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Optimum MV Feeder Routing and Substation siting and rating in Distribution Network

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***Abstract*— A distribution network planning consists of several complexity aspects due to the multiple decision variables. The main objective of the distribution system planning is to find the optimum number of substation, location, size and feeders routing.This paper proposes an evolutionary algorithm to determine the optimum distribution substation placement and sizing by using the particle swarm optimization algorithm and optimum feeder routing using modified minimum spaning tree algorithm. The proposed algorithm evaluates on the distribution network case with 164 load blocks. The results showed the effectiveness of the proposed algorithm to find the acceptable location and sizing of distribution substations with a proper routing of the feeder.**

***Keywords*— MV Feeder Routing, Distribution Substation placement, MST, PSO, OpenDSS.**

I. Introduction

The electrical energy produced at the generating station is transferred to the consumers through transmission and distribution networks. Power generated by power plant and sent to the high-voltage transmission lines (765,500,400,220 or 132 KV). These transmission lines carry the power to medium voltage (e.g. 33 or 11 KV). The distribution networks supply power to consumers. The major objective of utility is to supply the power demand with good quality of service, through a proper planning for the distribution networks. Distribution planners are always be faced with several difficulties in designing due to the numbers of decision variables which are influenced to distribution networks. Feeder routing for MV and LV network and MV/LV substation placement and sizing are always one of the important challenges in distribution network planning. Meanwhile, it is crucial to reconfigure the existing distribution network due to the high load density and incremental cost of power distribution equipment and significant power losses in LV network which is 50% of the total losses of power system.

Serveral works has been carried out in field of distribution system planning. The first step in distribution system planning is to determine the location of distribution transformers. In [1] the authors codified the coordinates of the candidate substations and applied an evolutionary computation by using genetic algorithms to find the optimal location. Since the placement of the transformers will somehow define the route of feeders, some researchers have tried to proceed both optimizations simultaneously. Some papers have applied the concept of minimum spanning tree to get an approximation of the initial work, as an indication of the optimal network layout electrical or geographical constraints are not take into consideration [2], [3]. Minimum Spanning Tree (MST) is a weighted connected graph whose total edge cost is minimized. Heuristic methods integrated in [4] to obtain the optimal feeder route (based on shortest path algorithm) and the optimal placement of substation on criteria of minimum losses. In reference [5] an attempt to minimize the cost of feeders by selecting the optimal conductor size and kind of feeders segment. The paper implemented a new computer algorithm and heuristic optimization technique.

In this paper [6] A comprehensive algorithm is developed to obtain optimal location, number and service area of substation using genetic algorithm and a generalized algorithm is modified for optimal feeder route on minimum total cost criteria. Power flow problem is one of the important issues of distribution network planning due to the large of the network. Therefore, this work has tried to use OpenDSS engine as power flow calculator in distribution network planning in order to determine the voltages, currents, real and reactive power flows and losses of the network during optimization procedures.

This paper presents the application of an efficient Particle Swarm Optimization (PSO) algorithm for the optimal design distribution system, solving the optimal placement and sizing of substation, also MST algorithm used for optimal feeder routing in MV networks. The total cost minimization is the objective function of proposed optimization algorithm. The objective function consists of the fixed and variable costs of substations and annualized cost of the total network losses.

II. PARTICLE SWARM OPTIMIZATION

The Particle Swarm Optimization has shown to be an efficient, robust and simple optimization and is one of the evolutionary computation techniques which has introduced to solve the optimization issues and since then, their efficiency to be applied in optimization problems has been explained in reference [7]. In this technique, the movement towards the optimal position is gained from the best information of each particle which is included in the initial population (Best Personal Position) and the optimal position that is found by the neighbor's positions (Best Global Position).

Several papers used PSO algorithm efficiently in complex non-linear engineering problem, especially in planning of distribution system, control applications, multi-objective optimization problems with multiple constraints, design application and etc. [8]. Since the capacitor installation in distribution system has the non-linear and discrete equation, therefore, this work used PSO algorithm as one of the efficient techniques to resolve the substation location and sizing problem. The steps of this algorithm have been described in [9], [10]. Fig. 1 shows the particle movements based on PSO algorithm.

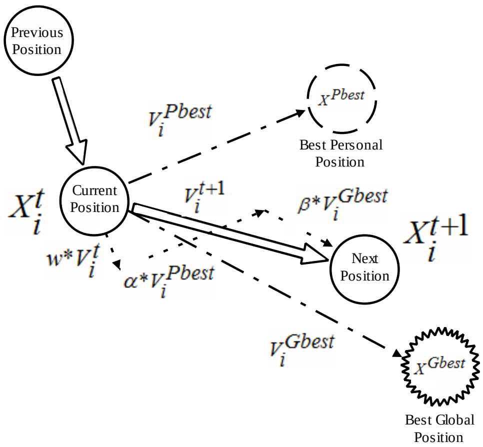

Fig. 1. Principle of the PSO particle movement

II. OPENDSS

The power flow solutions are needed in planning of distribution network to evaluate the network. To get this purpose, the Open Distribution System Simulator (OpenDSS) is a comprehensive electrical system simulation tool for electric utility distribution systems. The OpenDSS is an open source developed by the Electric Power Research Institute [11]. The OpenDSS engine comprise the COM interface which can be used in other simulation programs such as MATLAB, VBA, C# and etc. The OpenDSS engine can assist the researchers to get a set of important knowledge about the simulated power system. In this paper, OpenDSS engine is used as a power flow calculator so as to determine the power system parameters such voltages, currents, real and reactive power flows and losses of the network during optimization procedures.

III. METHODOLOGY

Based on the new prospect of distribution networks planning which is aim to bring the small scale of substation beside the load centers so as to minimize the distribution network losses, this paper has tried to introduce the initial adjustments of the algorithm based on this purpose. Therefore, the minimum numbers of distribution substations are estimated based on the maximum branching rate and number of load block (load centers) for each branches. These are the constraints of the minimum substation selection. In this paper, three branching rate and maximum 10 load blocks has been selected for each substation. Which means; minimum S_n substations are need for a network with n branches and m numbers of load blocks for each branch, which S_n can be written as follows:

$$S_n = \frac{\mathrm{N}}{\mathrm{m} \times \mathrm{n}} \tag{1}$$

where, N is the numbers of the load blocks. Therefore, the estimation of minimum required substation can be consider as a first step of optimization algorithm that shown in Fig. 2.

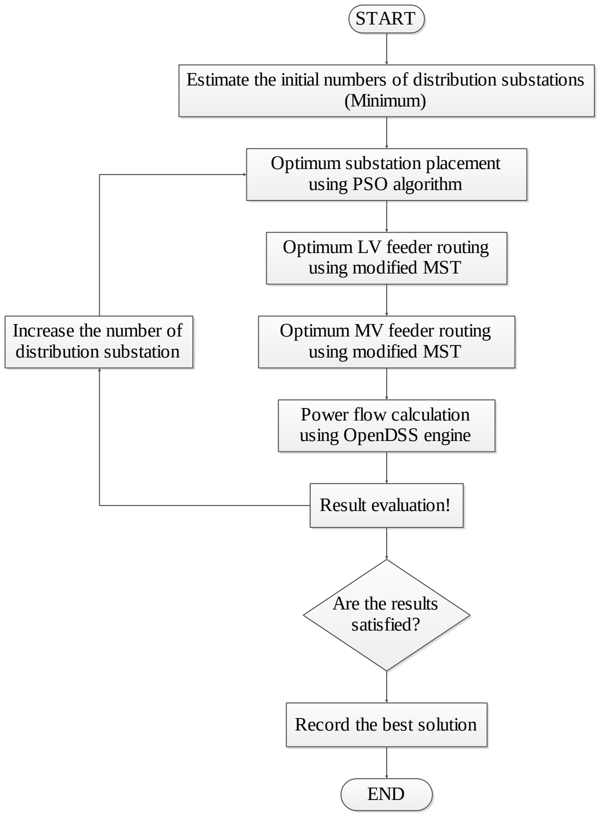

Fig. 2. The proposed flow chart of optimum substation placement and sizing and feeder routing for distribution networks

The optimum substation location will implement after estimating the number of minimum required substations. For this purpose, the PSO algorithm which has been used in this paper will be demonstrated in following subsection in details. The optimum substation placement algorithm will generate the coordinates of each substation, which has been connected to the particular load blocks with adequate substation require sizing based on the number of supplied load blocks as shown in Fig. 3. The next optimization step is optimum LV and MV feeder routing using modified MST algorithm. There are a few constraints and details that will be demonstrated in following related sections. After indicating the routes of feeders the next algorithm step is the power flow solution utilizing OpenDSS engine. Therefore, the algorithm generates OpenDSS codes for designing the network to run the power flow and capturing the required information for network evaluation. The obtained results will be evaluated in the next step. The algorithm will record the captured solution, if the results have satisfied in terms of substation placement standards, desire losses and in range voltage profile. If not, the algorithm will repeat once more time by increasing the number of distribution substation. This loop will continue to get the best possible solution to the substation location, routing and sizing whenever find the optimum network designing.

A. *Optimum Substation Placement Using PSO:*

An adequate placement of distribution substation can be affected the other parts of network such as primary/secondary substations and feeders routing. In other word, if the placement of substation is not done with appropriate precision, the economic and technical difficulties will be encountered to MV feeders and other parts of the distribution networks. Therefore, define the suitable location of distribution substations is decisive. In this paper a comprehensive algorithm for substation placement and defining the number of distribution substation has been applied. The Particle Swarm Optimization (PSO) method is applied to optimize the best reasonable location of distribution substations. The only substation placement problem has considered in this section. Fig. 4 illustrates the PSO algorithm flowchart in terms of optimum distribution substation placement. Fig. 3 shows the numbers of selected distribution substations after optimization. Nine numbers of distribution substations have been selected among the 81 candidate substations. Meanwhile, this figure indicates the numbers of load blocks which assigned to their particular substation.

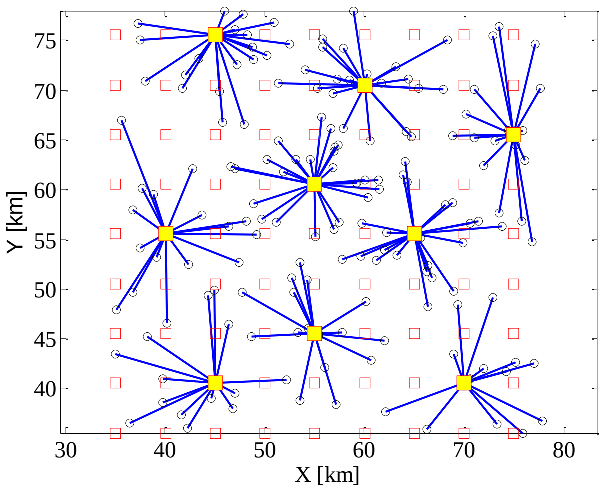

Fig. 3. Selected MV substations after optimization

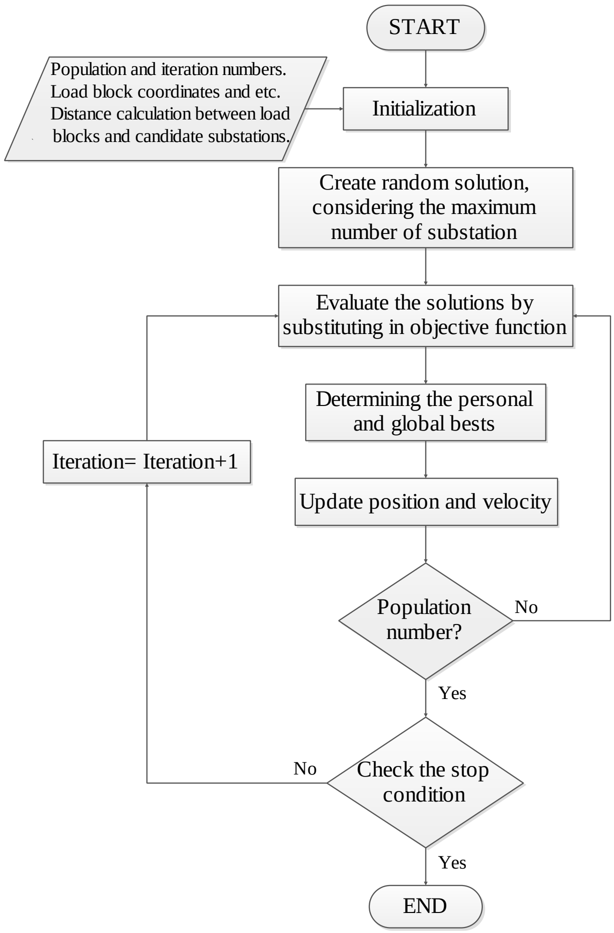

Fig. 4. The optimum substation placement flowchart using PSO

B. *Optimum Feeder Routing Using MST*

As described in the introduction the prim's algorithm has been used in this paper to locate the paths of optimum feeders for distribution networks. But the only prim's algorithm cannot perform our desire optimal routing. The modified prim algorithm needs to be implemented because of some technical requirement such as, open loop feeders and not allowed branches pass through each other.

Fig. 5 shows the proposed modified algorithm using the prim's algorithm in MST so as to locate the optimum feeder routing in the distribution network.

Fig. 6 shows the obtained results after MV feeder routing using modified MST algorithm. It describes the 11KV feeders path with purple line color and 33KV conductors by black line color. The MV feeders are connected adequately without passing each other as shown in Fig. 6. It demonstrated the modified algorithm has successfully resolve the feeder routing problem by considering the constraints of the problem.

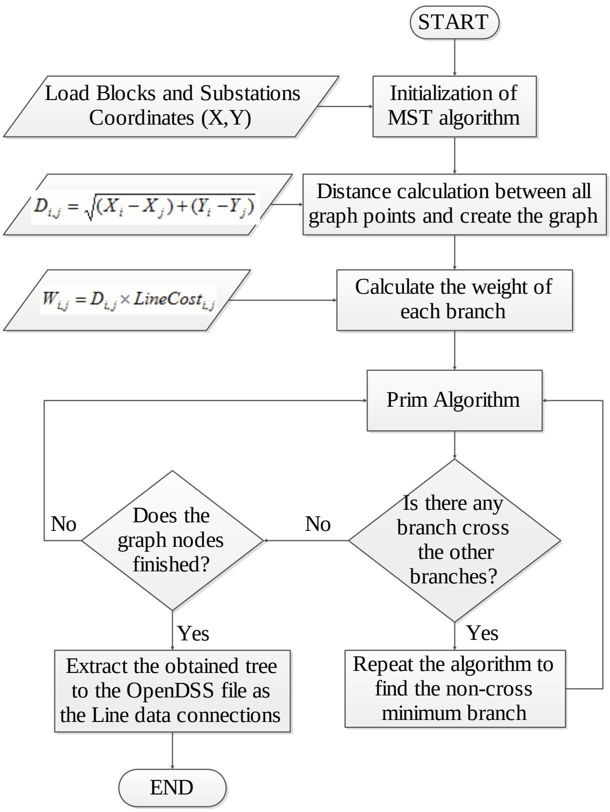

Fig. 5. The flowchart of modified MST algorithm in order to solve the optimum feeder routing in distribution network

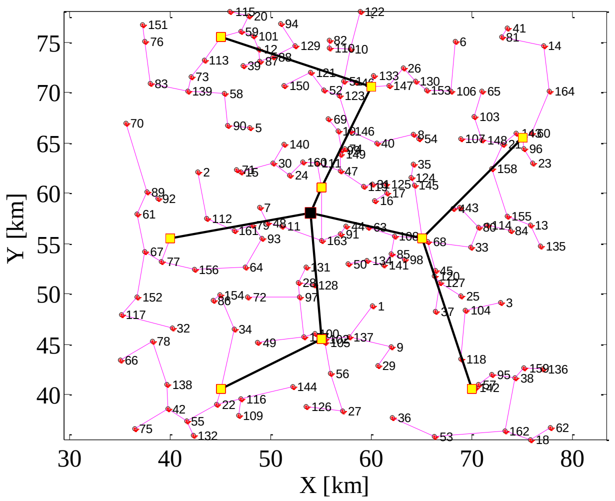

Fig. 6. Obtained network after optimum feeder routing for MV in 164 load blocks distribution network

IV. PROBLEM FORMULATION

In distribution system planning, the distribution of loads density and allocation of feasible candidate substations are the important information in the study year. Based on optimization viewpoint, the following candidates must be satisfied so as to optimal distribution substation allocation and feeder routing, which are: a) supplying all the load blocks of the networks, b) accepted voltage drop at the receiving bus, c) Maximum load capacity of all substation, and d) Minimization cost of new substation construction. As, the objective functions of substation placement and sizing can be formulated as follows:

$$CL = C_L.\sum_{i=1}^{nlb} P_{Loss}^{i}.8760 \qquad (2)$$

where CL is the total losses cost for a study year, C_L *[\$/kWh]* is the cost of real power losses which is provided in [12] (C_L*=168 \$/kW/year]*), P_{Loss}^{i} *[kW]* is the real power losses at load block *i* and *nlb* is the number of load blocks.

The investment cost of distribution substations have to be annuitized to able for accumulate with other network costs [13]. Thus, to annuitize the investment cost of distribution network, the considerations have to be implemented.

$$VC_S = \sum_{j=1}^{ns} C_{\text{var}}(j).\left(\sum_{i=1}^{nlb} d_{lb}(j,i)\right) \qquad (3)$$

$$FC_S = \sum_{j=1}^{ns} C_{fix}(j) \qquad (4)$$

$$C_S = VC_S + FC_S \qquad (5)$$

where VC_s is the total substation variable cost, $C_{var}(j)$ is the cost of substation *j* per MVA, $d_{lb}(j,i)$ is the load block demand *i* which connected to substation *j*. FC_s represents the total fixed cost of substations and $C_{fix}(j)$ is the fixed cost of substation *j*. The variable cost of substation included the cost of operation and maintenance, and the fixed cost consists of installation and other related fix cost of substation such as land and equipment prices and etc.

$$IC = \sum_{j=1}^{ns} C_S^j * C_l \qquad (6)$$

$$CC = IC * \frac{d(1+d)^T}{(1+d)^T - 1} \qquad (7)$$

where *IC* stand for Investment Cost [\$], C_S is the total substation installation and operation costs [\$], C_l is the total cost of the lines [\$], *CC* is the annuitized capital cost [*\$/year*], *d* is the discount rate and *T* is the number of operation years.

Thus, the main objective function that needs to be minimized can be written as follows:

$$Min\ Z = CL + CC + PF \qquad (8)$$

where *Z* is the total cost function and *PF* is the penalty factor which is calculated by the optimization constraints. The first constraint of distribution network planning is acceptable voltage drop at receiving bus (V_i) which voltage should be within the specified range.

$$0.95 \le V_i \le 1.05 \quad (9)$$

The next constraint of distribution network planning is the longest distance of each load block from the distribution substation which introduced by substation radius based on maximum voltage drops in distance which has been obtained from reference [14]. To consider this constraint the following condition must be considered:

$$D_j^i \le R_{\max}^j \quad (10)$$

where D_j^i is stand for distance between substation j to load block i and $R_{\max}^j$ is the maximum acceptable radius of substation j that can supply the load blocks (11/0.4 transformer). Based on the standard, in 11kV feeders in generally up to 3km and for rural networks is up to 20km.

V. RESULTS AND DISCUSSION

A generated model of distribution networks with details in APPENDIX has been used so as shown the efficiency of the proposed algorithms of substation placement and sizing in distribution network and feeder routing in MV. The candidate MV substations are generated randomly based on load density, which after optimum placement, nine numbers of substation have selected as shown in Fig. 3 3. The optimization progressive is illustrated in **Error! Reference source not found.** for selecting the number of required substations with considering the acceptable voltage drop and minimum losses of networks. Table 2 indicates the selected the distribution substation placement and transformers sizes after optimization. The voltage drop based on distance for all distribution substations and 164 load blocks are shown in Fig. 7. It indicates all the buses allocated within the standard range of voltage drop which stated in previous sections. A HV/MV substation is placed at the fix position that was shown in Fig. 6 and the selected substation size is shown in

Substation Name 33/11 kV	Xs	Ys	Distribution transformer size (33/11) [kVA]	Numbers of load blocks (11/0.4 transformer)	Supplied load block [kVA]
S1	40.02	55.53	7500	16	4123
S2	45.02	40.53	7500	14	3607
S3	45.02	75.53	10000	19	4896
S4	55.02	45.53	7500	17	4380
S5	55.02	60.53	12000	24	6184
S6	65.02	55.53	10500	21	5411
S7	60.02	70.53	10000	22	5669
S8	70.02	40.53	7500	14	3607
S9	75.02	65.53	7500	17	4380

Table 3. To select the size of substation sizing has been tried to follow the standard of distribution transformer by IEEE/ANSI C57.12.00 [15].

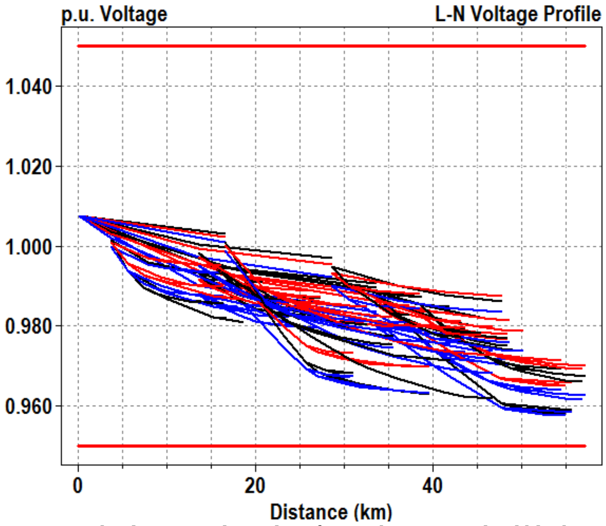

Fig. 7. The distance voltage drop from substations to load blocks

TABLE 1: The PSO progress in different number of substations

Number of transformer (33/11 kV)	Minimum Voltage [p.u]	Total Losses [kW]	Best Cost [$/year]
5	0.87064	1795.9265	1595427
6	0.88847	1781.0730	1807879
7	090635	1138.7664	2022740
8	0.92004	1303.9305	2236497
9	0.95748	881.0599	2455879

Table 2: Selected size of MV transformers after optimization

Substation Name 33/11 kV	Xs	Ys	Distribution transformer size (33/11) [kVA]	Numbers of load blocks (11/0.4 transformer)	Supplied load block [kVA]
S1	40.02	55.53	7500	16	4123
S2	45.02	40.53	7500	14	3607
S3	45.02	75.53	10000	19	4896
S4	55.02	45.53	7500	17	4380
S5	55.02	60.53	12000	24	6184
S6	65.02	55.53	10500	21	5411
S7	60.02	70.53	10000	22	5669
S8	70.02	40.53	7500	14	3607
S9	75.02	65.53	7500	17	4380

Table 3: Selected size of MV transformer after optimization

Number of transformer (HV/MV) (132/33 kV)	HMS1
X	54.0
Y	58.0
Substation capacity [kVA]	100000
Number of supplied distribution substation (33/11 kV)	9
Total apparent power demand [kVA]	42257

VI. CONCLUSION

In conclusion, this paper has proposed the algorithm based on integration of PSO and MST to solve the distribution network planning in terms of substation placement, sizing and feeder routing. The proposed algorithm evaluates on the distribution network case with164 load blocks. The results show the proposed algorithm has successfully find the suitable placement and sizing of distributed generation with adequate feeder routing.

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APPENDIX

The initial assumptions of the utilized distribution network model are as, 81 MV candidate substations and 164 load blocks. Tables A1 and A2 show the X and Y coordinates of the test network and Table A3 illustrates the load block demand which is considered for all the load blocks as same value.

Table A1: X coordinates of each load block

No	X_L	No	X_L	No	X_L	No	X_L	No	X_L
1	60.11	**34**	42.77	**67**	72.88	**100**	68.18	**133**	47.94
2	68.32	**35**	48.86	**68**	64.15	**101**	61.99	**134**	57.88
3	51.12	**36**	48.81	**69**	75.79	**102**	77.13	**135**	46.98
4	60.38	**37**	61.55	**70**	75.87	**103**	56.68	**136**	47.84
5	73.13	**38**	44.64	**71**	76.1	**104**	51.87	**137**	68.92
6	63.16	**39**	57.16	**72**	52.73	**105**	60.65	**138**	50.26
7	60.09	**40**	40.18	**73**	69.88	**106**	46.36	**139**	64.14
8	62.09	**41**	66.41	**74**	74.29	**107**	47.21	**140**	60.53
9	73.54	**42**	39.76	**75**	68.81	**108**	57.48	**141**	66.35
10	58.46	**43**	56.88	**76**	49.68	**109**	48.7	**142**	57.74
11	57.29	**44**	55.29	**77**	66.31	**110**	64.75	**143**	41.62
12	55.99	**45**	70.61	**78**	45.41	**111**	47.02	**144**	75.94
13	36.75	**46**	77.84	**79**	59.72	**112**	47.45	**145**	71
14	35.02	**47**	37.51	**80**	65.66	**113**	55.73	**146**	35.58
15	46.64	**48**	47.69	**81**	42.06	**114**	57.35	**147**	36.43
16	37.47	**49**	39.12	**82**	38.19	**115**	48.12	**148**	70.61
17	72.93	**50**	55.82	**83**	38.01	**116**	73.81	**149**	61.98
18	44.26	**51**	48.92	**84**	50.25	**117**	37.67	**150**	45.77
19	56.95	**52**	38.77	**85**	49.16	**118**	50.94	**151**	71.98
20	75.21	**53**	52.9	**86**	63.31	**119**	57.06	**152**	54.36
21	48.25	**54**	55.38	**87**	70.24	**120**	69.38	**153**	55.39
22	67.93	**55**	68.87	**88**	62.26	**121**	46.8	**154**	55.84
23	54.61	**56**	43.67	**89**	43.4	**122**	71.5	**155**	45.99
24	47.03	**57**	35.14	**90**	68.92	**123**	59.22	**156**	66.3
25	54	**58**	58.89	**91**	56.83	**124**	63.92	**157**	61.44
26	53.57	**59**	66.82	**92**	54.27	**125**	52.47	**158**	64.39
27	53.5	**60**	42.29	**93**	60.25	**126**	59.6	**159**	76.87
28	77.03	**61**	57.75	**94**	39.71	**127**	41.73	**160**	51.37
29	61.23	**62**	70.31	**95**	74.44	**128**	52.18	**161**	64.27
30	57.87	**63**	61.75	**96**	71	**129**	56.94	**162**	51.37
31	37.26	**64**	36.7	**97**	65.48	**130**	44.91	**163**	73.48
32	42.37	**65**	53.3	**98**	72	**131**	75.18	**164**	53.15
33	46.34	**66**	73.29	**99**	55.06	**132**	77.7		

Table A2: Y coordinates of each load block

No	Y_L	No	Y_L	No	Y_L	No	Y_L	No	Y_L
1	48.76	**34**	62.05	**67**	49.14	**100**	58.52	**133**	66.52
2	75.09	**35**	58.59	**68**	65.88	**101**	44.77	**134**	74.25
3	56.7	**36**	74.29	**69**	56.86	**102**	74.67	**135**	62.08
4	59.23	**37**	60.02	**70**	35.53	**103**	66.15	**136**	77.6
5	64.88	**38**	39.02	**71**	62.92	**104**	61.82	**137**	49.76
6	72.37	**39**	38.37	**72**	51.13	**105**	42.81	**138**	63.02
7	60.91	**40**	46.55	**73**	54.63	**106**	46.5	**139**	62.85
8	37.66	**41**	48.24	**74**	41.66	**107**	72.61	**140**	64.9
9	76.39	**42**	38.63	**75**	58.63	**108**	56.68	**141**	52.34
10	70.99	**43**	62.16	**76**	57	**109**	45.19	**142**	53
11	71.07	**44**	70.18	**77**	35.86	**110**	65.36	**143**	37.39
12	42.08	**45**	40.97	**78**	69.92	**111**	76.04	**144**	65.92
13	57.94	**46**	36.68	**79**	56.61	**112**	52.65	**145**	70.07
14	43.42	**47**	54.16	**80**	55.17	**113**	67.32	**146**	66.97
15	62.29	**48**	49.63	**81**	71.56	**114**	64.44	**147**	36.55
16	75.03	**49**	53.24	**82**	45.23	**115**	56.79	**148**	56.61
17	75.47	**50**	75.18	**83**	70.88	**116**	56.28	**149**	53.94
18	49.4	**51**	73.04	**84**	73.54	**117**	60.11	**150**	66.72

19	55.98	**52**	59.5	**85**	55.45	**118**	76.8	**151**	42.02
20	64.45	**53**	49.71	**86**	53.39	**119**	64.3	**152**	46.03
21	75.6	**54**	45.54	**87**	67.63	**120**	48.39	**153**	45.22
22	70.07	**55**	65.37	**88**	55.72	**121**	37.95	**154**	74.37
23	63.02	**56**	57.47	**89**	73.16	**122**	56.77	**155**	77.98
24	39.56	**57**	47.92	**90**	43.5	**123**	60.64	**156**	51.72
25	72.02	**58**	78	**91**	69.68	**124**	61.51	**157**	60.92
26	38.79	**59**	51.11	**92**	50.88	**125**	74.6	**158**	71.16
27	52.69	**60**	35.98	**93**	71.65	**126**	53.29	**159**	54.73
28	42.49	**61**	45.67	**94**	40.96	**127**	70.16	**160**	64.85
29	52.87	**62**	40.7	**95**	65.95	**128**	40.83	**161**	60.73
30	66.16	**63**	70.7	**96**	65.25	**129**	63.83	**162**	70.68
31	76.74	**64**	49.69	**97**	70.18	**130**	49.86	**163**	57.69
32	52.43	**65**	45.68	**98**	62.43	**131**	42.66	**164**	63.05
33	56.3	**66**	36.43	**99**	55.29	**132**	70.14		

Table A3: Load Block Demand Data

Load Blocks Model	**Active power**	**Power factor**
Commercial + Residential	250 *kW*	0.8