Improvement of MV/LV Power System Planning Using Integrated Optimization Technique

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Abstract: *− A novel optimization technique is proposed for optimal planning of medium voltage (MV) and low voltage (LV) areas of distribution system in this paper. The target is to obtain the optimum ratings and locations of distribution transformers and substations along with the route and type of LV conductors and MV feeders. Both uniform and non-uniform load density areas are discussed. Linearized Biogeography Based Optimization (LBBO) technique is used to solve the previously stated problem optimally. The results obtained are compared with the results of Genetic Algorithm (GA), Discrete Particle Swarm Optimization (DPSO) and Biogeography Based Optimization (BBO) techniques.*

Key words: *Linearized Biogeography based optimization techniques, Integrated optimization technique, Power system planning*

1. Introduction

Distribution systems consist of medium voltage (MV) and low voltage (LV) networks. the main aim of distribution planning is to obtain the optimum locations and rating of the transformers and substations, as well as, the MV and LV conductors so as the total cost is minimized. the total cost includes the loss cost, maximizing the system reliability and improving the voltage profile. Distribution planning was discussed before in several papers. Although those papers provides a separate optimal planning for MV and LV networks. As a result the planning of this network was inaccurate. Reference [1] discussed the optimization of only the MV networks serving urban areas. Evolutionary algorithm is an efficient algorithm for such optimization demands. In this paper, investment and loss costs are evaluated along with the constraints of the voltage drop and the capacity of the conductors. In [2], the Ant Colony System (ACS) is only applied to the primary MV distribution planning problem without the need of the using the traditional load flow analysis. In [3], Tabu search is used to solve a fuzzy model for the planning problem of distribution system. This algorithm is applied to three objective functions which includes the economic cost, the reliability level and the optimum reserve feeders placement and size that maintains minimum cost. In [4], a two multi-objective techniques are used to solve the problem of power distribution system design, which are, Non-dominated Sorting Genetic Algorithm (NSGA) and Strength Pareto Evolutionary Algorithm (SPEA). In [5], the optimal planning of radial distribution networks is solved using simulated annealing. In [6], an optimal design of distribution system using Genetic Algorithm is proposed. The optimal size and locations of both high voltage (HV) and medium voltage (MV) substations along with the MV feeders are obtained.

Some other papers focuses on both MV and LV planning. As in [7] and [8], these two part paper that discusses the optimal distribution system planning problem. The model proposed provides an optimal horizon planning that covers all the necessary parameters and constraints. In [9], discrete particle swarm optimization technique is applied on the problem of the optimal planning of a distribution system (ODPS). This paper discussed MV and LV networks and both uniform and non-uniform load density areas. In [10], a new technique, called BBO, was applied on the distribution system planning problem. However, in this paper only the locations and ratings of the transformers and substations are obtained in case of non-uniform without calculating the overall cost.

In this paper, an optimal planning procedure for distribution system, where both MV and LV networks are covered. The optimal locations and sizes of the distribution transformers, substations, MV feeders and LV conductors are obtained to minimize the total cost. The cost function (objective function) consists of three parts which are the capital cost, the loss cost and the reliability cost. The constraints are to maintain the voltage drop and the value of the feeder current within acceptable ranges. As a result, an effective optimization technique must be applied to solve the planning problem. In this paper, LBBO is applied to the planning problem in order to obtain the optimal variables that minimizes the cost function.

2. Problem formulation

The main objective is to minimize the cost of the transformers, substations and accordingly find their optimal ratings and locations, along with the LV conductors and MV feeders. Also the bus voltage and feeder current must be maintained within acceptable ranges. The cost function is illustrated as follows:

$$OF=C_{CAPITAL}+\sum_{t=1}^{T}\frac{C_{O\&M}+C_{INTERRUPTION}+C_{LOSS}+SP}{(1+r)^{t}} \quad (1)$$

Where, $C_{CAPITAL}$ is the total capital cost, $C_{O\&M}$ is the total operation and maintenance cost, $C_{INTERRUPTION}$ is the interruption cost, C_{LOSS} is the loss cost, r is the discount rate, T is the number of years in the study time-frame and SP is the penalty factor [10].

The interruption cost is the summation of the cost of interruption's duration and the number of interruptions. The duration based interruption cost is calculated by multiplying the cost of average interruption duration in a year and the average interruption duration. The average interruption duration is calculated by multiplying the SAIDI (as a reliability index) by the number of customers. Also, the number based interruption cost is calculated by multiplying the SAIFI (the cost of average interruption number per customers), by the number of customers. The overall cost of interruption is calculated as follows:

$$C_{INTERRUPTION} = W_{SAIDI} \times SAIDI + W_{SAIFI} \times SAIFI \quad (2)$$

$$W_{SAIDI} = NC \times C_{ID} \quad (3)$$

$$W_{SAIFI} = NC \times C_{IN} \quad (4)$$

Where, W_{SAIDI} and W_{SAIFI} are the reliability weight factors, C_{ID} and C_{IN} are the cost of average interruption number per customer ($/interruption) and the cost of average interruption duration per customers ($/minute) respectively. NC is the number of customers served.

The loss cost consists of two parts, the energy loss which is proportional to the cost per MWh and the peak power cost which is proportional to the cost saving per MW reduction in the peak power. The overall loss cost is calculated as follows:

$$C_{LOSS} = P_{LOSS} \times (k_{PL} + k_{L} \times 8760 \times l_{sf}) \quad (5)$$

Where P_{Loss} is the loss power, K_{pL} is the saving per MW reduction in peak power, K_L is the cost per MWh and I_{sf} is the loss load factor.

The constraints in this objective function include the bus voltages and the feeder currents. The bus voltage (V_{bus}) should be maintained within acceptable range.

$$V_{min} \le V_{bus} \le V_{max} \quad (6)$$

The feeder current (I_{fi}) should be less than the feeder rated current (I_{fi}^{rated}) in the i^{th} feeder.

$$I_{fi} \le I_{fi}^{rated} \quad (7)$$

The static penalty method is used to include the constraints in the procedure. In equation (1), the penalty factor is addressed by SP. the value of SP is equal to zero when all the constraints are satisfied. Else, SP will be replaced by a large number if any of the constraints is not satisfied to exclude the corresponding solution.

3. Methodology

Both MV and LV networks are covered in the planning procedure. The planning area is divided into regions with uniform load density. Each region includes a certain number of LV zones. Each LV zone is supplied by a MV/LV transformer. In the first step, the optimizing variables are the dimensions of the LV zones, location and rating of the transformers, as well as, the route and type of the LV conductors. The second step, a MV zone is formed in order to supply the MV/LV transformers. The optimizing variables in this case are the location and rating of the substation and the type of the MV feeders.

- Step (1): LV network planning

  Assume that each customer is represented by a rectangular shape [10] as illustrated in figure (1), which is called load block. Each load block has a specified power demand. The dimension of the load block and its power demand depends on the region's average load density. As shown in Appendix I, figure (1), a distribution transformer [T] is used to supply a number of load blocks. Those load blocks represents the LV zones. The white blocks represents the customers and the grey parts represents the streets. The dimension of each load block are expressed by LLB and LWB, respectively. The width of the streets is denoted by ws.

  In this step, the optimum values of the LV zone dimensions, as well as, the distribution ratings and locations and the types and routes of the LV conductors shall be obtained in order to minimize the total cost per load block. The length and accordingly the cost of the MV feeder are obtained in this step as well.

- Step (2): MV network planning
  In this step, another rectangular area called MV zone, is assigned for the MV network planning procedure. The MV zone consists of a number of LV zones. As shown in Appendix I figure (2), TLB and TWB are the dimension of LV zone [10]. As stated before, transformers are denoted by [T]. Also substations are represented by [SS]. The dimensions of LV are obtained from the previous step.
  TLB=LLB×HNLB
  (8)
  TWB=(LWB+0.5×WS)×VNLB
  (9)

  Where, HNLB and VNLB are the optimal number of load blocks supplied by each distribution transformer in the horizontal and vertical axes which have been optimized in the LV zone planning section, respectively.

  The optimization procedure variables obtained from the planning of MV network includes the dimensions of MV zone, the rating and locations of the substations, along with the type and route of MV feeder.
  The objective function includes the capital cost of distribution substation and MV feeders, cost of line loss and system reliability cost. Also the constraints regarding the bus voltage and feeder currents shall be considered in this step too.

An iterative, integrated based optimization techniques called Linearized Biogeography Based Optimization (LBBO) technique is proposed to solve the integrated planning problem of both LV and MV networks. LBBO is applied to the planning problem, then comparing the results with the results established previously from the Genetic Algorithm (GA), Discrete Particle Swarm Optimization (DPSO) and Biogeography Based Optimization (BBO) techniques.

4. Integrated Optimization technique

Linearized Biogeography Based Optimization (LBBO) technique was proposed in 2015. It was developed from the Biogeography Based Optimization (BBO), which was proposed in 2008 by Dan Simon. Biogeography is the environmental science that deals with the geographical distribution of species and ecosystem in geographic space. BBO is inspired from the island biogeography. The island biography is the study of the species composition and species richness on islands. The island biogeography is a study that explains the factors that affect species diversity on a specific community. The distribution of the species is affected by certain factors such as the area of the land, the temperature, food and topographic features etc. Species movement between areas enables the features sharing with each other. As a result, some improvement occurs due to the exchange of features. BBO algorithm operates on a population of individuals called a habitat. A habitat is a geographically isolated island. A habitat suitability index (HSI) is an index that indicates the fitness of a habitat. A certain area that has good features such land area, temperature, etc is considered to have a high HSI. Suitability index variables (SIVs) are the variables that characterize habitability. One of the important factors that affects the species distribution on the islands is the Migration. Migration, which is represented by two process, the emigration and the immigration between islands. the emigration in biogeography is that the species leave the island but the species don't become extinct. Likewise, in BBO Emigration is the sharing of any solution features from one individual to another so that the solution features remains unchanged in the emigrating individual. While the immigration is the process in which the solution features of an individual is replaced by a new solution feature from another individual.

Figure (3) Appendix I, shows the relationship between the immigration rate λ and the emigration rate μ and the species count [10]. The maximum immigration rate is I, in which it is achieved when there is no species in the habitat. The maximum number of species can be found in the habitat is S_{max} in which the immigration rate is equal to zero. Also, at S_{max}, the emigration rate is at its maximum (E) , while, when there is no species in the habitat the emigration rate is equal to zero.

The other factor affecting the species richness of an island is the mutation. Similar to Genetic Algorithm, the mutation operator is used to retain the diversity of individuals and break away local optimums. For each candidate solution S, there is a mutation probability associated as illustrated in [15]:

$$M(S)=\frac{M_{max}(1-P_s)}{P_{max}} \quad (10)$$

Where, M_{max} is a user defined parameter, P_s is the species count of habitat and P_{max} is the maximum species count.

Mutation is achieved based on the mutation probability of a habitat by replacing a certain SIV with a random generated one.

The BBO algorithm is illustrated as follows:

1. Select the BBO parameters, that includes the maximum migration rates E, I, S_{max} the maximum mutation rate m_{max}, the minimal emigration rate θ.
2. Select a random set of habitats.
3. For each habitat, select the immigration rate λ and the emigration rate μ.
4. By using the migration rates, compute the habitats fitness.
5. Update the species count for each habitat, then re-compute the new fitness.
6. From step (3), to perform the next iteration until the predefined number of generations is reached or an acceptable solution is found.

To overcome the BBO drawbacks, LBBO was developed by using the following:

1. Linearization of BBO migration: To make the migration more rotationally invariant.
2. By applying the gradient descent to BBO: To overcome the weakness of the local search ability.
3. A global grid search strategy: To cover the search space.
4. Constraints.
5. Latin hypercube strategy: To cover the whole search space nearby the current best individual.
6. Initialization and restart.

5. Test Cases and Results

Two cases are discussed in this paper. Planning of both MV and LV zones in uniform and non-uniform load density is proposed.

5.1 Planning of MV and LV zones in uniform load density:

Assume that the planning procedure is applied on a specific area that have the characteristics illustrated in Appendix II, Table (I) as presented in [9]:

Two types of configurations are inspected in this case, which are the H-type and branch-type configuration. The H-type configuration maintains lower capital cost than that of Branch type one, while the Branch-type has a lower reliability cost. Reliability weight factors are responsible for selecting the better configuration.

As presented in [9], The reliability parameters are selected according to [7, 8]. The peak load power is assumed to be 2.5 KW per block and the maximum permissible voltage is 1.03 pu due. The maximum allowed voltage drops are assumed to be 3% and 5% in the MV and LV sides, respectively. Also the loss factor is assumed to be 0.35.

By solving the planning procedure, the results of the LV planning is illustrated in Appendix II, Table (II). Those results are compared with results of GA, DPSO [9] and BBO [10].

From the results, it was observed that the optimal transformer rating is 200 KVA. The rectangular LV zone area is found to be 0.039 km^2. The LV conductor cost is (377 $) 32% of the total cost (1185 $). The types of the conductor are found to be 1 and 5, which are illustrated in Appendix II, Table (VIII). Accordingly the minimum bus voltage obtained is 0.9514pu.

Similarly, apply the same planning procedure on MV zone. In case of H-type configuration, the results are illustrated in Appendix II, Table (III).

By observing the results obtained, it was found that the optimal substation rating is 25 MVA and the MV zone area is 3.48 Km^2. The substation cost is K$ 31.38, which is 50% of the total cost. The minimum bus voltage is found to be 0.99 pu which satisfies the constraints.

Comparing the results obtained for H-type configuration using LLBO with the GA and DPSO as per Table 3, it is found that the LBBO gives a lower total cost per km^2 than the GA ($212000), DPSO ($127000) and BBO ($58000).

The other configuration, which is called the branch-type configuration, is also investigated to improve the reliability. In the branch-type, as shown in Appendix I, figure (4), each substation is connected directly to the nearest transformer [10].

The results of MV zone planning using branch-type configuration is illustrated in Appendix II, Table (IV).

One advantage of branch-type configuration over the H-type that the voltage drop is not a main concern as each substation is connected to the nearest transformer. As result, a narrower zone and a higher number of LV zones in each branch are obtained.

Comparing the results obtained for H-type configuration using LLBO with the GA and DPSO as per Table 4, it is found that the LBBO gives a lower total cost per km^2 than the GA ($83000) and DPSO ($5000). Also, LBBO gives a slightly higher total cost per km2 than BBO ($12000).

By comparing the value of the total cost of H-type configuration ($62,795) and the Branch-type configuration ($68,831), it was observed that the cost of H-type is lower than the branch-type using the previously assumed reliability factors.

Nevertheless, if those reliability factors are decreased as the cost value of the branch-type will decrease. As a result, the branch-type configuration is preferred.

5.2 <u>Planning of MV and LV zones in non-uniform load density:</u>

Similarly, by applying the same planning procedure proposed previously, in which the planning area is assumed to be composed of three different load densities. The average load block dimensions are assumed to be 10 m × 10 m, 20 m × 15 m, and 30 m × 20 m in regions 1–3, respectively. The average street width is 5 m, 10 m, and 15 m in regions 1–3. The average peak power in all load blocks is assumed to be 5 kW. After applying the uniform LV zone planning, the optimal length and width of LV zones in these regions are found as 150 m × 50 m, 315 m × 180 m, and 750 m × 95 m in regions 1–3, respectively. The corresponding transformer sizes are calculated as 300 kVA, 300 kVA, and 150 kVA, respectively, as presented in [9].

In this case, the non-uniform load density condition is applied to the LV zones in region 1. The transformer rating and location as well as the LV feeders' types and routes are re-optimized according to the non-uniform load density conditions. Figure (5), Appendix I shows the distribution of the loads of an LV zone in region 1 for non-uniform load density [10].

For MV zone planning, it is assumed that the length of region 1 is 900 m (LD1), the length of region 2 is 1260 m (LD2), and the length of region 3 is unlimited (LD3). The width of regions is also assumed to be unlimited as presented in [9].

As a result, the substation rating is found to be 15 MVA located at of 540m on the x-axis. The dimensions of MV zone are found to be 5160 m and 300 m as shown in Appendix I, Figure (6).

By comparing the results obtained from the proposed GA, DPSO [9] and LBBO, as illustrated in Appendix II, Table (V). LBBO gives more optimal solution with a cost benefit of ($3589000) than the DPSO and ($3975000) in case of GA.

The characteristics of the available MV/LV transformers, substations , the characteristics associated with the available LV conductors and MV feeders [10] are listed in Appendix II, Tables (VI) and (IX).

Conclusion

A new technique was proposed to solve the problem of optimal MV/LV planning of a distribution system. The optimal size and location of distribution and substation, along with the types and routes of LV conductors and MV feeders are found. The objective function comprises the capital cost of transformers, substations, LV conductors and MV feeders in addition to the loss cost and reliability cost. The feeder current and the voltage drop represents the constraints of the planning problem.

Linearized Biogeography-Based optimization technique is applied to solve the optimal MV/ LV power system planning. The results are compared to those obtained using Biogeography-Based optimization technique , Genetic Algorithm and Discrete Particle Swarm optimization. The proposed technique can be applied to both cases, uniform and non-uniform load density. It is found that the LBBO gives more optimal results than that of GA and DPSO with higher accuracy in all cases, and low computational effort. Unlike reference [9], the total cost of MV/LV planning incase of non-uniform load density is obtained. It was observed that the LBBO gives more optimal results compared with the GA and DPSO.

Appendix I

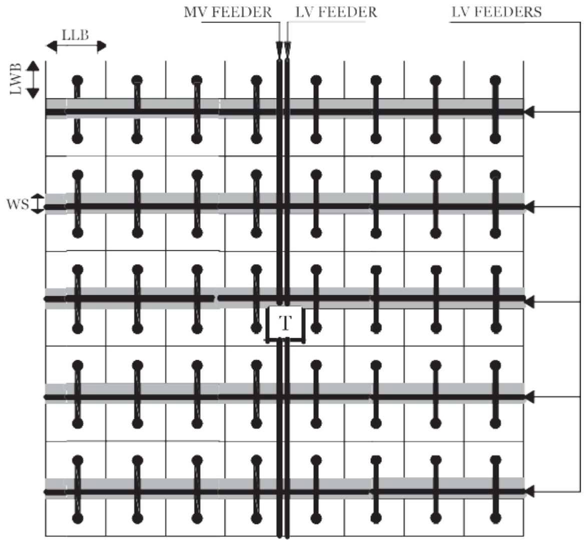

Figure (1): LV Zone supplied by a distribution transformer (T).

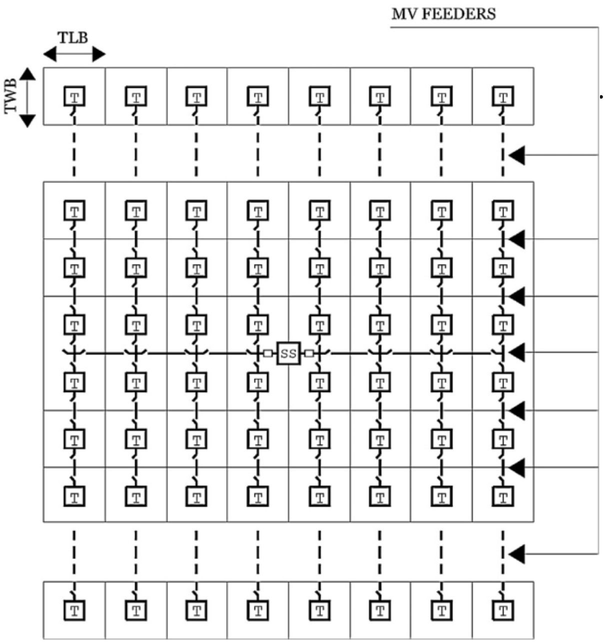

Figure (2): MV Zone supplied by substation (SS).

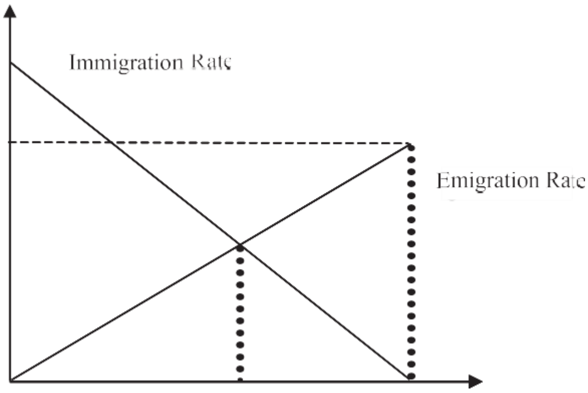

Fig. 3. Immigration rate, emigration rate vs species count curve.

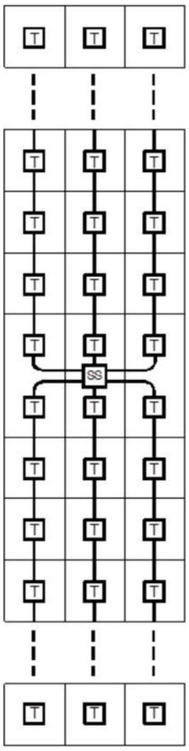

Figure (4): MV zone using Branch-type configuration.

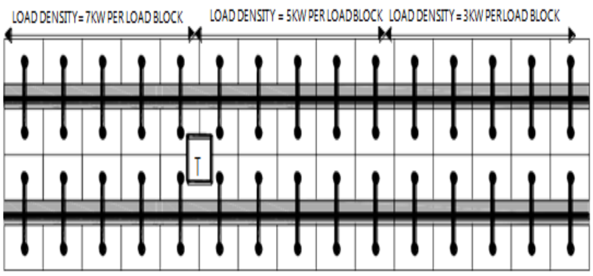

Figure (5): LV zone in case of non-uniform load density (region 1).

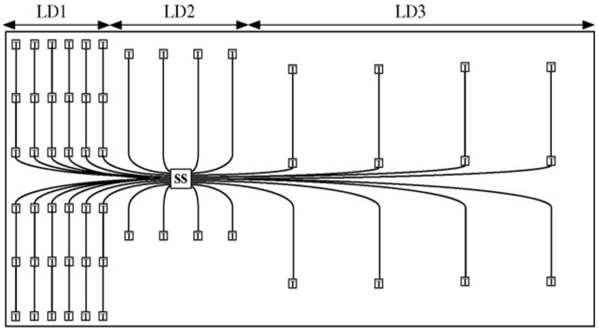

Figure (6): MV zone in case of non-uniform load density.

Appendix II

TABLE I
CHARACTERISTICS OF TEST SYSTEM

Parameters	Value
LOAD POWER	2.5 (KW)
LENGTH OF LOAD BLOCK	20 m
WIDTH OF LOAD BLOCK	20m
WIDTH OF THE STREET	10 m
BASE LV VOLTAGE	415 (V)
BASE MV VOLTAGE	33 (KV)
POWER FACTOR	0.8
FAILURE RATE	0.1864 (fault/km yr)
LOAD IMPEDENCE	44+j33 (Ω)
K_{PL}	168,000 $/MW
K_L	4¢/kWh
L_{SF}	0.3
r	0.07
T	20 years
C_{ID}	0.02 ($/min)
C_{IN}	6 ($/interruption)
SWITCHING TIME	30 min
REPAIR TIME	90 min

TABLE II
THE OUTPUT OF LV PLANNING

Parameters	*VALUE*			
	LBBO	*BBO*	*DPSO*	*GA*
LV zone size (blocks x blocks)	*8 x 10*	8 x 10	13 x 6	8x10
LV zone dimensions (km x km)	0.16x0.2	0.16 × 0.25	0.26 x0.15	0.16x 0.25
LV zone area (km²)	0.039	0.04	0.039	0.04
Transformer rating (KVA)	200	200	200	200
Transformer cost ($)	396	389	800	780
LV conductor cost ($)	377	374	2233	2323
MV construction cost ($)	136	141	216	352
Loss cost ($)	285	245	664	652
LV conductor types	1,5	1,5	1,7	1,6
Minimum bus voltage (PU)	0.9514	0.951	0.9531	0.9535
Total cost per load block ($)	1185	1149	3914	4107
Total cost per km² ($)	2371	2298	7828	8214

TABLE III
THE OUTPUT OF MV PLANNING FOR H-TYPE CONFIGURATION

Parameters	Value			
	LBBO	*BBO*	*DPSO*	*GA*
MV zone size (blocks x blocks)	8x15	8 × 15	5x15	9x8
MV zone dimensions (km x km)	1.28x3	1.28 × 3.75	1.3x2.25	2.34x1.2
MV zone area (Km2)	3.84	4.80	2.925	2.808
Substation rating (MVA)	25	25	15	15
Substation cost ($)	31.38	31.81	43.89	45.72
MV construction cost ($)	0.646	0.5052	8.66	9.01
MV construction Type	1	1	1	1
Reliability cost ($)	24.33	25.76	11.35	11.45
Loss cost ($)	7.38	7.49	2.71	3.75
Minimum bus voltage (PU)	0.994	0.994	0.9776	0.9795
Total cost per load block ($)	62.79	65.56	66.61	69.94
Total cost per km2 (k$)	1581	1639	1708	1793

TABLE IV
THE OUTPUT OF MV PLANNING FOR BRANCH-TYPE CONFIGURATION

Parameters	Value			
	LBBO	*BBO*	*DPSO*	*GA*
MV zone size (blocks x blocks)	3x24	3 × 25	3x24	3x34
MV zone dimensions (km x km)	0.48x4.8	0.48 × 6.25	0.78x3.6	0.78x5.1
MV zone area (Km2)	2.304	3.00	2.808	3.978
Substation rating (MVA)	15	15	15	25
Substation cost ($)	46.28	43.89	45.72	37.42
MV construction cost ($)	0.519	0.48	9.29	18.20
MV construction Type	1	1	1	9
Reliability cost ($)	15.17	16.86	10.65	14.95
Loss cost ($)	7.38	7.69	2.23	0.34
Minimum bus voltage (PU)	0.994	0.99	0.9776	0.9795
Total cost per load block ($)	68.83	68.91	67.88	70.91
Total cost per km2 (k$)	1735	1723	1740	1818

TABLE V
THE OUTPUT OF MV/LV ZONE PLANNING

Parameters	Value		
	LBBO	*DPSO*	*GA*
Total cost per km2 (k$)	5331	8920	9306

TABLE (VI)
THE CHARACTERISTICS OF THE AVAILABLE TRANSFORMERS

TRANSFORMER RATING (KV A)	CAPITAL COST (K$)	O&M COST ($/YEAR)
25	10	300
30	12.3	301
50	16.8	325
63	18.5	348
100	22	376
150	24.8	408
200	26.3	455
250	37	503
300	40.2	564
350	45.7	607

TABLE (VII)
THE CHARACTERISTICS OF THE AVAILABLE SUBSTATIONS

SUBSTATION RATING (MV A)	CAPITAL COST (M$)	O&M COST ($/YEAR)
3	1.6	16,000
8	2.47	16,800
15	3.1	18,100
25	3.6	20,500
30	3.8	23,700
50	4.1	28,000

TABLE (VIII)
THE CHARACTERISTICS OF THE AVAILABLE LV CONDUCTORS

LV CONDUCTORS	IMPEDANCE	CURRENT RATING (A)	CAPITAL COST (K$/KM)	O&M COST ($/YEAR/KM)
NO. 1	2.50 + J 0.200	84	40	255
NO. 2	2.20 + J 0.100	96	41.5	364
NO. 3	1.90 + J 0.100	110	43	364
NO. 4	1.60 + J 0.080	145	45	546
NO. 5	1.30 + J 0.050	197	48.5	632
NO. 6	0.74 + J 0.080	244	56	749
NO. 7	0.44 + J 0.070	312	51.5	698
NO. 8	0.25 + J 0.068	387	63	780
NO. 9	0.10 + J 0.067	443	75	807

TABLE (IX)
THE CHARACTERISTICS OF THE AVAILABLE MV FEEDERS

MV FEEDERS	IMPEDANCE	CURRENT RATING (A)	CAPITAL COST (K$/KM)	O&M COST ($/YEAR/KM)
NO. 1	1.75 + J 0.100	198	52	405
NO. 2	1.40 + J 0.100	212	53	553
NO. 3	1.00 + J 0.100	232	54.5	695
NO. 4	0.90 + J 0.080	275	56.7	821
NO. 5	0.75 + J 0.050	332	60	940
NO. 6	0.63 + J 0.090	300	68.5	1042
NO. 7	0.47 + J 0.087	386	76	1122
NO. 8	0.47 + J 0.087	486	86	1197
NO. 9	0.15 + J 0.076	601	100	1258

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