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Optimal Sizing and Control Strategy of Hybrid PV-Diesel-Battery Systems for Isolated Island*

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***Abstract*—A method for optimal sizing of hybrid system consisting of PV-Diesel-Battery systems in isolated area is presented. The aim of this paper is to provide a reference for total cost reduction of the system related to constraints and satisfactions of load demand. The cost objective functions include the total cost for minimizing CO_2 emissions and customer damage cost function for the compensation cost due to the electricity shortages. Particle Swarm Optimization (PSO) method has been applied for the minimization of the objective function. The PSO algorithm is a relatively simple computation technique to reach the global optimum, compared with other optimization method. The proposed method is used to simulate in the hybrid power generation system in East Nusa Tenggara, Indonesia (latitude 09.30S and longitude 122.0E). The simulation results has been confirmed from costs reduction and environmental point of views and the optimum size of PV panels, battery banks and diesel generator units are 75,300×165W, 3×5MWh and 12MW, respectively. This study also reveals the importance of PV and battery systems. Without their connections, the annual cost of diesel generator becomes considerably high. Moreover, the proposed method is effectively used to deal with the cost reduction of a hybrid system under non-existence or unmet load condition.**

Keywords: PV system, battery bank, diesel generator, PSO, optimal size, cost reduction

I. INTRODUCTION

Diesel generator (DG) unit is one of the suitable options for supplying electricity in remote areas due to their compact design and high specific power. However, the operational cost of DG system is influenced by load profiles. In remote area, such as in East Nusa Tenggara of Indonesia, the load profile seems to be influenced by daily activities which are related to cultural and economic conditions. The maximum efficiency of the DG can be approached when the DG unit is operated close to the rated capacity. It is not recommended to operate the diesel unit below its minimum power specified by the manufacturer [1]. As a single power source, the DG system has problems, such as hard maintenance, required fuel supply and high generation cost [1-3]. To solve such kind of problems, hybrid generation system with utilization of renewable energy sources is one of the promising methods.

The hybrid combination of PV-battery-diesel systems is economically feasible in many cases for electric energy supply in isolated areas where the electric utility is not available. PV-Diesel system has greater reliability for electricity production than a PV-only system or diesel-only system. It means that hybrid power systems have greater flexibility, higher efficiency and lower costs for the same quantity of energy production [4]. In addition, the integration of PV system with battery storage and diesel unit as a back-up system provides a reduction in the operational costs and emitted air pollutants to the atmosphere [5]. Several methods can be found in literature for optimal design of hybrid PV-Diesel-Battery system [6-10]. Senjyu et al. [7] developed an optimal configuration of power generating systems in isolated islands with renewable energy using Genetic Algorithm (GA). This methodology can be used to determine the optimum number of solar array panels, wind turbine generators and battery banks configurations. El-Hefnawi [8] presented an optimization method to design hybrid PV-Diesel-Battery system. The optimization method starts by modeling of diesel generator and then optimizing the PV and battery sizes in terms of minimum number of storage days and the minimum PV array area. Dufo Lopez and Bernal-Agustin [9] developed the hybrid optimization by genetic algorithms program that uses GA to determine the sizing and operation control of a PV-diesel system. However, these methods fail to find the optimal solution in case of complex system problems and not suitable to be used widely for software application.

Recently, some researchers attempt to implement PSO method for optimal sizing of hybrid stand-alone power systems by assuming continuous and reliable supply to the load [11,12]. However, they do not consider compensation cost due to electricity shortage as well as CO_2 emission.

This paper presents an optimization method for optimal sizing of PV-Diesel-Battery systems using PSO. PSO is an adequate and fast search technique for solving complex problems when other techniques are unable to reach the optimal solution. The structure of the paper includes the program and control strategy using PSO. All details about modeling of PV system, battery bank and DG unit will be provided in the next section.

II. MATHEMATICAL MODELING

A. Photovoltaic system

The system configuration of PV-Diesel-Battery system in this study is shown in Fig.1. PV model follows *I-V* characteristic modeling from Sandia National Laboratory [14-16]. The input variables of this model are solar insolation as shown in Fig. 2 and cell temperature of PV panel. Detail equation of PV model can be described as follows:

$$I_{sc}(t) = I_{sc}\left(\frac{E(t)}{E_o}\right)\left(1 + \alpha_{Isc}(T_c(t) - T_o)\right) \quad (1)$$

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Maximum power point current (I_{mp}), open circuit voltage (V_{oc}) and maximum power point voltage (V_{mp}) can be generated as follows:

$$V_{oc}(t) = V_{oco} + N_s\delta\big(T_c(t)\big)ln\big(E_e(t)\big) + \beta_{Vco}E_e(t)(T_c(t) - T_o) \quad (2)$$

$$I_{mp}(t) = I_{mpo}(C_oE_e(t) + C_1E_e(t)^2)\big(1 + \alpha_{Imp}\big)(T_c(t) - T_o) \quad (3)$$

$$V_{mp}(t) = V_{mpo}C_2N_s\delta\big(T_c(t)\big)lnE_e(t) + C_3N_s\delta\big(T_c(t)\big) ln(E_e(t)^2) + \beta_{Vmpo}E_e(t)(T_c(t) - T_o) \quad (4)$$

The concept of the effective insolation (E_e) is utilized the fact that the PV panels cannot respond to all wavelengths of light contained in the solar spectrum. It can be described as follows:

$$E_e(t) = \frac{I_{sc}(t)}{I_{sco}\big(1+\alpha_{Isc}(T_c(t)-T_o)\big)} \quad (5)$$

Thermal voltage per cell $\delta T_c(t)$ in (2) and (3) is given by:

$$\delta\big(T_c(t)\big) = \frac{nk(T_c(t)+275.15)}{q} \quad (6)$$

Finally, total output power from PV panels can be obtained by using following equation.

$$P_{PV}(t) = V_{mp}(t).I_{mp}(t).N_{PV} \quad (7)$$

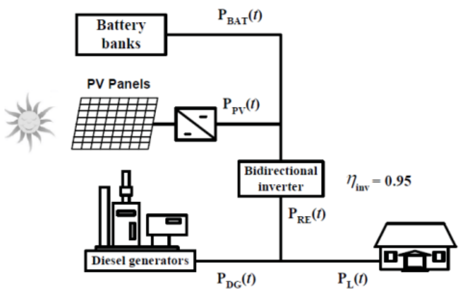

Figure 1. Configuration of the system

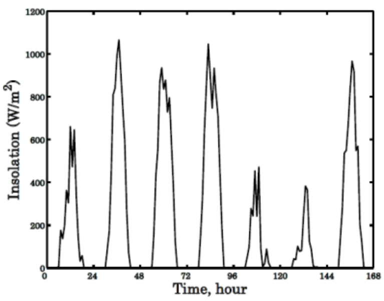

Figure 2. Weekly insolation data

B. Battery Banks

Here power from battery banks is required whenever PV or DG power are fail to supply load demand. Energy production and absorption of battery system during the time from *t*-1 to t is described in the equation below:

$$C_B(t) = C_B(t-1).(1-\sigma) + P_{BAT}(t) \quad (8)$$

Where; $C_B(t)$ and $C_B(t\text{-}1)$ are availability power of battery banks at hour *t* and at previous hour (*t*-1), respectively. The term σ is the self-discharge rate of battery banks, in study it is assumed 0.002.

TABLE I. PARAMETER OF PV MODULES

Vintage	2002(E)
Area (m^2)	1.301
N_s	36
I_{sco}(A)	5.46
V_{oco}(V)	43.1
I_{mpo}(A)	4.77
V_{mpo}(V)	34.6
α_{Isc} $^oC^{+1}$	0.00079
α_{Imp} oC¡1	-0.00001
β_{Voco} (V/^{o}C)	-0.171
β_{Voco} (V/^{o}C)	-0.178
n	1.486
C_o	0.988
C_1	-0.012
C_2	0.20456
C_3(V^{-1})	-5.4788

The value of $C_B(t)$ could not be lower than minimum allowable energy level remained in battery banks (C_{Bmin}), and it could not be higher than maximum allowable energy level (C_{Bmax}) during charging operations as follow:

$$C_{Bmin} \leq C_B(t) \leq C_{Bmax} \quad (9)$$

Power from PV system through the inverter is hourly measured as follows:

$$P_{RE}(t) = \eta_{inv}.P_{PV}(t) \quad (10)$$

Where, η_{inv} is the inverter efficiency. Principles of charging and discharging scenarios are dependent on the state of $P_{RE}(t)$ and the load power demand at hour *t* ($P_L(t)$).

1. If the value of $P_{RE}(t) > P_L(t)$: The remaining power will be used to charge battery banks:

$$P_{BAT}(t) = P_{PV}(t) - (P_L(t)/\eta_{inv}) \quad (11)$$

2. $P_{RE}(t) < (P_L(t)$: Insufficiency power will be supplied from DG unit or/and the battery banks according to the following dispatch strategy:

   - If the amount of power from battery banks is enough to handle the remaining power, the strategy allows the discharging process of battery banks and turning-on state of DG unit. Power from battery can be determined from the following equation.

$$P_{BAT}(t) = P_L(t) - P_{RE}(t) \quad (12)$$

   - Whenever battery banks are fail to supply the remained power or the strategy does not allow for the battery banks to discharge, then DG unit is started and battery banks will be neither charged nor discharged

$$P_{DG}(t) = P_L(t) - P_{RE}(t) \quad (13)$$

- If the power from DG unit exceeds the load demand then the excess energy will be used to charge the battery banks.

$$P_{BAT}(t) = \left(P_{DGmin} - \left(P_L(t) - P_{RE}(t)\right)\right).\eta_{inv} \quad (14)$$

- If the load demand exceeds the DG rated capacity then the DG will run at full capacity and the battery banks will attempt to make up the difference [9].

$$P_{DG}(t) = P_R \quad (15)$$

$$P_{BAT}(t) = Min\left[\frac{P_{BATmax}, P_L(t) - (P_{RE}(t) + P_{DG}(t))}{\eta_{inv}}\right] \quad (16)$$

C. Diesel Generator

The fuel consumption of DG unit is related with the rated power and its generated power. The fuel cost is calculated for a year as follows [19].

$$AFC = C_f \sum_{t=1}^{Tend} F(t) \quad (17)$$

Where; $F(t)$ is the hourly fuel consumption (US\$/hour), based on load characteristic of the diesel generators [19]. This parameter is calculated as follows.

$$F(t) = (0.246 \times P_{DG}(t) + 0.08415 \times P_R) \quad (18)$$

where; P_R is the rated power of diesel generators in kW, $P_{DG}(t)$ is the power generated by diesel generators in kW and C_f is the fuel cost per liter in US\$/l.

D. Pollutant Emission

The amount of CO_2 is obtained from combustion process of diesel engine by multiplying emission function (E_f) of CO_2 per kWh. In this case, the emission function is set at 0.699 kg/kWh [1,19].

E. Objective Function and Economic Model

Annual cost of system (ACS) is to be the objective function of the system. Annual cost of system covers the annual capital cost (ACC), annual operation maintenance cost (AOM), annual replacement cost (ARC), annual fuel cost of DG (AFC), annual emission cost (AEC) and annual damage cost (ADC). ACS is calculated using the following equation:

$$ACS = ACC + AOM + ARC + AFC + AEC + ADC \quad (19)$$

Annual capital cost of each units that does not need replacement during project lifetime such as DG, PV, inverter is calculated as follows:

$$ACC = C_{cap}.CRF(i, y) \quad (20)$$

Where; C_{cap} is the capital cost of each component in US\$, y is the project lifetime in year. CRF is capital recovery factor, a ratio to calculate the present value of a series of equal annual cash flows. This factor is calculated as follows:

$$CRF = \frac{i(1+i)^y}{(1+i)^y - 1} \quad (21)$$

Where; i is the annual real interest rate. Here, annual real interest rate consists of nominal interest i and annual inflation rates f. This rate is calculated as follow:

$$i = \frac{(i' - f)}{(1+f)} \quad (22)$$

Annual operation and maintenance cost of system (AOM) as a function of capital cost, reliability of components (λ) and their lifetime can be determined using the following equation [19, 20].

$$AOM = C_{cap}.(1 - \lambda)/y \quad (23)$$

ARC is annual cost value for replacing battery banks during the project lifetime. Economically, annual replacement cost is calculated using the following equation [19].

$$ARC = C_{rep}.SFF\left(i, y_{rep}\right) \quad (24)$$

Where; C_{rep} is the replacement cost of battery banks in US\$, y_{rep} is lifetime of battery banks in year. SFF is the sinking fund factor, a ratio to calculate the future value of a series of equal annual cash flows. This factor is calculated as follows:

$$SFF = \frac{i}{(1+i)^y - 1} \quad (25)$$

AEC is annual emission cost to capture CO_2 emission generated from DG system. Emission cost factor (E_{cf}) CO_2 is around US\$30/Ton-US\$50/Ton [19]. On the basis of this assumption, the AEC can be expressed using the following equation [19].

$$AEC = \sum_{t=1}^{Tend} E_f.E_{cf}.P_{DG}(t)/1000 \quad (26)$$

Finally, to calculate the expected annual customer damage cost (ADC), the customer damage function (CDF) curve as depicted in Fig. 3 is utilized in this study [19].

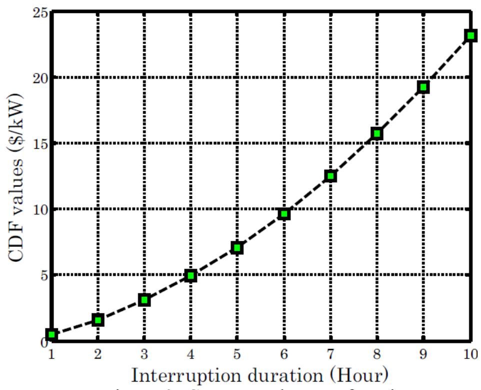

Figure 3. Customer damage function

III. OPTIMIZATION PROCEDURE

Inputs required for system optimization are the capital costs, replacement costs, operation and maintenance costs of all components, as well as the efficiency, lifetime of components and lifetime of the project, specifications of all the components, hourly load demand in a year and the hourly meteorological data in a year. Then, the next step is the initialization of the first population of particles. The initial position as well as the its initial velocity of particle consists of three random vectors x_1, x_2, x_3 for position and v_1, v_2, v_3 for velocity. All procedures are applied for all particles in the population. Here, the value of x_1, x_2 and x_3 as representation of the size of PV panels, battery banks and the rated capacity of DG unit respectively. After initialization of the first population is completed, the target of simulation as depicted in Fig. 4 is established to determine the annual fuel consumption of DG unit, CO_2 emission and also annual unmet load. Then, PSO calculates the ACS value as a objective function and choose one of the particles which has a smaller objective function as the best position of particle and the best position of the group. Each iteration, the objective function is calculated for each particle and compared with the previous values. The best position of each particle is evaluated and the best position of the group is determined by comparing the best positions of the particles. In this stage, the best value of the group becomes the optimum solution of the problem. In order to satisfy the load demand, the ADC is required to penalize the system whenever electricity shortage is occurred. Under electricity shortage condition, the system must provide compensation cost. Therefore, the PSO attempts to find the optimal size of the system economically as possible without any electricity shortage conditions.

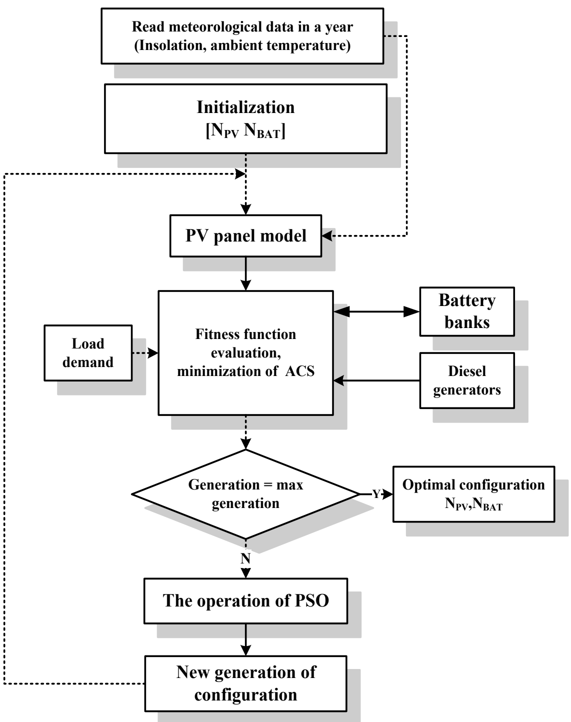

Figure 4. Flowchart of the algorithm for simulating hybrid system.

IV. APPLICATION AND RESULTS

PSO based Matlab m-file code has been developed to determine the optimal configuration of PV-Diesel- Battery system for East Nusa Tenggara (Indonesia). The daily load profiles are represented by a sequence of powers which is constant over a step time of one hour as shown in Fig. 5 another data used for the optimization is shown in Table 2. In this simulation, PSO parameters consist of 10 particles, and 100 maximum iteration. Each particle consists of 3 vectors which represent the size of PV panels, battery banks and the capacity of diesel generator. The values of ω, c_1 and c_2 are 0.7, 2 and 2 respectively. The convergence curves of the PSO algorithm for 5 independent runs are depicted in Fig. 6. It can be seen that the optimal values are obtained after about 25 iterations. Hence, 100 iterations can be considered as a fair termination criterion. Moreover, it can be observed that the optimal value for all the runs almost converges to the same optimal value (global optimum). On the other hand, Fig. 7 shows convergence curves for 5 independent runs of GA with the parameters of crossover, mutation rate and number of population are 0.75, 0.01, and 10 respectively. With 100 iterations the fitness values are difficult approaching to the same optimal value. The time to compute the problem by using GA is about 18.32 minutes and PSO is 9.66 minutes. So, optimization using PSO is two times faster than using GA.

Table 3 shows the optimization result for the system under study. The optimal size of components obtained from the optimization process consists of (75,300 × 165W) of PV panels, (3 × 5MWh) of battery banks and a DG unit with their capacity of 12 MW. An inverter capacity of 12.4 MW is utilized in this system. The inverter size is taken according to the maximum power from battery banks, PV panels or DG unit. It can be written as follows.

TABLE II. ECONOMIC PARAMETER CONSIDERED FOR SYSTEM OPTIMIZATION

Nominal interest rate *i'* (%) [19]	8.25
Inflation rate *f* (%) [19]	8.17
Project Lifetime (years)	20
PV panel lifetime (years)	20
Battery banks lifetime (years)	10
Inverter lifetime (years)	20
Reliability of PV panels	0.98
Reliability of inverter	0.98
Reliability of battery banks	0.98
Reliability of DG unit	0.9
Cost of diesel generator (US$/kW) [1]	600
Cost of PV panel of 165W (US$) [19]	1,300
Cost of battery banks of 5 MWh (US$) [6,19]	1,000,000
Cost of inverter (US$/kW) [19]	138
Fuel cost (*Cf* US$/l) [19]	0.75
Emission factor (kg/kWh) [19]	0.699
Emission cost factor(US$/Ton) [19]	30

$$\text{Inveter capacity}=\max[C_{Bmax},P_{PVmax}, P_R] \quad (27)$$

Using the optimal parameters obtained from PSO method, the ACS can be minimized to be US$ 21,405,239.34. Moreover, this configuration is able to satisfy the load demand without any unmet load during simulation time. Hence, the value of ADC and percentage of unmet load as an indicator of unmet power is 0. In this case, the percentage unmet load is expressed as follows.

$$\% \text{ unmet Load} = \frac{\text{Total Unmet load (MWh/yr)}}{\text{Total demand (MWh/yr)}}$$

Fig. 8 depicts the energy balance in the system. From this figure, it can be observed that all power generators are enough to satisfy the load demand without any unmet load. Total energy production for each component can be seen in Fig. 9. During a year, DG unit produce the energy about 69%, PV 28% and battery banks only 3%. DG system is remained the important unit for supplying the load demand in the rural area although it's operational and maintenance cost are expensive. It can be seen from Fig. 10 that the most expensive cost component in overall cost system is AFC. The most dominant cost is the capital cost of PV panels as shown in Table 4. The AFC and AEC values obtained from PSO as indicators of portion of power and amount of emission generated from DG unit are US$ 14,339,047.88 and US$ 1,092,620.41 respectively. Table 2 also reveals that proposed system is able to secure the energy supply to the load demand with only operating 12 MW of DG units. The value of ACS value under this condition is US$ 21,743,085.40. Hence, the proposed configuration is able to cut down the cost about US$ 337,846.

TABLE III. OPTIMIZATION RESULT

	PSO	Diesel
PV power	75,300 x 165W	-
Battery bank capacity (kWh)	3 x 5000 kWh	-
Diesel generator (MW)	12	12
Unmet load	0	0
Inverter capacity (MW)	12.42	0
Annual excess energy (MWh/yr)	71,591	0
Annual DG operation (h)	6,240	8,760
Annual Co2 Emission (Ton/yr)	36,420	50,042
ACC (US$)	5,532,663.53	362,802.14
AOM (US$)	141,604.58	35,999.99
ARC (US$)	299,002.92	0
AFC (US$)	14,339,047.88	19,843,010.34
AEC (US$)	1,092,620.41	1,501,272.91
ADC (US$)	0	0
ACS (US$)	**21,405,239.34**	**21,743,085.40**

TABLE IV. ANNUAL CAPITAL COST OF COMPONENT

PV (US$)	Battery (US$)	Diesel (US$)	Inverter (US$)
4,932,597.48	151,167.56	362,802.14	86,396.34

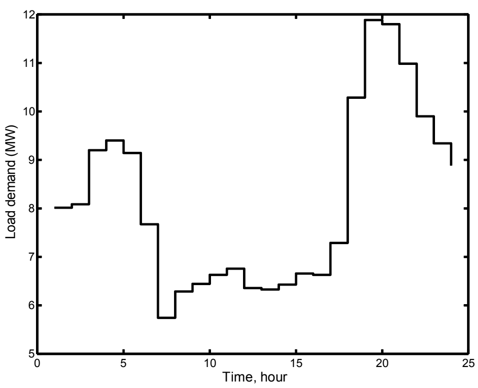

Figure 5. Load demand

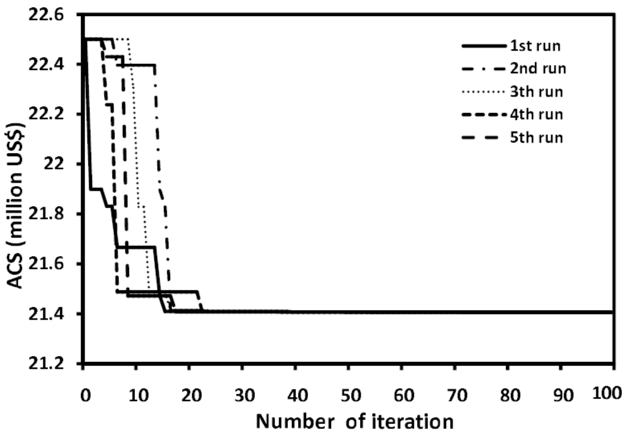

Figure 6. Convergence of the optimization algorithm using PSO

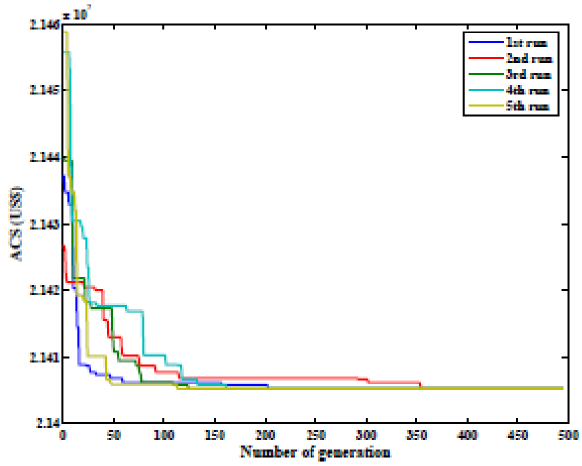

Figure 7. Convergence of the optimization algorithm using GA

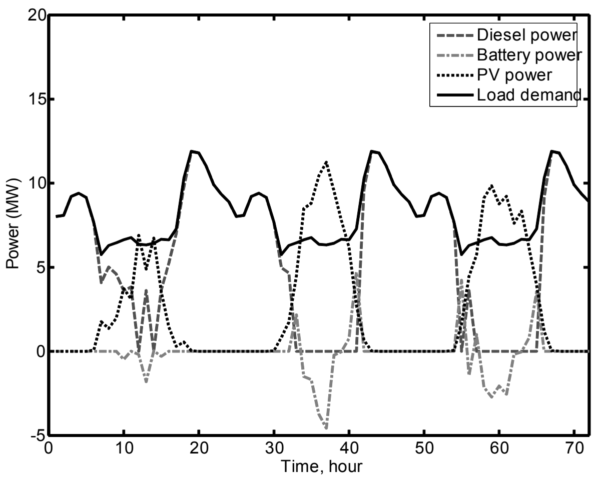

Figure 8. Variations in load, PV power, diesel power, and battery energy.

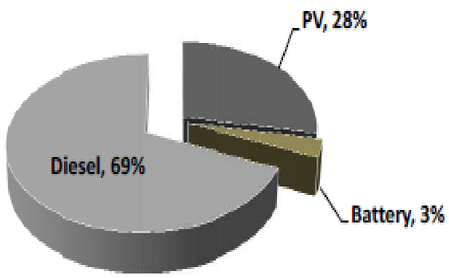

Figure 9. Annual energy production each component

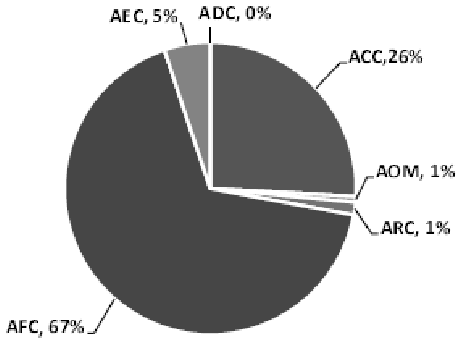

Figure 10. Costs of the different elements throughout the life of the system optimized by PSO, in percentage of ACS.

V. Conclusion

A method for optimal sizing of hybrid PV-Diesel system with battery storage based on PSO method has been presented in this paper. The PSO method has ability to reach global optimum with relatively simple computation requirement. The proposed system with optimal sizing consists of 75,300 × 165W PV panels, 3×5MWh of battery banks and 12MW of DG unit. Using the parameters obtained from the optimization, ACS could be minimized from US$ 21,743,085.40 to be US$ 21,405,239.34. In addition, utilization of hybrid energy system could minimize operational cost of DG unit and reduce CO_2 emission. Further, the proposed optimization method could be used to optimize hybrid PV-Diesel-Battery system for varieties of regions with different load and meteorological condition.

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Nomenclature

E_o	Reference insolation, 1000 W/m^2
V_{oco}	V_{oc} at E_e=1, T_c=T_o
I_{mpo}	I_{mp} at E_e=1, T_c=T_o
V_{mpo}	V_{mp} at E_e=1, T_c=T_o
α_{Imp}	Normalized temperature coefficient for I_{mp}
$\beta_{V oco}$	Temperature coefficient for V_{mp} at 1000 W/m^2
$\beta_{V mpo}$	Temperature coefficient for V_{mp} at 1000 W/m^2
C_0, C_1	Empirically determined coefficient relating I_{mp} to insolation.
C_2, C_3	Empirically determined coefficient relating V_{mp} to insolation.
N_s	Number of cells in series in a cell-string
α_{Isc}	Normalized temperature coefficient for I_{sc}
T_c	Temperature of cells inside module
T_o	Reference temperature for performance model, 25^{o}C
n	Empirically determined diode factor for each cell in module.
k	Boltzmann's constant, 1.38066×10^{-23} J/K
q	Elementary charge, 1.60218×10^{-19} coulomb
P_{PV}	Photovoltaic output power W
N_{PV}	Number of PV panel