OPTIMAL CAPACITOR PLACEMENT IN UNBALANCED RADIAL DISTRIBUTION NETWORKS

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ABSTRACT

This paper presents a novel method to determine the best locations for capacitor placement in unbalanced radial distribution networks and simple GA is used to find the optimal sizing of the capacitor bank. The objective function formulated includes the energy cost, capacitor installation cost and purchase cost, so that the fitness function is to be maximized for the net saving.

Key words: radial distribution networks, capacitor placement, unbalanced, energy cost

1.0 INTRODUCTION

Reactive currents in an electrical utility distribution system produce losses and result in increased ratings for distribution components. Shunt capacitors are commonly used in distribution systems for several reasons, in particular in order to reduce power losses, to improve the voltage profile along the feeders and to increase the maximum flow through cables and transformers. These benefits depend greatly on how capacitors are placed in the system. The general capacitor placement problem is how to optimally determine the locations to install capacitor and sizes of capacitors to be installed in the buses of radial distribution systems [1-3]. Numerous researches were done on optimal capacitor placement in balanced distribution feeders [4-10]. These solutions mainly utilize the positive sequence network model and the associated power flows in formulating the problem. Hence, the results do not directly apply for systems containing feeders with missing phases, unevenly loaded feeders or shunt capacitors on single or double phase feeders. Chiang et. al [11] has used the method of simulated annealing to obtain the optimum values of shunt capacitors for radial distribution networks. H. Kim and S.K You [12] have used genetic algorithm for obtaining the optimum values of shunt capacitor bank. They have treated the capacitors as constant reactive power loads and no method is used to reduce the cpu time. Genetic algorithm based solution is capable of determining a near global solution with lesser computational burden than the simulated annealing method.

In this paper a novel method to determine the best locations for capacitor placement in unbalanced radial distribution networks and simple GA is used to find the optimal sizing of the capacitor bank. The objective function formulated includes the energy cost, capacitor installation cost and purchase cost, so that the fitness function is to be maximized for the net saving.

2.0 MATHEMATICAL FORMULATION

The objective function of the present work is to determine the optimal sizes of the capacitors.
The problem may be stated as,

Max.f

$$= \left\{ KE \times T \times \left[P - P^{|}\right] - \alpha \times \left[KI \times \text{no.of capacitor nodes} + \sum_{j=1}^{m} KC \times u(j) \right] \right\}$$

Where

KE = Energy Cost (3.0 Rs./kwh)

T = Time Period (8760 hrs)

P = Active power loss before capacitor placement

$P^{|}$ = Active power loss after capacitor placement

α = Depreciation factor is 0.2

KI = Installation cost (Rs.50,000 /each location)

KC = Cost of the capacitor (Rs.200/kVAR)

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$u(j)$ = Capacitor bank rating

Unbalanced three phase power flow

In a three phase unbalanced load flow of distribution system the following components are modeled by their equivalent circuits in terms of inductance, capacitance, resistance and injected current.

Conductors – Individual phase representation for both primary and secondary with capacitive line charging on primary conductor only.
Transformers – A general approach is recommended where by all transformer connections, including the common core transformer, are represented as individual transformers.
Capacitors – Capacitors are represented by their equivalent injected currents.
Loads – The unbalanced loads are basically considered because of single phase, two phase and unequal three phase loads which exist in different types viz. constant power, constant Impedance and constant current.

Shunt admittance and series impedance are represented by the actual phase quantities

3.0 ALGORITHM FOR CANDIDATE NODE IDENTIFICATION

Following algorithm is used to identify the candidate nodes, which are more suitable for capacitor placement.

Step 1: Read the given data for unbalanced radial distribution system.

Step 2: Perform the load flows and calculate the base case total active power loss.

Step 3: By compensating the reactive power injections (Q_C) at each node (except source node) in all the phases, run the load flows and calculate the active power losses in each case.

Step 4: Calculate the power loss reduction and power loss indices using the following equation

$$PLI(i) = \frac{(X(i) - Y)}{(Z - Y)} \quad \forall\, i = 2,3, \ldots .n.$$

Whereas X = Loss reduction; Y = Minimum reduction; Z = Maximum reduction;

Step 5: Select the candidate node whose PLI > Tolerance.

Step 6: Stop.

3. 1 Candidate node identification

Example: 1 25 bus system

The proposed candidate node identification method for capacitor placement is explained with 25- bus system whose line and load data are given in ref [10]. After performing the load flows, the base case total active power loss obtained is **150.1225** KW.

After compensating the reactive power injection at each node in all the phases equal to local reactive load at that particular node, the load flow is performed and the total active power loss and loss reduction in each case are recoreded.table-1 shows the results for 25- bus system.

Table-1 power loss reductions for 25-bus URDS

Node no.	Total Active Power loss after compensating Qc at each node (in all the phases)(KW)	Loss reduction(KW)
2	150.1225	0
3	147.8025	2.3200
4	146.6871	3.4354
5	147.4755	2.6470
6	146.8649	3.2576
7	150.1225	0
8	146.6567	3.4658
9	143.3385	6.7839
10	144.7280	5.3945
11	144.5633	5.5592
12	142.4946	7.6279
13	144.5035	5.6189
14	143.3311	6.7914
15	134.1132	16.0093
16	145.4619	4.6606
17	145.0712	5.0512
18	147.2179	2.9046
19	145.9406	4.1818
20	147.1387	2.9837
21	147.0366	3.0859
22	145.8084	4.3141

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23	146.3854	3.7370
24	147.2501	2.8724
25	146.4120	3.7104

The power loss indices (PLI) are calculated as

$$PLI[i] = \frac{(Loss\ reduction\ [i] - Min\ reduction)}{(Max\ reduction - Min\ reduction)} \quad \ldots.(1)$$

The power loss indices (PLI) for 25-node system are given in table-2

Table-2 power loss indices for 25-bus URDS

Node no.	Power loss Index(PLI)
2	0
3	0.1449
4	0.2146
5	0.1653
6	0.2035
7	0
8	0.2165
9	0.4238
10	0.3370
11	0.3472
12	0.4765
13	0.3510
14	0.4242
15	1.0000
16	0.2911
17	0.3155
18	0.1814
19	0.2612
20	0.1864
21	0.1928
22	0.2695
23	0.2334
24	0.1794
25	0.2318

The most suitable nodes for the capacitor placement are chosen based on the condition PLI greater than a PLI tolerance value between '0' and '1'. The tolerance value is selected by experimenting with different values in descending order of the PLI limits. The best value of the tolerance value gives the highest profit, satisfying the system constraints

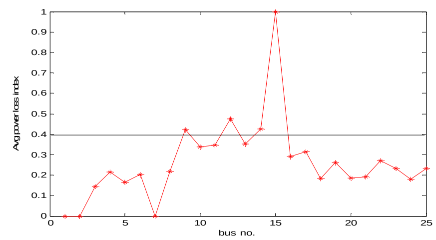

Fig.1 plot between nodes and PLI

For the above case 0.4 is set as the tolerance. From above plot and table-3, it is concluded that nodes **9,12,14,15** are the best candidate nodes for the capacitor placement.

Table-3 Selection of candidate nodes in 25-bus URDS for capacitor placement

Tolerance	Node numbers	Total capacitor size (kVar)	Net Saving (Rs)
0.9	15	550	634786
0.4	**9,12,14,15**	**1400**	**10,53,346**
0.3	9,10,11,12,13,14,15,17	2000	830751

Example: 2 - IEEE 37-node system

Node no.	Total Active Power loss after compensating Qc at each node (in all the phases)(KW)	Loss Reduction (KW)	PLI
2	80.1108	5.5638	1.0000
3	85.6746	0	0
4	85.6746	0	0
5	83.6361	2.0385	0.3664
6	85.6746	0	0
7	85.6746	0	0
8	82.7652	2.9094	0.5229
9	84.5301	1.1445	0.2057
10	80.3769	5.2977	0.9522
11	80.6849	4.9896	0.8968
12	85.6746	0	0

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13	84.5531	1.1215	0.2016
14	83.8054	1.8692	0.3360
15	83.1241	2.5505	0.4584
16	83.1251	2.5494	0.4582
17	85.6746	0	0
18	84.8850	0.7896	0.1419
19	85.6746	0	0
20	84.6465	1.0281	0.1848
21	84.7147	0.9599	0.1725
22	84.5671	1.1075	0.1991
23	84.5672	1.1074	0.1990
24	85.6746	0	0
25	84.7100	0.9646	0.1734
26	85.6746	0	0
27	85.6746	0	0
28	83.5239	2.1507	0.3865
29	83.7076	1.9670	0.3535
30	84.9775	0.6971	0.1253
31	84.0278	1.6468	0.2960
32	85.6746	0	0
33	80.7635	4.9111	0.8827
34	83.9917	1.6828	0.3025
35	83.2244	2.4502	0.4404
36	85.0683	0.6063	0.1090
37	81.7348	3.9398	0.7081

Table-4 Selection of candidate nodes in IEEE

Tolerance	**Node numbers**	**Total capacitor size (kVar)**	**Net Saving (Rs)**
0.8	2 10 11 33	700	3,65,963
0.6	**2 10 11 33 37**	**900**	**3,72,739**
0.5	2 8 10 11 33 37	850	3,41,610

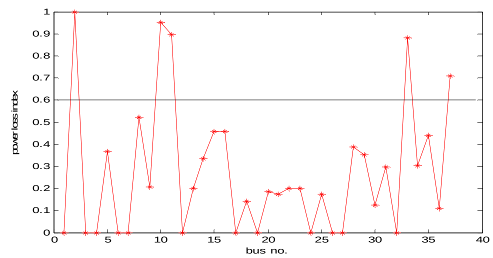

Fig.2 Plot between nodes and PLI

5. Results and Analysis

Example 1: 25-bus system

The proposed algorithm is tested on 25-bus unbalanced radial distribution system shown in Fig.3.The line and load data are given in Appendix .The voltage profile with out compensation and with compensation is given in table.5.The summary of test results are given in table.6. The net saving after capacitor placement is shown in table. 3

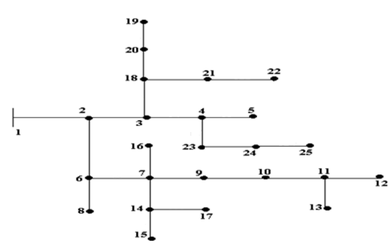

Fig. 3 - SLD of 25-bus URDS

Example:2 IEEE 37-bus system

The proposed algorithm is tested on IEEE 37 bus test system shown in Fig.5. The load data has changed with some modifications and regulator is not included in the system. The line and load data are given in reference [14]. The capacitor bank considered here is delta connected. The voltage profile with out compensation and with

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Bus No.	Without compensation			with compensation		
	|Va| (p.u)	|Vb| (p.u)	|Vc| (p.u)	|Va| (p.u)	|Vb| (p.u)	|Vc| (p.u)
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	0.9702	0.9711	0.9755	0.9797	0.9808	0.9843
3	0.9632	0.9644	0.9698	0.9728	0.9742	0.9788
4	0.9598	0.9613	0.9674	0.9694	0.9711	0.9763
5	0.9587	0.9603	0.9664	0.9684	0.9700	0.9754
6	0.9550	0.9559	0.9615	0.9708	0.9722	0.9763
7	0.9419	0.9428	0.9492	0.9641	0.9658	0.9701
8	0.9529	0.9538	0.9596	0.9688	0.9701	0.9744
9	0.9359	0.9367	0.9438	0.9611	0.9640	0.9683
10	0.9315	0.9319	0.9395	0.9587	0.9611	0.9659
11	0.9294	0.9296	0.9376	0.9578	0.9599	0.9651
12	0.9284	0.9284	0.9366	0.9582	0.9601	0.9654
13	0.9287	0.9287	0.9368	0.9571	0.9590	0.9643
14	0.9359	0.9370	0.9434	0.9615	0.9624	0.9667
15	0.9338	0.9349	0.9414	0.9606	0.9609	0.9659
16	0.9408	0.9418	0.9483	0.9631	0.9648	0.9691
17	0.9347	0.9360	0.9420	0.9603	0.9613	0.9653
18	0.9573	0.9586	0.9643	0.9670	0.9684	0.9733
19	0.9524	0.9544	0.9600	0.9621	0.9643	0.9690
20	0.9548	0.9563	0.9620	0.9645	0.9662	0.9710
21	0.9537	0.9549	0.9605	0.9634	0.9647	0.9695
22	0.9518	0.9525	0.9585	0.9615	0.9623	0.9675
23	0.9565	0.9584	0.9648	0.9661	0.9682	0.9738
24	0.9544	0.9565	0.9631	0.9641	0.9663	0.9721
25	0.9520	0.9547	0.9612	0.9617	0.9645	0.9702
15	0.9338	0.9349	0.9414	0.9606	0.9609	0.9659
16	0.9408	0.9418	0.9483	0.9631	0.9648	0.9691
17	0.9347	0.9360	0.9420	0.9603	0.9613	0.9653
18	0.9573	0.9586	0.9643	0.9670	0.9684	0.9733
19	0.9524	0.9544	0.9600	0.9621	0.9643	0.9690
20	0.9548	0.9563	0.9620	0.9645	0.9662	0.9710
21	0.9537	0.9549	0.9605	0.9634	0.9647	0.9695
22	0.9518	0.9525	0.9585	0.9615	0.9623	0.9675
23	0.9565	0.9584	0.9648	0.9661	0.9682	0.9738
24	0.9544	0.9565	0.9631	0.9641	0.9663	0.9721
25	0.9520	0.9547	0.9612	0.9617	0.9645	0.9702

Table.5 Voltage profile of 25busURDS

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37-bus URDS for capacitor placement

Node No.	Without compensation			with compensation		
	|Vab| p.u	|Vbc| p.u	|Vca| p.u	|vab| p.u	|Vbc| p.u	|Vca| p.u
799	1.0000	1.0000	1.000	1.0000	1.0000	1.0000
701	0.9863	0.9855	0.9817	0.9900	0.9898	0.9859
702	0.9781	0.9772	0.9719	0.9841	0.9837	0.9791
703	0.9709	0.9715	0.9645	0.9789	0.9791	0.9738
730	0.9652	0.9667	0.9588	0.9747	0.9746	0.9696
709	0.9634	0.9651	0.9571	0.9733	0.9732	0.9685
708	0.9607	0.9631	0.9547	0.9713	0.9714	0.9670
733	0.9582	0.9621	0.9527	0.9695	0.9702	0.9654
734	0.9547	0.9606	0.9494	0.9671	0.9685	0.9630
737	0.9512	0.9596	0.9472	0.9648	0.9672	0.9618
738	0.9501	0.9592	0.9461	0.9641	0.9668	0.9609
711	0.9498	0.9590	0.9451	0.9639	0.9666	0.9600
741	0.9497	0.9589	0.9448	0.9638	0.9666	0.9596
713	0.9763	0.9749	0.9697	0.9824	0.9818	0.9773
704	0.9740	0.9718	0.9672	0.9803	0.9792	0.9754
720	0.9727	0.9683	0.9647	0.9793	0.9766	0.9738
706	0.9726	0.9679	0.9646	0.9792	0.9761	0.9737
725	0.9725	0.9675	0.9645	0.9791	0.9758	0.9736
705	0.9761	0.9746	0.9701	0.9823	0.9819	0.9776
742	0.9757	0.9738	0.9699	0.9820	0.9810	0.9774
727	0.9697	0.9709	0.9635	0.9778	0.9785	0.9728
744	0.9690	0.9705	0.9631	0.9771	0.9781	0.9724
729	0.9686	0.9704	0.9630	0.9767	0.9780	0.9723
775	0.9634	0.9651	0.9571	0.9733	0.9732	0.9685
731	0.9632	0.9642	0.9569	0.9731	0.9723	0.9683
732	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
710	0.9542	0.9595	0.9478	0.9666	0.9674	0.9614
735	0.9541	0.9593	0.9473	0.9664	0.9672	0.9609
740	0.9497	0.9588	0.9445	0.9637	0.9665	0.9594
714	0.9737	0.9717	0.9671	0.9800	0.9791	0.9753
718	0.9723	0.9714	0.9667	0.9786	0.9789	0.9749
707	0.9709	0.9629	0.9631	0.9776	0.9725	0.9733
722	0.9707	0.9624	0.9629	0.9774	0.9721	0.9732
724	0.9705	0.9619	0.9629	0.9773	0.9715	0.9731
728	0.9686	0.9701	0.9627	0.9767	0.9777	0.9720
736	0.9536	0.9578	0.9475	0.9660	0.9657	0.9611
712	0.9751	0.9737	0.9691	0.9816	0.9814	0.9768

Table.6 Summary of test results for 25 bus URDS

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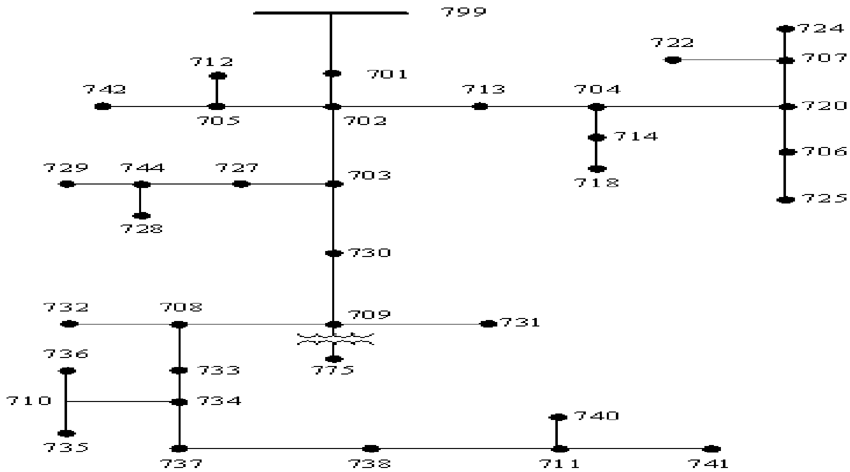

Fig. 5 - single line diagram of 37-bus URDS

compensation is given in table.7.The summary of test results are given in table .8. The net saving after capacitor placement is shown in table.4

Description	25 Node system	
	Without compensation	**with compensation**
Total Q_C required (kVAR)	800	1400
Total reactive power Demand (kVAR)	2560.30	2512.17
Total reactive power release (kVAR)	-----	48.13
Min. voltage (p.u)	0.9311	0.9566
Voltage regulation (%)	7.3	4.53
Improvement of voltage regulation (%)	----	2.77
Total losses (kW)	150.1225	106.3117
Total Loss reduction (%)	------	29.18
Total Demand (kW)	3390	3346.2117
Total Released demand (kW)	-------	43.8108
Total Feeder demand (kVA)	4248.2	4184.0
Total Released feeder demand (kVA)	-------	64.2
Net savings (Rs)	Best ---	Rs 10,53,346
	Worst ---	Rs 10,29,789
	Avera --	Rs 10,52,603

Table -7 Voltage profile of 37 bus URDS

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Table -8 Summary of test results for 37 bus URDS

Description		37 Node system	
		Without comp.	with comp.
Total Q_C required (kVAR)		800	900
Total reactive power Demand (kVAR)		1419.227	1405.59
Total Release reactive power (kVAR)		—	13.63
Average Min.voltage (p.u)		**0.9506**	**0.9629**
Average Voltage regulation (%)		5.19	3.85
Improvement of voltage regulation (%)		—	1.34
Total losses (kW)		85.6746	68.2187
Total Loss reduction (%)		——	20.37
Total Demand (kW)		2838.67	2821.22
Total Released demand (kW)		——	17.45
Total Feeder capacity (kVA)		3173.7	3152.0
Total Released feeder capacity (kVA)			21.7
Net savings (Rs)	Best	——	Rs 3,72,739
	Worst		Rs 3,44,237
	Average		Rs 3,69,621

6.0 CONCLUSIONS

In this paper a simple and efficient candidate node identification method algorithm has been presented for the optimal placement of capacitors in unbalanced radial distribution networks and simple GA is used to find the optimal sizing of the capacitor bank. The objective function formulated includes the energy cost, capacitor installation cost and purchase cost, so that the fitness function is to be maximized for the net saving. The effectiveness of the proposed method has been demonstrated through the 25-bus unbalanced radial distribution system and the IEEE 37-bus system examples

REFERENCES

[1] J. J. Grainger and S. H. Lee, "Optimum size and location of shunt capacitors for reduction of losses on distribution feeders", *IEEE Trans. on Power Apparatus and Systems,* Vol. PAS-100, pp.1105-1116, March, 1981.

[2] M. Baran, F. Wu, "Optimal capacitor placement on radial distribution system", *IEEE Trans. on Power Delivery,* Vol. 4, No. 1, pp.725-734, January, 1989.

[3] H. Chiang, "Optimal capacitor placements in distribution system: Part I, Part II", *IEEE Trans. on Power Delivery,* Vol. 5, No. 2, pp.634-649, January, 1990.

[4] J.J.Grainger and S.H.Lee, "Capacity release by shunt capacitor placement on distribution feeders: A new voltage dependent model", *IEEE Trans. on Power Apparatus and Systems,* Vol.100, pp.1236-1244, May 1982.

[5] J.J.Grainger, S.Civanlar and S.H.Lee, "Optimal design and control scheme for capacitive compensation of distribution feeders: A new voltage dependent model", *IEEE Trans. on Power Apparatus and Systems,* Vol.102, pp.3271-3278, October 1983.

[6] H.D.Chiang, J.C.Wang, O.Cockings and H.D.Shin, "Optimal capacitor placements in distribution systems", Part-I and Part-II, *IEEE Trans. on Power Delivery*, Vol.5, pp. 634-649, January 1990.

[7] S.Sundharrajan and A.Pahwa, " Optimal selection of capacitors for radial distribution systems using a genetic algorithm", IEEE Trans. on Power Systems. Vol.9, pp.1499-1507, August 1994.

[8] S. Sivanagaraju, M.S.Giridhar, E.Jagadeesh Babu, and Y.Srikanth, "A novel load flow technique for radial distribution system", National Power System Conference, NPSC-2, 2004, IIT, Chennai, India, pp. 140-144.

[9] D. Das, et.al, "Novel method for solving redial distribution Networks", IEE Proc.-C, Vol.141, No. 4, pp. 291-298, July 1994.

[10] M.E. Baran and F.F. Wu, "Optimal sizing of capacitor placed on a radial distribution system", IEEE Trans. on Power Delivery, 1989, PWRD-2, pp. 735-743.

[11] H-D. Chiang, J-C. Wang, J. Tong and G. Darling, "Optimal Capacitor placement in Large-Scale Unbalanced Distribution System: System Modeling and A new Formulation," *IEEE Trans. on Power systems*, vol.10, No. 1, Feb 1995, pp.355-362.

[12] H. Kim, S-K. You, "*Voltage Profile Improvement by capacitor Placement and control in unbalanced distribution Systems using GA"*, IEEE power Engineering SocietySummer Meeting, 1999, Vol. 2, pp. 18-22.

[13] Goldberg, D.E., 1989, "*Genetic algorithm in search, optimization, and machine learning"*, Addison-Wesley Publishing Company, Inc., Reading, MA.

[14] Radial Distribution test feeders, http:/www.ewh.ieee.org/soc/pes/dsacom/testfeeders.html.

APPENDIX: The data for 25-bus unbalanced system:

Base kV: 4.16; Base MVA: 30

Table 9: Load data and line conductivity of unbalanced system

branch	Sending End	Receiving End	Conductor type	Length, ft	Receiving end load in kW		
					A phase	B phase	C phase
1	1	2	1	1000	0	0	0
2	2	3	1	500	35 + j25	40 + j30	45 + j32
3	2	6	2	500	40 + j30	45 + j32	35 + j25
4	3	4	1	500	50 + j40	60 + j45	50 + j35
5	3	18	2	500	40 + j30	40 + j30	40 + j30
6	4	5	2	500	40 + j30	40 + j30	40 + j30
7	4	23	2	400	60 + j45	50 + j40	50 + j35
8	6	7	2	500	0	0	0
9	6	8	2	1000	40 + j30	40 + j30	40 + j30
10	7	9	2	500	60 + j45	50 + j40	50 + j35
11	7	14	2	500	50 + j35	50 + j40	60 + j45
12	7	16	2	500	40 + j30	40 + j30	40 + j30
13	9	10	2	500	35 + j25	40 + j30	45 + j32
14	10	11	2	300	45 + j32	35 + j25	40 + j30
15	11	12	3	200	50 + j35	60 + j45	50 + j40
16	11	13	3	200	35 + j25	45 + j32	40 + j30
17	14	15	2	300	133.3 + j100	133.3 + j100	133.3 + j100
18	14	17	3	300	40 + j30	35 + j25	45 + j32
19	18	20	2	500	35 + j25	40 + j30	45 + j32
20	18	21	3`	400	40 + j30	35 + j25	45 + j32
21	20	19	3	400	60 + j45	50 + j35	50 + j40
22	21	22	3	400	50 + j35	60 + j45	50 + j40
23	23	24	2	400	35 + j25	45 + j32	40 + j30
24	24	25	3	400	60 + j45	50 + j30	50 + j35

Table 10: Impedance for different types of conductors

Type	Impedance in ohms/miles		
1	0.3686+0.6852i	0.0169+0.1515i	0.0155+0.1098i
	0.0169+0.1515i	0.3757+0.6715i	0.0188+0.2072i
	0.0155+0.1098i	0.0188+0.2072i	0.3723+0.6782i
2	0.9775+0.8717i	0.0167+0.1697i	0.0152+0.1264i
	0.0167+0.1697i	0.9844+0.8654i	0.0186+0.2275i
	0.0152+0.1264i	0.0186+0.2275i	0.9810+0.8648i
3	1.9280+1.4194i	0.0161+0.1183i	0.0161+0.1183i
	0.0161+0.1183i	1.9308+1.4215i	0.0161+0.1183i
	0.0161+0.1183i	0.0161+0.1183i	1.9337+1.4236i

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