Optimal Sizing of Grid Connected Hybrid PV/Wind/Battery Power System using Satin Bowerbird Optimization

K. Ranjith Kumar, M. Surya Kalavathi

Abstract*: Renewable energy sources are gaining more attention due to quick reduction of fossil fuels, global warming and energy crisis over the past few decades. Photovoltaic and Wind are the outstanding sources among the various offered renewable sources owing to the complementary nature of these sources. But the availability of the generated energy and the cost of the system are the two major limitations of these sources. Hybrid Power System (HPS) can alleviate the deviations in energy generated with the assistance of energy storage systems like batteries. On the other hand the cost of the energy needs to be minimized. Therefore, optimization of energy generation with storage system in light of investment cost and unpredictability alleviation is imposing to the monetary achievability of Hybrid Power System. This work presents a novel methodology based on Satin Bower Bird optimization to obtain the optimal sizing and power management of hybrid photovoltaic/wind/battery power system. The HPS has been simulated using MATLAB using practical load and weather data of PV and wind system: which gives better performance under all operating conditions.

***Index Terms*: Photovoltaic, Wind, Battery, Hybrid Power System, multi-objective optimization, and Satin Bower Bird**

I. INTRODUCTION

India is the sixth largest economy in the world but still 32 million homes in the dark according Bloomberg report [1], has apparently greedy desire of vitality. One blasting outcome of this dramatic progression is wide gap among the supply and the demand; hence, the nation is paying enlarged attention to fill the gap through size accumulation. These days, the nation is encouraging renewable energy to enhance the aggregate energy feed as well as to encounter country necessities also by supplementing energy. Renewable energy sources gained the popularity mainly because of depletion and environmental effects of fossil fuels. These sources are advantageous when compared to the conventional sources in many aspects but the foremost shortcomings are the accessibility of the energy generation and cost. Renewable sources basically have arbitrary behavior and cannot have precise forecast. Therefore hybrid power system associated with battery storage system is the best solution to alleviate variations in the source. Storage system would receive the excess energy and feed insufficient energy. On the other hand cost of the equipment needs to be minimized. Therefore, improvement of energy production with backup system in light of investment as well as unpredictability alleviation is imposing to the monetary achievability of Hybrid Power System [2]. The important involvement of this work is to utilize an obtainability of energy generation technical assessment in combination with monetary evaluation to attain the optimum sizing of the suggested configuration, and the power procured from grid so as to choose the hybrid power system will assure a consistent power production through the minimum capital. The optimal sizing of source components is highly significant to proficiently as well as economically utilize the sustainable resources. Optimal sizing techniques can support to assure minimum capital cost along a sensible and complete usage of HPS constituents [3]. Optimal sizing of sources is essentially a technique of defining the size of the HPS by reducing the system components though maintain reliability of system. Optimum source supervision in a HPS is vital to attain adequate price and consistency. These proposal goals are typically contradictory with each other and consequently a sensible compromise among them is necessary. Oversizing of the HPS apparatuses will rise cost of system while under sizing can cause power failure. In this manner satisfactory consideration ought to be occupied to plan a consistent power system at lowest expense [4]. Many researchers [5--20] have published the papers on sizing methods implemented to design optimal configuration HPS. Most basic goals considered for designing of HPS are technical and economic goals. The literature in this paper specifies few of the equivalent works carried out to develop hybrid system. This paper manages the design of HPS through optimal size of renewable resources to realize a sustainable design and finally, optimal energy utilization is accomplished by the proposal of power management scheme. Bogdan et.al [5] designed a HPS based on long term weather data to select the optimum size of solar and battery by using the idea of LLP. The optimum cost is obtained through making a curve that characterizes the association among the quantity of solar PV panels and batteries. Riad et.al [6] presented linear programming procedure to minimize the cost of electricity through considering the environment factors for designing an optimum wind-solar system. Kellogg et.al [7] developed a standalone optimum wind-solar system with energy storage using a simple algorithm for isolated location in Montona with a distinctive domestic demand. Said et.al [8] discussed the influence of sustainable resource assessment of a site on the capacity of isolated hybrid PV/wind power system. Jun-Hai et al [9] suggested a robust design technique for optimum configuration of isolated HPS which is insensitive to

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the parameter variations using NSGA-II. Yang et.al [10] discussed a process to develop a hybrid wind-solar power generation to feed power to telecommunication location, China. In this paper, five decision variables are considered to minimize the LCE. Mukhtaruddin et al [11] obtained the finest arrangement size of autonomous hybrid system with maximum reliability and minimum cost using the Iterative Pareto Fuzzy (IPF) technique. Jui-Yuan et. Al [12] proposes a superstructure-based mathematical model to develop hybrid systems. In [13], HOMER software tool was utilized for optimum structure of integrated renewable system for particular locality reliant on the Net Present Cost. Effective optimization procedures are required to decide the sizing and power management since it is non-linear and complex problem. Artificial intelligence methods like Genetic algorithm (GA), particle swarm optimization (PSO) and artificial neural networks (ANNs), are extensively applied for calculating the optimum size by reducing the cost of the system [14]. Adel et.al [14] suggested ANN-GA to produce LLP sizing curves of the hybrid system using ecological data. Rajkumar et.al [15] designed the optimal hybrid power system using ANFIS method and the obtained results compared by HOGA and HOMER software tools. The optimum configuration of a hybrid power system is the multi-objective design problem through contradictory goals of reliability as well as cost. Owing to unpredictability in sustainable sources and load, probabilistic techniques like Monte Carlo simulation is needed to compute consistency of system. Luo et al [16] calculated the optimal capacity of the storage using GA and comprehended a sequential model for hybrid system. Sharafi et al. [17] executed a Multi-Objective based Particle Swarm Optimization (MOPSO) for sizing optimization. Maleki et al. [18] suggested an Artificial Bee Colony Optimization (ABCO) method to reduce the total annual system cost based on LPSP constraints. Pavan et al [19] developed an optimal grid connected hybrid power system using HOMER software tool which solves single objective function but it does not solve multi-objective function. Many authors investigated the performance of optimal configuration for stand-alone systems of isolated locations, wherever it is moreover problematic or difficult to prolong the grid facility and nonspecific manner of loads considered in studies. These work emphases on the grid-connected HPS designed for a real system. Reliability is more important criteria for standalone systems; evaluated by using reliability indices like Loss of power supply probability (LPSP). Since the considered hybrid system is grid connected in this study is continuously consistent for any size of hybrid system constituents. Conversely, the optimum sizing of grid associated HPS comprises on the restriction of grid power utilized through demand. A new Power Imported from Grid Ratio (PIGR) is proposed as performance indices for considered grid connected system with analogous to Loss of power supply probability (LPSP) for standalone system. PIGR is the fraction that the system required to procure electrical energy form grid, when solar and wind impotent to supply the demand.

II. HYBRID POWER SYSTEM CONFIGURATION

Figure 1 shows the grid connected HPS containing of solar, wind as well as battery. PV and Wind are the prime energy resources of HPS to yield complete benefit of renewable source, and battery is also utilized to feed deficit power and stores the excess power. The energy resources and storage system in the considered system are combined over DC bus. When the demand is not met by the PV, wind and battery it will be procured from the grid.

A. PV Panel Modeling

The power generated through solar panel is determined by solar irradiation and temperature of the location moreover the panel characteristics itself. The output power of photovoltaic is determined through the below equations [20]

$$T_C = T_A + I_S(\frac{T_{NO}-20}{0.8}) \quad (1)$$

$$I = I_S(I_{SC} + K_I(T_C - 25)) \quad (2)$$

$$V = V_{OC} - K_V \times T_C \quad (3)$$

$$P_{PV} = N \times FF \times V \times I \quad (4)$$

$$FF = \frac{V_{MPP} I_{MPP}}{V_{OC} I_{SC}} \quad (5)$$

Where T_C=Temperature of cell in ^oC, T_A=Atmosphere Temp. in ^oC, T_{ON}=Nominal Temperature in ^oC, I_S=Solar Insolation, I=solar current in Amps, V=solar voltage in Volts I_{SC}=Short Circuit (SC) Current, V_{OC}=Open Circuit (OC) Voltage in Volts, K_I=Current Temp. Coefficient in A/ ^oC, K_V=Voltage Temp. Coefficient in V/ ^oC, FF=Fill Factor.

Table 1 shows the proposed hybrid power system cost and range of size selected for this work.

B. Wind Turbine power unit modeling

Wind system transforms kinetic energy of wind to electrical energy rendering to a specific power curve. The power generated from wind system is relies upon the wind speed at the location and also the parameters of the power performance curve. The wind output power is determined using the equation no.6 [20].

From the equation no. (6) P_{WT} is wind power depends on velocity of wind. V_a, V_r, V_{ci} & V_{co} are the average wind velocity, rated wind velocity, cut-in wind velocity and cut-off wind velocity correspondingly. The Range of 2 to 20 number of wind turbines is considered for optimal size each of 50 kW.

$$P_{WT}(v) = \begin{cases} 0, & 0 < v_a < v_{ci} \\ P_r \frac{(v_a - v_{ci})}{(v_r - v_{ci})}, & v_c \le v_a \le v_r \\ P_r, & v_r \le v_a \le v_{co} \\ 0, & v_{co} \le v_a \end{cases} \quad (6)$$

Table 1 System Component Characteristics

Parameter	PV Size(kW)	Wind Size (kW)	Battery Size (kW)	Converter Size (kW)
Range	[100 1500]	[100 1500]	[50 100]	[100 500]
Initial Cost	3500 $/kW	181035 $	475 $	110 $/kW
Maintenance Cost	20($/year)	50($/year)	30($/year)	30($/year)
replacement cost	--	1600	140	120

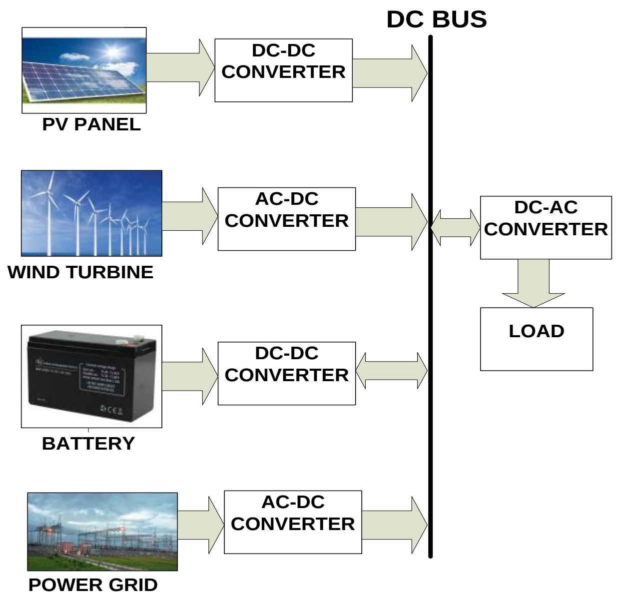

Figure 1: Hybrid Power System

III. PROBLEM STATEMENT

The main aim of this effort is to reduce the total system cost and maximize the availability of energy generation. The generation from PV and wind sources has main precedence to feed the load, also if the generated energy is insufficient, energy backup can feed the load demand. On the off chance that there is as yet unsatisfactory power, a definite extent power can be procured from power grid to feed the load. Therefore, power procured from the grid has lowermost importance.

A. System Cost

The total cost of proposed system contains the cost of solar system, wind system, and battery system. The total cost of system ($s/year) contains initial cost and operational & maintenance cost (O&M) expressed as [21]

Total Cost of the system = $C_{PV}+C_{wind}+C_{Battery}+C_{Grid}$ (7)

C_{PV} =Cost of Power generated by PV=$\frac{I_{PV}+OM_{PV}}{N}$ (8)

The initial and O&M cost of PV system, wind turbine system and battery system can be expressed as using equations (9 to 16)

$$I_{PV} = L_{PV} \times N_{PV} \quad (9)$$

$$OM_{PV} = OM_{yearly} \times N_{PV} \times \sum_{i=1}^{N} \left(\frac{1+\vartheta}{1+\gamma}\right)^{I} \quad (10)$$

C_{wind}=Cost of Power generated by wind=$\frac{I_{wind}+OM_{wind}}{N}$ (11)

$$I_{wind} = L_{wind} \times N_{wind} \quad (12)$$

$$OM_{wind} = OM_{yearly} \times N_{wind} \times \sum_{i=1}^{N} \left(\frac{1+\vartheta}{1+\gamma}\right)^{I} \quad (13)$$

$C_{Battery}$=Cost of Power delivered by battery =$\frac{I_{Battery}+OM_{Battery}}{N}$ (14)

$$I_{Battery} = L_{Battery} \times P_{CB} \quad (15)$$

$$OM_{Bttery} = OM_{yearly\_Batt} \times P_{yaerly\_Batt} \times \sum_{i=1}^{T_b} \left(\frac{1+\vartheta}{1+\beta}\right)^{(i-1)N_{Batt}} \quad (16)$$

Subsequently the operative life cycle of battery is lesser than PV system and wind, it is anticipated that they need to be changed numerous times throughout system life period. Battery replacement cost is considered as Operation & Maintenance cost in (16)

The minimization of cost objective function can be expressed as

$$\underset{cost}{Minimize}\,(N_{PV}, N_{wind}, P_{CB}, \rho) \quad (17)$$

The cost of grid power can be expressed as

$$Cost_{grid} = \sum_{i=1}^{T} P_{grid,t} \times L_{grid} \quad (18)$$

B. Energy Availability

Energy Availability is, energy is accessible from solar PV and Wind, during the period of time. The Energy availability can be expressed for period under consideration T as [21]

$$E_A = 1 - \frac{DNM}{D} \quad (19)$$

The DNM can be formulated as

$$DNM = \sum_{i=1}^{T} (P_{Batt\_Min}(t) - P_{Batt_{SOC}}(t) - (P_{RES}(t) + P_{grid}(t) - P_D(t))) \quad (20)$$

$$P_{grid} = \rho \times (P_D(t) - P_{PV}(t) - P_{wind}(t) - P_{Batt}(t)) \quad (21)$$

Where

$$P_{wind} = P_{WT} \times N_{wind} \times \eta_{wind} \quad (22)$$

$$P_{PV} = I_S \times N_{PV} \times \eta_{PV} \quad (23)$$

The maximization of energy availability objective function can be expressed as

$$\underset{Availability}{Maximize}\,(N_{PV}, N_{wind}, P_{CB}, \rho) \quad (24)$$

C. Design constraints

The considered design constraints to the optimization algorithm are the :N_{PV},N_{wind},P_{bc} and ρ

$N_{PVmin}, < N_{PV} < N_{PVmax}$ (25)

$N_{windmin} < N_{wind} < N_{windmax}$ (26)

$P_{bcmin} < P_{bc} < P_{bcmax}$ (27)

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The considered hybrid power system in this study is any time consistent for all size of system constituents, because it is grid associated. But, optimum size of proposed system contains the constraint of grid electrical energy utilization by load demand. A new Power Imported from Grid to Load Ratio (PIGLR) is considered with equivalence to LPSP of isolated systems. The PIGLR is the ratio of electrical energy procured from grid to load not met by PV/Wind/Battery during the time.

Pgridmin < Pgrid <Pgridmax (28)

$0 < \rho < 1$ (29)

The total power generated must not go beyond the load demand to circumvent more than required size of hybrid power system also additional excessive cost, is expressed as:

$$P_{PV}(t) + P_{wind}(t) + P_{Batt}(t) + P_{grid}(t) \leq P_D(t) \quad (30)$$

IV. SATIN BOWERBIRD OPTIMIZATION ALGORITHM

The Satin Bowerbird Optimization is bio-inspired by the attitude of the male-mesmerizing-the-female for mating; the male bowerbird constructs a specialized bower to attract the female [22]. This algorithm is novel for power system .It exposed improved execution related to other optimization algorithms.

Male birds make dedicated twig buildings, called bowers, wherever wooing and intercourse happen. Bowers are adorned with blossoms, quills, berries and so on. These beautifications are imperative in feminine optimal and male coupling realization. Males contest by robbing adornments from different males and will abolish the neighbor's bowers. Male wooing activities contain demonstration of beautifications and dancing shows convoyed through noisy communications, and then feminine desire males show at excessive strength. An additional signal of resilient sensual opposition is that not entire mature birds are effective at building, continuing also protecting bowers; consequently, there is significant unpredictability in male copulating achievement. In basic, male satin bowerbirds fascinate mates through making a bower. Female bird's visit quite a few bowers previously selecting a mating companion and coming back to bower. Rendering to standards of satin bowerbird regular life, SBO system is sorted out in a few phases as pursues:

1) Initializing a random population of bowers in search space: SBO technique starts by generating an initial population arbitrarily comparable to soft computing algorithms. In detail, early population contains a collection of bowers positions. Every position is distinct as an n dimensional vector of constraints should be improved.

2) Computing the Probability of Every Bower: Attraction of a bower is the probability. This probability is determined through using the equation (31) where, f_i is fitness of i^{th} position and N is bower number. The value of fitness f_i is attained by equation. (32).

$$Prob = \frac{f_i}{\sum_{i=1}^{N} f_n} \quad (31)$$

$$f_i = \begin{Bmatrix} \frac{1}{1+f(x_i)}, & f(x_i) \geq 0 \\ 1 + |f(x_i)|, & f(x_i) < 0 \end{Bmatrix} \quad (32)$$

3) Elitism: Elitism plays a crucial part in evolutionary algorithms. It permits the most effective solution to be conserved at each stage of the optimization.

4) Defining new changes in any position

$$x_{ik}^{new} = x_{ik}^{old} + \delta_k\left(\left(\frac{x_{jk} + x_{elite,k}}{2}\right) - x_{ik}^{old}\right) \quad (33)$$

New variations at any bower are determined using eqn (33), in each cycle of the algorithm. In equation (33), x_i is the i^{th} position vector & x_{ik} is k^{th} member. x_j is calculated as objective solution between all the solutions in present iteration. δ_k gives the desirability influence in target bower. δ_k gives the extent of step to be intended for every variable, is given by Eq. (34).

$$\delta_k = \frac{\emptyset}{1+P_j} \quad (34)$$

5) Mutation: While males are hectic in making the bower then attack is possible by any other bird which wanted his bower best and may steal some material that is using for decoration of bowers. So, some changes will occur in the probability. This random change is useful to x_{ik} with a definite probability. A normal distribution (N) is adopted with average of x_{ik}^{old} and variance of σ^2, as seen in Eq. (35) for mutation process

$$x_{ik}^{new} \sim N(x_{ik}^{old}, \sigma^2) \quad (35)$$

$$N(x_{ik}^{old}, \sigma^2) = x_{ik}^{old} + (\sigma * N(0,1)) \quad (36)$$

$$\sigma = Z * (var_{max} - var_{min}) \quad (37)$$

V. RESULTS AND DISCUSSION

A. Case study description

In this work, an educational institute situated in Hyderabad, India is represented as case study. The existing architecture of building is that it is connected to the grid that supplies the total connected load. The proposed hybrid power system is combination of PV, WT and BESS supplements the grid supply to feed the demand.

B. Load Profile

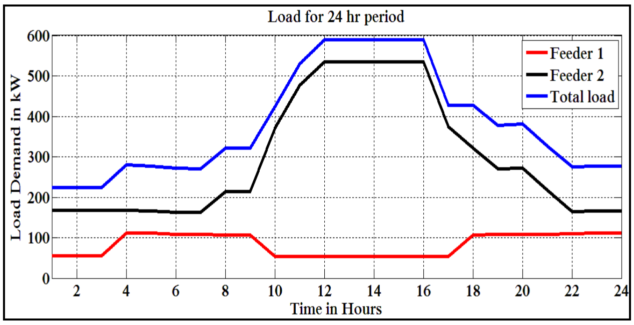

Figure 2: Loads in a Day.

Figure 2 shows the day-to-day demand of the

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considered case study. From the load data daily average energy utilization is 4580 kWh/day and maximum load is 600 kW. Selected site (JNTU University) buildings are supplied with two feeders each 11 kV rating from distribution substation. One feeder is supplied to JNTU quarters and another feeder is supplied to JNTU college campus.

C. Renewable Sources Assessment

The selected site is situated at latitude of 17.3850^0 N, longitude of 78.4867^0E, and an elevation of around 500 m. The selected place is sanctified with 5.35 kWh/m^2 annual average daily solar radiations and the average wind speed is 4.54 m/s in a year. Solar and wind data can be found from the NASA database [43].

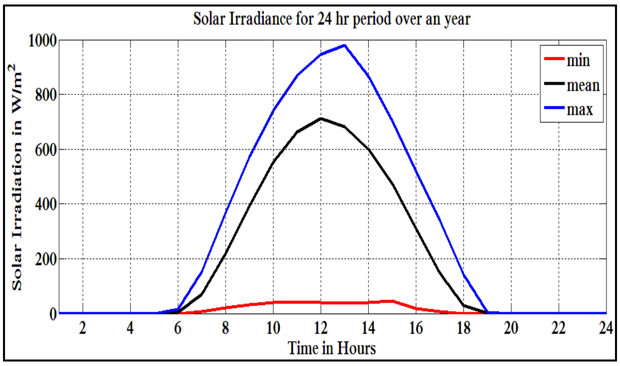

Figure 3: Solar Irradiation

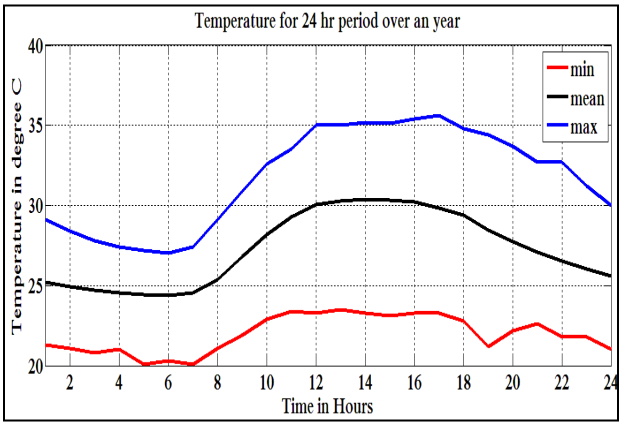

Figure 4: Temperature

The suggested algorithm is implemented in MATLAB to design an optimal configuration and power management of proposed hybrid power system for a selected location. The input data for simulation contains of the annual hour-wise information of solar radiation, ambient temperature, wind speed and demand data are shown in figure 2 to figure 5. The power produced from the each source shown in figures 6 to 9. Table 2 shows the parameters of SBO algorithm and table 3 demonstrations the factors utilized to run model. The SBO algorithm attempts to calculate the optimum number of PV's, wind & batteries capacity of proposed system to reduce the total cost also PIGR at the same time. Simulation results of optimization under SBO algorithm are shown in table 4 and table 5.

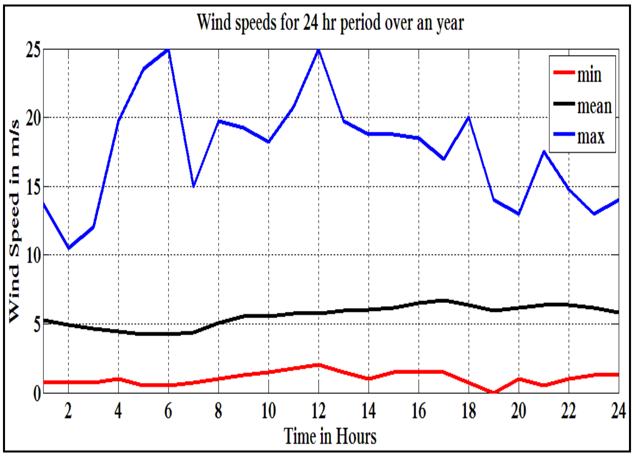

Figure 5: Wind Speed

Table 2: Algorithm parameters

S.No.	Parameters of SBO
1.	Maximum Iteration = 1000
2.	Population = 30
3.	Alpha φ= 0.94
4.	Probability of mutation = 0.1
5.	Variation of limits Z = 0.05

Table 3: Simulation parameters

S. No	Parameter	Value
1	Life Cycle (N)	20 years
2	Battery Life Cycle	5 years
3	Inflation Rate b	0.08
4	Interest Rate y	0.12
5	Escalation rate ϑ	0.12
6	Initial SOC	0.7
7	SOC_{min}	0.1
8	Fraction of power importing from grid ρ	0.35
13	Cost per unit grid power (1 kWh)	7.8

Table 4: Optimal configuration of the proposed HPS using SBO

S. No	No. of Solar Panels	No. of Wind Turbines	No. of Batteries
1.	3230	17	30

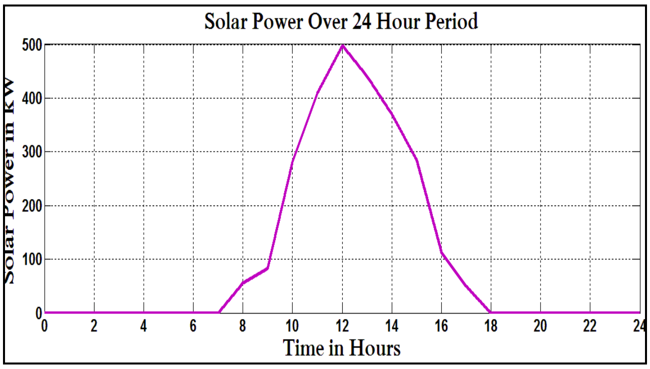

Figure 6: Solar Power *output*

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Table 5: Optimization results of proposed hybrid power system

PV(kW)	1050
WT(kW)	832
Battery(kW)	70.73
Grid(kW)	600
Converter(kW)	528
Capital Cost($)	2768078
Operating Cost($/year)	308299
Total Cost($)	7988127

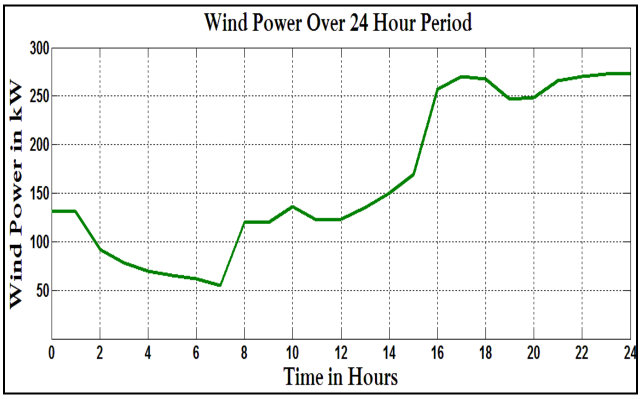

Figure 7 Wind Power Output

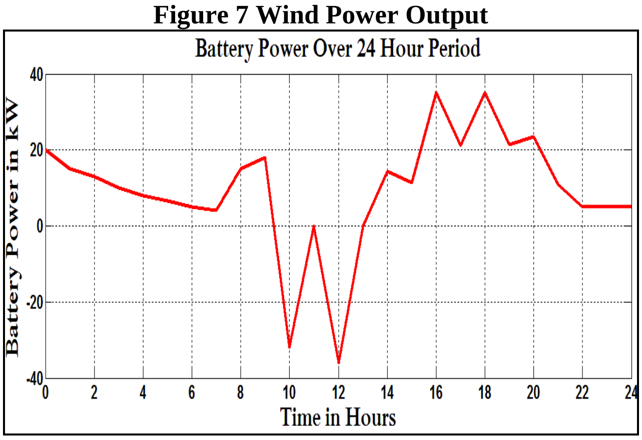

Figure 8 Battery Power

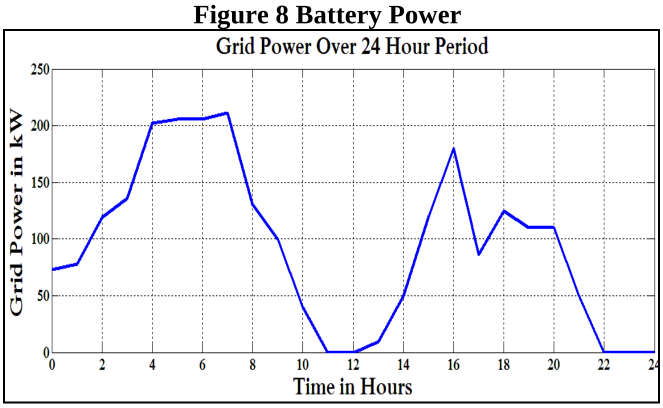

Figure 9 Grid Power

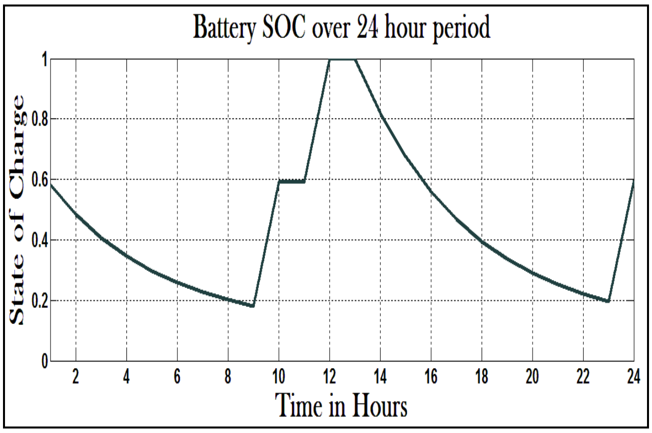

Figure 10 Battery SOC

VI. CONCLUSION

In this work, a new Satin Bowerbird Optimization method is applied for optimal sizing and power management of proposed system. The main involvement of this work is minimization of cost and maximization of energy availability with the constraint of PIGLR is achieved by using SBO technique. This optimization method is depends on the utilization of long term information of the solar irradiation, wind speed, and load profile of the selected site. From the optimization results, it observes that the optimal hybrid power system configuration contains of 3230 number of PV panels, 17 numbers of wind turbines and 30 numbers of batteries. The NPC of this system is 7988127$ and also caused in an usual saving of 19.7%/day in annual cost. It can also be concluded from simulation results that power at each instant in a day balanced i.e. power management strategy is also achieved.

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