Optimization of Energy and Reserve in a Centralized Electricity Market

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Abstract—**The objective of this project is to develop a programming model to minimize the overall cost of providing electrical and reserve in a centralized electrical market. The model is used to calculate the power produced and ancillary provided by different generators, then to find the price for energy and ancillary service considering that the energy and reserve market is co-optimized. Using the prices, the revenue, the cost and the profit of each of the generating unit are calculated. It is important to the system operator to determine the minimum cost through a cost benefit analysis in order to determine the optimum amount of services purchased to what is truly necessary to maintain the security. On the other hand there will be no generator that will receive a disadvantage when being asked to provide reserve. The relationship between the energy price and the ancillary price is discussed. Linear programming (Linprog) and genetic algorithm (GA) technique are used to solve the problem.**

Keywords-component; linear programming (Linprog); genetic algorithm (GA); ancillary;

I. INTRODUCTION

Electricity market is the lifeblood of human life today. The importance of using electricity in their daily activity is not denied. Indirectly, the coast of electricity service has expended. Since the beginning of power market's liberalization the power plant business has been changing fundamentally and the power plants find themselves in a much more challenging market environment with the presence of strong competition, higher fluctuation of fuel prices and missing long term power purchase agreements. But apart from these new challenges, market's liberalization also comes along with new business opportunities, it is an ancillary service. Because of that, the power plant must provide some services to support capacity and the transmission of energy from resource to load while maintaining reliable operation of the transmission system in accordance with good utility practice. Therefore, by knowing this opportunity, the generating company can get more profit and also it can help to keep the system in balance.

Ancillary services are supplementary contributions to system operation made by the system operator to have a secure and reliable system operation. Ancillary needed by the system operator to maintain the security so that the system is always in stable and balance condition. Main ancillary service includes the frequency control, transmission system security, voltage stability and system restoration. In order to maintain the market for electricity, the system operator needs some resources to maintain the security of the system that must be obtained from other participants in the form of ancillary service [1].

The market for ancillary service is dividing into two types, which is in long-term contract and spot market. Long-term contract are preferable for service in which the amount needed does not change or less with time. While for the spot market, it is needed for the services in which the needs is vary substantially over the course of the day and offers change because of the interactions with the energy market. Last part of the necessary reserve is often provided by a short-term market mechanism [2].

Through a market mechanism, the system operator has been given the responsibility to buy the ancillary service on behalf of the users of the system. Assuming that the market mechanism has been adopted for the procurement, the providers of these services need to be paid by the system operator while the costs can be recovered from the users. To get the payment from the users in a fair share of the costs, the system operators have to buy the optimal amount of service and pay at the right price [2].

The co-optimization is necessary to minimize the overall cost of providing electrical energy and reserve in the market because of the strong interaction between the supply of energy and the provision of reserve. Energy and reserve should be offered in joint market that should be cleared simultaneously to optimize costs. For this problem statement, it must consider the generators must operate part-loaded to provide a spinning reserve. As a result, generators which are more expensive may have to produce more energy in the market and the generator that provide spinning reserve may be less efficient that if they would be running at full load. Therefore, the price of electrical energy may be higher when meeting reserve requirements [2].

This paper proposes a model to find the optimal energy and ancillary services that will provide by the generators using linear programming and genetic algorithm technique. Linear programming is a mathematical method that deals with solving optimization problems such as maximized and minimized the

cost. Linear programming problem consist of an objective function, linear equalities constraints and linear inequalities constraints that have consist a certain number of variables [3]. Linear programming is heavily used in company management such as production, planning and other issues because of most companies like to maximize profit or minimize cost with limited resources.

II. METHODOLOGY

The methodology of this project consist of six steps such Literature Review and problem analysis, understanding the linear programming and genetic algorithm technique, design the linear programming using matlab, running the programming, analysis the result and documentation as shown in Fig. 1.

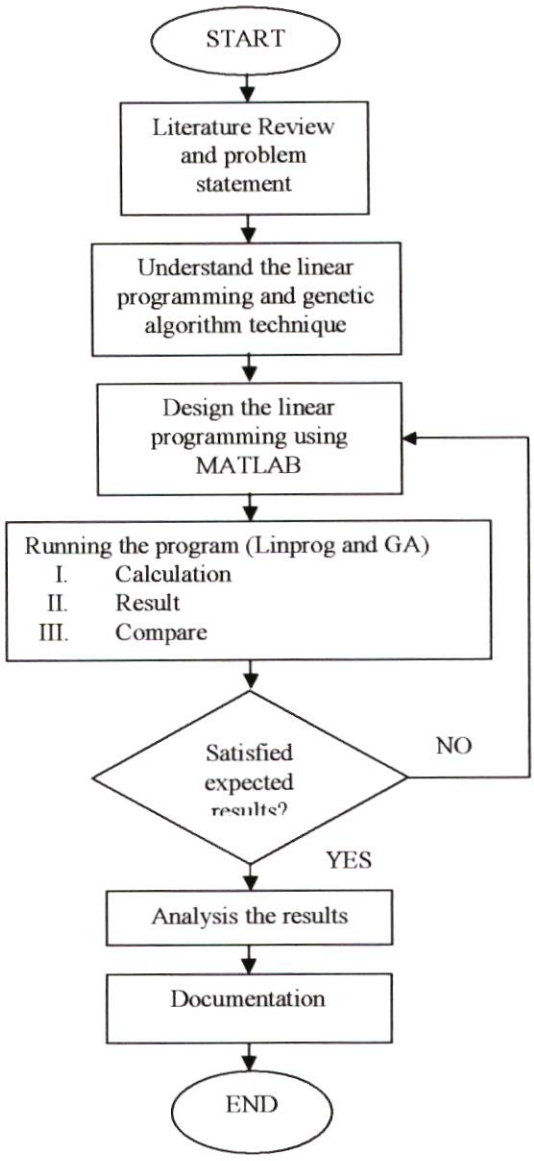


Figure 1. Flow chart of the project

III. MATHERMATHICAL FORMULATION

The co-optimization of energy and reserve market is modeled as an optimization problem with the objective to minimize the total cost as expressed in Equation 1.

$$min\{\sum_{i=1}^{N} MCB_i P_i\} \quad (1)$$

The objective function is subjected to several constraints:

$$\sum_{i=1}^{N} Pi = D \quad (2)$$

$$\sum_{i=1}^{N} R_i \geq RS_{min} \quad (3)$$

$$P_{i,min} \leq P_i \leq P_{i,max} \quad (4)$$

$$R_{i,min} \leq R_i \leq R_{i,max} \quad (5)$$

$$P_i + R_i \leq P_{i,max} \quad (6)$$

where MCB_i is the marginal cost of producing energy for generating unit i, P_i is the power produced by the generating unit i, N is the total generating unit in the system, D is the demand in MW, R_i is the ancillary service provided by the generating unit i, RS_{min} is the minimum reserve requirement in the system, $P_{i,min}$ and $P_{i,max}$ is the minimum and maximum output power that can be produced by generating unit i, $R_{i,min}$ and $R_{i,max}$ is the minimum and maximum reserve that can be provided by generating unit i.

The first constraint in Equation (2) is subjected to the power balance. Equation 3 constraint the reserve in the system must at least equal to the minimum reserve requirement in the system. Each of generating unit is also constrained by its minimum and maximum energy that can be supplied as in Equation 4 and minimum and maximum reserve that can be provided as in Equation 5. Equation 6 shows the interaction between energy and reserve.

IV. MODELINNG CO-OPTIMIZATION OF ENERGY AND RESERVE MARKET

A. Linear Programming

Linear programming is a technique for the optimization for a linier objective function, subject to linear equality an linear inequality constraints. Linear programs are problem that can be expressed in form [4]:

Linprog: $\min_x f^T x \{Ax \leq b, A_{eq}x = b_{eq}, lb \leq x \leq ub\}$

where x represent the vector of variables, A and b is matrix coefficients for inequalities, A_{eq} and b_{eq} is matrix coefficients for equalities and lb and ub is the lower and upper bounds for the constraints. The entire problem is expressed in matrix form. There is a step to be done while using this technique in Matlab, first, all bounds, linear equalities and inequalities has to separate. Then all variables combined in one vectors. After that, all the bounds, equalities, inequalities constraints and the objective function was write in matrix or vector form. Finally, call the solver form the Matlab toolbox and it will automatically calculate to find the value of variables and the minimization cost of the objective function.

B. *Genetic Algorithm (GA)*

Genetic algorithm is proposed by Holland in university of Michigan in 1975. Genetic algorithm is the process of natural evolution and organism adapts to external environment through heredity and mutation. The organisms which have more excellent characteristics can survive and reproduce, while those without excellent characteristics will eventually disappear [5].

For the Genetic Algorithm (GA), it simulates the phenomena of reproduction, crossover and mutation that occur in the process of natural heredity. From that, an initial population is randomly generates and produce individual with higher fitness through reproduction, crossover and mutation. For the result, it generates a group of individuals with best fitness and finally it can obtain the optimal solution [6]. This technique has a flow chart to be understood by using a matlab toolbox as shown in Fig. 2 [7].

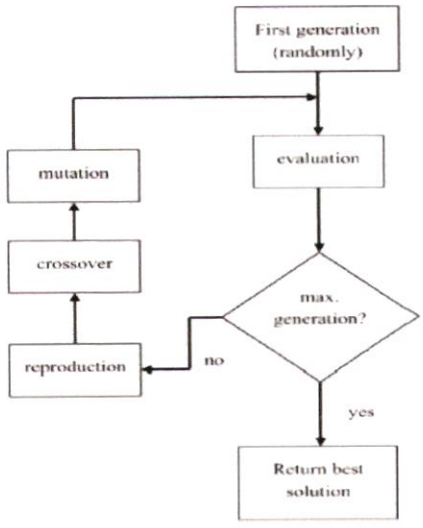


Figure 2. Genetic algorithm flow chart.

The specific operation of GA can be described as follows [5]:

i. Initialization: certain number of chromosomes encoded by binary numbers is generated to form an initial group.

ii. Fitness values calculation: the function value has been regarded as the individual fitness values.

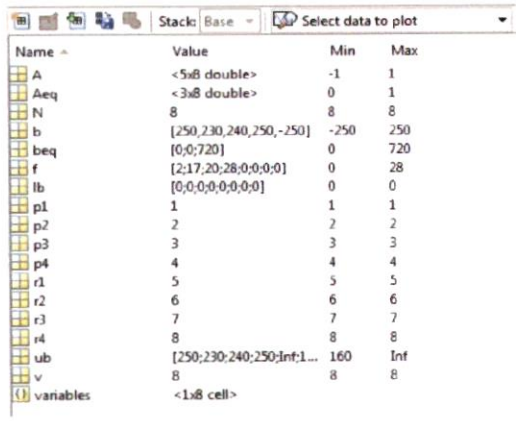
iii. Selection: excellent individuals been selected from the current group and get the opportunities as a parent to reproduce.

iv. Crossover: crossover operations are the process to produce a new generation who combines the characteristics from their parents.

v. Mutation: process to change the individual's encoding information to generate a new individual.

C. *Linear programming and GA using Matlab toolbox*

From this problem, all the constraint and objective function determined. By using matlab, all the variable, equalities and inequalities, bounds and objective function was easily written on the command windows and save it on workspace and It will shown in Fig. 3.



Name	Value	Min	Max
A	<5x8 double>	-1	1
Aeq	<3x8 double>	0	1
N	8	8	8
b	[250,230,240,250,-250]	-250	250
beq	[0;0;720]	0	720
f	[2;17;20;28;0;0;0;0]	0	28
lb	[0;0;0;0;0;0;0;0]	0	0
p1	1	1	1
p2	2	2	2
p3	3	3	3
p4	4	4	4
r1	5	5	5
r2	6	6	6
r3	7	7	7
r4	8	8	8
ub	[250;230;240;250;Inf;1...	160	Inf
v	8	8	8
variables	<1x8 cell>		

Figure 3. The variable in worspace.

After the entire variable saved in workspace, the final step is calling the solver either Linprog solver or GA solver by choosing in the matlab toolbox so then the final result can compared and the best result can selected. The "main" Linprog and GA toolbox is shown in Fig. 4 and Fig. 5.

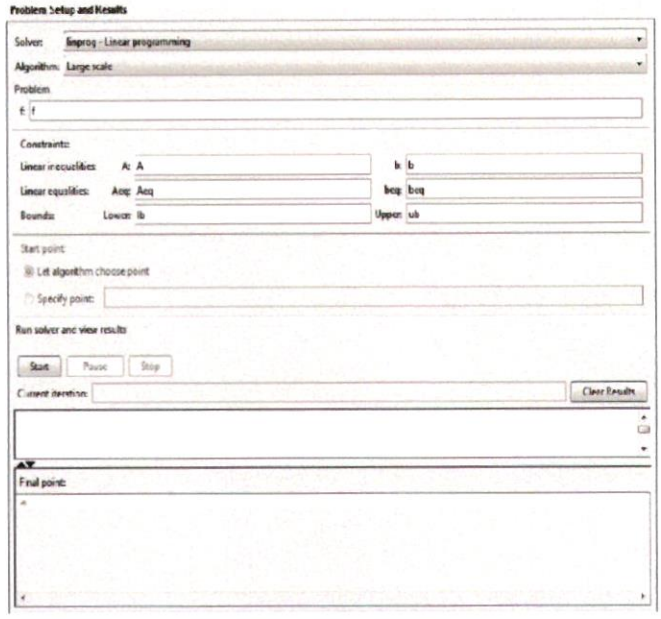


Figure 4. Linprog toolbox

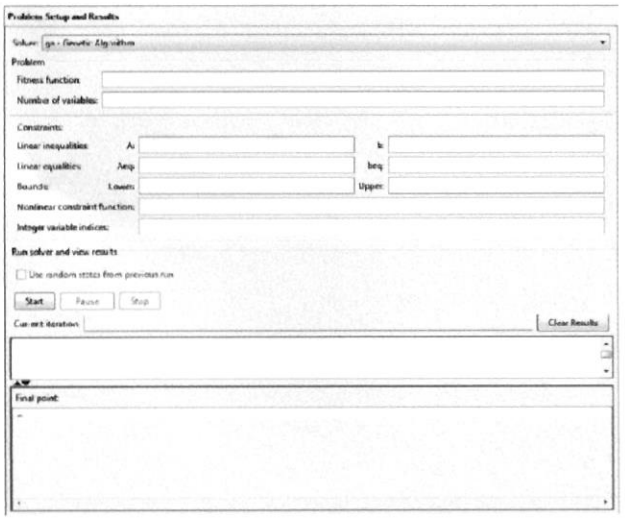


Figure 5. GA toolbox

V. TEST DATA

The proposed techniques i.e. Linprog and GA have been tested using a test system consist of four generating units. The marginal costs and the minimum and maximum power that the unit can deliver are shown in Table 1.

These generators are assumed to have a constant marginal cost. From that, their respective abilities to provide reserve are quite different for each others. Unit 1 and unit 4 cannot provide any reserve. By the way, unit 2 and unit 3 can provide a limited reserve not only by their capacity but also by their ability to respond.

This market electricity problem was assumed a small market where the demand varies between 300 to 720MW. Then, only one type of reserve is needed to maintain the security for all loading condition and that is 250MW of reserve is required. Four generators were connected to this system and the system operator was responsible to for purchasing security on behalf of the users of the system. Then, this market also has to operate on centralized model, that the generators bid to produce electrical energy are equal to their marginal coast and that the market rules do not include separate bids for the provision of reserve. Other than that, the generators do not incur a direct cost when providing reserve. The dispatches that minimize the cost of production were determined by the system operator. As a result, there is no generator having a disadvantage when being asked to provide reserve rather than produce electrical energy.

Table 1: marginal cost, maximum output and reserve capability of the generating units

Generating Units	Marginal cost of energy ($/MWh)	P max (MW)	R max (MW)
1	2	250	0
2	17	230	160
3	20	240	190
4	28	250	0

VI. RESULTS AND DISCUSSION

The main purpose in this problem issue is to minimize the overall cost of providing electrical energy and reserve according to the objective function and constraints given. The final result for each technique was selected and compared to find the best result for a range of value of the demand (300-720MW). For the final result, the value from Linprog was selected because it given the minimal objective value compare to the GA technique. For the example, it showed in figure 6 and 7. From the result, it shown that the Linprog is more accurate in calculating the linear equation objective function

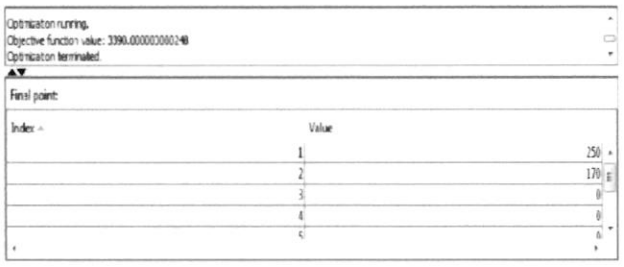


Figure 6. The objective function and all variable value for demand 420MW using Linprog

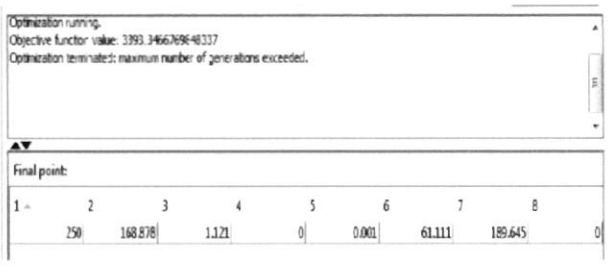


Figure 7. The objective function and all variable value for demand 420MW using GA

The entire variable and the objective function calculated for each demand. The solution of the optimization problem for a range of value of the demand is shown in table 2.

Table 2: Result for value of the demand D ranging from 300 – 720MW

Demand (MW)	P1 (MW)	P2 (MW)	P3 (MW)	P4 (MW)	R1 (MW)	R2 (MW)	R3 (MW)	R4 (MW)
300 - 420	250	50 - 170	0	0	0	60	190	0
420 - 470	250	170	0 - 50	0	0	60	190	0
470 - 720	250	170	50	0 - 250	0	60	190	0

For a better understanding of this physical meaning of the price of reserve and its evolution as the demand changes can easily check by hand. Given that the minimum demand is 300MW, it can be conclude immediately that unit 1 must produce its maximum output of 250MW because it has the lowest marginal operating coast and cannot provide reserve. Other than that, unit 1 also has to provide their maximum

output for all value of demand. From the table 2, it shown that unit 2 is the marginal generator for the demand in the range between 300-420MW. It is because, it have to produce between 50 - 170MW of energy. So then, the price for energy in this range of demand is set to the marginal cost of unit 2, which is 17$/MWh. The price of the reserve of this range of demand is set to zero because units 2 and 3 provide more than enough reserve.

When the demand is in range of 420-470MW, unit 3 becomes the marginal generator and the price for this range is set to 20$/MWh. Unit 3 is chosen as a marginal generator because it progressively increases its output from 0 to 50MW. Unit 2 is capped at 170MW of output energy because its must provide at least 60MW of reserve according to the minimal objective function solution. The price of reserve for this range of demand is set by the cost affected when an additional megawatt of reserve is requirement. From the table 2, it shown that unit 3 already provides the maximum reserve which is 190MW. When an additional megawatt of reserve needed, unit 2 have to reduce the output of energy so than its can increase reserve output. To compensate for this reducing of energy on unit 2, unit 3 have to increase their output and it cost 20$/MWh, while the reduction in the output of unit 2 would save 17$/MWh. Finally, the price of reserve is equal to the net cost of getting an additional megawatt of reserve which is 20 – 17 = 3$/MWh.

When the demand is in range of 470 to 720MW, unit 4 become the marginal generator and the price for this range is set to 28 $/MWh because it is progressively increases it output from 0 to 250MW. Unit 3 is capped at 50MW of output energy because its must provide at least 190MW of reserve. The price of reserve for this range of demand become 28 – 17 = 11$/MWh. This is because unit 2 must to reduce their output of energy to get an additional megawatt of reserve and it would save 17$/MWh. So then, unit 4 was increases their output to compensate for that reduction and it would cost 28$/MWh. Summarizing of the price of energy and reserve is shown in figure 8.

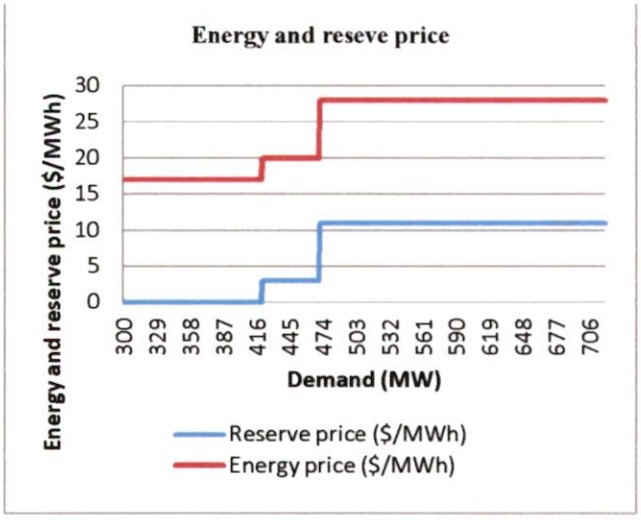


Figure 8. Energy and reserve price

From this result, unit 1 is always operating at full output and the marginal cost is determined by the other generators. That mean, it always makes a healthy operating profit since its own marginal cost is always lower than this price. The overviews of the revenues cost and profit for unit 1 is shown in figure 9. For unit 4

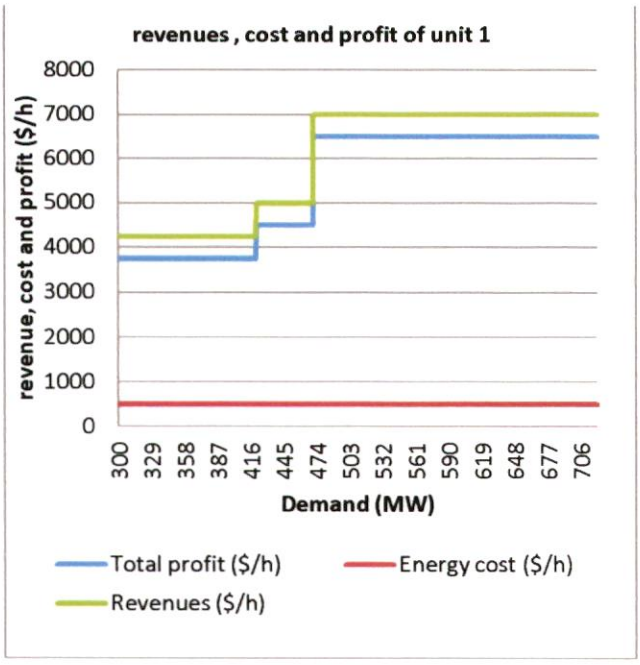


Figure 9. Revenues, cost and profit of unit 1

In the range of demand between 300 to 420MW, the market price is 17$/MWh for energy and 0$/MWh for reserve. Unit 2 does not make an economic profit since the price is equal to their marginal cost. By the way, when the range of demand is between 420 to 470MW, the energy price is 20$/MWh and the reserve price is 3$/MWh. Which means that unit 2 make a profit on each megawatt-hour it produce because the marginal cost for producing energy of unit 2 is 17$/MWh. This unit 2 also makes additional revenues from selling the reserve since it is also provided 60MW of reserve. But, it is exactly equal to the opportunity cost of not selling energy. In the same range of demand, unit 3 does not make a profit from the sale of energy since the price of energy is equal to the marginal cost for unit 3. But, it make a profit for sell a reserve since it provide 190MW at price of 3$/MWh.

In the range of demand between 470 to 720MW, the market price is 28$/MWh for energy and 11$/MWh for reserve. Unit 4 does not make an economic profit since it become the marginal producer and it is not produce a reserve. Unit 2 and 3 is still making a profit for selling energy and reserve since it has a lower marginal cost than the price. Summarizing of the revenues, cost and profit for unit 2, 3 and 4 is shown in figure 10, 11 and 12.

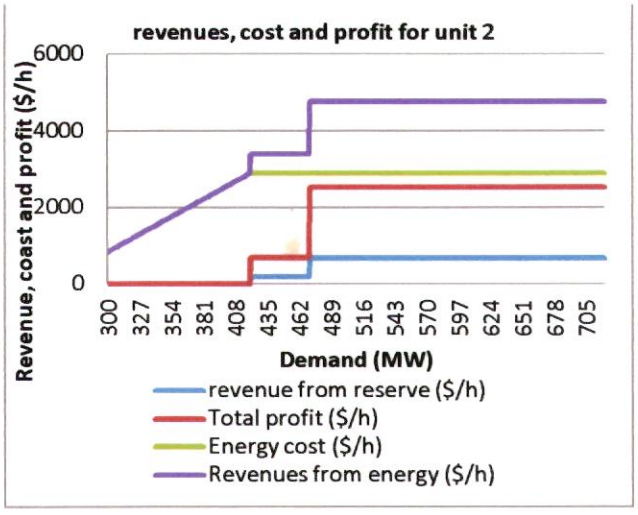


Figure 10. Revenues, cost and profit of unit 2

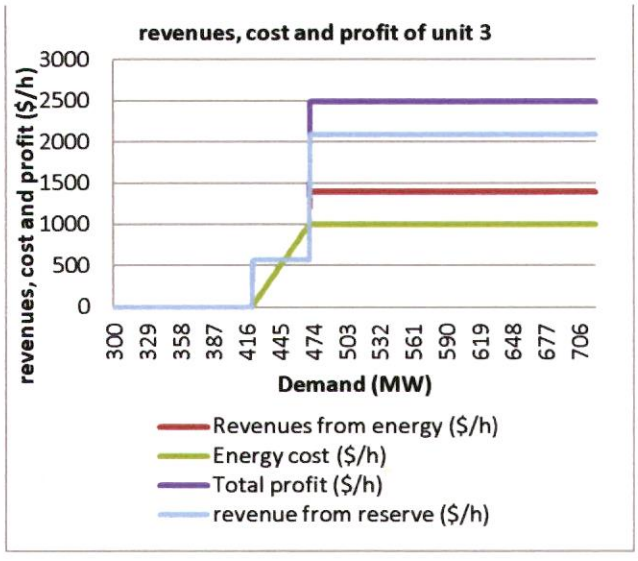


Figure 11. Revenues, cost and profit of unit 3

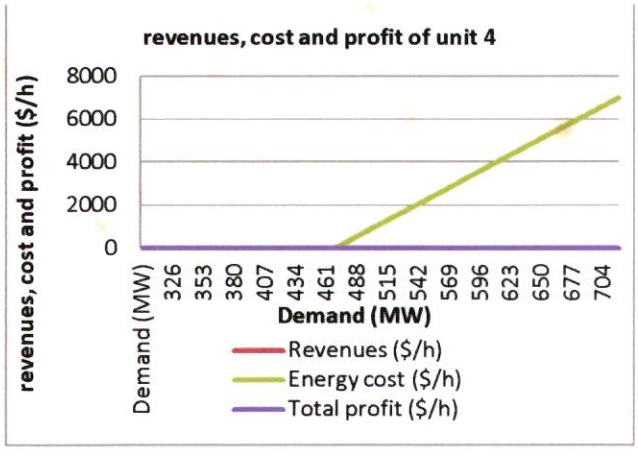


Figure 12. Revenues, cost and profit of unit 4

VII. CONCLUSION

This paper proposes a framework to find an optimal cost of production to be done by the system operator as measured by the bid price from the generating company. This model exactly can be used to estimate an optimal cost of production and seting the price in electricity market. From the result obtained, there is no generator is at disadvantage when being asked to provide reserve rather than produce an energy. The relationship between generators that produce reserve and energy to the market can be seen on the result and discussion when it clearly shown that the generator can get an additional profit when it sell the reserve even though it does not sell an energy. Other than that, this paper shown the different between linear programming compare to the genetic algorithm technique. The linear programming technique clearly has an advantages when the objective function is in linear form. The genetic algorithm technique may have an advantages when the problem was including the multiple objective function and non-linear constraints.

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