Optimal Step-Function Approximation of Load Duration Curve Using Evolutionary Programming (EP)

Eda Azuin Othman

***Abstract*— This paper proposes Evolutionary Programming (EP) to determine optimal step-function approximation of load duration curve (LDC) at minimum error. The EP model optimally discretized a load duration curve based on Malaysia's hourly load data in year 2012 for three and six segments of discretized LDC. The EP is developed using MatLab programming software. Results show that EP technique is able to provide optimum break points of discretized LDC at minimum error. In the analysis, it shows that the 6-step functions of LDC has a lower total error than the 3-step functions of LDC. The EP technique proposed in this paper is also compared with Dynamic Programming (DP) technique. Results show that EP provides a much shorter elapsed time than DP and have a lower total error for 3-step function of LDC. This EP-based model step function approximation of LDC is very useful for the power system planner to develop accurate generation expansion planning.**

Keywords-Evolutionary Programming (EP), Load Duration Curve, Minimization of Error

I. INTRODUCTION

In electrical utilities, load can be considered as the total electricity used during a given period time, such as an hour. These loads can be plotted for a day, or a week even for a year, and these curves are known as load curves. However, it is a considerable value to rearrange the loads into a cumulative curve with the hour of highest usage plotted that called as Load Duration Curve (LDC). From the LDC plotted, we can get the approximated load generation curve by a step function normally, of three or six steps. For example, the PIES model of the Department of Energy uses a three-step approximation for a LDC extending over a full year which is 8760 hours. This is based on the concepts of base load and peak load electrical generation, with the remainder being intermediate or cycling generation thus forming three classes of generation.

The step function of LDC is usually produced by sketching or in some other ad hoc manner. This approximated discretized LDC is usually used for planning generation expansion. However, because the expected result of expansion plant is very dependent on the shape of this discretized LDC, it is necessary to use a more rigorous technique to discretize the LDC. Thus, an optimum and rigorous technique to determine a more accurate step function approximation of LDC is developed in this paper using Evolutionary Programing (EP). This new method is tested to get the optimal step-function approximation for Malaysia's LDC in 2012.

A. Load Duration Curve

LDC analysis looks at the cumulative frequency of historic load data over a specified period. A load duration curve relates load values to the percent of time those values have been met or exceeded. The y-axis represents the load value associated with the time in a year hourly. LDC development typically uses daily average load used, which are sorted from the highest value to the lowest.

The first attempt was proposed by Loney [2] who used Dynamic Programming with six steps of approximation. The LDC considered the F and T as the number of hours the three segments are defined by the break points $t1$ and $t2$ and the corresponding heights $g1$, $g2$ and $g3$. Since the area under the LDC is equal to the total electrical generation in the period, the area under the step-function approximation should be equal to the area under the LDC for each step. They also introduced a penalty function, $p(e(x))$, to solve the optimization problem where $p(e(x))$ is the penalty to be paid per unit of mismatch at x and $e(x)$ is the amount of mismatch at x. The authors of [1] extended Loney's to widen the application.

The authors of [3] used the same concept as [1,2] to discretized LDC. Since the price duration curve (PDC) is sensitive to the shape of the LDC and calculated according to each segment of the discretized LDC, an optimal approach to discretize the LDC is introduced prior to the investment evaluation model using dynamic programming.

II. METHODOLOGY

Evolutionary Programming (EP) is a useful method to minimize the error in approximating the step-function of LDC using MatLab software. The objective of EP is to optimize any fitness which can be represented using mathematical equation. The evolutionary programming consists of three types which are classical, adaptive and

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Meta. The mutation technique for each type of EP is different.

A. EP-based Optimal Step Function of Load Duration Curve (LDC).

Figure 1 shows a three-step approximation of a typical LDC that is used to illustrate the methodology.

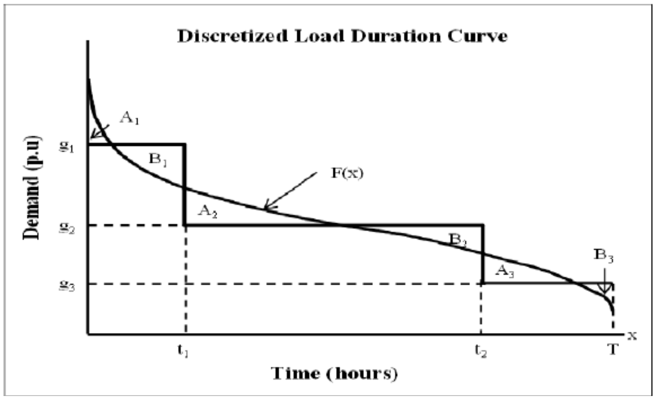

Figure 1: Typical LDC with three step approximations

The LDC is denoted by F and T is the number of hours being considered. The three segments are defined by the break points t_1 and t_2 and the corresponding heights g_1, g_2 and g_3. Since the area under the LDC is equal to the total electrical generation in the period, the area under the step-function approximation should be equal to the area under the LDC for each step. Each g_i can be expressed mathematically as a function of t_1 and t_2 as follows;

$$g_1 = \frac{1}{t_1}\int_0^{t_1} F(x)dx \qquad (1)$$

$$g_2 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} F(x)dx \qquad (2)$$

$$g_3 = \frac{1}{T - t_2}\int_{t_2}^{T} F(x)dx \qquad (3)$$

In Figure 1, area A_1 above the first segment and under the LDC can be interpreted as representing a deficit of electrical generation and the area B_1 above the LDC but below the first segment as representing an excess of generation. Areas A_2, B_2, *A3* and B_3 can be interpreted in the same way.

The optimization problem is solved by minimizing the amount of mismatch *e(x)* i.e. the error between the discretized LDC and actual LDC, where *e(x)* can be expressed as |*F(x)–g(x)*|. The goal of this optimization problem is to find the value of t_1 and t_2 in such a way that the total mismatch is minimized. This problem can be solved using EP where the amount of mismatch to be minimized is the fitness value and the random *x* values is the break points of the optimum discretized LDC.

The simulations were carried out for a three and six steps approximation of an LDC. The hourly load data is from the Malaysia's LDC for the load from 1st January 2012 to 31st December 2012 with 8784 hours.

Flowchart in Figure 2 shows the steps taken in determining the break points *x* for the optimum step function approximation of LDC using EP optimization technique.

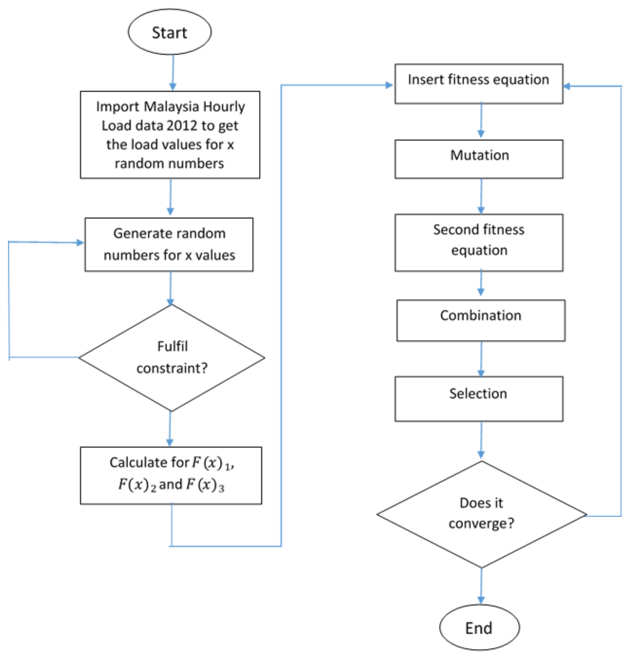

Figure 2: Flowchart of Evolutionary Programming

B. Evolutionary Programming (EP)

Evolutionary Programming (EP) is one of the methods that can be used in optimizing the fitness which normally represented in mathematical equations. The evolutionary programming (EP) is a method for simulating evolution and it is similar to evolutionary strategy (ES). In EP, selection is performed using comparison of randomly chosen set of other individuals whereas ES typically uses deterministic selection in which individuals are purged from the population. It is similar to a genetic algorithm, but models only the behavioral linkage between parents and their offspring rather than see the king to emulate specific genetic operators for nature such as the encoding of behavior in a genome and recombination by genetic crossover.

The fitness can either be maximized or minimized depending on the desired output needed. In this paper, the objective function is to minimize the error, *e(x)* between the discretized LDC and actual LDC. Below are the steps of EP method based on the pseudo code in MatLab programming;

i. Initialization

Initialization is functioning to generate the random numbers. These random numbers are basically the controlled variables in objective function equation. In this EP-based 3-step functions approximation of LDC, the controlled variables are x_1, x_2, and x_3, where represents the break points of optimum discretized LDC i.e. hours in data from 8760 hours per year. The constraints or the limit range of each variable are set in this phase. The command used to generate random numbers is as follows:

$$Xi = random\ (x, y) \times (A + B) \qquad (4)$$

$where$: x : $no\ of row$
y : $no\ of column$
A : $the\ offset$
B : $the\ minimum\ number$

In this step, an initial twenty populations of trial solutions are chosen at random. The populations are generated to meet the constraint set, but no definite answers are available as to how many solutions are appropriate (other than >1). While the random numbers generated does not complies the requirement, the program will keep running until it meets a number that fulfill the constraints. The sets of accepted numbers generated will form a population which will be used later in other steps ahead. In this paper for a 3-steps function approximation of LDC, the generated random numbers are x_1, x_2, and x_3, where basically these numbers are consider as the parents.

ii. Fitness

Next step is fitness which acts as a function or equation to be optimized, it can be a single mathematical equation or a set of sub-program or subroutine. There have two types of fitness which are fitness 1 and fitness 2, but the fitness 2 is calculated after the mutation. Fitness equation can be either a single mathematical equation or a set of sub-program. In this study, the fitness is to minimize the error of discretized load duration curve.

iii. Mutation

The mutation function is to generate offspring or children and normally, it use Gaussian Mutation Technique. In mutation process, offspring is produced from the parent generated in initialization step. There are various obtainable techniques that can be used to carry out the mutation process. The basic Gaussian's formula is shown below:

$$x_{i+m,j} = x_{i,j} + N[0, \beta(x_{jmax} - x_{jmin})\left(\frac{fi}{fmax}\right)] \qquad (5)$$

$where$: $x_{i+m,j}$: $offsprimg$
$x_{i,j}$: $parents$
β : $search\ step$
x_{jmax} : $max\ parents$
x_{jmin} : $minparents$
f_{max} : $maxfitess$

iv. Combination

After the new offspring has been produced, the combination process which combine the parents and offspring in series (by rows) and number of rows will be doubled.

$$Combination = \frac{parents}{offsprings} \qquad 2mxn = \frac{mxn}{mxn} \qquad (6)$$

v. Selection

The selection process is needed to select the survival of the fittest. One method is elitism and used in the MatLab syntax. This syntax is for objective function which is to minimize the fitness. In the selection process, the survivors from the combination of parent and offspring are determined. The sets of variables are ranked according to their fitness value; ascending order or descending order. In this study, the fitness value is ranked in an ascending order which is from the minimum value to the maximum value.

vi. New Generation Definition

New generation definition displays the new sets of variables from the fitness function that have been optimized.

vii. Convergence Test

The last stage for EP method is the convergence test which determine the stopping criterion and define the minimum and maximum fitness. If the convergence test success, the programming will be end. The value of accuracy was set to 0.0001 as shown in the equation below:

$$fitness(maximum) - fitness(minimum) =< 0.0001 \qquad (7)$$

III. SIMULATION AND RESULTS

A. Before Optimization (Parents)

Table 1 shows the first 20 population for a 3-steps function approximation of LDC. The simulation gives the minimum total error of 4,357,002 MWh and maximum total error of 3.76×10^9 MWh when the first 20 generating random numbers are selected as parents. On the other hand, Table 2 shows the first 20 population for a 6-steps function approximation of LDC. It is obviously seen that for the first generation of population, the error is not yet converged. The first population for 6-segments discretized load gives the minimum total error of 3,036,718 MWh. However, a more optimum output result is expected after the optimization is performed.

Table 1: Total error produced by each population before the optimization process for 3-step functions of LDC

x1	x2	g1	g2	g3	y1	y2	y3	total error
3055	5967	14184.24	12195.51	10471.38	1506159	1539392	1311451	4357002
2337	7299	18542.08	7157.058	19863.89	13313216	14671970	26458705	54443891
156	470	277774.7	113099.8	3547.977	8.05E+08	2.94E+08	19503230	1.12E+09
2384	5895	18176.53	10114.87	10210.41	12196452	6058810	1552738	19807999
35	3368	1238081	10655.06	5446.433	3.74E+09	4485781	14155279	3.76E+09
301	3667	143963	10550.6	5764.683	3.96E+08	4789973	13258770	4.15E+08
3090	5174	14023.58	17040.94	8171.158	1540230	14109900	6486461	22136592
4187	7433	10349.38	10940.64	21834.11	11715497	3654174	32008804	47378474
2943	3654	14724.04	49948.42	5750.074	2017682	1.1E+08	13299922	1.25E+08
3155	7996	13734.66	7335.948	37433.86	1812463	14151044	75953300	91916806
214	6466	202489.9	5680.314	12725.57	5.75E+08	18972249	6350062	6.01E+08
1477	5557	29338.42	8704.246	9140.961	46296029	10166559	3858166	60320754
3404	8705	12729.98	6699.363	373390.9	4442763	16004779	1.02E+09	1.04E+09
1644	2170	26358.18	67515.83	4459.915	37191392	1.61E+08	16934299	2.15E+08
4421	6348	9801.594	18429.33	12109.15	13388978	18152893	4613585	36155455
3390	5723	12782.55	15222.17	9636.681	4282155	8813637	2629882	15725673
327	5548	132516.4	6802.016	9115.538	3.62E+08	15705854	3924358	3.81E+08
1964	6733	22063.57	7446.702	14382.19	24071353	13828526	11016761	48916640
1237	3156	35030.6	18506.16	5241.272	63685625	18376618	14733217	96795460
749	4274	57854.27	10074.7	6540.55	1.33E+08	6175792	11073151	1.51E+08

Table 2: Total error produced by each population before the optimization process for 6-step functions of LDC

x1	x2	x3	x4	x5	g1	g2	g3	g4	g5	g6	y1	y2	y3	y4	y5	y6	Error
258	3316	4301	5061	6491	15245.86	14003.44	12714.32	12060.74	11348.91	10322.46	34379.02	1461358	160212.6	116731	260423.3	1003614	3036718
260	706	4341	6759	8205	15128.58	96014.6	3445.283	3790.803	11223.33	40879.79	36677.35	2.51E+08	9130000	6285152	285334.7	70067965	3.37E+08
2043	3831	4124	7565	8584	1925.322	23949.95	42742.68	2663.808	15926.34	118347	3436699	30416438	29577932	7141668	6545726	2.48E+08	3.25E+08
2068	3632	5248	6878	8083	1902.046	27380.12	7749.755	5623.412	13468	33765.19	3442704	40905904	4890095	4892369	3030300	53754187	1.11E+08
851	1791	3400	7234	7899	4622.129	45555.86	7783.47	2390.757	24404.42	26745.08	2740923	96487322	4856886	7349187	18669384	37657079	1.68E+08
213	2479	4249	8212	8500	18466.82	18897.84	7075.482	2312.935	56350.49	83342.96	831006.8	14967092	5554254	7408331	64352263	1.67E+08	2.61E+08
329	1117	1632	2057	7442	11955.72	54343.29	24317.68	21567.44	3013.731	17637.41	848856.1	1.23E+08	11429309	7225092	11919307	16773174	1.72E+08
2989	4008	5018	7059	8073	1315.969	42024.06	12399.61	4491.015	16004.87	33290.3	3593912	85687050	311005.1	5752990	6658027	52665247	1.55E+08
1297	3941	3960	4725	5236	3032.715	16196.11	659137.1	11981.91	31759.18	6671.195	3150991	6705189	6.37E+08	124187.1	29186688	8372350	6.84E+08
487	2189	5289	6265	7687	8076.862	25160.11	4039.872	9391.559	11412.76	21576.48	1849601	34117114	8544330	2028577	272200.5	25805472	72617294
688	2732	4324	6580	7721	5717.198	20950.35	7866.585	4063.015	14223.44	22266.6	2458395	21243654	4775017	6078271	4110573	27387923	66053833
402	1947	3907	7247	8398	9784.657	27716.84	6389.594	2744.36	14099.86	61319.69	1408991	41935574	6229854	7080448	3933862	1.17E+08	1.78E+08
1094	3439	5986	6539	8177	3595.459	18261.2	4917.002	16575.34	9907.779	38994.07	3005804	13020235	7680357	3431095	2060818	65744001	94942310
849	1239	1538	3801	7521	4633.018	109801.3	41884.96	4050.447	4362.619	18740.62	2738113	2.93E+08	28733085	6087822	9990397	19302836	3.6E+08
550	817	2777	4156	7105	7151.695	160383.9	6389.594	6646.963	5503.202	14097.32	2088295	4.48E+08	6229854	4114470	8359363	8655754	4.77E+08
859	1028	1522	3621	6884	4579.083	253387.7	25351.43	4366.919	4973.626	12457.58	2752029	7.32E+08	12447550	5847304	9116657	4895829	7.67E+08
155	1121	2061	6332	6495	25376.98	44329.72	13322.98	2146.14	99564.06	10340.5	2613829	92737782	599534.2	7535096	1.26E+08	995423.3	2.31E+08
682	1409	2757	5434	8060	5767.496	58903.04	9290.507	3424.043	6180.1	32692.54	2445418	1.37E+08	3372454	6563890	7391399	51294598	2.08E+08
3843	4121	4751	6523	6529	1023.532	154037.8	19878.74	5172.778	2704824	10496.41	3669361	4.28E+08	7056951	5234851	3.85E+09	972348.7	4.3E+09
1511	2114	2953	5333	7078	2603.198	71015.78	14926.82	3851.329	9300.253	13874.21	3261807	1.74E+08	2179316	6239152	2929580	8144160	1.97E+08

B. After Optimization (Converged)

Table 3 shows the minimum total error for 3-step functions of LDC after optimization process is 3,515,179 MWh. This proves that after optimization has been performed, the result gives the most minimum value of error that need to be minimized by get optimum discretized LDC. The break points which are *g1*, *g2* and *g3* can be determined using the equation (1), (2) and (3). From the results obtained in Table 4, it shows that a minimum total error of discretized LDC also achieved for 6-step functions of LDC, where the minimum total error is 3,036,718 MWh. Results also show that the 6-step functions of LDC has a lower total error than the 3-step functions of LDC. This concludes that higher number of segments of discretized LDC will result in a lower total of mismatch.

Table 3: Total error produced by each population after the optimization process for 3-step functions of LDC

x1	x2	g1	g2	g3	y1	y2	y3	total error
3055	5967	14184.24	12195.51	10471.38	1506159	1539392	1311451	4357002
3055	5967	14184.24	12195.51	10471.38	1506159	1539392	1311451	4357002
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Table 4: Total error produced by each population after the optimization process for 6-step functions of LDC

x1	x2	x3	x4	x5	g1	g2	g3	g4	g5	g6	y1	y2	y3	y4	y5	y6	Error
258	3316	4301	5061	6491	15245.86	14003.44	12714.32	12060.74	11348.91	10322.46	34379.02	1461358	160212.6	116731	260423.3	1003614	3036718
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258	3316	4301	5061	6491	15245.86	14003.44	12714.32	12060.74	11348.91	10322.46	34379.02	1461358	160212.6	116731	260423.3	1003614	3036718
258	3316	4301	5061	6491	15245.86	14003.44	12714.32	12060.74	11348.91	10322.46	34379.02	1461358	160212.6	116731	260423.3	1003614	3036718
258	3316	4301	5061	6491	15245.86	14003.44	12714.32	12060.74	11348.91	10322.46	34379.02	1461358	160212.6	116731	260423.3	1003614	3036718
258	3316	4301	5061	6491	15245.86	14003.44	12714.32	12060.74	11348.91	10322.46	34379.02	1461358	160212.6	116731	260423.3	1003614	3036718

C. Optimum Break Points for 3-Step and 6-Step Functions of LDC

The optimum break points for 3-steps and 6-step functions of Malaysia's LDC in year 2012 are shown in Figure 3 and Figure 4 respectively. For 3-steps function of LDC, the break points are x_1= 3,055 h and x_2= 5,967 h with respective load of y_1= 14,184 MW, y_2 = 12,195 MW and y_3 = 10,471 MW.

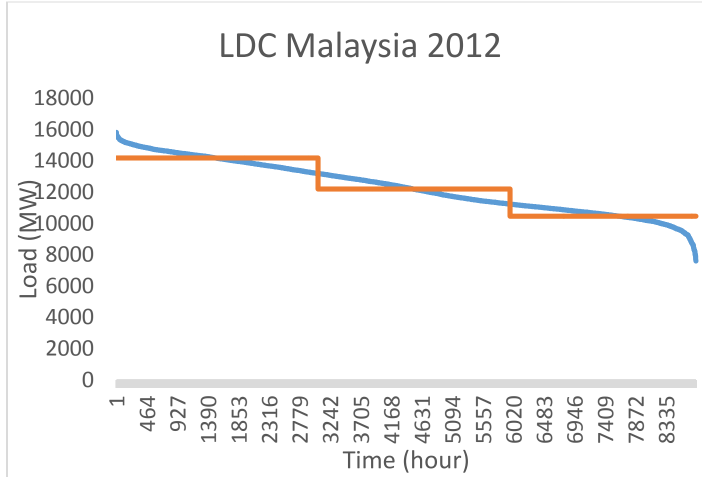

Figure 3: The load duration curve graph for 3-step functions of LDC

On the other hand, for 6-steps function of LDC, the break points are x_1 = 258 h, x_2 = 3,316 h, x_3 = 4,301 h, x_4 = 5,061 h, and x_5 = 6,491 h with respective load of y_1 = 15,245 MW, y_2 = 14,003 MW, y_3 = 12,714 MW, y_4 = 12,060 MW, y_5 = 11,348 MW and y_6 = 10,322 MW as shown in Figure 4.

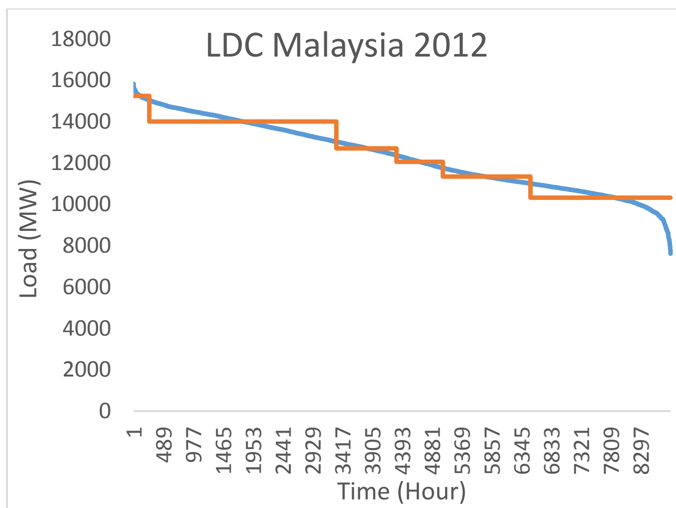

Figure 4: The load duration curve graph for 7-step functions of LDC

D. Comparison Between Evolutionary Programming (EP) and Dynamic Programming (DP)

In this case, the results of discretized LDC using EP is compared with Dynamic Programming (DP) technique as in [3]. Table 7 shows the differences between DP and EP techniques in term of elapsed time, optimum break points and total error. The techniques have been tested using Malaysia's LDC in year 2012.

Results show that, for the 3-step functions of LDC, the optimum break points are comparable. However, EP provides a lower total error compare to DP. EP also provides a much shorter elapsed time i.e. 29.08s than DP i.e. 766.11 s. On the other hand, for 6-step functions of LDC, DP gives a lower total error compare to EP. However, in term of the elapsed time, EP still shows a much shorter time i.e. 29.07s than DP i.e. 3,463.11s.

Table 5: Comparison between EP and DP

3-segments		DP	EP
	Elapsed time (s)	766.118965	29.084227
	X1	4,398	3,055
	X2	8,201	5,967
	Total Error (MWh)	5,197,020	4,357,002
	Elapsed time (s)	3463.110517	29.071741
6-segments	*X1*	1,966	258
	X2	3,766	3,316
	X3	5,271	4,301
	X4	7,193	5,061
	X5	8,701	6,491
	Total Error (MWh)	2,566,869	3,036,718

IV. CONCLUSION

This study proposes Evolutionary Programming (EP) to determine optimum break points of discretized LDC at minimum error. The EP is developed using MatLab programming software. The proposed EP-based optimal step functions of LDC has been tested on Malaysia's LDC in year 2012 for three and six segments of discretized LDC. Results show that EP technique is able to provide optimum break points of discretized LDC at minimum error. Results also show that the 6-step functions of LDC has a lower total error than the 3-step functions of LDC. The EP technique proposed in this paper is also compared with DP technique. Results show that EP provides a much shorter elapsed time than DP and have a lower total error for 3-step function of LDC.

For future work, a Graphical User Interface (GUI) is recommended to ease user to determine optimal discretized LDC at various segments. With this GUI, user can load their own annual hourly load data and choose the number of segments that they want their LDC to be discretized.

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