Optimal sizing of PV-FC-Battery hybrid system with Energy Based Approach and PSO

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Abstract— **The intermittent nature of renewable energy sources is a major challenge in designing standalone hybrid systems. Over sizing of system components increases the cost of the system and under sizing causes a lack of reliability. In this paper optimal hybrid system sizing method has been proposed using particle swarm optimization algorithm. The optimal system size has been determined for a photovoltaic-fuel cell-battery hybrid system considering annualized cost of the system and reliability constraint. The hybrid system is simulated to determine the size of all system components and to test the effectiveness of the proposed algorithm over the energy based system sizing method. Simulation results show that optimal system configuration is able to supply the stand alone load throughout the year and system cost is also less with the proposed algorithm.**

Keywords- Energy Management, Hybrid System, Optimization, PSO, Sizing.

I. INTRODUCTION

DUE to increasing price of fossil fuel and environmental pollution caused by them renewable energy systems have become effective alternatives as electric power sources However choice of correct type of system and sizing of all components is significant to optimize the system [1] and the main constraint is to match the intermittent energy supply with dynamic load demand. For stand-alone photovoltaic (PV) systems the practice is to add energy storage devices that convert the excess available solar energy into electrical energy and store it to meet the load demand during the period when solar is unavailable [2, 3]. Presently lead-acid batteries are most commonly used as short term energy storage device. Fuel Cell (FC) along with electrolyzer is another efficient energy storage device due to the high mass energy density of hydrogen (H_2), moreover the hydrogen can easily be stored for a long period without any energy loss.

PV-FC-Battery hybrid stand-alone systems have been studied extensively in the past few decades [4, 5] and many different methods have been adopted for the sizing of hybrid energy system [6]. A systematic sizing study has been used to match the available solar power and fluctuating load demand with optimal energy management strategy in [1]. In every possible operational scenario the higher priority is given to the path having maximum transmission efficiency irrespective of the cost of the system components. In the present work system sizing has been formulated with two different sizing methods. Firstly, energy based systematic system sizing method is used to find the optimal system size and total annualized cost of the system. Secondly, system components size is determined using particle swarm optimization algorithm (PSO) using the same solar irradiation, load demand data and identical system configuration considering reliability indices and energy balance constraint. The aim of the study is to obtain optimal system size having minimum system cost under reliability constraint. Effectiveness of the proposed PSO algorithm is validated by comparing the results obtained by energy based systematic system sizing method.

Section II describes the hybrid system description followed by problem formulation in Section III. In Section IV hybrid system components size is obtained using energy based sizing approach and energy management strategy is described in Section V. In Section VI sizing optimization with PSO is presented. Section VII comprise of a comparative study of the proposed approach with energy based approach following the conclusion in Section VIII.

II. SYSTEM DESCRIPTION

The PV-FC-Battery hybrid system considered in this work is shown in Fig.1. PV modules are used to convert solar energy to electrical energy. The DC/DC converter along with MPPT algorithm is used to extract maximum amount of power. As the solar irradiation is varying in nature a battery bank is used to eliminate the intermittence of available solar power and for short term energy storage. FC is used as the second back-up source of energy. Electrolyzer converts water into hydrogen and oxygen and that hydrogen is used as a fuel in FC. The hydrogen generation rate is directly proportional to current drawn by the electrolyzer. The electrolyzer and compressor operates together to generate compress Hydrogen at high pressure and store into cylinders for future use.

The main objective of the proposed hybrid system is to continuously meet the load demand. After meeting the load demand the excess PV power will charge the batteries. When the solar PV power is not sufficient to meet the total load then the PV and Battery together supply the load. When the battery starts discharging and comes to its minimum state of charge then PV and FC will supply the load together. The performance index of energy efficiency is measured by energy management and reliability constraint, and in terms of annualized cost of the system. The system size will be optimal only when hybrid system is able to supply the load throughout

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the year with least cost. In Table I unit cost and lifetime of all the components are presented.

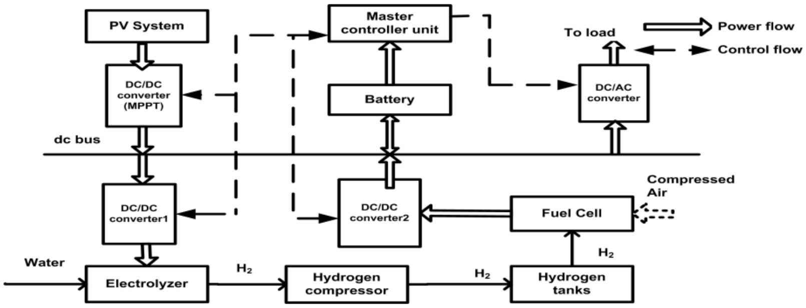

Figure 1. Power and Control Signal flow within a PV-FC-Battery hybrid system

III. PROBLEM FORMULATION

The goal of this study is to design an off-grid hybrid generation system in terms of both economic and reliability aspects subject to various economical and operational costraints. The problem has been formulated as a non-linear multivariable optimization problem and two different methods have been implemented as optimization algorithm and compared through a comparative case study of them.

A. *Cost Function*

There are many aspects such as cost, efficiency, energy balance that are taken into account to do the sizing of hybrid system. Among all these aspects the function that must be minimized is cost function [7]. In this study, capital cost of installation of all components, replacement cost, operation and maintenance cost has been taken into account while calculating Annualized System Cost (ASC) of the system over the whole project lifetime of 25 years. ASC can be calculated as follows

$$\mathrm{ASC} = \sum_{j=1}^{N} \mathrm{Ccap}(j) + \mathrm{Crep}(j) + \mathrm{Com}(j) \tag{1}$$

Where, Ccap(j) is Initial investment cost of each component, Crep(j) is replacement cost of each component and Com(j) is operation and maintenance cost of all components [8]. Where, j represents the component of the system i.e PV array, Battery, FC, Electrolyzer and Hydrogen Tank. The problem is formulated for minimization of ASC as objective function.

B. *System Constraints*

a) Reliability constraint: Reliability is used to measure the quality of power supply. Where, Energy Index of Reliability (EIR) is used as a inequality constraint. This index has been considered in various studies [9] as a parameter to measure reliability of each candidate of the hybrid system. EIR can be calculated as follows

$$\mathrm{EIR} = 1 - \frac{\mathrm{EENS}}{\mathrm{E}} \tag{2}$$

Where, EENS is expected energy not served. E is the total energy demand of the load. EENS can be represented as

$$\mathrm{EENS} = \sum_{t=1}^{8760} P_L(t) - \mathrm{Pav}(t) \tag{3}$$

Where, $P_L(t)$ is Load demand in t^{th} hour. Pav(t) is the available power in t^{th} hour. When PV is good enough to supply full load on its own then $\mathrm{Pav}(t)=P_{PV}(t)$ where, $P_{PV}(t)$ is the solar energy available at t^{th} hour, when PV is not enough to supply the whole load $\mathrm{Pav}(t)= P_{PV}(t)+Pb_{sup}(t)$ or $P_{PV}(t)+H_{sup}(t)$ depending on what source (FC or Battery) is sharing load with PV. During night period when PV is not there $\mathrm{Pav}(t)=Pb_{sup}(t)$, if battery has enough energy to supply the load, else $\mathrm{Pav}(t)=H_{sup}(t)$, when battery has been reached to its minimum SoC. Where, $Pb_{sup}(t)=(Pb_{soc}(t)-Pb_{min})$, $H_{sup}=(H_{soc}(t)-H_{min})$. Where, $Pb_{sup}(t)$, H_{sup} are the surplus battery energy and surplus storage capacity of hydrogen tank in kWh during t^{th} hour respectively, $Pb_{soc}(t)$ is the battery energy available during t^{th} hour, Pb_{min} is minimum allowable battery capacity, $H_{soc}(t)$ is the storage capacity of H_2 tank in t^{th} hour, $H_{min}(=0)$ is minimum allowable storage capacity of H_2 tank. The system configuration will be optimal only when EIR becomes 1 that means the load demand is fully served by the system components throughout the year.

b) Energy balance constraint: During any period the total energy available from the hybrid generation system must be at least able to supply the load demand. If some excess power is present after supplying the load demand it will be used to charge the battery up to its maximum SoC. If battery is fully charged it will run electrolyzer to produce hydrogen and store it to hydrogen tank. Energy balance constraint can be expressed as

$$P_{PV}(t) + \mathrm{Pbat}(t) + \mathrm{Pfc}(t) \geq P_L(t) + \mathrm{Pelec}(t) \tag{4}$$

Where, Pbat(t), Pfc(t), Pelec(t) are the energy available in kWh from Battery bank, Fuel Cell, Electrolyzer in t^{th} period respectively.

c) Bound on variables: In the sizing method all sizing parameters like area of PV panel (Apv), Battery Capacity(Pbat), Fuel Cell capacity (P_{FC}), Electrolyzer Power

TABLE I. UNIT COST OF COMPONENTS

(Pelec), Maximum allowable state of charge (SoC) of battery (SoCmax), Minimum allowable SoC of battery (SoCmin) are allowed to vary between lower and upper bounds. Value of all parameter bounds are presented in Table I.

IV. SIZING OF THE SYSTEM WITH ENERGY BASED APPROACH

To design an optimal hybrid system all the components should be properly sized to provide uninterrupted load demand. An energy based system sizing method is presented in following subsections. To verify the energy management strategy mean solar irradiation data of Kolkata (22° 35'N, 88° 21'E) has taken over a year [10]. TABLE II represents efficiency of all system components with all efficiency symbols.

1) Battery Sizing: The battery energy capacity (E_{BT}) for short term energy storage can be expressed as

$$E_{BT} = \frac{P_{LMAX} \times 24h}{EL_{up} - FC_{low}} \times M_{BT} \tag{5}$$

Where, M_{BT} (=2) is margin co-efficient of battery and Battery DoD is given by (EL_{up}-FC_{low}) [11, 12]. Where, P_{LMAX} is maximum value of load power and EL_{up} (=0.9) and FC_{low} (=0.4) is upper SoC of battery (SoC_{BT}) to start electrolyzer and lower SoC_{BT} to start the FC respectively.

2) PV Sizing: If only PV supply the power then considering direct transmission [1] of power from PV to load PV area (A_1) can be expressed as

$$A_1 = \frac{P_{LAVG}}{I_{SAVG} \times \eta_{PV} \times \eta_{MP} \times \eta_2} \tag{6}$$

However due to intermittence in solar power ($SPA1=I_S.A_1.\eta_{PV}.\eta_{MP}$) and dynamic behavior of load (P_L) as shown in Fig. 2 the solar panel area (A_{PV}) in actual condition will different than A_1, where I_S is available solar insolation. As illustrated in Fig.2, during the time interval [T1, T2] the available solar power is more than the load demand, therefore the excess power charges the battery and supply to electrolyzer. During intervals [T0, T1] and [T2, T3] when solar power is not sufficient to meet the load, partial sharing is taking place among the sources to meet the load. In this case required PV area can be calculated by equation (7) and (8)

$$A_{PV} = Mpv\left(\frac{P_{LAVG}}{I_{SAVG} \times \left(\frac{\eta_A + \eta_B}{2}\right)} + P_1\right) \tag{7}$$

Where
$$P_1 = \frac{1}{T3 - T0}\left(\frac{\int_{T1}^{T2}(1-K)(SPA1 - P_L/\eta_2)dt}{(I_{SAVG}(\eta_C + \eta_D))/(2\times\eta_2)}\right) \tag{8}$$

Where P_{LAVG} is the average load power, I_{SAVG} is average solar irradiation, $K=\eta_{D1}.\eta_{EL}.\eta_{FC}.\eta_{D2}$, Mpv (=1) is margin coefficient of PV panel, $\eta_A = \eta_{PV}.\eta_{MP}.\eta_2$, where η_A is efficiency of the path considering direct transmission of power from PV to load, $\eta_B = \eta_A.\eta_{BT}$, where, η_B is efficiency of the path considering transmission of power from PV to load through battery. $\eta_C=\eta_{PV}.\eta_{MP}.\eta_{D1}.\eta_{EL}.\eta_{FC}.\eta_{D2}.\eta_2$, where η_C is efficiency of the path considering power transmission from PV to load through electrolyzer and FC. $\eta_D=\eta_C.\eta_{BT}$, where, η_D is efficiency of the path considering power transmission from PV to load through electrolyzer , FC and battery.

PSO Parameters	Lower Bound	Upper Bound	Per Unit Cost (INR)	Lifetime Of Component (Years)
PV Area (m^2)	1	50	70/module	25
Battery (Wh)	100	40,000	70000/kWh	4
Electrolyzer (W)	0.5	3	150000/W	10
Fuel Cell (kW)	2	15	150000/W	5
H_2 tank (m^3)	1	20	400/m^3	20
SOCmin (%)	25	55	-	-
SOCmax (%)	75	100	-	-

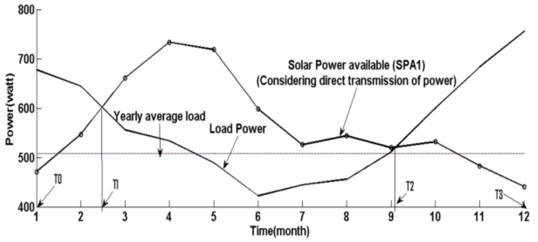

Figure 2. Initial estimated solar power and load (considering direct energy flow from PV to load)

TABLE II. EFFICIENCY OF SYSTEM COMPONENTS

Symbol Used	Meaning Of Symbol	Numerical Values
η_{PV}	Efficiency of PV panel	0.13
η_{MP}	Conversion efficiency of MPPT	0.90
η_{BT}	Round trip efficiency of Battery	0.90
η_{D1}	Efficiency of DC/DC converter 1	0.95
η_{D2}	Efficiency of DC/DC converter 2	0.95
η_{EL}	Efficiency of Electrolyzer	0.88
η_{FC}	Efficiency of Fuel cell	0.50
η_2	Efficiency of DC/AC converter	0.90

3) Electrolyzer Sizing: The rated capacity of electrolyzer (P_{EL}) can be determined by equation (9)

$$P_{EL} = M_{EL} \times A_{PV} \times \eta_{PV} \times \eta_{MP} \times \eta_{D1} \tag{9}$$

Where, M_{EL} (=0.88) is margin coefficient of electrolyzer.

*4) Fuel Cell Sizing:*The rated power of fuel cell (P_{FC}) could be calculated by

$$P_{FC} = (M_{FC} \times P_{LMAX})/\eta_2 \tag{10}$$

Where, M_{FC} (=2) is margin coefficient of fuel cell. Where, P_{LMAX} is maximum value of load power.

5) Hydrogen Tank Sizing: According to ideal gas law 1mol (2g) H_2 gas at 25^0C is 22.4L. The volume of H_2 tank can be obtained by

$$V_H = \frac{\int_{T11}^{T22} \eta_{D1}\eta_{EL}(I_S.A_{PV}.\eta_{PV}.\eta_{MP} - \frac{P_L}{\eta_2}).dt}{65.8H_P} \qquad (11)$$

Considering margin co-efficient, the final capacity of H_2 tank in cubic meter can be obtained as $0.00244V_HM_{HT}$. Where, H_P is storage pressure of tank (200 bar), M_{HT} (=2.5) is margin coefficient of H_2 tank. Fig.3 shows variation of actual solar power ($PS=Is.A_{PV}.\eta_{PV}.\eta_{MP}$) with load. During the time interval [T11, T22] actual solar power is more than load power. After supplying the load the extra solar power charges the battery and supply to the electrolyzer. During the time interval [T00, T11] and [T22, T33] solar power is insufficient to meet the load demand. Then sharing among the sources takes place to supply the power.

V. ENERGY MANAGEMENT STRATEGY

To balance the energy throughout the year the energy management strategy has been implemented in yearly basis using MATLAB programming. The main objective is to meet the load demand first and then storing and utilizing the excess energy properly. In this program the available solar power is compared with load power instantaneously. Solar energy, load energy, battery energy, all parameters are in Wh. As the battery energy cost is lower than the hydrogen cost so battery is used as the first back-up source. The optimal energy management flow chart has been formulated and shown in in Fig.4 to evaluate the reliability. As per the energy based approach after one year of continuous operation, larger the hydrogen present in storage tank larger will be the efficiency of the system. For optimal energy management at the end of the year the state of charge of hydrogen tank (SoC H_2) should at least equal to its initial starting value. According to above energy management principle, reliability of the system can also be estimated. The system will be reliable if it is able to supply full load over one year and EENS comes to zero. Then EIR is coming as 1 as per equation (2). Fig.5 shows the variation of battery energy and hydrogen tank energy with energy demand and solar energy.

VI. SIZING WITH PARTICLE SWARM OPTIMIZATION ALGORITHM

A simulation model of standalone hybrid system has been designed consisting of solar panel, Battery Bank, Fuel Cell and Electrolyzer. In Order to verify system performance this model has been tested with the same insolation data and load data and identical system configuration as used in energy based approach. The model of various components has been discussed below.

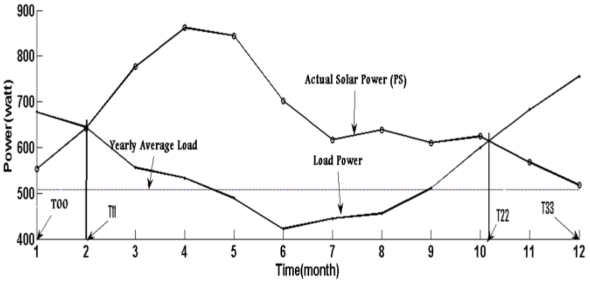

Figure 3. Variation of actual solar power and load

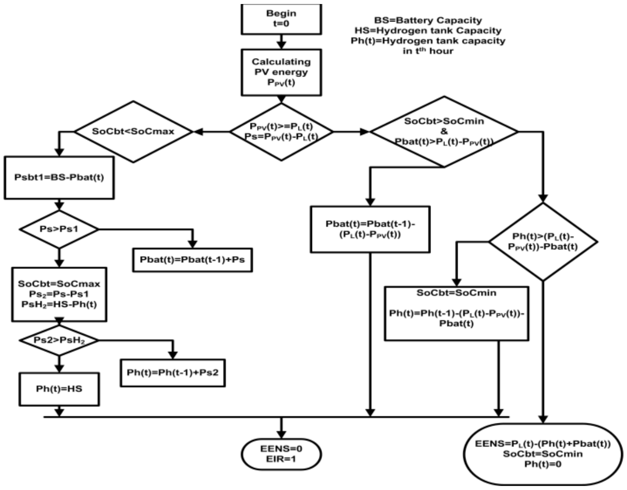

Figure 4. Energy management strategy and EIR calculation

A. System Modelling

a) PV model: Monthly average Solar Insolation data available in [10] has been converted to power output using following equation

$$P_{pv} = I(t) \times \eta_{PV} \times \eta_{MP} \times A_{PV} \qquad (12)$$

Where, I(t) is the solar insolation data available for t^{th} hour.A_{PV} is the required area of PV panel. Total number of PV panels required can be calculated from A_{PV} and area of each module.

b) Battery model: In this hybrid generation system battery is operating as the primary backup source. Battery is charging or discharging depending on load demand (P_L) and available PV power (P_{PV}) and fuel cell power (P_{FC}). Battery power can be obtained as follows

$$P_{BT} = P_{PV} + P_{FC} - P_L \qquad (13)$$

Fuel Cell will be activated only when battery power will be lower than minimum SoC level and charge the battery up to a maximum SoC.

c) FC model: In this study, Proton Exchange membrane FC (PEMFC) has been taken as it possess a good startup and shutdown performance. Once FC is activated it operates at a

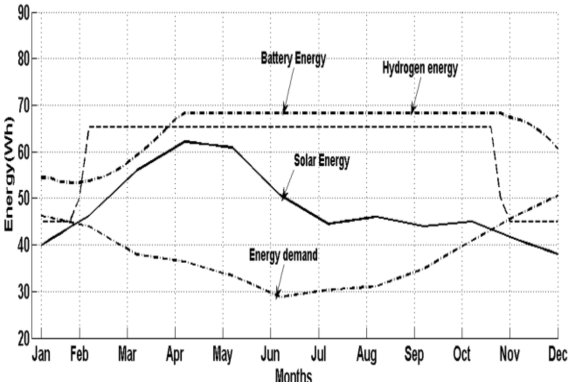

Figure 5. Variation of battery SoC and SoC H_2 tank with solar power and load for one year

same nominal power (P_{FC}) throughout its operation. The mole of hydrogen consumption by FC to produce 1kWh of energy can be find as follows

$$M_{FC} = P_{FC} \times 3600/(2 \times V_{FC} \times \eta_{FC} \times F) \qquad (14)$$

Where, V_{FC} (=1.48V) is the output voltage of FC, F is Faradays constant. According to above equation to produce 1kWh electrical energy 26.8 mol/h hydrogen is consumed in working condition [13].

d) Electrolyzer model: Electrolyzer is a device that produces Hydrogen and Oxygen from water. In this model same equation (9) has been taken for electrolyzer modeling. When PV power is excess after supplying the load and battery power then it will run the electrolyzer to produce hydrogen and store it to H_2 tank. It is assumed that electrolyzer and compressor can produce 1kwh power with 8.86 mol of H_2 gas [13] at 20 bar pressure.

e) Minimum and maximum state of charge of battery: At the time of discharging, battery should discharge to a minimum SoC level (SoCmin), after which FC has to be started. At the time of charging when battery charged upto maximum SoC level (SoCmax) FC will stop.

$$SoC_{bt} = (\int (P_{charging} \times \eta_{BT}) - P_{discharging})/P_{BT} \qquad (15)$$

Where, SoC_{bt} is the battery SoC level, $P_{charging}$, $P_{discharging}$ are the battery charging and discharging power respectively.

f) Capacity of hydrogen tank: In this study capacity of hydrogen tank (in m^3) is passing as a PSO variable. Through the energy management calculation the optimal size of H_2 tank is obtained. The effective mole of Hydrogen present in the tank can be calculated as follows

$$M_{H2} = P_t \times 1000 \times V_t/(T_t \times R) \qquad (16)$$

Where, V_t is volume of H_2 tank in m^3, P_t is pressure of H_2 tank in atm, T_t temperature of H_2 tank in Kelvin, R is gas constant (=0.08211 in atm $mol^{-1}K^{-1}$).

B. PSO Algorithm

Particle swarm Optimization (PSO) algorithm has been used to obtain optimal size of the system components. It was developed in 1995 by James Kennedy and Russel Eberhart through simplified social model simulation [14]. It stimulates the behavior of bird flocking or fish scooling [15].

The standard PSO algorithm consists of various numbers of randomly generated particles. Each particle has its own position $P_i=(P_{i1},P_{i2},\ldots\ldots,P_{in})$ and velocity $V_i=(V_{i1},V_{i2},\ldots\ldots,V_{in})$. Each particle has memory of its best position found so far ($Pbest_i$) and the best position, obtained so far, by any particle in the population ($gbest_k$). In every iteration this Pbest and gbest value will keep updating to get optimal configuration. PSO algorithm for determining optimal sizes of hybrid system components is shown in Fig.6. In each iteration the particles velocity will be updated by following equation

$$V_i^{k+1} = V_i^k \times w + c_1 r_1 (Pbest_i - P_i^k) + c_2 r_2 (gbest^k - P_i^k) \qquad (17)$$

Where, V_i^{k+1} is velocity of i^th^ particle at (k+1)th iteration. V_i^k is velocity of ith particle at kth iteration. r_1, r_2 are random numbers between [0, 1].c_1, c_2 are number in the range of 1.5 to 2.5. w is inertia weight which can be calculated from following equation.

```
Particle swarm optimization algorithm for determining optimal sizes of hybrid system components
 Begin
      Input solar irradiation data, load demand, component
      efficiency and cost details.
      Initialize PSO parameters; randomly generate initial
      population   of particles position and velocity.
  While maximum iterations not reached
     Do checking constraint
        Extract   constraint satisfying particles.
        Calculate   fitness value of particles using   equation(1).
        Obtain next generation by updating velocity and
        position of particles.
        Update Pbest  and gbest for each particle .
 Return Constraint satisfying global best solution
```

Figure 6. PSO algorithm for determining optimal sizes of hybrid system components

$$w = w_{max} - \frac{w_{max} - w_{min}}{Itr_{max}} \times Itr \qquad (18)$$

Where w_{max},w_{min} are initial and final inertia weight, Itr_{max} is maximum iteration number, Itr is current iteration number. After velocity update each particle position is again update by following equation.

$$P_i^{k+1} = P_i^k + V_i^{k+1} \qquad (19)$$

Where, P_i^{k+1} is the position of ith particle in (k+1)th iteration and P_i^k is position of ith particle in kth iteration. The PSO parameter values taken into account are number of iteration (=300), number of particles (=80), [w_{max},w_{min}]=[0.9,0.4], [c_1,c_2]=[2,2].

VII. COMPARATIVE CASE STUDY AND DISCUSSION

Table III and Table IV shows the sizes obtained by above two methods along with the total cost of the system. A comparative case study has been conducted to compare results obtained by two methods. As per the sizes of all system components total cost of the system has been calculated in INR for the total project lifetime. Fig.7 shows convergence of PSO to optimal global best solution. In energy based approach system sizing is not dependent on cost of system component, where in PSO total annualized cost of system components is the major optimization parameter. In systematical approach calculation has been done in monthly basis, so the system parameters obtained move towards a weak solution (large system size), where in PSO all the calculation has been done on hourly basis i.e full 8760 hours of the year has been taken into account. Energy based approach is consisting of direct one way solution of the problem. But PSO algorithm involves a two-way sharing mechanism and thus only best solutions can be obtained at the end of iterations [16]. Fig.7 shows that after 50 iterations PSO cost function converges to its minimum value and optimal system sizes are obtained. The system component sizes obtained by PSO is said to be optimal because it is satisfying all constraints and also total annualized cost of the system is minimum. For this values PSO parameters as shown in Table IV, the reliability constraint EIR is also evaluated as 1. So the system is becoming optimal than energy management approach as cost is minimum in PSO and reliability aspect is also conserved.

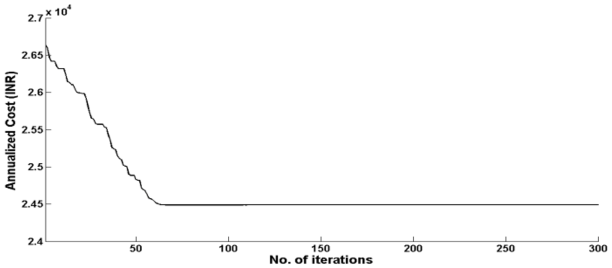

Figure 7. PSO convergence curve

TABLE III. COMPONENT SIZES OBTAINED BY ENERGY BALANCE APPROACH

Parameters	**PV Area (m^2)**	**Battery (Wh)**	**Electrolyzer (W)**	**Fuel Cell (kW)**	**H_2 Tank (m^3)**	**SoCmin (%)**	**SoCmax (%)**	**Total cost (INR)**
Values	30.35	65.28	2.8339	1.51	8.47	35	100	40249

TABLE IV. OPTIMAL COMPONENT SIZES OBTAINED BY PSO

Parameters	**PV Area (m^2)**	**Battery (Wh)**	**Electrolyzer (W)**	**Fuel Cell (kW)**	**H_2 Tank (m^3)**	**SoCmin (%)**	**SoCmax (%)**	**Total cost (INR)**
Values	23.09	51.54	1.05	0.91	2	25	88.07	24488

VIII. CONCLUSIONS

This paper presented a study on sizing of hybrid PV-FC-Battery system with energy based system sizing method and PSO. Both the methods have used same solar irradiation and load demand. Energy management strategy has been implemented to determine energy efficiency and reliability of system components. The optimal system component sizes obtained by PSO satisfy all constraints with minimum total annualized cost. This methodology can be easily extended to type of load demand and solar insolation.

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