Innovative Systems Design and Engineering www.iiste.org
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online)
Vol 2, No 4, 2011

Calculation of Power Loss and Voltage Regulation for Different Static Loads

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Abstract

The Voltage regulation and power losses computations for distribution systems are strongly dependent on power flow solutions. The classical constant power load model is typically used in power flow studies of transmission or distribution Systems; however, the actual load of a distribution system cannot just be modeled using constant power models, requiring the use of constant current, constant impedance, exponential or a mixture of all these load models to accurately represent the load. This paper presents a study of voltage regulation and power losses of a distribution system using different Static load models.

Keywords: Distribution systems, power flow, static load models, voltage regulation, power loss.

1. Introduction

The Voltage regulation is an important subject in electrical distribution engineering. It is the utilities responsibility to keep the customer voltage within specified tolerances. The performance of a distribution system and qualities of the service provided are not only measured in terms of frequency of interruption but in the maintenance of satisfactory voltage levels at the customers' premises. On the other hand, a low steady-state voltage leads to low illumination levels, shirking of television pictures, slow heating of heating devices, motor starting problems, and overheating in motors. However, most equipment and appliances operate satisfactorily over some 'reasonable' range of voltages; hence, certain tolerances are allowable at the customer's end. Thus, it is common practice among utilities to stay within preferred voltage levels and ranges of variations for satisfactory operation of apparatus as set by various standards such as ANSI (American National Standard Institution). For example, power acceptability curves given by IEEE (IEEE orange book, IEEE standard 446) and FIPS (United States Federal Information Processing Standard) indicate that steady-state voltage regulation Should be within+6% to−13% for satisfactory operation of various electrical devices.2 Voltage regulation calculations depend on the power flow solutions of a system. Most of the electrical loads of a power system are connected to low voltage/medium-voltage distribute on systems rather than to a high-voltage transmission system. The loads connected to the distribution system are certainly voltage dependent; thus, these types of load characteristics should considered in load flow studies to get accurate results and to avoid costly errors in the analysis of the system. For example, in voltage regulation improvement studies, possible under- or over-compensation can be avoided if more accurate results of load flow solutions are available, as demonstrated in this paper. However, most conventional load flows use a constant power load model, which assumes that active and reactive powers are independent of voltage changes. In reality, constant power load models are highly questionable in distribution systems, as most nodes are not voltage controlled; therefore, it is very important to consider better load models in these types of load flow problem.

In this paper, distribution system voltage regulation and the power losses for different static load models are studied. The paper is organized as follows: the next section briefly reviews different types of static load models. Power flow equations and a MATLAB based solution technique, as well as the definition of voltage regulation. Details of the distribution test system used in this paper follow, together with a discussion of some interesting simulation results. Finally, major contributions of this paper are highlighted.

2. PROPOSED METHOD:

The load flow of distribution system is different from that of transmission system because it is radial in nature and has high R/X ratio. Convergence of load flow is utmost important. Literature survey shows that the following works had been carried out on load flow studies of electric power distribution systems.

In this method of load flow analysis the main aim is to reduce the data preparation and to assure computation for any type of numbering scheme for node and branch. If the nodes and branch numbers are sequential, the proposed method needs only the starting node of feeder, lateral(s) and sub lateral(s) only. The proposed method needs only the set of nodes and branch numbers of each feeder, lateral(s) and sub-lateral(s) only when node and branch numbers are not sequential. The proposed method computes branch power flow most efficiently and does not need to store nodes beyond each branch. The voltage of each node is calculated by using a simple algebraic equation. Although the present method is based on forward sweep, it computes load flow of any complicated radial distribution networks very efficiently even when branch and node numbering scheme are not sequential.

One example has been considered to demonstrate the effectiveness of the proposed method. The first example is **34 node** radial distribution network (nodes have been renumbered with Substation as node 1) shown in Figure 1 minimum voltage occurs at node number 27 in all cases. Base values for this system are **11 kV and 1 MVA** respectively

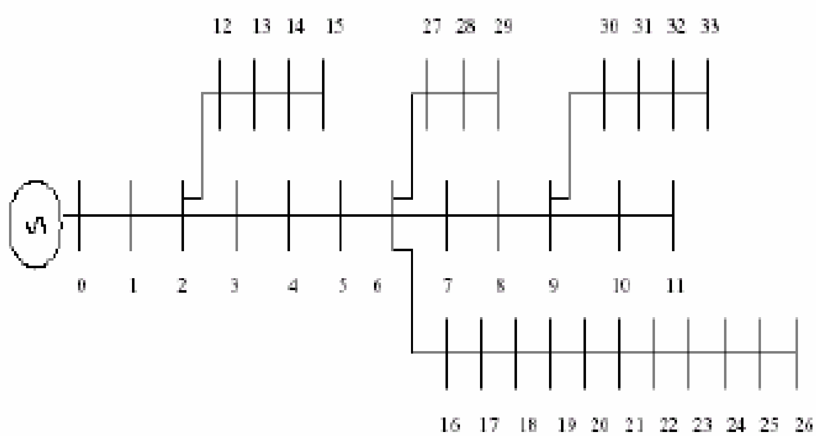

Figure 1. 34 bus distribution system

Innovative Systems Design and Engineering www.iiste.org
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online)
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Assumptions:

1) A balanced three-phase radial distribution network is assumed and can be represented by its equivalent single line diagram.
2) Line shunt capacitance is negligible at the distribution voltage levels.

3. SOLUTION METHODOLOGIES:

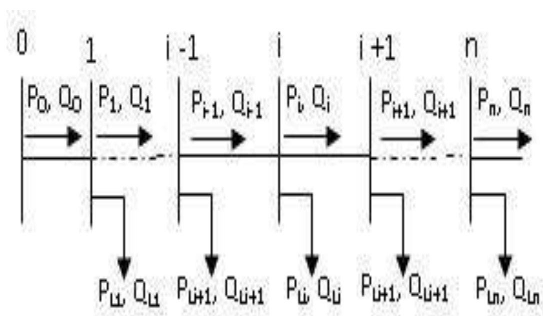

Fig 2. Radial main feeder

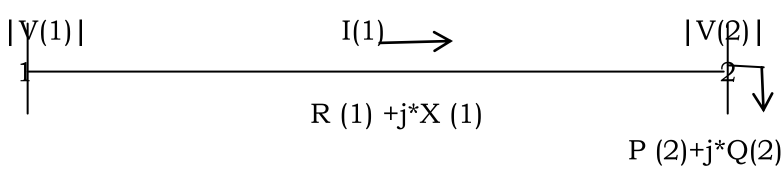

Fig 3.Electrical equivalent of fig 2

Consider a distribution system consisting of a radial main feeder only. The one line diagram of such a feeder comprising n nodes and n-1 branches is shown in Fig. 2. From Fig.2 and 3, the following equations can be written

$$I(1) = \frac{|V(1)|\angle\delta(1) - |V(2)|\angle\delta(2)}{(R(1)+j*X(1))} \qquad (1)$$

$$P(2)-j*Q(2)=V^*(2)I(1) \qquad (2)$$

From eqns. 1 and 2 we have

$$|V(2)|=[\{P(2)R(1)+Q(2)X(1)-0.5|V(1)|^2)^2 - (R^2(1)+X^2(1))(P^2(2)+Q^2(2))\}^{1/2} -(P(2)R(1)+Q(2)X(1)-0.5|V(1)|^2)]^{1/2} \quad (3)$$

Eqn. 3 can be written in generalized form

$$|V(i+1)|=[\{P(i+1)R(i)+Q(i+1)X(i)-0.5|V(i)|^2)^2 - (R^2(i)+X^2(i))(P^2(i+1)+Q^2(i+1))\}^{1/2} -(P(i+1)R(i)+Q(i+1)X(i)-0.5|V(i)|^2)]^{1/2} \quad (4)$$

Eqn. 4 is a recursive relation of voltage magnitude. Since the substation voltage magnitude |V(1)| is known, it is possible to find out voltage magnitude of all other nodes. From Fig. 2.2 the total real and reactive power load fed through node 2 are given by

$$P(2) = \sum_{i=2}^{nb} PL(i) + \sum_{i=2}^{nb-1} LP(i) \quad (5)$$

$$Q(2) = \sum_{i=2}^{nb} QL(i) + \sum_{i=2}^{nb-1} LQ(i)$$

It is clear that total load fed through node 2 itself plus the load of all other nodes plus the losses of all branches except branch 1.

$$LP(1)=(R(1)*[P^2(2)+Q^2(2)])/(|V(2)|^2) \quad (6)$$

$$LQ(1) =(X(1)*[P^2(2) +Q^2(2)])/(|V(2)|^2)$$

Eqn. 5 can be written in generalized form

$$P(i+1) = \sum_{i=2}^{nb} PL(i) + \sum_{i=2}^{nb-1} LP(i) \quad \text{for } i=1, 2\ldots nb-1 \quad (7)$$

$$Q(i+1) = \sum_{i=2}^{nb} QL(i) + \sum_{i=2}^{nb-1} LQ(i) \quad \text{for } i=1, 2\ldots nb-1$$

Eqn. 6 can also be written in generalized form

$$LP(i) =(R(i)*[P^2(i+1) +Q^2(i+1)])/(|V(i+1)|^2) \quad (8)$$

$$LQ(1) =(X(i)*[P^2(i+1) +Q^2(i+1)])/(|V(i+1)|^2)$$

Initially, if LP (i+1) and LQ (i+1) are set to zero for all I, then the initial estimates of P (i+1) and Q (i+1) will be

$$P(i+1) = \sum_{i=2}^{nb} PL(i) \quad \text{for } i=1, 2\ldots NB-1 \quad (9)$$

$$Q(i+1) = \sum_{i=2}^{nb} QL(i) \quad \text{for } i=1, 2\ldots NB-1$$

Eqn. 9 is a very good initial estimate for obtaining the load flow solution of the proposed method.

The convergence criteria of this method is that if the difference of real and reactive power losses in successive iterations in each branch is less than 1 watt and 1 var, respectively, the solution has converged

Technique of lateral, node and branch numbering:

Fig.2 shows single line diagram of a radial distribution feeder with laterals. First, we will number the main feeder as lateral 1 (L=1) and number the nodes and branches of lateral 1 (main feeder). For lateral 1, source node SN (1) =1, node just ahead of source node LB (1) =2 and end node EB(1)=12. For lateral 1 there are 12 nodes and 11 branches. Next we will examine node 2 it does not have any lateral. Next, we will examine node 3 of lateral 1. It also has one lateral. The lateral number is 2. For lateral 2, it is seen that source node SN (2) =3, node just ahead of source node LB(2)=13 and end node EB(1)=16. For lateral 2 there are 5 nodes including source node (node 3). The remaining nodes are numbered as 13, 14, 15 and 16. The branch numbers of lateral 2 is shown inside brackets (.). Next, we will examine node 4, 5. It does not have laterals. Next, we will examine node 6 of lateral 1. The lateral numbered as 3. For lateral 3, source node SN(3)=6, node just ahead of source node LB(3)=17 and end node EB(3)=27. For lateral 3 there are 11 nodes including source node (node 6). The remaining nodes are numbered as 17, 18, 19… 27. The branch numbers of lateral 2 is shown inside brackets (.). Similarly we have to examine each node of lateral 1 and lateral, source node, node just ahead of source node, end node and branch numbering have to be completed by using above mentioned technique. Details are given in table.1

Table1: Details of the numbering scheme of figure 1

Laterals number	Source node SN(L)	Node just ahead of source node LB(L)	End node EB(L)
Lateral 1	1	2	12
Lateral 2	3	13	16
Lateral 3	6	17	27
Lateral 4	9	28	30
Lateral 5	10	31	34

Any numbering each lateral and nodes we follow the steps described below. Generalized expressions for TP(L) and TQ(L) are given below.

$$TP(L) = \sum_{j=LB(L)}^{NN(L)} PL(j) + \sum_{j=LB(L)}^{NN(L)-1} LP(j) \quad \text{for } L=1, 2 \ldots NL \qquad (10)$$

TQ(L)=j=LB(L)NN(L)QLj+$\sum_{j=LB(L)}^{NN(L)-1} LQ(j)$ for L=1,2,….,NL ,Where

NN(1)=EB(1)

NN(2)=EB(2)

….

NN(L)=EB(L)

Now we will define one integer variable F(i), i=1, 2,…,NB-1,the meaning of which is as follows:

From Fig. 1, it can be seen that four laterals are connected with different nodes of lateral 1(main feeder). Laterals are connected with node i.e. two laterals are connected with node therefore only one lateral is connected with node i.e. similarly other values of F(i) can easily be obtained. From Table

Table 2: Non Zero integer values of F(i)

Source node SN(L)	F(i)
3	F(3)=1
6	F(6)=1
9	F(9)=1
10	F(10)=1

It is clear that F(i) is positive only at the source nodes {i=SN(L),L>1}.other values of F(i) are zeros.

4. Explanation of the proposed algorithm:

From Fig.2 it is seen that for L = 1, total real and reactive power loads fed through node 2 are TP(1) and TQ(1) (eqn. 10). At any iteration voltage magnitude of node 2 can easily be obtained by using eqn.4 {P(2) = TP(1) and Q(2) = T Q (1) }**.** After solving the voltage magnitude of node 2 one has to obtain the voltage magnitude of node 3 and so on. Before proceeding to node 3, we will define here four more variables which are extremely important for obtaining exact load feeding through nodes 3, 4, ..., EB(1) of lateral 1 or in general obtaining exact load feeding through LB(L) + 1, LB(L) + 2, ..., EB(L) of lateral L. It is seen from the flow chart (Fig. 6) that

SPL(1) = 0 + PL(2) + LP(2) = PL(2) + LP(2)

SQL(1) = 0 + QL(2) + LQ(2) = QL(2) + LQ(2)

Where

SPL(1) = real power load of node 2 which has just been left plus real power loss of branch 2 which has just been left. SQL(1) = reactive power load of node 2 which has just been left plus reactive power loss of branch 2 which has just been left.

Next, we have to obtain the value of K . In this case K = 0 + F (2) = 0. K =0 indicates that we have no laterals. After that we have to check whether F(2) is positive or not? But in this case F(2) < 0. Therefore it will compute PS (1) and QS (1) .

PS (1) =0.0

QS (1) =0.0

PS (1) =0+$\sum_{i3=P1=1}^{k=2} TP(L+i3)$=TP (2)

QS (1) =0+$\sum_{i3=P1=1}^{k=2} TQ(L+i3)$=TQ (2)

TP (2), TP (NL) and TQ (2), TQ (NL) can easily be computed from eqn. 10 and P1 = P1 + F(2) = 1 + 0 = 1.

Therefore, real and reactive power loads fed through the node 3 are given as:

P(3) = TP(1) - PS(1) - SPL(1)

= TP(1) - PL(2) - LP(2)

Q(3) = TQ(1) - QS(1) - SQL(1)

= TQ(1) - QL(2) - LQ(2

After computing P(3) and Q(3), eqn. 4 has to be solved to obtain the voltage magnitude at node 3. Before obtaining the voltage magnitude of node 4, computer logic will perform the following computations

SPL (1)=PL(2)+LP(2)+PL(3)+LP(3)

SQL(1)=QL(2)+LQ(2)+QL(3)+LQ(3)

and k=0+F(3)=0+1=1.

Next it will check whether F(3) is positive or not? But Total real and reactive loads fed through the node 4 are: F(3) = 1, therefore

P(4) = TP(1) - PS(1) - SPL(1)

PS(1)=0+$\sum_{i3=P1=1}^{K=1} TP(L+i3)$ = TP(2)

QS(1)=0+$\sum_{i3=P1=1}^{K=1} TQ(L+i3)$ = TQ(2)

P (4) =TP (1)-PS (1)-SPL (1)

=TP(1)-TP(2)-PL(2)-LP(2)-PL(3)-LP(3)

Q(4)=TQ(1)-PQ(1)-SQL(1)

=TQ(1)-TQ(2)-PQ(2)-LQ (2)-QL(3)-LQ(3)

And solve eqn. 4 for .obtaining the voltage magnitude of node 4. For lateral 1 (L = 1, main feeder) similar computations have to be repeated for all the nodes. At any iteration, after solving the voltage magnitudes of all the nodes of lateral 1 one has to obtain the voltage magnitudes of all the nodes of laterals 2, and so on. Before solving voltage magnitudes of all the nodes of lateral 2 the voltage magnitude of all the nodes of lateral 1 is stored in the name of another variable, say V1, i.e. I Vl(J) I = 1 V(J) I for J = P2 to EB(1) (Fig. 6). For lateral 1 (main feeder) P2 = 1 and EB(1) = 12.

For lateral 2, P2=EB(L)+1=12+1=13. L=L+1=1+1=2, K2 = SN(L) = SN(2) = 3, |V(EB(1))|=|V(K2)| or |V(12)| = |V(3)| and solve the voltage magnitudes of all the nodes of lateral 2 using eqn. 4. The proposed computer logic will follow the same procedure for all the laterals. This will complete one iteration. After that it will compute total real and reactive power losses and update the loads. This iterative process continues until the solution converges.

5 .STATIC LOAD MODELS:

In power flow studies, the common practice is to represent the composite load characteristic as seen from power delivery points. In transmission system load flows, loads can be represented by using constant power load models, as voltages are typically regulated by various control devices at the delivery points. In distribution systems, voltages vary widely along system feeders as there are fewer voltage control devices; therefore, the v-i characteristics of load are more important in distribution system load flow studies. Load models are traditionally classified into two broad categories: static models and dynamic models.

Dynamic load models are not important in load flow studies. Static load models, on the other hand, are relevant to load flow studies as these express active and reactive steady state powers as functions of the bus voltages (at a given fixed frequency). These are typically categorized as follows

Constant impedance load model (constant z): A static load model where the power varies with the square of the voltage magnitude. It is also referred to as constant admittance load model.

Constant current load model (constant I): A static load model where the power varies directly with voltage magnitude.

Constant power load model (constant p): A static load model where the power does not vary with changes in voltage magnitude. It is also known as constant MVA load model.

6. ALGORITHM FOR LOAD FLOW COMPUTATION:

The complete algorithm for load flow calculation of radial distribution network is shown in below.

Step1 : Read the system voltage magnitude |v(i)|, line parameters and load data.

Step2 : Read base KV and base MVA.

Step3 : Read total number of nodes nb,

Step4 : compute per unit values of load powers at each node i.e. pl(i) And ql(i) for i=1, 2, 3,…nb, as well as resistance and reactance of each branch i.e. r(j) and x(j) for j=1, 2, 3,……..nb-1.

Step5 : By examine the radial feeder network note down the lateral number l, source node Sn(l), node just ahead of source node lb(1), end node eb(l).

Step6 : Read the nonzero integer value f(i), i.e. whether node consists of lateral or not. If yes f(i)=1, otherwise f(i)=0, for i=1, 2, 3,…nb

Step7 : Initialize the branch losses lp(i)=0.0, lq(i)=0.0 for i=1, 2, 3, .nb-1

Step8 : set iteration count IT=1, ε(0.0001).

Step9 : compute TP(l) and TQ(l) by using eqn. 10

Step10: compute TP(1)=sum(TP), TQ(1)=sum(TQ).

Step11 : set the losses ploss(i)=lp(i), qloss(i)=lq(i) for i=1, 2, 3,…..nb-1

Step12: l=1, p2=1

Step13: for i=1

Step14: set k=0, p1=1

Step15: initialize spl(l)=0.0, sql(l)=0.0, ps(l)=0.0, qs(l)=0.0

Step16: k=k+f(i)

Step17: If f(i) is greater than zero go to next step otherwise go to step20

Step18: compute ps(l) and qs(l) by using the formulae are

ps(l)=ps(l)+TP(l+i3), qs(l)=qs(l)+TQ(l+i3).

Step19: p1=p1+f(i)

Step20: compute node real power and reactive powers by using eqn. 7

Step21: solve the eqn. 4 for |v(i+1)|

Step22: i is incremented by i+1

Step23: If i is not equal to eb(l) go to next step otherwise . go to step26

Step24: compute spl(l), sql(l) by using eqns.

SPL(l)=SPL(l)+PL(i)+LP(i)

SQL(l)=SQL(l)+QL(i)+LQ(i)

Step25: Then go to step 16

Step26: |v1(j)|=|v(j)| for j=p2 to eb(l).

Step27: If i is not equal to nb then go to next step otherwise go to step32

Step28: set k1=eb(l), p2=eb(l+1)

Step29: l is incremented by l+1.

Step30: set K2=Sn(l)

Step31: set |v(k1)|=|v(k2)| then go to step step5.

Step32: compute lp(i), lq(i) by using eqn.8 for i=1, 2, 3,…nb-1

Step33: compute dp(i) and dq(i) by using eqns

dp(i)=lp(i)-ploss(i)

dq(i)=lq(i)-qloss(i) for i=1, 2, 3,…nb-1

Step34: If (max |(dp(i))| & max|(dq(i))|) is less than not equal ε go to next step otherwise go to step36

Step35: IT is incremented by IT+1, then go to step8

Step36: write voltage magnitudes and feeder losses.

Step37: stop

7. Test Results:

Table 3: Voltage magnitudes for different static load model.

Node number	**Voltages of constant power load model**	**Voltages of constant current load model**	**Voltages of constant impedance load model**
1	1.0000	1.0000	1.0000
2	0.9940	0.9942	0.9945
3	0.9888	0.9893	0.9897
4	0.9817	0.9825	0.9833
5	0.9756	0.9767	0.9777
6	0.9699	0.9712	0.9725
7	0.9658	0.9673	0.9688
8	0.9636	0.9652	0.9667
9	0.9611	0.9628	0.9644
10	0.9599	0.9617	0.9633
11	0.9595	0.9612	0.9629
12	0.9593	0.9611	0.9628
13	0.9885	0.9889	0.9894
14	0.9882	0.9886	0.9891

15	0.9881	0.9886	0.9890
16	0.9881	0.9885	0.9890
17	0.9654	0.9670	0.9685
18	0.9617	0.9635	0.9652
19	0.9576	0.9596	0.9615
20	0.9543	0.9565	0.9586
21	0.9515	0.9538	0.9561
22	0.9482	0.9507	0.9532
23	0.9455	0.9482	0.9508
24	0.9430	0.9459	0.9486
25	0.9418	0.9447	0.9475
26	0.9413	0.9443	0.9471
27	**0.9412**	**0.9442**	**0.9470**
28	0.9655	0.9670	0.9685
29	0.9653	0.9668	0.9683
30	0.9652	0.9667	0.9682
31	0.9596	0.9613	0.9630
32	0.9594	0.9612	0.9629
33	0.9592	0.9610	0.9627
34	0.9591	0.9609	0.9626

Base voltage=11kv **Base MVA=1MVA**

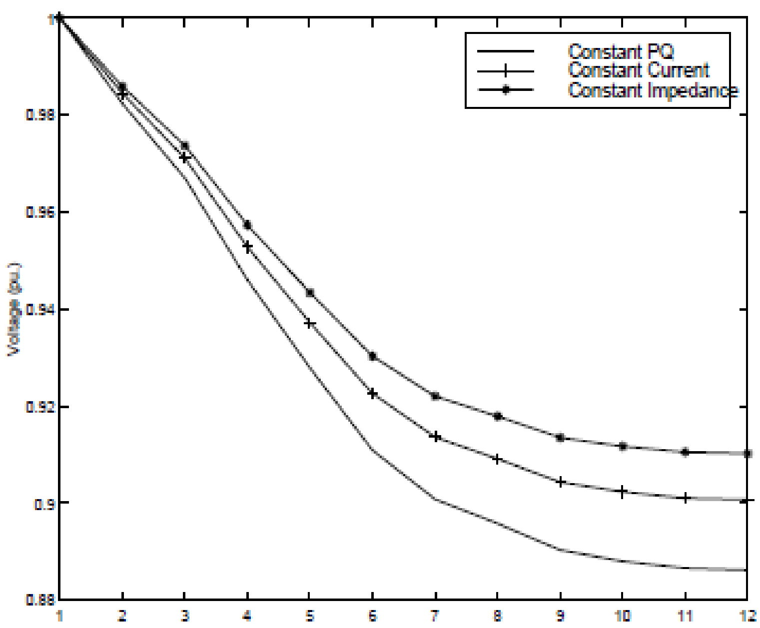

Figure 4: Voltage profiles for constant power, constant current and constant impedance load models

Type of load model	**Real power losses (per unit)**	**Reactive power losses (per unit)**
Constant power load	0.2276	0.0668
Constant current load	0.2066	0.0607
Constant impedance load	0.1877	0.0553

Table 4**:** Power losses of different static load models

Type of load model	**Voltage regulation (in %)**
Constant power load	6.2497
Constant current load	5.9143
Constant impedance load	5.5996

Table 5**:** voltage regulation for different static load models

5. Conclusion

A novel load flow technique, named "FORWARD SWEEPING METHOD", has been proposed for solving radial distribution networks. It completely exploits the radial feature of the distribution network. A unique lateral, node and branch numbering scheme has been suggested which helps to obtain the load flow solution of the radial distribution network. The forward sweeping method always guarantees convergence of any type of practical radial distribution network with a realistic R/X ratio.

In this thesis work a method of load flow analysis has been proposed for radial distribution networks based on the forward sweeping method to identify the set of branches for every feeder, lateral and sub-lateral without any repetitive search computation of each branch current. Effectiveness of the proposed method has been tested by an example 34-node radial distribution network with constant power load, constant current load, and constant impedance load for each of this example. The power convergence has assured the satisfactory convergence in all these cases. The proposed method consumes less amount of memory compared to the other due to reduction of data preparation. Several Indian rural distribution networks have been successfully solved using the proposed forward sweeping method.

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