The Study of Economics of Power Generation

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Abstract

This paper presents a study on operating cost of thermal power generation. The study include Economic Load Dispatch (ELD) concept, in a power system by using MATLAB software package. Comparison in total cost for increases total loss case was made in order to determine the difference on the total generation cost and identify advantage for the total loss minimization. The proposed technique is tested on IEEE 9-bus power system network. Hybrid Optimization Model for Electric Renewables (HOMER) is software used to analyze generation cost of thermal power generation and net present cost (NPC) to choose the best operation system for different fuel which is coal and natural gas either in stand alone application or combined operation. The study identifies how to find minimum cost for this type generation systems and identify the solution to minimize the total loss.

Keywords:
Economics of Power Generation, Economic Load Dispatch (ELD), Economic Dispatch (ED), Optimal Power Flow (OPF), Thermal, Combined Cycle.

1.0 INTRODUCTION

Power has become an inevitable ingredient in every day human life and a universal input for economic growth [1]. With steadily growing population, increasing urbanization and rapid diversification of the economies, the demand for electrical power has been increasing every year. Electricity is the only form of energy which has to produce, transport, use and control [2]. In a large plant and certainly over an entire power system many generators may cooperate in meeting the power needs of all connected loads [1]. Thermal power plants generate more than 80% of the total electricity produced in the world. Fossil fuel, viz. coal, fuel oil and natural gas are the energy source, and steam is the working fluid. Steam is also required in many industries for process heat. To meet the dual need of power and process heat, cogeneration are often installed [2]. The increasing demand for an optimal power flow (OPF) tool for assessing state and recommended control actions for off-line and on-line studies has been on the increase since the first OPF paper was presented in the 60's [3]. The main purpose of an OPF is to determine the optimal operating state of a power system by optimizing a particular objective while meeting the constraints of economics [5].

This study used an optimization technique by using MATLAB to solve Optimal Power Flow (OPF) and study on concept of Economic Dispatch (ED). The objective of the ED is to minimize the total cost of generation and total losses in a system while satisfying all other constraints. HOMER software was used to proof the concept or theory on effect of increases losses to total cost same as MATLAB simulation result and then choose the best system of thermal power plant either single or combined operation.

2.0 OPERATING COST OF A THERMAL PLANT

The factors influencing power generation at minimum cost are operating efficiency of generators, fuel cost, and transmission losses. The most efficient generator in the system does not guarantee minimum cost as it may be located in area where fuel cost is high. Also, if the plant is located far from the load centre, transmission losses may be considerably higher and hence the plant may be overly uneconomical. The input to thermal plant is generally measured in Btu/h, and the output power, **Pi** is measured in MW. A simplified input-output curve of thermal unit known as heat-rate curve is given in Figure 2.1

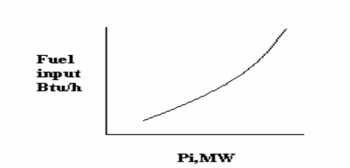

Figure 2.1: Heat-rate curve

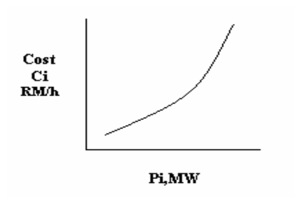

Figure 2.2: Fuel-cost curve

Converting the ordinate of heat-rate curve from Btu/h to RM/h results in the fuel-cost curve shown in Figure 2.2. In all practical cases, the fuel cost of generator i can be represented as a quadratic function of real power generation.

$$C_i = ai + biP_i + ciP_i^{\,2} \qquad (2.1)$$

An important characteristic is obtained by plotting the derivative of the fuel-cost curve versus the real power. This is known as the incremental fuel-cost curve shown in Figure 2.3.

$$\frac{dCi}{dPi} = bi + 2ciP_i \qquad (2.2)$$

The incremental fuel-cost curve is a measure of how costly it will be to produce the next increment of power. The total operating cost includes labour, supplies and maintenance. These costs are assumed to be fixed percentage of the fuel cost and are generally included in the incremental fuel-cost curve.

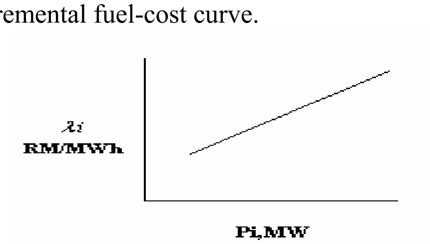

Figure 2.3: Typical incremental fuel-cost curve

3.0 ECONOMIC DISPATCH PROBLEM

The objective of economic dispatch problem is to operate our power system in a manner that minimizes the costs of generator. It assumes that there are *N* units already connected to the system. The economic dispatch problem can be formulated mathematically as follows:

Equation (3.1) represents the total cost of the generation, which is the objective function of choice.

$$FT = \sum_{i=1}^{N} Fi\,(Pi) \qquad (3.1)$$

Where F_T is the total cost in supplying the indicated load in Ringgit Malaysia per hour (RM/h). F, represent the total cost for unit i in Ringgit Malaysia per hour (RM/h). N is the number of generators in the power generation system and Pi, is the power generated by unit i in (Megawatts).

Equation (3.2) computes the cost of power generation for unit *i* where a_i, b_i, and c_i are the constant for the input-output curve.

$$F_i(P_i) = a_i + b_iP_i = c_iP_i^{\,2} \qquad (3.2)$$

Equation (3.3) and (3.4) are the equality constraints, while equation (3.5) is the inequality constraints for the economic dispatch problem.

$$P_T = P_D + P_L \qquad (3.3)$$

Where, P_T is the total power generated in MW, P_D, is the total demand of the system in MW. P_L is the total transmission losses in MW.

$$P_{i\,\min} \le P_i \le P_{i\,\max} \quad for\ \ i = 1,\ldots N \qquad (3.4)$$

Where P_{imin} is the lower limit of power generated for unit i in MW and P_{imax} is upper limit of power generated for unit i in MW.

Using Lagrange Multiplier Technique equation s(3.5), (3.6) and (3.7) are the Lagrange function for the Economic Dispatch problem.

$$L = F_T + \lambda\phi \qquad (3.5)$$

$$\phi = P_D - P_L - \sum_{i=1}^{N}(P_i) \qquad (3.6)$$

$$L = \sum_{i=1}^{N} F_i(P_i) + \lambda\left(P_D - P_L - \sum_{i=1}^{N} P_i\right) \qquad (3.7)$$

where λ= Lagrange multiplier

ϕ = The error function

To get the minimum points or optimal solution we take the first partial derivative of LaGrange function with respect to individual output and then equating it to zero. This equation is shown as below

$$\partial L / \partial Pi = dFi(Pi) / dPi - \lambda i = 0 \qquad (3.8)$$

or

$$\lambda i = \partial L / \partial Pi \qquad (3.9)$$

The problem is solved subject to the equality and the inequality constraints are described by equation (3.3) and equation (3.4) respectively.

4.0 METHODOLOGY

Most of the steps can only be taken after the preceding step has been performed. Several steps are to be taken to realize the objective and they are as mentioned as the followings:

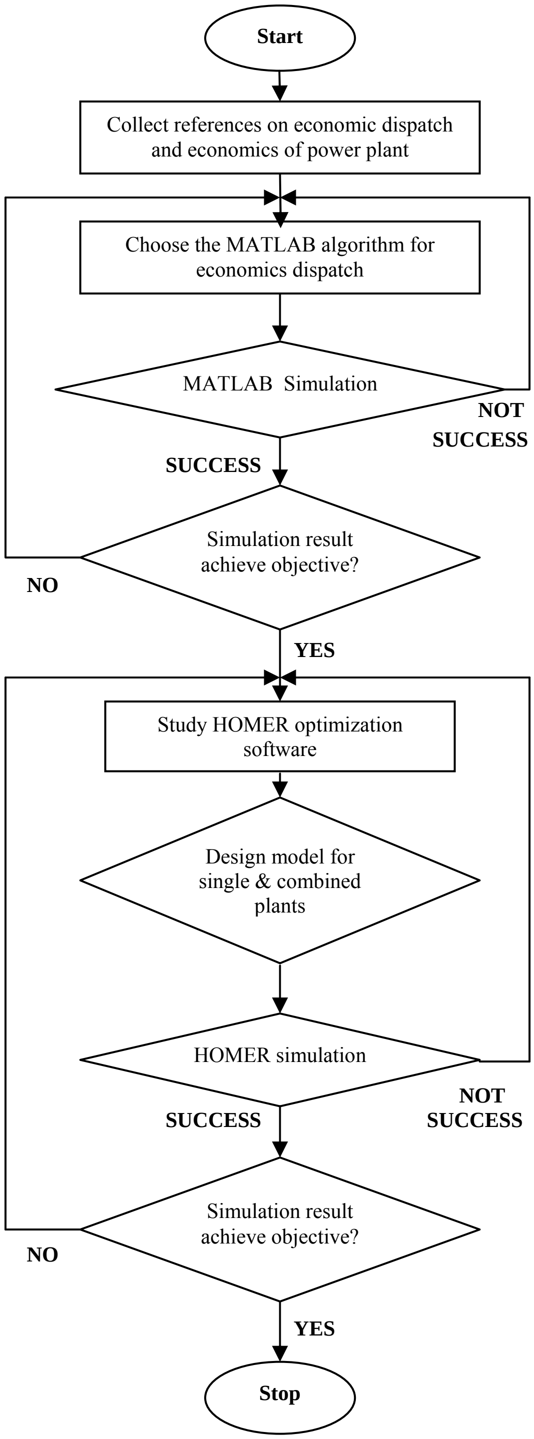

Figure 4.1: Process of completing project

5.0 B-COEFFICIENT METHOD

B-coefficient method developed by Kron and adopted by Kirchmayer is one of the major steps in the optimal dispatch of generation is to express the system losses in terms of the generator's real power output. The overall algorithm of this method is shown below:

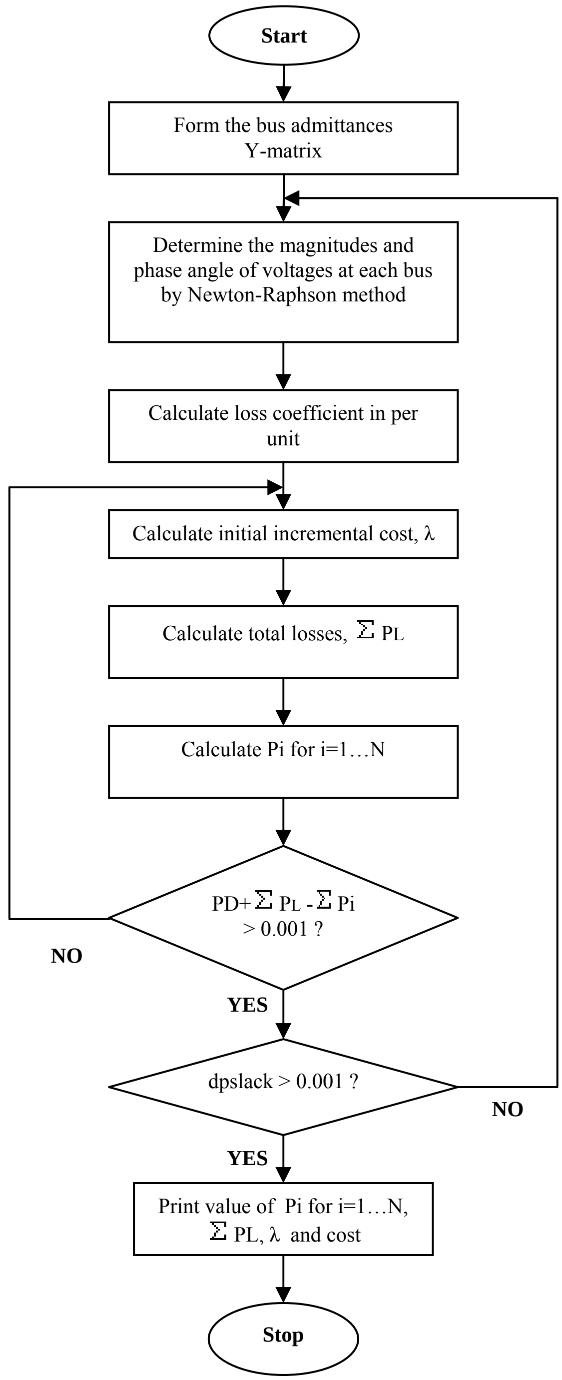

Figure 5.1: Flow chart for B-coefficient algorithm

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To find the loss coefficients, first a power flow solution is obtained for the initial operating states. This provides the voltage magnitude and phase angle a at all buses. Next the bus matrix is found. This can be obtained by converting the bus admittance matrix. The *B*-coefficient obtained are based on the generation in per unit. When generation express in MW, the loss coefficient are:

$B_{ij} = B_{ij\,pu}/S_B \quad B_{0i}\,pu$ and $B_{00} = B_{00}\,pu \times S_B$

A variable named dpslack is the difference (absolute value) between the schedule slack generation determined by coordination equation, and the slack generation obtained from the power flow solution. A power solution obtained with the new scheduling of generation results in new loss coefficients, which can be used to solve coordination again. This process can be continued until dpslack is within a specified tolerance which is 0.0001 in the present project.

6.0 HOMER OPTIMIZATION

HOMER is the small power system optimization model, simplifies the task of evaluating design of power system for a variety application either stand alone application or combined operation. HOMER simulates the operation of a system by making energy balances calculations for each of the 8760 hours in a year. HOMER performs these energy balance calculations for each system configuration. This software can determine whether a configuration is feasible or not, and estimates the cost of installing and operating the system over the lifetime of project.

6.1 Net Present Cost (NPC)

The net present defines as a value of the cost of installing and operating the system over the lifetime of the project. The total net present cost is a main economic output. All systems are ranked according to net present cost, and all other economic outputs are calculated for the purpose of finding the net present cost. The net present cost is calculated according to the following equation:

$$NPC = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \quad (6.1)$$

where:

$C_{ann,tot}$ = total annualized cost [RM/yr]
CRF = capital recovery factor
i = interest rate [%]
R_{proj} = project lifetime [yr]

6.2 Cost of Energy (COE)

Cost of energy (COE) defines as the average cost per kWh of useful electrical energy produced by the system. COE calculated by divide the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total useful electric energy production. The equation for the COE is as follows:

$$COE = \frac{C_{ann,tot} - C_{boiler} * E_{thermal}}{E_{prim,AC} + E_{prim,AC} + E_{def} + E_{grid,sales}} \quad (6.2)$$

or

$$COE = \frac{\Sigma \text{ Generation Cost (\$)}}{\Sigma \text{ Units Generated (kWh)}} \quad (6.3)$$

where:

$C_{ann,tot}$ = total annualized cost of the system [RM/yr]
C_{boiler} = boiler marginal cost [RM/kWh]
$E_{thermal}$ = total thermal load served [kWh/yr]
$E_{prim,AC}$ = AC primary load served [kWh/yr]
$E_{prim,DC}$ = DC primary load served[kWh/yr]
E_{def} = deferrable load served [kWh/yr]
$E_{grid,sales}$= total grid sales [kWh/yr]

The second term in the numerator is the portion of the annualized cost that results from serving the thermal load. In systems that do not serve a thermal load ($E_{thermal}$=0) this term will equal zero.

6.3 Total Generation Cost

From the equation (6.3)

$$COE = \frac{\Sigma \text{ Generation Cost (RM)}}{\Sigma \text{ Units Generated (kWh)}}$$

Hence,

The total generation cost in RM,

$$\Sigma \text{ Gen. Cost} = \Sigma \text{ Unit Generated} \times COE \quad (6.4)$$

However HOMER ranks systems by total NPC, not by the cost of energy.

7.0 PROBLEM ANALYSIS

7.1 B-coefficient method for Optimal Dispatch Problem

A. The OPF problems were tested on the 9-bus test system. Bus 1 is a slack bus and the system has 2 generator buses. The generator's operating costs in RM/h, for each generating units are as follow:

$C_1 = 240 + 6.7P_1 + 0.0090P_1^2$ (7.1)
$C_2 = 220 + 6.1P_2 + 0.0050P_2^2$ (7.2)
$C_7 = 220 + 6.5P_3 + 0.0080P_3^2$ (7.3)

$P_D = 345$ MW

Bus no	**Pgmin** MW	**Pgmax** MW
1	50	200
2	50	200
7	50	100

Table 7.1: Generator data for the 9-bus test system

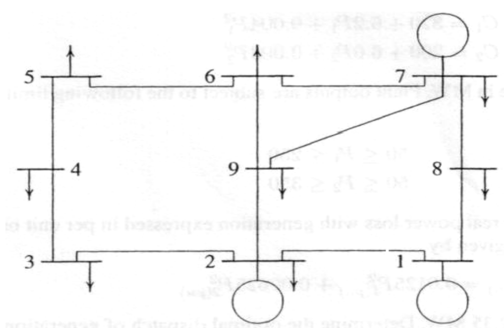

Figure 7.1: The IEEE 9- bus test system

B. Graph of total cost versus total loss and total power generated were plotted to identify effect for the total loss minimization.

7.2 HOMER

A. Graph of total cost versus total loss and total power generated were plotted to compare the graph by MATLAB simulation**.**

B. Net present cost (NPC), cost of energy (COE) and generation cost of thermal power generation for fuel coal and natural gas for was analyzed. The best system was chosen for following type of operations:

i. stand alone application
ii. combined cycle operation

8.0 RESULT AND DISCUSSION

8.1 MATLAB Simulation

A. B-Coefficient method has been used in this study and tested for validity on 9-bus test system. The objective function is to minimize the total active power losses and cost of generation in the power system. The results are show as below:

Table 8.0: Result for OPF technique

Terms	**Before OPF**	**B coefficients**
P1(MW)	93.4	70.3366
P2(MW)	161.2244	181.5760
P7(MW)	100.0000	97.1034
Total loss(MW)	5.4148	4.01613
Total Cost (RM/h)	12,641.726	12,140.43
Saving (RM/h)	-	501.30

When we refer to Before ED result, the total loss is 5.4148 MW and the total generation cost for the initial operating condition is 12,641.726 RM/h. However when we use B-coefficient method, the result is better than Before ED result. The total loss and total cost for this method is 4.01613 MW and 12,140.4 RM/h. This result in a savings of 501.30 RM/h. Hence the total annual saving is over RM4.391 million.

Table 8.1: MATLAB simulation result

PL(MW)	4.02	4.03	4.12	5.46
PT(MW)	349.0	349.1	349.3	354.7
Cost (RM/h)	12140.62	12141.76	12171.40	12641.84

ii. Graph Total Cost vs Total Loss

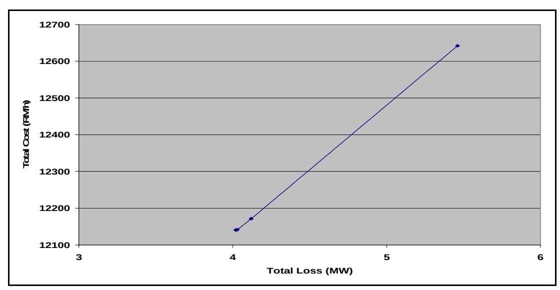

Figure 8.1: Graph Total Cost vs Total Loss

From the graph above shows that when the total system loss increases, the total generation cost also increases.

iii. Graph Total Cost vs Total Power

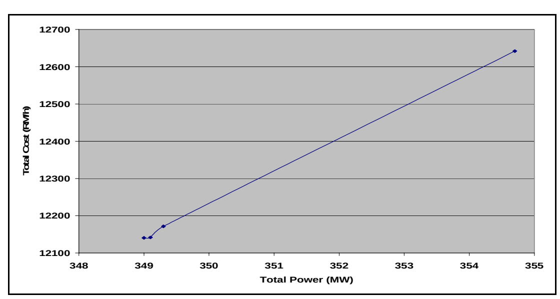

Figure 8.2: Graph Total Cost vs Total Power

From the graph above shows that when the total generated power increases, the total generation cost also increase.

8.2 HOMER Simulation

Assumptions:
a) Same daily load factor for all case for a year
b) No variation in fuel cost for a year

A) Coal-fired power plant

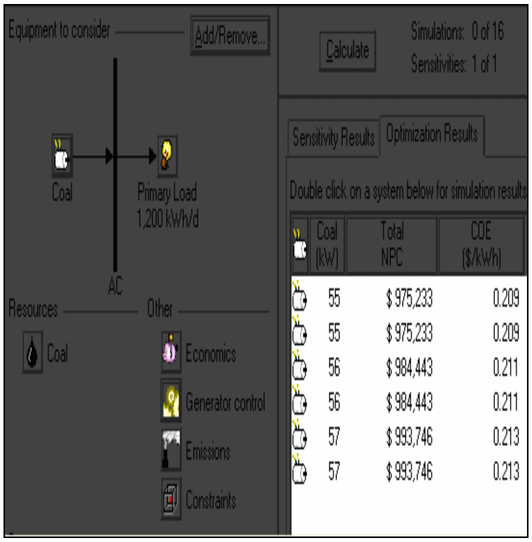

Figure 8.3: HOMER Simulation for coal fired power plant

P_D = 438000 kWh

Table 8.2: Simulation Result for coal-fired power plant

PT (kWh)	481800	490560	499320
PL (kWh)	43800	52560	61320
COE ($/kWh)	0.209	0.211	0.213
Cost (RM)	382,644.8	393,330.4	404,149

i. Graph Total Cost vs Total Loss

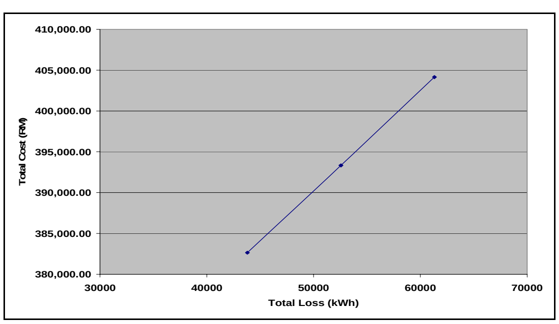

Figure 84: Graph Total Cost vs Total Loss

ii. Graph Total Cost vs Total Power

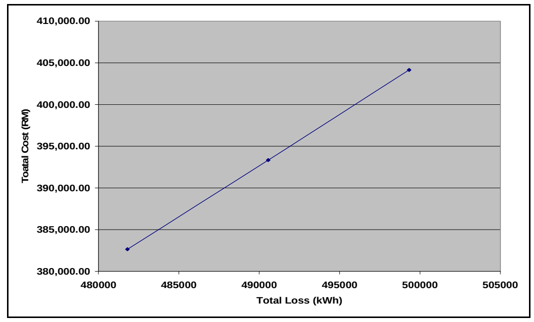

Figure 8.5: Graph Total Cost vs Total Power

From the both graph above, when the total loss and total power generated increases, the total also cost increase. This plotted graph proof that the effect of increasing losses to total cost is same like the graph plotted by MATLAB simulation.

B) i. Result for single power plant

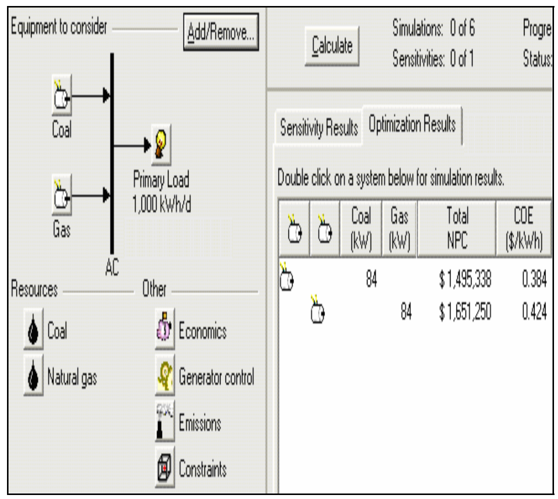

Figure 8.6: HOMER Simulation for single operation power plant

Total unit generated = 365000 kWh

Table 8.3: Result for Single Operation

Terms	**NPC**	**COE ($/kWh)**	**Gen. Cost (RM)**
Coal	1.495	0.384	532,608
Gas	1.651	0.424	588,088

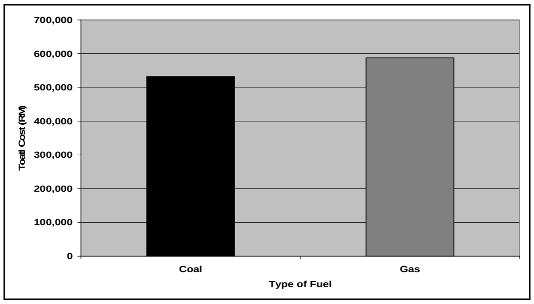

Figure 8.7: Graph Total Cost vs Type of Fuel for single operation

From the graph above, the lowest generating cost for stand alone application is coal-fired power plant with RM 532,608 for a year. The total annual saving is over RM55480. And the coal-fired power plant is the best system with minimum net present cost (NPC) than gas-fired power plant.

ii. Result for Combined Cycle

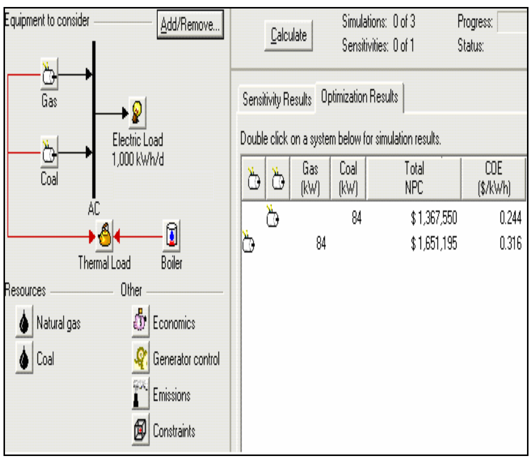

Figure 8.8: HOMER Simulation for combined cycle operation (stream 1 & 3)

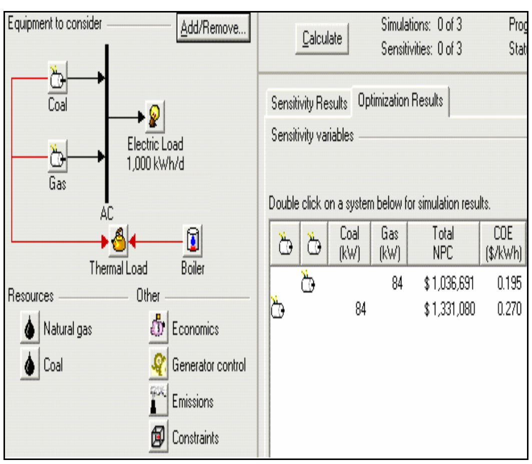

Figure 8.9: HOMER Simulation for combined cycle operation (stream 2 & 4)

Total unit generated = 365000 kWh

Table 8.5(c): Result for combined cycle operation

Stream / Terms	1	2	3	4
Gen.	Coal	Coal	Gas	Gas
Boiler	Coal	Gas	Coal	Gas
NPC	1.368	1.313	1.651	1.041
COE	0.244	0.270	0.316	0.196
Gen.Cost (RM)	338,428	374,490	438,292	271,852

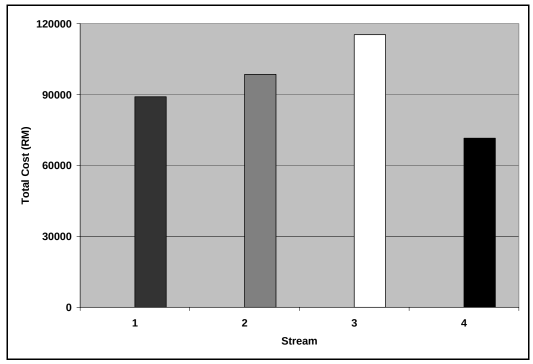

Figure 8.5(d): Graph Total Cost vs Stream

From the table and graph above, combined cycle plant which used fully gas as fuel at generator and boiler is the best system the lowest net present cost (NPC) and generation cost for a year.

9.0 CONCLUSION

From the result above, it can be seen that the B-coefficient is a optimization technique in solving the non linear economic dispatch problem and obtained that economic dispatch is concerned with the minimization of the objective function, which is minimizing total cost and total loss of a system mention, while satisfying all constraint. From the graph, when the total loss and total power generated increases, the total cost increased. The best objective function is total cost minimization. From HOMER result, it can prove that the total cost will increase when the total loss and total power increases. Otherwise, it can be conclude that the combined cycle power plant is the best system compared to single thermal power plant operation. not only by the generation cost but by net present cost too. Therefore from the result, the best system for thermal system is combined cycle system with gas is the fuel for generator and boiler compared to single thermal power plant and other fuel used for the same system.

10.0 FUTURE DEVELOPMENT

For future development, the HOMER software proposed to be implemented in comparing the generation cost to MATLAB by the cost function and all constraint. Otherwise, the software proposed to optimize the best power plant with minimum net present cost (NPC) and generation cost for more big and complicated system which use another type of fuel like renewable resources i.e. hydro, solar, wind energy etc.

11.0 REFERENCES

[1] Hadi Saadat, Milwaukee School of Engineering, Power System Analysia 2nd Edition “Optimal Dispatch of Generation”, June 2002, pp. 257 – 313

[2] P K Nag, Department of Mechanical Engineering Indian Institute of Technology Kharagpur, Power Plant Engineering 2nd Edition “Introduction: Economics of Power Generation”, McGraw Hill, 2002, pp.1-18

[3] J.A. Momoh, Senior Member Howard University Washington, DC *Challenges to Optimal Power Flow*” IEEE Transactions on Power Systems December 21,1995.

[4] Vincent Del Toro, Electric Power System “Optimal Dispatch of Generator”, Prentice Hall, New York, 1992, pp.334-362

[5] Kyu-Ho Kim, Jae-Kyu Lee, Department of Electrical Engineering Ansan College of Tech, Korea *“Security Constrained OPF by Hybrid Algorithms in Interconnected Power System*”, IEEE Transactions on Power Systems 2001.

[6] R.K Rajput, Power Plant Engineering 3rd Edition, Laxmi Publication (P) Ltd, New Delhi India, 2005, pp.696-779

[7] El Howary, Department of Mechanical Engineering, Electric Power System, Prentice Hall , Virginia, 1983, pp.701-732

[8] H. Lee Willis & Walter G Scott, Distributed Power Generation *“ Planning & Evaluation”*, Markel Dekkar Inc, 2000.

[9] Wood, A.J. and Wollenberg, B.F., "Power Generation, Operation, and Control", John Wiley & Sons. Inc., 1996.

[10] http://www.nrel.gov/homer

[11] Miller, R.H. and Malinnowski, J.H., "Power System Operation", McGraw-Hill Inc., 1994.

[12] Stevenson, W.D., Jr., "Elements of Power System Analysis", 4 th edition, McGraw-Hill, Inc., 1982.

[13] Nagrath, I.J. and Kotnari, D.P., "Power System Engineering", Tata McGraw-Hill Publishing Company Limited, New Delhi, 1995.

[14] Glover, J.D. and Sarma, M, "Power System Analysis and Design", PWS Publishing Company, Boston, 1994.

[15] http://www.wikipedia.com