# Economic Dispatch Strategy for Solar Hybrid System using Lambda Iteration Method

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***Abstract*—A method for optimal power dispatch of hybrid system consisting of Solar-Diesel-Battery systems in remote area is presented. The aim of this paper is to provide a performance analysis of the method applied for cost reduction related to the constraint and satisfaction of load demand. The method presented utilizes the data and parameter of the Bario Solar Hybrid Central Station, Bario, Sarawak, Malaysia (3.7350° N, 115.4793° E). This work proposes a MATLAB software package to estimate optimal real power value with the least generating cost for the system. The operation, maintenance and investment costs are specified in the cost functions of the energy sources and will consider the assumption of equal incremental cost. Different case study has been carried out to solve the system equation and finally, the result from the proposed method is to be compared to a reduced gradient optimization method. It is found out the method in this study proved to be effective by giving an improved optimization results and efficiency for obtaining optimal power dispatch with few parameters in various tested conditions.**

***Index Terms*—Economic Dispatch; Solar Hybrid; Lambda Iteration; Reduced Gradient Method.**

## I. INTRODUCTION

Solar Hybrid system is expected to become part of the next electric power system evolution, targeting rural and remote area, where the grid connection is almost impossible in term of cost and geography concern. [1]. A typical hybrid energy station consisting two or more energy systems, energy storage system, power converting equipment and a controller. They are generally islanded and centralized electric power grid that used in remote areas [2]. The higher cost to transport the fuels to this area is considered one of the major issues in reducing the cost of power generation. [3]. To overcome the increment of power generating cost for diesel system, photovoltaic system is one of the solutions as solar power is often the most economical alternative energy source for remote regions. [4]. The investment and fuel cost need to be minimized while meeting the power demand thus various optimization techniques are being introduced to give minimal cost on fuel and operation of the whole system. [6]-[7].

In this paper, an economic dispatch optimization is considered and the computational Lambda Iteration and Reduced Gradient Method is implemented to obtain the minimum cost of the system. The Lambda Iteration Method is considered based on its effectiveness to achieve optimal cost condition of the generating system. [5]-[8].

In this paper, economic dispatch optimization in solar hybrid system is considered. The Lambda Iteration Method and Reduced Gradient Method is implemented to obtain the minimum cost of the system. However, this computational method works well by considering generator constraints without the transmission loss and it heavily depends on the selection of initial generator value [9].

The structure of hybrid system with different energy sources is discussed in Section II followed by the elaborations of mathematical formulation for the economic dispatch in Section III. Section IV discusses the Lambda Iteration Method and Reduced Gradient Method for optimization analysis and the comparison results by with different scenarios are presented in Section V. Section VI concludes the comparative findings followed by the references.

## II. SOLAR HYBRID STRUCTURE

Figure 1 shows the Solar Hybrid system with the capacity 200kW, 550kW, 250kW diesel generator, 385kW battery as storage and 887kW at standard test condition photovoltaic array. The system is considering 3696 unit of solar panels and 720 unit of lead-acid batteries with the capacity of 2680AH supplying 2.072MW at full running capacity. Generator 3 is used to provide a reliable source of energy during power outage while battery is used as energy storage. The 24 hours of a day load data for the analysis is presented in Table 1.

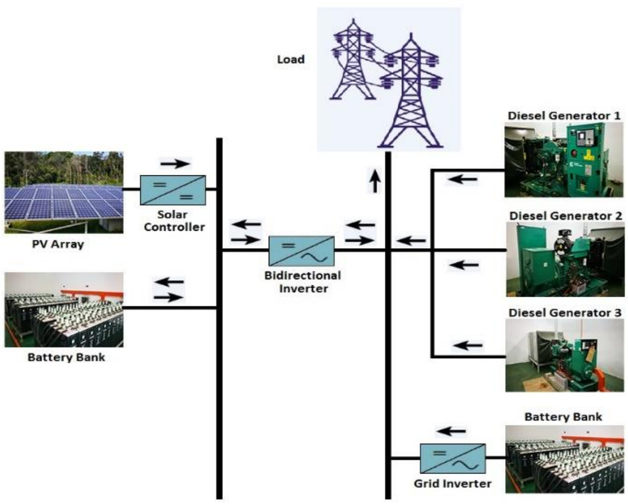


Figure 1: A Solar Hybrid System with Load and All Energy Sources

Table 1
A 24 Hours Load Demand

| Time | Houses | School | Offices | Load (MW) |
|---|---|---|---|---|
| 00H | 0.5 | 0.15 | 0.02 | 0.67 |
| 01H | 0.5 | 0.15 | 0.02 | 0.67 |
| 02H | 0.5 | 0.15 | 0.02 | 0.67 |
| 03H | 0.5 | 0.15 | 0.02 | 0.67 |
| 04H | 0.5 | 0.15 | 0.02 | 0.67 |
| 05H | 0.6 | 0.25 | 0.02 | 0.87 |
| 06H | 0.6 | 0.25 | 0.02 | 0.87 |
| 07H | 0.7 | 0.25 | 0.03 | 0.98 |
| 08H | 0.8 | 0.35 | 0.03 | 1.18 |
| 09H | 0.8 | 0.35 | 0.04 | 1.19 |
| 10H | 0.8 | 0.35 | 0.04 | 1.19 |
| 11H | 0.8 | 0.55 | 0.04 | 1.39 |
| 12H | 0.7 | 0.55 | 0.04 | 1.29 |
| 13H | 0.7 | 0.35 | 0.04 | 1.09 |
| 14H | 0.7 | 0.35 | 0.04 | 1.09 |
| 15H | 0.7 | 0.45 | 0.04 | 1.19 |
| 16H | 0.7 | 0.45 | 0.04 | 1.19 |
| 17H | 0.7 | 0.45 | 0.04 | 1.19 |
| 18H | 0.8 | 0.5 | 0.03 | 1.33 |
| 19H | 0.8 | 0.5 | 0.01 | 1.31 |
| 20H | 0.8 | 0.5 | 0.01 | 1.31 |
| 21H | 0.8 | 0.45 | 0.01 | 1.26 |
| 22H | 0.7 | 0.25 | 0.01 | 0.96 |
| 23H | 0.6 | 0.15 | 0.01 | 0.76 |

## III. Mathematical Model of Solar Hybrid

The economic dispatch problem is mathematically described with the operation of N generating unit with real power output (MW). It is based on Second order Lagrangian cost function as given by this following equation [8].

$$Fi(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \tag{1}$$

where:

$i$ = Generating source of $i$
$P_i$= Real power output of each energy source $i$
$F$= Operating cost in $/hr of each unit of $i$
$\alpha, \beta, \gamma$ = Quadratic cost function in $/hr of each unit of $i$

This study is analyzing a system without transmission losses as explained in following equations.

The total cost for the station is the sum of the cost of each individual unit as given by:

$$P_D = \sum_{i=1}^{N} (P_i) \tag{2}$$

This equation can be rearranged as:

$$P_D - \sum_{i=1}^{N} (P_i) = 0 \tag{3}$$

where $P_D$ is the power demand in the hybrid station.

The generating unit has its minimum and maximum generating limit as described by:

$$P_i min \leq P_i \leq P_i max \tag{4}$$

where $P_i min$ is the minimum generation limit of unit $i$ and $P_i max$ is the maximum generation limit of unit $i$.

The incremental cost of each unit in the system is considered to be equal in order to achieve optimal dispatch,

$$\frac{\delta Fi}{\delta Pi} = \frac{\delta F_2}{\delta P_2} \dots\dots \frac{\delta F_N}{\delta P_N} \tag{5}$$

$$\frac{\delta Fi}{\delta Pi} = \lambda \tag{6}$$

where $\lambda$ is named as incremental cost of the system.

The optimal condition as described in Equation (5) and (6) is now simplified to:

$$\frac{\delta Fi}{\delta Pi} = \beta_i + 2\gamma_i P_i \tag{7}$$

$$\beta_i + 2\gamma_i P_i = \lambda \tag{8}$$

Therefore:

$$P_i = \frac{\lambda - \beta_i}{2\gamma_i} \tag{9}$$

$$P_i + P_i^2 \tag{10}$$

### A. Battery

The cost function of the battery is given as:

$$F_5(P_5) = aI^P P_5 + G^E P_5 \tag{11}$$

$$F_5 = 117.52 P_5 \tag{12}$$

For the steady-state condition the battery charges at the rate of C/2 and discharges at C/3. In this system, the battery bank act as a load during the charging mode with the amount of total load of 1.0MW. Investment per unit installed, $I^P$ and the total operation and maintenance cost, $G^E$ are considered 1000$/kW and 2.0cent/kW respectively. For this analysis, a battery bank of 385kW rating is considered.

### B. Solar Energy

A total number of 3696 photovoltaic panels are combined to generate 887kW of total power. Each panel will produce the allocation of 240W total power to feed the required power demand for the analysis. By considering the plant is last for 20 years with the projected interest rate and other parameters, the data sources are presented in Table 2. The load data for solar hybrid station for 24 hours is shown in Table 1. Mathematical cost formulation is given as in this following equation:

$$F(P_4) = aI^P P_4 + G^E P_4 \tag{13}$$

where:

$$a = \frac{r}{[1 - [(1+r)^{-N}]} \tag{14}$$

where:

$P_4$ = Solar generation (kW)
$a$ = Annuitization coefficient
$r$= Interest rate; 10 per cent
$N$= Lifetime; 20 years
$I^P$= Investment cost per unit; 3000$/kW
$G^E$= Operation and maintenance cost; 2.0 cent/kW

Table 2
Input Data for Solar panel

| Item | Value |
|---|---|
| Number of panels (Unit) | 3696 |
| Output Power (Watt) | 240 |
| Interest Rate (%) | 10 |
| Lifetime (Years) | 20 |
| Investment Cost per Unit($/kW) | 3000 |
| Operation and maintenance cost (cent/kW) | 2.0 |

Finally, the cost function that based on equation (13) is given as:

$$F_4\ (P_4) = 352.52\ P_4 \tag{15}$$

### C. Diesel Generator

The operating costs of the generators are in $/h. The optimal scheduling of the generators has to be within the maximum and minimum limits of each of the generators. [6]. The total load demand of the system is scheduled to be at 2.07MW. The fuel cost coefficients are shown in the following Table 3.

Table 3
Cost Coefficients of the Generators

| Cost Coefficient | Energy Sources Gen 1 ($P_1$) | Gen 2 ($P_2$) | Gen 3 ($P_3$) |
|---|---|---|---|
| *α ($/hr)* | 9.0 | 15.0 | 10.0 |
| *β ($/hr)* | 0.15 | 0.3 | 0.2 |
| *γ ($/hr)* | 0.00010 | 0.00025 | 0.00015 |

### D. Constraint Functions

The energy source should be always meet the load demand.

$$P_1 + P_2 + P_3 + P_4 + P_5 = P_{LOAD} \tag{16}$$

All the energy sources have lower and upper limits.

$$P_i min \le P_i \le P_i max \tag{17}$$

The battery has to be within its state of charge (SOC) range. [10].

$$P_5\ (min) \le P_5\ (k) \le P_5\ (max) \tag{18}$$

Finally, the constraints for all energy source based on analyzed data are given in the following table.

Table 4
Equality Constraints of All Energy Sources

| P1 | P2 | P3 | Solar Energy | Battery |
|---|---|---|---|---|
| $0 \le P_1 \le$ 250kW | $0 \le P_2 \le$ 550kW | $0 \le P_3 \le$ 200kW | $0 \le P_4 \le$ 887kW | $100 \le P_5 \le$ 385kW |

## IV. Implementation

### A. Lambda Iteration Method by Matlab Computation

1. The input data such as tolerance, number of iteration, coefficient, generator limits and load demand will be initialized.
2. Power output for each unit is calculated using Equation (15).
3. If generation limits are exceeded the non-convergence procedure will be taken. Else, it will go to Step 5.
4. The iteration limit should not be exceeded. Else, it will go to Step 5.
5. The power output for each plant has to be less than the set limit and increment counter. Else, Step 6 is considered.
6. The power output for each plant has to be more than set limit and increment counter. Else, Step 7 is considered.
7. The total output power is calculated using equation (16).
8. The total power has to be less than set tolerance value so that the iteration will be stopped.
9. If the total power is greater than zero, the incremental cost, iteration counter has to be reduced. Else, increase the value and go to step

The sequences are simplified in the following Figure 2.

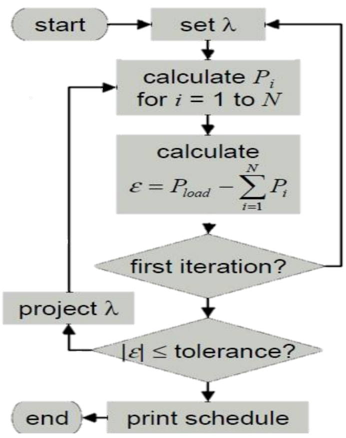


Figure 2: Simplified Lambda Iteration Process

### B. Reduced Gradient Method

1. A hybrid system with 2 unit running diesel generator ($P_1$ , $P_2$), solar ($P_4$) and battery ($P_5$) is considered.
2. Initial power of $P_1$, $P_2$, $P_4$ and $P_5$ is considered.
3. $P_3$ is always considered as backup generating unit and expressed as:

$$P_3 = P_{Load} - P_1 - P_2 - P_4 - P_5 \tag{19}$$

where $P_{LOAD}$ is the load demand.

4. The total cost to be minimized is based on cost function $P_1$, $P_2$, $P_3$, and $P_4$ respectively.

$$C = F_1 P_1 + F_2 P_2 + F_4 P_4 + F_5 P_5 + F_3 \tag{20}$$
$$(P_{Load} - P_1 - P_2 - P_4 - P_5) \tag{21}$$

5. Do the iteration by finding:

$$\nabla \text{ COST} = \begin{bmatrix} \frac{d(COST)}{dP_1} \\ \frac{d(COST)}{dP_2} \end{bmatrix} \tag{22}$$

6. Find power generated after each iteration for each unit using:

$$X_1 = X_2 - \nabla \text{COST} \times (\alpha) \quad (23)$$

where:

$X_1$ = power ration $[\frac{P_1}{P_2}]$

α = acceleration factor for the experimental value of 10.

7. The iteration of step 5 until 6 is completed when the incremental cost at energy source 3 is equal to energy source 1 and 2, for a three-unit hybrid system.
8. The above gradient has been 0. Else repeat the step 6.

## V. RESULTS AND DISCUSSION

The lambda iteration method is used to obtain and economic dispatch in hybrid system is obtained using MATLAB operation discussed in this following section.

1. A solar hybrid system with 2 running generators ($P_1$ and $P_2$), solar ($P_4$) and battery ($P_5$) is considered with the total maximum output power of 2.072MW.
2. Generator 3 ($P_3$) is considered as a backup power supply during outage for both analysis.
3. The total cost to be minimized is the cost function in Equation 21.
4. $F_1$, $F_2$, $F_3$, $F_4$ are the cost function of $P_1$, $P_2$, $P_3$, and $P_4$ respectively.
5. The implementation of the method and its flow is based on sequence explained in Section IV.

Table 4
Power Generated to Satisfy Total

| Power Source | Power Generated (MW) Lambda Iteration Method | Power Generated (MW) Reduced Gradient Method |
|---|---|---|
| P1 (Generator) | 0.21 | 0.22 |
| P2 (Generator) | 0.53 | 0.55 |
| P3 (Generator) | 0.00 | 0.00 |
| P4 (Solar) | 0.88 | 0.85 |
| P5 (Battery) | 0.38 | 0.38 |
| Total Power | 2.00 | 2.00 |

From the result obtained when all sources are included, with the exemption of Generator 3 as a power backup, the lambda iteration method initialized a total power value of $/MWh with the incremental cost of 21.652$/MWh, while for the same power value the genetic algorithm contributes an incremental cost of 22.903$/MWh. The incremental cost of all power unit is based on successive approximation and equal incremental cost principle. This is carried out using the proposed MATLAB 7.11.0 (2010b) software.

As shown in Figure 3, the total power demand is 1.33MW with an incremental cost of 14.399$/MWh and 15.230$/MWh for respective lambda iteration method and reduced gradient method. In the next case of minimum power demand of 0.61MW at 0100 hours, only diesel generator 2 and battery bank are supplying load meet the demand for both methods with the incremental cost of 6.604$/MWh and 6.985$/MWh respectively. The particular result is shown in Figure 4.

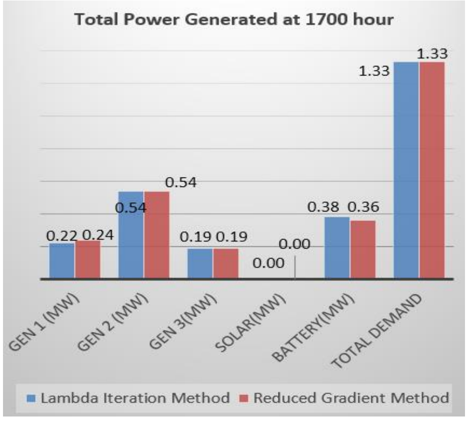


Figure 3: Power Generated at 1700 Hour

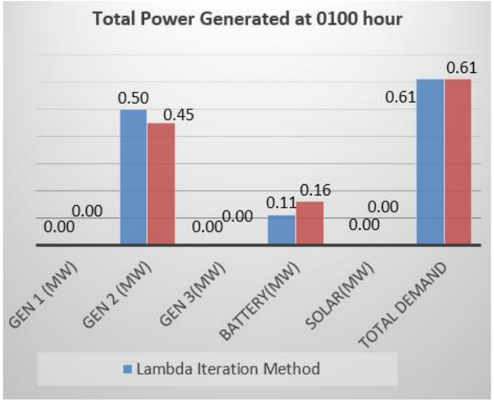


Figure 4: Power Generated at 0100 Hour

In the next case, the total cost will be reduced due to the exemption of generator 2 and generator 3 as shown in Figure 5. Since the solar energy is fully running at it full capacity, the system is considered to more economic due to the least usage of a diesel generator.

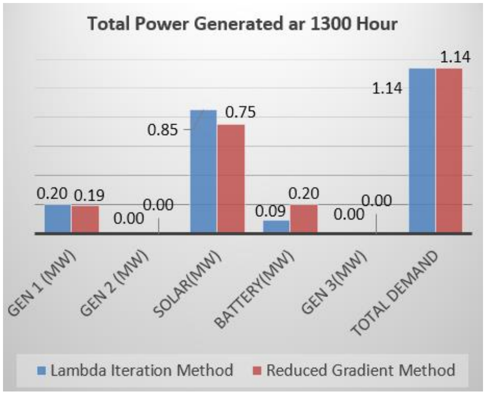


Figure 5: Power Generated at 0100 Hour

## VI. CONCLUSION

This paper explores the possibility of the proposed method to solve an economic dispatch by respecting all energy source constraints. The method was implemented using MATLAB software considering 3 different energy source in the hybrid station. The computational result shows that in various case studies the proposed method generates a capability and efficiency results when compared to a reduced gradient method. In addition, the proposed technique provides the best optimal value of an incremental cost with relatively lesser computational time and a number of iteration. Further, the proposed optimization method could be used to optimize a hybrid Solar-Diesel-Battery system at different region and peak sun-hours condition.

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