Optimal Sizing Of An Off-Grid Small Hydro-Photovoltaic-Diesel Generator Hybrid Power System For A Distant Village

Adebanji B., Adepoju G.A., Oni J.O, Olulope P.K.

Abstract: This paper presented an optimal sizing technique for an off-grid hybrid system consisting of Small Hydro (SHP) system, Photovoltaic (PV) modules, Battery (BATT) banks and Diesel Generator (DG). The objective cost function (Annualized Cost System) and the Loss of Power Supply Probability (LPSP) were minimized with application of Genetic Algorithm (GA) in order to reduce the Cost of Energy (COE) generation. GA compared to other convectional optimization methods has the ability to attain global optimum easily. The decision variables are the number of small hydro turbines, N_{SHP}, number of solar panels, N_{PV}, number of battery banks, N_{BATT} and the capacity of DG, P_{DG}. The proposed method was applied to a typical rural village, Itapaji-Ekiti in Nigeria. The monthly average solar irradiance data were converted into hourly solar irradiance data for uniformity. Sensitivity analysis was also performed to identify the most important parameter influencing the optimized hybrid system. The optimal sizing result of the HPS is 954 kW of SHP, 290 kW of PV panels, 9500 sets of (600Ah) battery strings and 350 kW of DG. The optimal Loss of Power Supply Probability (LPSP) is 0.0054 and the Renewable Fraction (RF) is 0.62, which is indeed a significant improvement on the environment and comparatively better than any other combinations in the system.

Index Terms: Energy, Genetic Algorithm, Hybrid, Off-Grid, Optimal, Photovoltaic, Small hydropower, stand-alone, sizing, Sustainable energy.

1 Introduction

Renewable energy source is the most effective solution for a sustainable energy supply system especially in remote villages, where the extension of the grid may be difficult and economically infeasible for the power supply companies [1]. However, a system which depends entirely on only one renewable energy source cannot be a reliable source of electricity, due to its fluctuating nature, especially for off-grid rural dwellers [2]. Moreover, a single source renewable energy usually tends to be oversized to accommodate load demand [3]. A combination of one or more resources of renewable energy such as solar, wind, hydro power and biomass with other technologies such as batteries and generator defined as hybrid renewable is a better option [4]. An optimal sizing method is necessary to efficiently and economically utilize renewable energy source. This helps to guarantee the lowest investment with full use of the system component, so that the hybrid system can work at the optimum conditions in term of investment and system power reliability requirement [5, 6]. Peterson *et al* [7] observed that 40% of the total energy losses are due to the non-optimal sizing of the system.

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The first papers on Hybrid Power System (HPS) came into existence in the mid-eighties [8], but it became more popular in the early 1990s. Genetic Algorithm (GA) was used to minimize the total system cost based on load energy requirements by Kontroulis *et al.* [9]. The methodology can find the global optimum system configuration with relative computational simplicity, but the configurations are sometimes not cost effective, because sometimes a tiny amount of load rejections are tolerable to the customers in order to gain an acceptable system cost. This is the inability of the optimization method [10]. PV/Wind/Battery system was designed and optimized by minimizing the Annualized Cost of Systems (ACS) and the Loss of Power Supply Probability (LPSP) in [11].The authors did not use Diesel Generator (DG) which can make the hybrid system to be more stable. Luna-Rubio *et.al*, in 2012 [12] used HOMER software for cost minimization of PV/Wind/Micro hydroelectric/diesel hybrid system in Malaysia. This method did not consider the reliability of the system. Genetic Algorithm (GA) was used in this work, to minimize the Annualized Cost System (ACS) and the Loss of Power Supply Probability (LPSP) for the proposed hybrid SHP-PV-BATT-DG system. The optimal sizing of the major components of the hybrid system was done using Genetic Algorithm (GA). The paper is organized into seven sections. The first section started with an introduction, followed by the Hybrid Power System (HPS) and its Power Management Strategy (PMS) in section two. The mathematical models of the major components were done in section three. A brief description of the study area and the GA methodology used appeared in sections four and five. The results were presented and discussed in section six. Finally, the paper was concluded in section seven with a brief on the work done in the paper.

2 The Proposed Hybrid Power System (HPS) Structure

The main components are small hydro (SHP) generator and Photovoltaic (PV) module to supply load demand, and battery (BATT) and DG are used as the back-up energy sources. Provisions for the availability of both AC and DC buses are made using electronic converters. The small hydro generator and the DG generate AC power output which is connected to the AC bus. On the other hand, PV module and batteries generate the DC power output which is going to the DC link and then converted to AC power by DC-AC converter. A schematic block diagram of an independent SHP-PV-BATT-DG system is as shown in Fig.1. The small hydropower and PV generators basically combined to meet the load demand. When there is sufficient generation, the excess generated power, after satisfying the load demand, will be applied to feed the battery until it is fully charged. However, when generated power is not sufficient to meet the load, the battery bank will be used to cover the energy deficit between generated power and demand until the State of Charge (SOC) of battery bank decreases to its minimum level. If the generated power is not enough to meet up, the DG will supply the load [13]. The major objective of the PMS is to meet the load demand using an optimum operation strategy while maintaining minimum component size, thus minimizing the Annualized Cost System (ACS). It controls the power flow of energy of individual power generating system and battery. The PMS in the hybrid control structure is very important for balancing between efficiency and performance of the hybrid system [14].

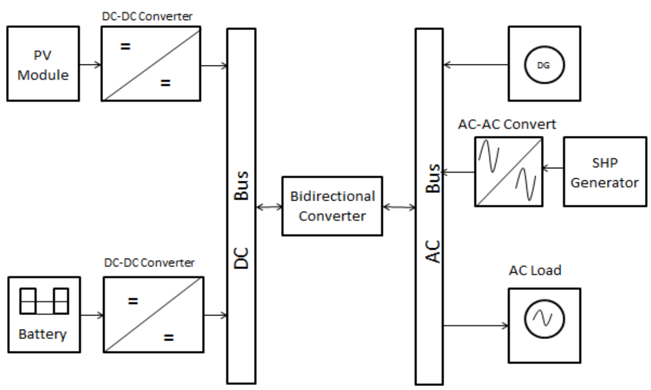

FIG. 1: *BLOCK DIAGRAM OF SHP-PV-BATT-DG SYSTEM*

3 MATHEMATICAL MODELS OF THE HPS COMPONENTS

There is the need to make optimal capacity configuration of the system in order for the HPS to be able to meet the load demand reliably and at an optimum cost [15]. The different HPS components are as described in the subsequent sections.

3.1 Small hydro Generator

The electrical power output of the small hydropower unit is given as in (1) [16]

$$P_{SHP} = \eta_h \rho_{water} g H_{net} Q \quad (1)$$

where P_{SHP} is the power output of the turbine, η_h is the hydro efficiency, ρ_{water} is the density of water, g is the acceleration due to gravity, H_{net} is the effective head, Q is the flow rate.

3.2 Photovoltaic (PV) model

The PV output power is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated as in (2) [17, 18,19].

$$P_{out-pv} = P_{r-pv}\left[\frac{G}{G_{ref}}\right]\left[1 + kT\left(T_c - T_{ref}\right)\right] \quad (2)$$

where P_{out-PV} is the output power from the PV cell, P_{r-PV} is the rated power at reference conditions, G is the solar radiation (W/m^2), G_{ref} is the solar radiation (1000W/m^2) at reference conditions, T_C is the cell temperature, T_{ref} is the cell temperature at reference conditions (25^{o}c), kT is temperature co-efficient of the maximum power (kT = -3.7x10^{-3}/1^{o}c for Mono and Poly crystalline, Si) T_c is the $T_{amb} + 0.0256 \text{ x } G$ where, T_c and T_{amb} are the cell and anti-temperature respectively [17].

3.3 Battery bank model

Koutroulis *et al*, [8] calculate the capacity of the battery at a point in time t, as follows in (3).

$$C(t) = C(t-1) - \eta_{batt}\left(\frac{P_B(t)}{V_{BUS}}\right)\Delta t \quad (3)$$

$C(t-1)$ is the battery capacity at the previous increment of time,η_{batt} is the battery round trip efficiency, $P_B(t)$ is the power supplied or used by the battery,V_{BVS} is the voltage of the bus that the system is connected to, Δt is the increment at time used.$P_B(t)$ is as in (4) [9].

$$P_B(t) = E_g(t) - E_i(t) \quad (4)$$

$E_{g(t)}$ is the energy generated in that hour by hydraulic generator and the PV panels, $E_i(t)$ is the load that needs to be supplied. $P_B(t)$ is therefore negative when the energy generated by the other energy sources is not sufficient to supply the system and the battery supplies additional power to the system. The value is positive when the battery is charging.

3.4 Diesel Generator (DG) model

The diesel generator is an energy conversion system from fuel to electricity with a conversion efficiency of, $\eta_{DG,}$ so that it can be described by (5) [18].

$$E_{DG} = \eta_{DG} E_{ff} \quad (5)$$

E_{ff} is the total energy content of oil which is roughly proportional to the volume of oil. It is being selected based on the peak load characteristics of the load characteristics. A linear model has been assumed for the fuel consumption rate (F) in litres/hour of operation by the DG [18] given in (6).

$$F = \left(0.246 \times P_{out}\right) + (0.08415 \times P_{Ngen}) litres / hour \quad (6)$$

where, P_{out} is the operating output power (kW),P_{Ngen} is the rated power of DG (kW).The fuel cost C_{fuel} can be calculated using the formula as in (7)

$$C_{fuel} = C_{diesel} F(R_s) \quad (7)$$

where, C_{diesel} is the fuel price per litre.

4 PROBLEM FORMULATION

The major consideration here, is to determine the size of each of the components in the HPS so that the load can be supplied at minimum cost and high reliability. Individual power sources have different overall impact on cost, performance and reliability of HPS system. Therefore, optimal sizing and economic power dispatch strategy needs to be considered [14]. The decision variables are the number of hydro turbines, N_{SHP}, number of the PV modules, N_{PV}, the DG power rating, P_{DG} and number of battery banks, N_{BATT}

4.1 Objective Function

The objective function to be minimized is as given in (8) [20]

$$Cost = \sum_{i} C_{acapi} + C_{aom} + C_{rep} + C_{af} + C_{aem} \quad (8)$$

where i is each component of the system, in this case, hydro, solar, battery and DG.

(i) C_{acapi} is the annualized capital cost of each of the component.

(ii) C_{aom} is the annual operation and maintenance cost.

(iii) C_{arep} is the annual value of replacing expenditure of components during the project lifetime.

(iv) C_{af} is the annual fuel cost

(v) C_{aem} is the annual emission cost generated from the DG.

The optimal configuration is the hybrid with the lowest annualized cost of system which can generates the required reliability of power supply.

4.2 Constraints

The minimization of the objective function is subject to the following constraints.

1) $P_p(t) > P_d(t)$ (Power Balance Constraint)
2) $SOC_{min} \leq SOC(t) \leq SOC_{max}$ (Battery capacity constraint)
3) $0 \leq N_{PV,P} \leq N_{PV,Pmax}$ (Non-Negative Constraints)
4) $0 \leq N_{SHP} \leq N_{SPV\ max}$
5) $0 \leq N_{BAT,P} \leq N_{BAT,Pmax}$
6) $LPSP_{min} \leq LPSP \leq LPSP_{max}$ (Reliability constraints)

5 Study Area

A typical rural village, Itapaji-Ekiti, Nigeria was used as a case study. It is located between longitude 5.25^0-5.28^0E and latitude 7.55^0-7.58^0N. The people of the area are predominantly arable farmers-they plant yams, rice and cassava. Diesel and petrol generators are being used individually as a major source of power generation. The average kWh/day load requirement for the community is 6831 while the average kilowatt is 285kW with a peak of 791 kW. The load factor is 0.360 [21]. The daily load demand of the village is shown in Fig. 2. The hydro resource data collected from the Nigerian Federal Ministry of Water Resources [22] showed that the annual average flow of the river is 4248 L/S. The monthly average solar irradiance of the site was converted into hourly solar irradiance. The average monthly stream flow, solar irradiance and temperature respectively are shown in Fig. 3, 4 and 5. The detailed parameter of the HPS components is shown in the appendix.

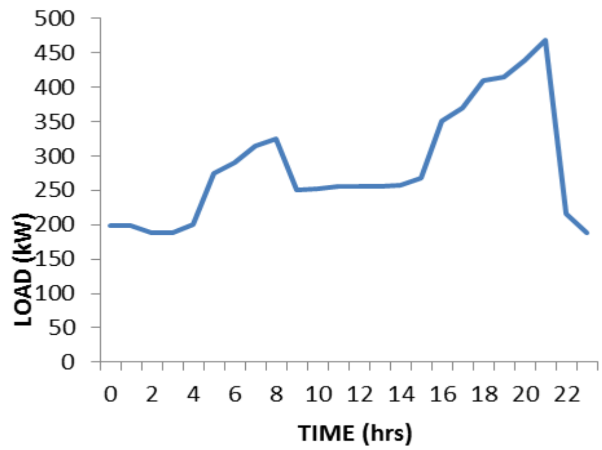

Fig. 2: *Daily load profile of the study area*

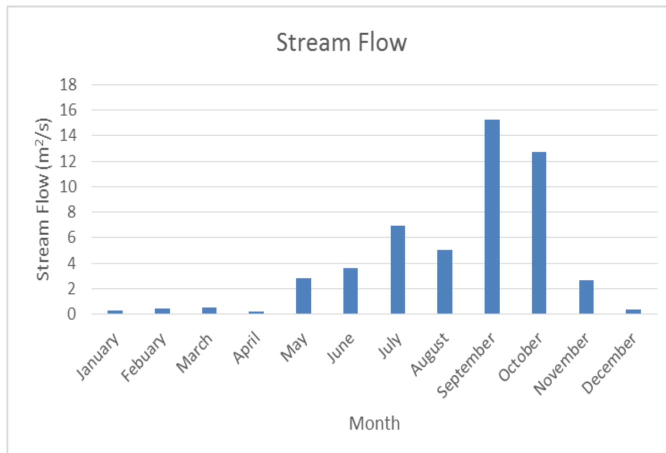

Fig. 3: *Average monthly stream flow of the river for the study area*

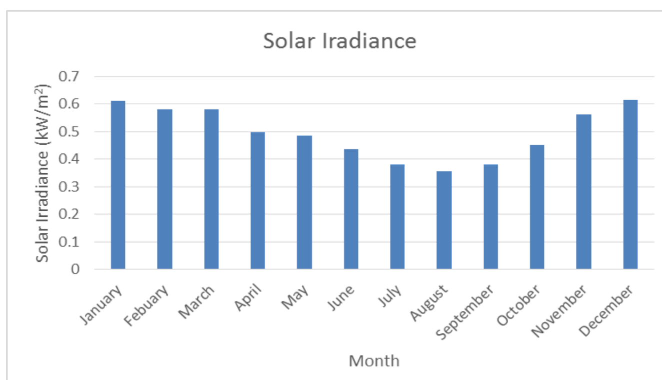

Fig. 4: *Average monthly solar irradiance for the study area*

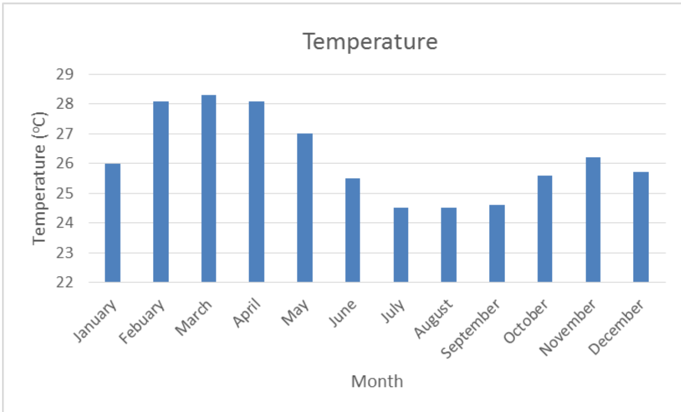

***Fig. 5:** Average monthly temperature for the study area*

6 METHODOLOGY

Genetic Algorithm (GA) can easily find global optimal solutions in both multimodal and multi-objective optimizations. It was developed to imitate the evolutionary principle of natural genetics. The HPS component output is calculated according to the details shown in the mathematical models in section 3. The flowchart of the optimization process is as shown in Fig.6.

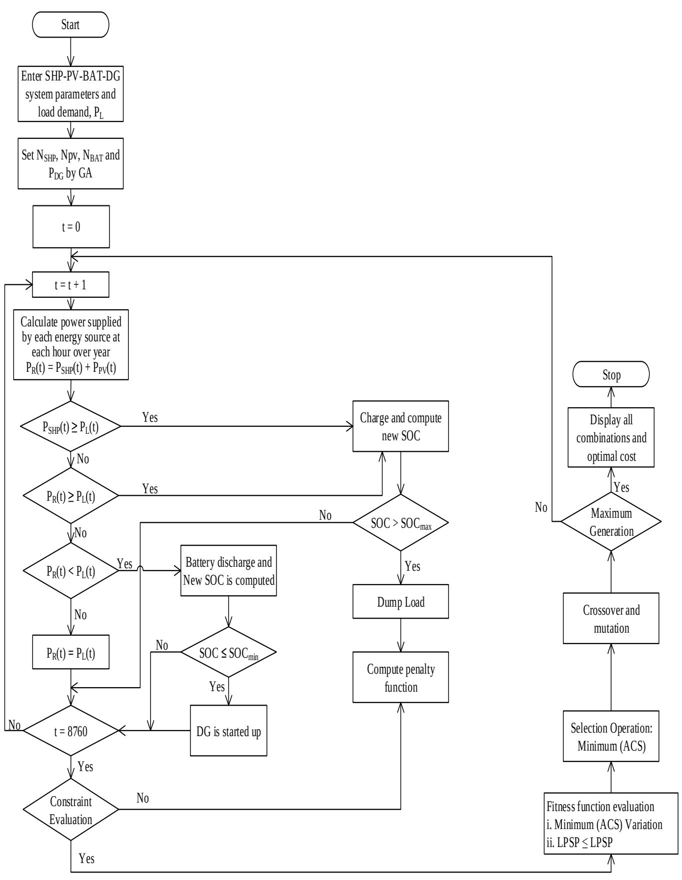

***Fig. 6:** Optimal sizing of SHP/PV/BATT/DG Hybrid Power System (HPS) using GA*

The decision variables are the number of small hydro turbines, N_{SHP}, Number of solar panels, N_{PV}, Number of battery bank, N_{BATT} and the capacity of DG, P_{DG}. GA is then used to optimize the system configuration. The GA dynamically searches for the optimal configuration to minimize the Annual Cost System (ACS). The Loss of Power Supply Probability (LPSP) in each system's configuration is examined to determine whether the load requirement is met. The configuration with satisfied lower cost load requirement will be subject to crossover and mutation operations of the GA, in order to produce the next generation population. This continues until a pre-specified number of generation populations is reached or when the criterion is satisfied

7 RESULTS AND DISCUSSION

The optimal composition of the HPS is 954 kW of SHP, 290 kW of PV panels, 9,500 sets of battery strings and 350 kW of DG. The COE of the hybrid system is $0.185/kW/hr. The Renewable Energy Fraction (RF) is 0.62 which is indeed a significant environmental issue and which is comparably better. The optimization result is as shown in Table 2. The optimal LPSP is 0.0054. The load is supplied 99.5% of the time. The sensitivity analysis of the optimized design result (in Table 1) is shown in Table 2 when the change in the future price of diesel is envisaged. It can be observed that as the prices of diesel increases from $0.55/litre to $1.2/litre, the COE also increases from $0.131/kW/hr to $0.206/kW/hr. This causes an increase in the Cost of Energy generation.

***Table 1:** optimization results for component sizing*

SHP (kW)	PV panel (kW)	BAT	DG(kW)	CON(kW)	RF	COE ($/kWhr)	LPSP
954	290	9500	350	400	0.62	0.185	0.0054

***Table 2:** Optimization results with variation of DG prices (sensitivity Analysis)*

DG price ($/L)	SHP (kW)	PV panel (kW)	BATT	DG (kW)	RF (%)	COE ($/kWhr)
0.55	954	-	29,000	400	0.54	0.131
0.60	954	-	29,000	400	0.54	0.139
0.75	954	290	9,500	400	0.62	0.160
0.8	954	290	9,500	400	0.62	0.166
1.0	954	490	9,500	400	0.68	0.188
1.2	954	790	9,500	400	0.75	0.206

8 PROBLEM FORMULATION

The optimal Hybrid Power System (HPS) configuration consisting of Small hydro turbines, PV panels, battery banks and DG has been performed in this simulation. Genetic Algorithm (GA) is utilized to optimally size the proposed SHP-PV-BATT-DG hybrid system. The GA was run using hourly values of meteorological data load profile taken from a typical rural village, Itapaji-Ekiti, Nigeria. The optimization was done in order to reduce the COE to a minimum affordable to the rural dwellers and at the same time serve the load reliably. The result showed that the proposed method is highly feasible for SHP-PV-BAT-DG hybrid system.

Appendix

Detailed Parameters of the Components [21]

Details of Small hydro power Turbine		Battery Specification		Details of DG model	
Nominal Power (kW)	75	Minimum life time	4yrs	Size	400kW
Life time	25years	Initial state of charge	100%	Quantity	1
Available Head	21.6m	DOD	80%	Life time	20,000 hrs
Design flow rate	4.33m^3/s	Voltage	6V	Price	$0.884 /litre
Turbine efficiency	75%	Capital cost	$1710/kAh	Capital cost	$503.08/kW
Capital cost	$430,247	Replacement cost	$1710/kAh	Operation and Maintenance cost	$15/hr
Replacement cost	$430,247	Operation and Maintenance cost	$76/kAh	Replacement cost	$503.08/kW
Operation and Maintenance cost	$10,308	Efficiency	80%		

PV Specification		Converter details	
Rated power	200W	Size	791Kw
Capital cost	$2500/kW	Capital cost	$8043
Replacement cost	$2500/kW	Replacement cost	$8043
Operation and Maintenance cost	$5	Operation and Maintenance cost	$0
Life time	20years	Life time	15years
Open circuit voltage	30.8V	Inverter efficiency	90%
Short circuit current	8.7A	Rectifier efficiency	85%

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