltages are then updated in the forward direction by applying the Kirchhoff’s voltage law (KVL). This process is also known as Forward sweep. In presence of constant P, Q loads, the network is nonlinear causing the process to become iterative. The voltage magnitudes at each bus in present iteration are compared with their values in previous iteration. If the error is within the tolerance limit, the procedure is stopped. Otherwise the steps of backward substitution, forward substitution and check for convergence are repeated.

II. SIMPLE & FLEXIBLE NUMBERIG SCHEME

A section is part of a feeder, lateral or sub lateral that connects two buses in the RDS, and the total number of sections (NS) is related to the total number of buses (NB) by this relation by the relation

$$NS=NB-1 \qquad \text{... (1)}$$

The three-phase power flow is more comprehensive and realistic when it comes to finding the three-phase voltage profiles in unbalanced RDS. Fig.1 shows an unbalanced Three- Phase RDS [4]. The missing sections and buses play a significant role in the multilevel phase loading and in elevating the unbalance state of such a three-phase DS. The RDS shown in Fig.1 includes 8three-phase buses ($3\Phi NB=8$) and 7 three-phase sections ($3\Phi NS=7$. As such, it has 13 single-phase buses ($1\Phi NB=13$), and 10 single-phase sections ($1\Phi NS=10$). The relations expressed in (2) govern the three-phase and single-phase buses to their corresponding sections

$$3\Phi NS=3\Phi\text{-}NB-1$$
$$1\Phi NS=1\Phi\text{-}NB-1 \quad \ldots (2)$$

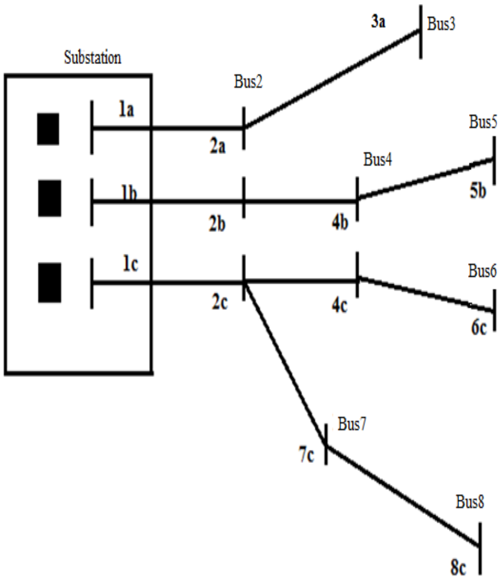

Fig.1 8Bus Three-Phase RDS Representation

It is simple to implement the numbering process in the unbalanced three-phase system like in the balanced case. That is, any group of phase buses to be found along a phase feeder or a sublevel of a feeder is to be numbered in a consecutive ascending order. Consequently, each phase section number will carry a number which is one less than its receiving end bus number, as shown in Fig.2.

III. SOLUTION TECHNIQUE

Given the voltage at the substation bus and assuming a flat profile for the initial voltages at all other buses, the iterative solution algorithm consists of three steps

A. Nodal Current Injection:

At iteration k, the nodal current injection, $[I_i^{abc}]^{(k)}$, at network node i is calculated as,

$$[I_i^{abc}]^{(k)} = (S_i^{abc} / V_i^{abc(k-1)})^* - (Y_i^{abc})(V_i^{abc})^{(k-1)}$$

$i=1,2,\ldots\ldots,n \quad \ldots (3)$

Where, $(V_i^{abc})^{(k-1)}$ is the voltage at node i calculated during the $(k\text{-}l)^{th}$ iteration and Si^{abc} is the specified power injection at node i. Yi^{abc} is the sum of all the shunt elements at the node i.

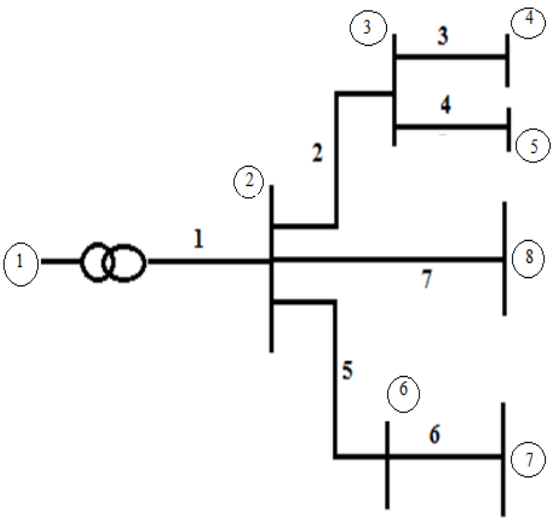

Fig.2 Numbering Scheme for 8Bus Three-Phase RDS

B. Backward Sweep:

At iteration k, starting from the branches in the last section and moving towards the branches connected to the substation node, the current in branch L, JL is calculated as

$$[J_L^{abc}]^{(k)} = - I_{L2}^{abc(k)} + \sum \text{(currents in branches emanating from node } L_2\text{)}$$

L=b, b-1 ,…….,1 … (4)

$I_{L2}^{abc(k)}$ is the current injection at node L_2.

This is the direct application of the KCL. (Note: current injection = - load current)

C. Forward Sweep:

Bus voltages are updated in a forward sweep starting from branches in the first section toward those in the last. For each branch, L, the voltage at node L_2 is calculated using the updated voltage at node L_1 and the branch current calculated in the preceding backward sweep

$$[V_{L2}^{abc}]^{(k)} = [V_{L1}^{abc}]^{(k)} - [Z_L^{abc}] * [J_L^{abc}]^{(k)} \qquad L=1,2,\ldots,b \qquad \ldots (5)$$

Z_L is the series impedance of branch L. This is the direct application of the KVL.

IV. CONVERGENCE CRITERION

The maximum voltage mismatches at the network nodes is used as convergence criterion. As described in the solution method, the nodal current injections, at iteration k, are calculated using the scheduled nodal power injections and node voltages from the previous iteration. The node voltages at the same iteration are then calculated using these nodal current injections .The voltage magnitudes at each bus in iteration are compared with their values in previous iteration. If the error is within the tolerance limit, the procedure is stopped. Otherwise the steps of backward substitution, forward substitution and check for convergence are repeated.

At k^{th} iteration, the voltage mismatch at bus i can be calculated as

$$\Delta Vi^{(k)} = Vi^{(k)} - Vi^{(k-1)} \qquad i=1,2,\ldots,n$$

… (6)

V. ALGORITHM

Step1. Read power system data, i.e., no. of buses, no. of lines, slack bus, base kV, base kVA, bus data and line data.

Step2. Starting from the substation bus, number the buses and sections in the network by using by using efficient and simple RDS numbering scheme.

Step3. Calculate the injected powers, i.e.,

$P_{inj}^{(i)} = P_{gen}^{(i)} - P_{load}^{(i)}$

$Q_{inj}^{(i)} = Q_{gen}^{(i)} - Ql_{oad}^{(i)}$

$S_{inj}^{(i)} = P_{inj}^{(i)} + j^* Q_{inj}^{(i)}$ Where i=1,2,……,n

Step4. Set iteration count k=1.

Step5. Set convergence ϵ=0.0001 or 0.001, ΔVmax=0.0.

Step6. Calculate nodal current injection using equation (3)

Step7. Backward sweep: Calculate currents in the branches in the backward direction using equation (4)

Step8 .Forward sweep: Calculate the voltage at nodes in the forward direction using equation (5)

Step9. Calculate the voltage mismatches using equation (6)

Step10. Check $\Delta Vi^{(k)} > \Delta V\text{max}$, then set $\Delta V\text{max} = \Delta Vi^{(k)}$

Step11. If ΔVmax <= ϵ then go to step 13, else go to step 12

Step12. Set k=k+1 and go to step 4.

Step13. Print that problem is converged in ‘k’ iterations

Step14. Stop

VI. RESULTS & DISCUSSIONS

IEEE 8BUS THREE-PHASE UNBALANCED RDS

The proposed method presented in this paper utilizes the simple and flexible numbering scheme in solving the power flow problem for unbalanced three-phase radial distribution systems. Simulations were carried out in the C++ programming language. The proposed algorithm has been tested by the three-phase 8-bus unbalanced radial distribution system and compared with two other different methods and given in Table.1. Out of all these, the proposed approach gives the better converged voltage values.

Table.1 Comparison of proposed method with existing methods for 8 bus system

Bus No.	**Phase**	**Ladder Approach[2]** $\lvert \mathbf{V} \rvert$	**Direct Approach[4]** $\lvert \mathbf{V} \rvert$	**Proposed Method** $\lvert \mathbf{V} \rvert$
1	A	1.0000	1.0000	1.0000
1	B	1.0000	1.0000	1.0000
1	C	1.0000	1.0000	1.0000
2	A	0.9830	0.9840	0.991177
2	B	0.9714	0.9714	0.974678
2	C	0.9745	0.9699	0.979496
3	A	0.9822	0.9833	1.0000
4	B	0.9655	0.9653	0.974678
4	C	0.9717	0.9672	0.978497
5	B	0.9644	0.9644	1.0000
6	C	0.9697	0.9652	0.976162
7	C	0.9739	0.9686	1.0000
8	C	0.9726	0.9674	0.979496

Test results of three-phase unbalanced radial distribution load flow method
1. The no. of iterations taken for convergence = 3
2. Convergence criteria = 0.0001

VII. CONCLUSION

Certain applications, particularly in distribution automation and optimization of power system require repeated load flow solution. In these applications it is very important to solve the load flow problem as efficiently as possible. Firstly, a mass of methods to solve the radial distribution power flow problem are discussed in this paper. Subsequently, the reason, why the convergence of these widely used methods deteriorates for the radial distribution network is presented. In this case, an improved solution is needed to deal with radial network. So, a theoretical formulation of improved backward/forward sweep distribution load flow method based on simple and flexible numbering scheme is developed in this paper. This method takes full advantage of the radial structure of distribution systems, to achieve high speed, robust convergence and low memory requirements. Effectiveness of proposed method has been tested by 8bus three-phase unbalanced radial system .The numerical test proved that; this method is very efficient and assured satisfactory convergence. In addition, the validity of results of the proposed method has also been verified by comparing them with the existing methods of power flow analysis.

APPENDIX

No. of buses = 8
No. of lines = 7
Substation bus = 1
Base kV = 14.4
Base kVA = 100

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