Load Flow Solution in Distribution Systems using Modified Forward Substitution Method

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Summary
An interconnected power system represents an electric network with a multitude of branches and nodes, where the transmission lines typically constitute the branches. In power lingo the nodes are referred to as "buses". Even medium sized power company serving a mixed urban and rural population of 2 to 3 million people operates a network that may contain typically hundreds of buses and thousands of branches, not even counting the distribution network.
Keywords:
Power system, buses, network

1. Introduction

Load Flow Studies are performed on Power Systems to understand the nature of the installed network. This understanding gives the knowledge of the installed Generation Systems, Loads connected, Losses incurred, and also the flexibility of the system to allow future load connections. So, Load Flow or Power Flow analysis becomes a vital part of any Power System, as without this information, maintaining the network and regulating it within specified limits becomes just a blind control of some wires, in which current flows.

2. Literature Review

An interconnected power system represents an electric network with a multitude of branches and nodes, where the transmission lines typically constitute the branches. In power lingo, the nodes are referred to as "buses". Even medium sized power company serving a mixed urban and rural population of 2 to 3 million people operates a network that may contain typically hundreds of buses and thousands of branches, not even counting the distribution network.At some of the buses power is being injected into the network, whereas at most other buses it is being tapped by the system loads. In between, the
power will flow in the network meshes. A given set of loads can be served from a given set of generators in an infinite number of "power flow " or "load flow" configurations. Power flow analysis concerns itself not only with the actual physical mechanism which controls the power flow in the network meshes but also how to select a "best" or "optimum" flow configuration from among the myriad of possibilities.
The following assumptions are made in developing the Distribution Power Flow.

2.1. Equations

(1) EPDS is normally a 3 phase 4 wire system.
(2) Shunt capacitor banks are treated as loads.
(3) As the Distribution lines are normally short lines, the line shunt capacitances other than the shunt capacitor banks are negligible.

3. Background Theory

(1) The total amount of real power in the network emanates from the generator stations, the location and size of which are fixed. The generation must equal the demand at each moment and since this power must be divided between the generators in a unique ratio in order to achieve optimum economic operations. We conclude that the individual generator outputs must be closely maintained at predetermined set points. It is important to remember to that the demand undergoes slow but wide changes throughout the 24h of the day. We must therefore slowly either continuously or in discrete steps, change these set points as the hours wear on. This means that a load flow configuration that fits the demand of a certain hour of the day may look quite different the next hour.
(2)Transmission links can carry certain amounts of power and we must make sure that we do not operate these links too close to their stability or thermal limits.
(3) It is necessary to keep the voltage levels of certain buses within close tolerance.
This can be achieved by proper scheduling of reactive powers.
(4) If the power system is a part of larger pool, it must fulfill certain contractual power- scheduling commitments via its "tie-lines" to neighboring systems.
(5) The disturbances following a massive network fault can cause system outages, the effects of which can be minimized by proper pre-fault power-flow

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strategies.
(6) Power-flow analyses are very important in the planning stages of new networks or addition to existing ones.

The overall power-flow problem can be divided into following sub-problems:
(1) Formulation of a suitable mathematical network model. The model must describe adequately the relationships between voltages and powers in the system.
(2) Specification of the power and voltage constraints that must apply to the various buses of the network.
(3) Numerical computation of the power flow equations subject to the above constraints.

These computations give us, with sufficient accuracy, the values of all bus voltages.
(4) When all bus voltages have thus been determined, we must, finally, compute the actual power flows in all transmission lines. The Real and Reactive Power flows, Voltages at the buses in pre/post fault PDN are calculated using the following recursive equations.
The lines are represented by impedances Zk = Rk + jXk, and the Real and Reactive Power Demands are represented as complex power sinks SL = PDL + jQDL. The substation voltage/root branch voltage has, assumed as 1.0 p.u. The remaining node voltages are calculated using following equations

R_i	Resistance of the ith Branch
X_i	Reactance of the ith Branch
Z_i	Impedance of the ith Branch
$\|V_i\|$	Voltage magnitude at the ith Bus
PD_i	Real Power Demand at the ith Bus
QD_i	Reactive Power Demand at the ith Bus
PLOSSi	Real Power Transmission Loss at the ith node
QLOSSi	Reactive Power Transmission Loss at the Ith node
Pi	Real Power injection at the ith node
Qi	Reactive Power injection at the ith node

4.Programming Methodologies

In India, all 11 kV rural distribution feeders are radial and too long. The voltages at the far end of many such feeders are very low with very high voltage regulation. Many of these practical rural distribution feeders have failed to converge while using NR and FDLF methods. Therefore, in this paper, the main motivation has been to develop a new load flow technique for radial distribution networks by using a unique, lateral, node and branch numbering scheme. The proposed method solves a recursive relation of voltage magnitude and can be called a Forward Sweeping Method. Computationally, the proposed method is very efficient. Another advantage of the proposed method is that all the necessary data can be stored in vector form, thus saving a lot of computer memory. Convergence is always guaranteed for any type of practical radial distribution network with realistic ***R/X*** ratios while using the proposed forward sweeping method. The 14-bus system diagram and the results are given in the figure 4.1, 4.2 and 4.3.

Loads have been represented as constant power.

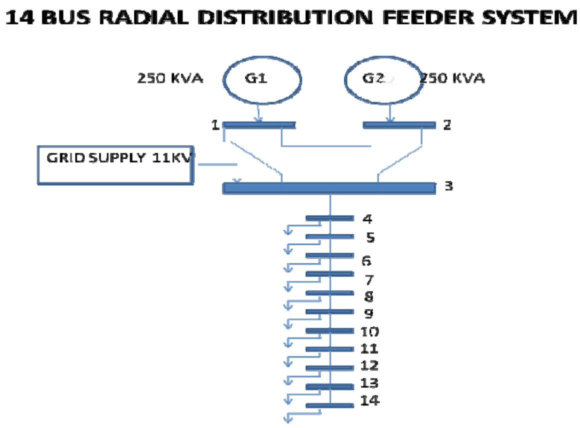

Fig 4.1 14 bus system

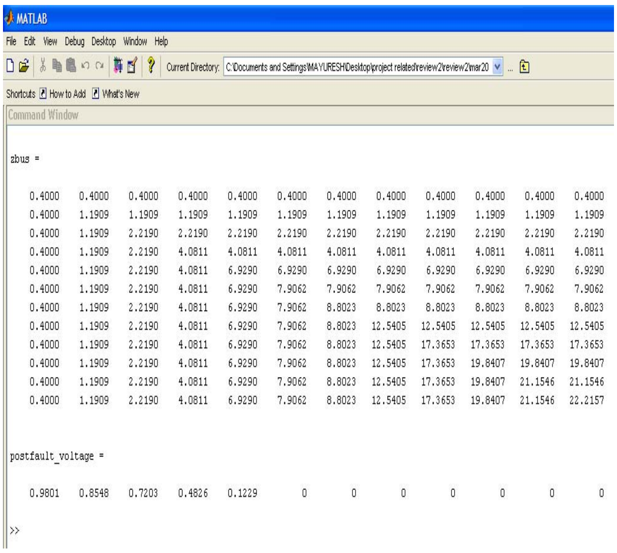

Fig 4.2

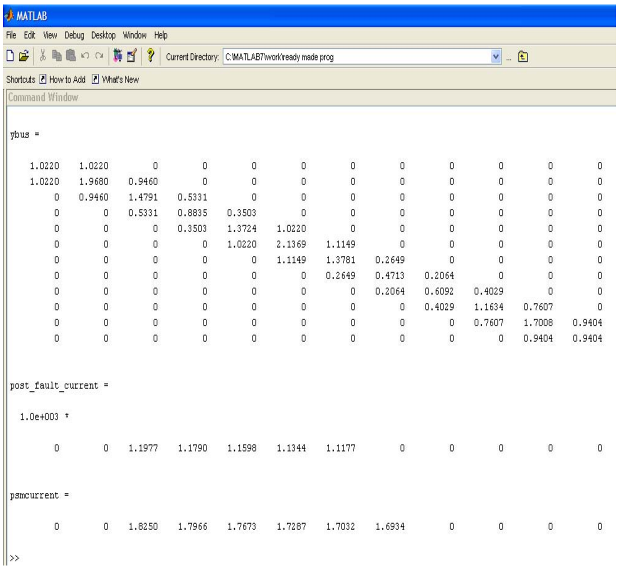

Fig 4.3

4.1. Assumptions

Distribution system is normally a 3 phase 4 wire system.

- Shunt capacitors banks are treated as loads
- Line shunt capacitor other than shunt capacitor banks are negligible at the distribution voltage level.

B.Derivation

$$I(1) = \frac{V(1)\,\alpha 1 - V(2)\,\alpha 2}{R(1)+JX(1)}$$

$$I(1) = \frac{P(2) - JQ(2)}{V^*(2)}$$

Equating both the equations and cross multiplying:-

|V(1)||V(2)| α(1)–α(2)-|V(2)|^2 = (P(2) – JQ(2))*(R(1)+JX(1))

Equating the real and imaginary parts :-

|V(1)||V(2)| COS(α1-α2) = |V(2)|^2 + P(2)*R(1) + Q(2)*X(1)------Eqn 4.1

|V(1)||V(2)| SIN(α1-α2) = P(2)*X(1) + Q(2)* R(1) -------------Eqn 4.2

Squaring and adding equation A & B:-

|V(2)^4+2[P(2)*R(1)+Q(2)*X(1)–(|V(1)|^2)/2] +(P(2)^2+Q(2)^2)(R(1)^2+X(1)^2 = 0

Solving the quadratic equation gives the roots as:-

A = [P(2)*R(1) + Q(2)*X(1)–(|V(1)|^2)/2]
B = (P(2)^2 + Q(2)^2)(R(1)^2+X(1)^2
|v(2)| = ((A^2–B)^0.5-A)^0.5

The generalized equation for voltage at (i+1)th bus :-

$|v(I+1)| = ((A^2–B)^{0.5}–A)^{0.5}$
$A = [P(i+1)*R(I)+Q(I+1)*X(I)–(|V(I)|^2)/2]$
$B = (P(I+1)^2 +Q(I+1)^2)(R(I)^2+X(I)^2$

CALCULATION OF LOSS AT $(i+1)^{th}$ BUS

Complex power ------- V(i+1)I(i+1)* = P(i+1) + JQ(i+1) ---------Eqn 4.3

Taking conjugate on both sides

Complex power conjugated ------- V(i+1)*I(i+1) = P(i+1) – JQ(i+1) ---------Eqn 4.4

Multiplying both sides on 4.3 & 4.4

(V(i+1)*I(i+1))* (V(i+1)I(i+1)*) = (P(i+1) - JQ(i+1))(P(i+1)+JQ(i+1))

$V(i+1)^2+I(i+1)^2 = P(i+1)^2+ Q(i+1)$

$$I(i+1)^2 = \frac{(P(i+1)^2+ Q(i+1)^2)}{(V(i+1)^2)}$$

REAL POWER LOSS: $I^2R = (P^2+ Q^2)R/(V^2)$
REACTIVE POWER LOSS: $I^2 X = (P^2+ Q^2)R/(V^2)$

TOTAL POWER INJECTED AT $(I+1)^{TH}$ BUS

$$PLOSS(I+1) = \sum_{K=I+1}^{n-1} LS(I+1) \quad PLOAD(I+1) = \sum_{K=I+1}^{n} L(I+1)$$

P(I+1)=PLOAD(I+1) + PLOSS(I+1)

$$QLOAD(I+1) = \sum_{K=I+1}^{n-1} L(I+1) \quad QLOSS(I+1) = \sum_{K=I+1}^{n-1} LS(I+1)$$

Q(I+1)=QLOAD(I+1) + QLOSS(I+1)

5. Algorithm For Forward Substitution Method

Step1: Read the number of buses and nodes in the given system. Read the line resistance and reactances for all the branches. Read real and reactive power at all the nodes.
Step2: Initialize the variables.
Step3: Set the convergence criteria i.e tolerance, tol=0.1.
Step4: Initialize the real and reactive power for all the nodes to zero.
Lossap(i)=0 ; Lossaq(i)=0
Step5: Set the bus count k=1.
Step6: Set initially Paloss(i)=lossap(i); Qaloss(i)=Lossaq(i);
Step7: Set the bus count i=1.
Step8: Calculate the total real and reactive power at the node(i+1), using equations (9) to (14).
Step9: Compute the voltage at all nodes at (i+1)node, i.e |va(i+1)| using equation (6).
Step10: Advance the bus count, i=i+1.
Step11: Whether bus count i=NB? ,if yes go to step3 otherwise go to next step.
Step12: Whether bus count i=(NB-1)? ,if yes set Pa(i+1)=Paload(NB).

Qa(i+1)=Qaload(NB).
Then go to step3 otherwise go to step8.
Step13: Calculate the real and reactive power at the i^{th} node Lossap(i), lossaq(i).
Step14: Calculate the difference of real and reactive power losses at all the nodes.
Dap(i)=|lossap(i)-Paloss(i)|
Daq(i)=|lossaq(i)-Qaloss(i)|
For i=1,2……..(NB-1).
Step15: Whether |Dap(i)|max and |Daq(i)|max is less than the convergence criteria. If yes go to next step, otherwise go to step6.
Step16: Print the voltage magnitude at all the nodes and also print the real and reactive power losses at all the nodes. Print the number of iterations taken.
Step17: Stop.

6. Results

A.Bus Load Flow Voltage

Bus number	Voltage magnitude(in p.u)
1	1.000
2	0.9943
3	0.9890
4	0.9804
5	0.9695
6	0.9662
7	0.9634
8	0.9549
9	0.9468
10	0.9440
11	0.9430
12	0.9428

7. Discussion

Load flow and service restoration time

This improved approach is tested on 14-bus with single feeder. The 14 bus system is shown in figure 1. Bus 3 is also fed from the grid of central electricity board. In the event of failure of supply, the two generators that are located at buses 1, 2, are started to restore the power supply to the radial feeder in minimum time.
The Stamford 250KVA two generators are driven by kirloskar diesel engines. The circuit breakers and relays are located at buses 1, 2 and 3 for grid supply isolation and protection purposes under abnormal conditions, respectively.
Under normal operation when the feeder is supplied with grid supply, buses 1 and 2 are not connected to the distribution network. In case of failure of power supply, the breakers connected to the grid network will be opened and breakers at buses 1 and 2 closed simultaneously for restoration of supply to the radial feeder after starting the EDG unit. The estimation of supply restoration time to the radial feeder, that is, from bus 3 to 14, is shown below; the bus data and line data for the 14 bus system are given in tables 3 and 4 respectively.
The pre fault voltages and currents are obtained by conducting the load flow study. These results are tabulated in table 5. The post fault voltages are obtained from the short circuit study.
The voltages after restoration, i.e. after isolating the faulty circuit from the healthy circuit, can be calculated by performing the load flow study. The results are shown in Table 5. The first two rows in the second, third and fourth columns of that table are not considered, as there is no supply from the generators under the healthy conditions.
The fault currents are calculated by performing the short circuit study, for the occurrence of balanced three phase fault at bus 8 with a fault impedance of 0 per unit , that is, for the bolted fault.

Total fault current= 1113.9943 A
CT Ratio= 525/1

OLS of the transformer breaker, which is located at bus 3, is taken as 25%, and PS of the relay is taken as 1.0. The PSM calculations are done. The results of post-fault currents and PSM are given in table 6.
The operating time of the relay has been obtained from the inverse time characteristics of the electromagnetic relay:
Operating time = *TMS* X time from the time current characteristics of the relay
Where TMS= Time Multiplier Setting
The estimation of restoration time for isolating the faulty circuit is calculated based on the operating -time the associated relays and breakers. Here it is assumed that all the relays are breakers. Here it is assumed that all the relays are of auto-reclosing electromagnetic type. By the time EDG unit is started, the circuit breakers would have closed automatically, and hence auto-reclosing time need not be considered explicitly.
The OT for the operation of the relay is taken as the operating time, which is mentioned in table 7. The PT and MT are considered based on discussions held with field engineers in the EDS. The PT is taken as less than one second of optimistic time to account for additional loading effects and switching transients under abnormal conditions. The MT is taken as one second more than the

OT to account for probability of failure due to ageing, poor maintenance, and defects in manufacturing of the relays. The results MT, ET, SD and variance are Table 8. Thus the total length along the critical path, that is, Total Restoration time TRT_2 (i.e., ET) for isolating the faulty circuit and reclosing healthy part of the circuit from is given by:

TRT_2 = 3.50+ 3.50+ 3.98+ 4.07++ 4.10+ 5.50 = 24.65s

The standard deviation for all the relays operation is given by:

$$\Sigma \sigma^2 = 0.1674s$$

Time of variance for isolating the faulty circuit:

$$\sigma_{T2}=(\Sigma \sigma^2)^{1/2} = 0.4091s$$

Thus the TRT for the restoration power supply to distribution network will be the sum of total restoration times of isolating the faulty circuit and starting of EDG.

$$TRT=TRT_1+ TRT_2$$
$$=270.83+24.65$$
$$=295.58s$$

Total overall standard deviation of the power supply restoration is given by:

$$\sigma_T=(\Sigma \sigma^2)^{1/2} =(209.04+0.1674)^{1/2}$$
$$=14.46 \text{ sec}$$

8. Conclusion

The newly developed single phase analysis of load flow technique for radial distribution main feeder suits for calculation of voltages at various nodes in the given system. The results show that the new technique is suitable for real time applications which can be utilized in distribution automation system power flow analysis. The validity of this new technique has been, tested on various Electric Power Distribution System, viz., 12-Bus, 16-Bus, 33-Bus, and 69- Bus systems. The results of all these test systems in addition to estimated time of service restoration are comparable with the practical testing conditions of the Electric Power Distribution System. The computational time of this new technique is very less compared to the previous approaches. The simultaneous consideration of priority order of the loads, feeder and transformer loading capacity violations, bus voltage violations, minimization of switch operations in addition to the estimation of time of service restoration, helps the Electric Power Distribution Engineers in efficient analysis of Restoration of Power Supply to the consumer localities. The system dependency elimination feature of this new approach makes it to use as general tool to solve the service restoration problems in the Electric Power Distribution System.

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