EFFICIENT REACTIVE POWER COMPENSATION ALGORITHM FOR DISTRIBUTION NETWORK

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ABSTRACT

The use of automation and energy efficient equipment with electronic control would greatly improve industrial production. These new devices are more sensitive to supply voltage deviation and the characteristics of the power system that was previously ignored are now very important. Hence the benefits of distribution automation have been widely acknowledged in recent years. This paper proposes an efficient load flow solution technique extended to find optimum location for reactive power compensation and network reconfiguration for planning and day-to-day operation of distribution networks. This is required as a part of the distribution automation system (DAS) for taking various control and operation decisions. The method exploits the radial nature of the network and uses forward and backward propagation technique to calculate branch currents and node voltages. The proposed method has been tested to analyze several practical distribution networks of various voltage levels and also having high R/X ratio.

Keywords : *Distribution automation system, Reactive Power Compensation, Network Reconfiguration, Power Quality, Deregulated Power*

1. INTRODUCTION

The power business is moving into new territory with market deregulation. Deregulation of the power industry has made power quality a distinguishing feature of distribution service. DAS is the key to address all these challenges to improve the operation of the distribution system and the quality of supply. Power system operators ensure the quality and reliability of supply to the customers by maintaining the load bus voltages within their permissible limit. Load flow is an important tool for the analysis of any power system. It is used in the operational as well as planning stages. The application programs like the network configuration and reactive power compensation require a robust and efficient load flow solution method. DAS is essential for efficient operation of the distribution networks. In view of the increasing use of SCADA, and distribution automation and control (DAC), distribution system reconfiguration becomes a more viable alternative for loss reduction. The networks are reconfigured to reduce system real power

loss, optimal linking of new loads, relieve overloads, and service restoration. Reactive power compensation improves the voltage profile at the user terminal and improves the quality of supply. It also reduces the losses and provides economic benefit to the supplier.

Many researches have addressed distribution network reconfiguration and reactive power compensation proposing different approaches. The optimum operating condition can be considered to be obtained when the network presents (i) minimum losses, (ii) minimum voltage deviations at the consumer feeding points, and (iii) maximum reliability. A branch exchange type, heuristic algorithm has been suggested. A filtering mechanism has also been suggested to reduce the number of candidate switching options¹. A power flow based heuristic algorithm for determining the minimum loss configuration of radial distribution networks has been reported². Capacitor placement problem on radial distribution systems is formulated and a solution algorithm is proposed. The problem is formulated as a mixed integer-programming problem³. The problem is formulated and solved using a quadratic integer programming based approach to determine the number, locations and sizing of capacitors to be placed in the distribution systems. The proposed method does not take into account the voltage constraint⁴. Distribution networks are radial and r/x ratio of lines is high. Conventional load flow methods based on Gauss-siedel and Newton-Rapson techniques are inefficient in solving distribution networks. An efficient and robust three-phase power flow algorithm for application to radial distribution networks was presented⁵. It uses the forward and backward propagation technique to calculate branch currents and node voltages. This method has been extended to network reconfiguration and reactive power compensation for application to the distribution networks.

2. METHODOLOGY

Distribution systems are usually unbalanced due to unbalanced loading of the different phases. This requires detail modeling of the special feature such as multiphase, grounded or ungrounded, unbalanced distribution loads and so on. The distribution feeders consist of three-phase overhead lines or underground cable sections. These have double-phase or single-phase line sections towards the end of the feeder. In the three-phase power flow algorithm the line branch has been model such that each node or line section in the network is numbered by a single index, regardless of the number of phases of this node or line or line section. The three-phase balanced/unbalanced loads can be represented as either constant power, or constant current, or constant impedance type or a combination of these based on the proportion of the type of consumer loads. There is no limitation on the type of load to be modeled in the proposed algorithm. The load flow solution is found using methods of network flow (paths) along the tree in forward direction and backward direction. Figure 1 shows the computational blocks in the algorithm.

3. COMPUTATIONAL ITERATIVE SCHEME

For a given network, first the nodes are reordered in such a way as to generate proper source node (Parent node) and load node (child node) paths. This is explained in block A. A table of parent nodes and child nodes is created. A source node (parent node) can be connected to

Figure 1 : Basic computational blocks in the proposed algorithm

more than a single load node (child node). A parent node can have more child nodes (children). But a load node (child node) has only one source node (parent node). This is due to radial nature of the distribution network. Each section of a radial distribution feeder is connected radially so that it has one predecessor (parent node) and possibly multiple descendants (Children nodes).

A backward walk is achieved by starting at the end nodes (Children nodes) and passing ‘backward’ over each section. During the backward propagation branch currents are calculated as explained in computational block B. The block C of the basic steps in the proposed algorithm, a forward walk is achieved by starting at the source that may be either the substation or the feeder and passing “forward” over each section. The node voltages are calculated. voltage convergence is executed in the block D. Computation of branch flows, losses, and degree of unbalance is done in computational block E. Node renumbering is the process of generating new node numbers for feeder nodes, which are initially numbered, arbitrarily. This is very useful particularly when the network is reconfigured using various switching options to meet the demand during different configuration.

Ordering of node numbers to generate proper parent-child relationship is known as the node renumbering process. The branch sequence of forward and backward paths is prepared. The optimally-ordered feeder nodes with new numbers starting from the source (parent) node and propagating in the forward path to load (child) node is obtained. A table is arranged to give the forward path from the source (parent) node to the load (child) node and backward path from the load (child) node to the source (parent) node. From the table the backward path and the forward path are created and stored in memory for further calculation⁵.

Initially, all the node voltage magnitudes are set to 1.0 p.u. and voltage angles are set to 0.0, -120, 120 degrees for phase A, phase B and phase C, respectively. And also all the branch currents (complex) are initialized to (0.0, 0.0) p.u. The source node phase voltage magnitudes are assumed to be known, also its angles are $\delta_a = 0$, $\delta_b = -120^\circ$, $\delta_c = 120^\circ$ (taken as reference). During the backward propagation the load current is calculated depending on the load type. The half line charging shunt currents of all the branches at the node are added to the load current. Once the child node current is calculated, the parent branch current is updated using the Equation (1) and considering that the loads are unbalanced constant power,

$$\begin{bmatrix} I_{La}(i) \\ I_{Lb}(i) \\ I_{Lc}(i) \end{bmatrix} = \begin{bmatrix} S_{La}(i)/V_a(i) \\ S_{Lb}(i)/V_b(i) \\ S_{Lc}(i)/V_c(i) \end{bmatrix}^* \quad (1)$$

Where $I_{La}(i)$, $I_{Lb}(i)$, $I_{Lc}(i)$ = Load current at i^{th} node for constant power loads; $S_{La}(i)$, $S_{Lb}(i)$, $S_{Lc}(i)$ = Complex power of constant power load at i^{th} node.

The branch current of the line sections is calculated using the equation (2).

$$\begin{bmatrix} I_a(m) \\ I_b(m) \\ I_c(m) \end{bmatrix} = \begin{bmatrix} i_{La}(i) \\ i_{Lb}(i) \\ i_{Lc}(i) \end{bmatrix} + \sum_{peM} \begin{bmatrix} I_{ap} \\ I_{bp} \\ I_{cp} \end{bmatrix} + \sum_{peM} [Y_{sh}] \begin{bmatrix} V_a(i) \\ V_b(i) \\ V_c(i) \end{bmatrix} \quad (2)$$

The purpose of forward propagation is to calculate the voltage and load at each node starting from the source node of the feeder. The feeder substation source voltage is set to its actual value. During forward propagation, the current in each branch is held constant to the value obtained in backward walk. The node voltages are calculated using the equation (3), starting from feeder source and proceeding along the forward

$$\begin{bmatrix} V_a(j) \\ V_b(j) \\ V_c(j) \end{bmatrix} = \begin{bmatrix} V_a(i) \\ V_b(i) \\ V_c(i) \end{bmatrix} - \begin{bmatrix} Z_{aa,m} & Z_{ab,m} & Z_{ac,m} \\ Z_{ab,m} & Z_{bb,m} & Z_{bc,m} \\ Z_{ac,m} & Z_{bc,m} & Z_{cc,m} \end{bmatrix} \begin{bmatrix} I_a(m) \\ I_b(m) \\ I_c(m) \end{bmatrix} \quad (3)$$

path. The convergence criteria are that the complex voltage real and imaginary parts at each node in all the three-phases are compared with their previous iteration values. Therefore the voltage mismatch for j^{th} node during k^{th} iteration is given by following Equation 4.

$$\Delta V^k(j) = V^k(j) - V^{k-1}(j) \text{ for a, b, and c phases} \quad (4)$$

$$\text{Real } |(\Delta V(j))| < \text{eps, } j \in \text{all the nodes} \quad (5)$$

$$\text{Imag } |(\Delta V(j))| < \text{eps, } j \in \text{all the nodes} \quad (6)$$

If both the conditions in Equations 5 and 6 are satisfied, the iterative process is stopped. Once the load flow solution is converged all the branch currents and voltage at each node are known. The real and reactive power flows and loss can be calculated.

4. NETWORK RECONFIGURATION

The proposed load flow technique is extended to network reconfiguration, as it is efficient and robust for analyzing larger distribution system with higher number of nodes. First we can define the switching option with the available switches and total system losses can be calculated for each switching option. These loss values are arranged in merit order to obtain the optimum configuration. One of the important functions of the distribution automation is configuration management. In a normal state, configuration management deals with the change of feeder configurations through remotely controlled switches. In a fully automated system, all switches would be remotely controllable and all feeder loads can be monitored from the dispatching center. Thus the dispatcher would be able to transfer loads from one feeder to another while minimizing interruptions to customers. When a significant change of load is detected, a loss-minimization algorithm can help the dispatcher generate a minimum-loss configuration. The distribution networks control was traditionally restricted to avoid overloading and voltage limit violations, under normal operating conditions. In recent years, the development in computer software and hardware has made the optimization of the network operation feasible.

5. REACTIVE POWER COMPENSATION

The application of the proposed load flow solution method has been tested for reactive power compensation and network reconfiguration in distribution system. The candidate location for reactive power compensation can be defined as the location where the feeder loss is found to be the lowest. This location is considered as the feeding source. The load flow is performed for a single iteration considering each node as possible feeding node and the losses are calculated. Then these losses are arranged in ascending order. The node, which is at the top of the merit order, is the optimum feeding node and it is the best location for reactive power compensation. Due to some geographical or other reason, if the first node in order is not suitable, the next node in the list is selected.

6. SYSTEM STUDIES AND RESULTS

A computer program has been developed based on the proposed algorithm and tested on a few distribution networks. Two typical systems, a 19-node practical system and a 38-node practical distribution network with multi-feeders are presented.

6.1 19-node practical system

The 19-node feeder is analyzed to find the merit order of the feeding nodes for load demand factor of 0.6. The loads were assumed balanced and load flow is performed for single iteration. The merit order for the given loading condition is presented in Table 1. The loss values shown are for single iteration of the load flow. The total loss at node 10 is 41.466 kW and the loss percentage is 3.29. The node 10 is the best location for reactive power compensation. The node 3 is the worst location for reactive power compensation. The total loss at node 3 is 322.584 kW and the loss percentage is 20.91. Figure 2 presents the merit order with every node as feeding

Figure 2 : Merit order of the feeding points of 19-node system

Table 1 : Merit order of the feeding point for the 19-node system

Merit order	Node No.	Total Losses (kW)	% Loss	Merit order	Node No.	Total Losses (kW)	% Loss
1	10	41.466	3.29	11	5	138.074	10.17
2	9	43.128	3.41	12	15	142.558	10.46
3	12	55.803	4.37	13	17	145.060	10.63
4	11	57.274	4.48	14	1	193.897	13.72
5	8	58.806	4.60	15	18	207.327	14.53
6	14	72.665	5.62	16	13	225.178	15.58
7	6	78.434	6.04	17	19	247.471	16.87
8	4	90.802	6.93	18	16	255.966	17.34
9	2	115.951	8.68	19	3	322.584	20.91
10	7	136.964	10.09				

point. As a single iteration is performed, the CPU time taken for a bigger system will also be in the range of millisecond. Reactive power compensation is provided at the best and worst nodes. The percentage loss without compensation is 13.715%. The candidate location for reactive power compensation is the node number 10. The node 10 is the location where the feeder loss is found to be the lowest. This location is considered as the feeding source. About 250kvar compensation is placed at node 10. The load flow is performed for a single iteration. The forward flows and losses are given in Table 2. The percentage loss with compensation at node 10 is 11.555%. Reactive power compensation of about 250kvar is placed at the worst node 3. The load flow is performed for a single iteration. The forward flows and losses are given in Table 3. The percentage loss with compensation at node 3 is 13.365%.

Table 2 : Forward flows and losses with reactive power compensation at the candidate location (node 10)

Node From	Node To	Forward Flows		Losses	
		kW	kvar	kW	kvar
1	2	1379.234	408.989	53.395	22.972
2	3	87.057	42.032	3.657	2.187
2	4	1152.380	302.138	19.871	8.549
4	5	54.078	26.176	0.079	0.022
4	6	1024.429	241.259	10.720	4.612
6	7	86.677	41.924	0.276	0.078
6	8	893.016	178.248	20.509	8.824
8	9	818.506	143.270	21.511	9.255
9	10	661.995	68.632	24.314	10.461
10	11	285.255	137.915	1.786	0.768
10	12	318.407	153.781	2.224	0.957
11	14	142.740	69.055	0.302	0.130
11	13	54.329	26.247	0.329	0.094
12	16	87.423	42.136	1.023	0.291
12	15	142.360	68.842	1.503	0.647
14	17	54.152	26.219	0.153	0.066
14	18	54.264	26.228	0.264	0.075
15	19	86.858	42.042	0.457	0.197

Table 3 : Forward flows and losses with reactive power compensation at the worst location (node 3)

Node From	Node To	Forward Flows		Losses	
		kW	kvar	kW	kvar
1	2	1408.050	420.946	55.723	23.974
2	3	89.991	207.136	3.591	1.020
2	4	1175.935	562.261	23.830	10.252
4	5	54.080	26.176	0.079	0.023
4	6	1044.028	499.681	13.041	5.610
6	7	86.678	41.924	0.279	0.079
6	8	910.287	435.669	25.403	10.929
8	9	830.885	398.586	26.870	11.561
9	10	669.014	321.642	30.993	13.334
10	11	285.373	137.962	1.860	0.800
10	12	318.628	153.869	2.318	0.997
11	14	142.767	69.065	0.315	0.135
11	13	54.343	26.251	0.343	0.097
12	16	87.467	42.149	1.067	0.303
12	15	142.444	68.878	1.567	0.674
14	17	54.159	26.222	0.159	0.068
14	18	54.275	26.231	0.275	0.078
15	19	86.877	42.050	0.477	0.205

6.2 38 node practical system

This feeder is analyzed to find the merit order of the feeding nodes for load demand factor of 1.0. The merit order for the given loading condition is presented in Table 4. The loss values shown are for single iteration of the load flow. The node 6 is the best location for reactive power compensation. The total loss at node 6 is 90.651 kW and the percentage loss is 2.38. The node 37 is the worst location for reactive power compensation. The total loss at node 37 is 5526.224 kW and the loss percentage is 59.80. Figure 3 presents the merit order with every node as feeding point.

Table 4 : Merit order of the feeding point for the 38-node system

Merit order	Node No.	Total Losses (kW)	% Loss	Merit order	Node No.	Total Losses (kW)	% Loss
1	6	90.651	2.38	20	11	431.602	10.41
2	26	101.788	2.67	21	35	436.298	10.51
3	7	103.720	2.72	22	20	442.890	10.65
4	5	108.842	2.85	23	31	469.866	11.23
5	27	118.930	3.10	24	38	484.791	11.54
6	4	119.879	3.13	25	12	488.700	11.63
7	3	134.327	3.49	26	34	518.935	12.26
8	8	160.317	4.14	27	21	525.836	12.40
9	23	170.117	4.38	28	32	532.209	12.53
10	2	189.277	4.85	29	33	618.423	14.27
11	28	194.238	4.97	30	22	705.733	15.96
12	1	202.826	5.18	31	13	791.726	17.57
13	19	210.051	5.35	32	14	963.415	20.59
14	24	255.209	6.43	33	36	1082.558	22.56
15	29	263.403	6.62	34	15	1197.901	24.38
16	9	269.023	6.75	35	17	1431.682	27.82
17	30	315.161	7.82	36	16	1632.895	30.53
18	25	382.165	9.33	37	18	1801.854	32.66
19	10	403.691	9.80	38	37	5526.224	59.80

A single iteration is performed, the CPU time taken for a bigger system will also be in the range of millisecond. Reactive power compensation is provided at the best and worst nodes. The percentage loss without compensation is 5.177%. The candidate location for reactive power compensation is the node number 6. The node 6 is the location where the feeder loss is found to be the lowest. This location is considered as the feeding source. About 250kvar compensation is placed at node 10. The load flow is performed for a single iteration.

The forward flows and losses are given in Table 5. The percentage loss with compensation at node 6 is 4.221%. Reactive power compensation of about 250kvar is placed at the worst node

Table 5 : Forward flows and losses with reactive power compensation at the candidate location (node 6) of the 38 node system

Node From	Node To	Forward Flows		Losses	
		kW	kvar	kW	kvar
1	2	3878.739	1412.719	9.803	4.997
2	3	3407.810	1186.649	40.266	20.509
2	19	361.139	161.081	0.161	0.154
3	4	2337.969	668.926	13.919	7.089
3	23	939.571	457.211	3.168	2.165
4	5	2204.053	581.839	12.898	6.569
5	6	2131.157	545.272	26.135	22.561
6	7	1094.877	529.557	1.878	8.216
6	26	950.126	973.140	2.547	1.297
7	8	893.000	421.345	4.746	1.575
7	35	0.000	0.000	0.000	0.000
8	9	688.253	319.770	4.100	2.946
8	34	0.000	0.000	0.000	0.000
9	10	624.157	296.827	3.492	2.475
10	11	560.659	274.348	0.543	0.182
11	12	515.111	244.165	0.864	0.286
12	13	454.254	208.881	2.614	2.057
12	36	0.000	0.000	0.000	0.000
13	14	391.642	171.826	0.715	0.941
14	15	270.923	90.881	0.350	0.312
15	16	210.574	80.571	0.277	0.202
16	17	150.298	60.369	0.247	0.329
17	18	90.054	40.043	0.052	0.041
18	37	0.000	0.000	0.000	0.000
19	20	270.976	120.925	0.832	0.749
20	21	180.143	80.174	0.101	0.118
21	22	90.046	40.060	0.044	0.058
23	24	846.407	405.050	5.122	4.044
24	25	421.280	201.002	1.282	1.003
25	38	0.000	0.000	0.000	0.000
26	27	887.597	946.851	3.260	1.660
27	28	824.332	920.189	11.066	9.757
28	29	753.269	890.434	7.671	6.685
29	30	625.600	813.750	3.815	1.943
30	31	421.784	211.807	1.560	1.542
31	32	270.218	140.259	0.209	0.243
32	33	60.014	40.022	0.013	0.020

Table 6 : Forward flows and losses with reactive power compensation at the worst location (node 37) of the 38 node system

Node From	Node To	Forward Flows		Losses	
		kW	kvar	kW	kvar
1	2	3921.055	1449.833	10.054	5.125
2	3	3449.840	1223.618	41.435	21.104
2	19	361.131	161.072	0.161	0.154
3	4	2378.837	705.302	14.497	7.383
3	23	939.583	457.220	3.170	2.166
4	5	2244.328	617.913	13.460	6.855
5	6	2170.873	581.059	27.304	23.570
6	7	1133.371	-435.702	1.876	8.204
6	26	950.193	973.190	2.552	1.300
7	8	931.491	-543.907	5.614	1.863
7	35	0.000	0.000	0.000	0.000
8	9	725.879	-645.771	6.642	4.772
8	34	0.000	0.000	0.000	0.000
9	10	659.237	-670.543	6.329	4.486
10	11	592.920	-695.023	1.128	0.379
11	12	546.777	-725.407	2.126	0.703
12	13	484.656	-761.109	8.237	6.481
12	36	0.000	0.000	0.000	0.000
13	14	416.423	-802.586	3.044	4.007
14	15	293.379	-886.593	3.526	3.139
15	16	229.847	-899.736	4.397	3.203
16	17	165.451	-922.939	7.689	10.266
17	18	97.761	-953.205	4.476	3.510
18	37	3.288	-996.712	3.287	3.287
19	20	270.976	120.925	0.832	0.749
20	21	180.149	80.181	0.101	0.118
21	22	90.044	40.058	0.044	0.058
23	24	846.406	405.049	5.124	4.046
24	25	421.285	201.005	1.283	1.004
25	38	0.000	0.000	0.000	0.000
26	27	887.656	946.897	3.267	1.663
27	28	824.381	920.229	11.088	9.776
28	29	753.293	890.453	7.686	6.698
29	30	625.610	813.757	3.822	1.947
30	31	421.785	211.808	1.563	1.545
31	32	270.227	140.269	0.209	0.244
32	33	60.011	40.017	0.013	0.020

Figure 3 : Merit order of the feeding point for the 38 node system

37. The load flow is performed for a single iteration. The forward flows and losses are given in Table 6. The percentage loss with compensation at node 37 is 5.255%.

7. CONCLUSIONS

The proposed technique is efficient and robust for analyzing practical and large distribution network having multi-conductor, multi-feeder with high r/x ratio. The technique always guarantees convergence and it is suitable to real time operation of distribution network. A three-phase load flow solution technique based on backward and forward propagation and its applications to reactive power compensation and network reconfiguration has been demonstrated. In the case of feeder problems, to bring down the unbalance or fault occurrence, feeder reconfiguration and reactive power compensation can be done on-line using the proposed algorithm. Several practical large distribution feeders with multi-conductors and multi-feeders have been analyzed. The proposed method is computationally very fast, efficient and robust.

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