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Research Article

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Optimization of a PV-Diesel hybrid Stand-Alone System using Multi-Objective Genetic Algorithm

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Abstract— The development of environment friendly and renewable energy systems has gained a lot of importance in the past few years due to depletion of fuel reserves and the harmful effects of environmental pollution. However, due to the erratic nature of renewable energy supplies and load variation, the system design is complex and unreliable. A hybrid system makes these energy systems more economical and reliable. In the design of these systems, the class of evolutionary algorithms is found to give quicker results than other conventional methods owing to the high number of constraints and variables. This paper aims at optimizing a PV-Diesel system with battery as backup storage to meet a particular load curve with solar irradiation data of Chennai, India obtained from the NASA meteorological website. The objectives are to minimize total net present cost and pollutant emissions using multi-objective optimization (NSGA-II).

Keywords— Diesel, Hybrid PV systems, Multi-objective design, NSGA-II, Renewable Energy

I. INTRODUCTION

The overall performance of a hybrid system is a function of the efficiency of each component of the system. In a PV system, the output of the Photovoltaic system is dependent on the climatic conditions of the region in which the plant is located, and is hence highly variable and erratic. It is also available only during fixed hours of the day. To make up for this uncertainty and suitably meet the load demand when the renewable energy is scarce or unavailable, additional energy sources are required as backup to improve the reliability of the system. Diesel generators are a very logical choice for this purpose. Diesel generators are very quick to start and can provide power almost instantaneously. However, due to high fuel and O&M costs, diesel-only systems tend to be very expensive, more so for large power systems. Hence, they are best utilized in a hybrid environment. To provide continuity of power supply and serve as backup for solar power, batteries are added. Batteries store excess energy produced by solar panels and diesel generator, if any, during day, and serve as a power source during night or when there is unmet load. Depending on the state of charge, and the availability of power after the load is met, batteries are charged by either the Photovoltaic panel or the diesel generator. In this paper, a program developed to optimize four variables to meet the objectives has been implemented. These are- Type of PV panels, number of PV modules in parallel constituting the panel, type of battery and the number of batteries in parallel constituting the battery pack. The design and operation of the system has to be economical, so minimization of the cost of the system is considered as one of the primary objectives. With addition of diesel generator, pollutant emissions are inevitable. The second objective is to minimize the CO_2 emissions (in Kg.) occurring during operation of the diesel generator.

II. SYSTEM COMPONENTS

The hybrid system consists of Photovoltaic panels, a diesel generator and batteries. The system is modeled entirely using system currents. The AC voltage of the system V_{AC}=230V, while the DC voltage V_{DC}=48V.The fig. 1 shows components of the system. The current directions are as indicated. The modelling and costs for each of these components have been described in the following sections.

A. Photovoltaic Energy

Photovoltaic cells provide DC current, denoted by I_{re}. This is one of the main inputs that decide current contribution of the diesel generator to meet the load, as well as the state of charge of the battery. The current from PV generator [1] in the i^{th} hour depends on the solar irradiation of the region, given by –

$$I_{rei} = G_i \text{ x } I_p \qquad (1)$$

where G_i is the global hourly irradiation in kWh/m^2, I_p is the peak current of the generator.

Ten types of PV panels with different specifications have been considered for the purpose of optimization, the details of which are shown in Table I.

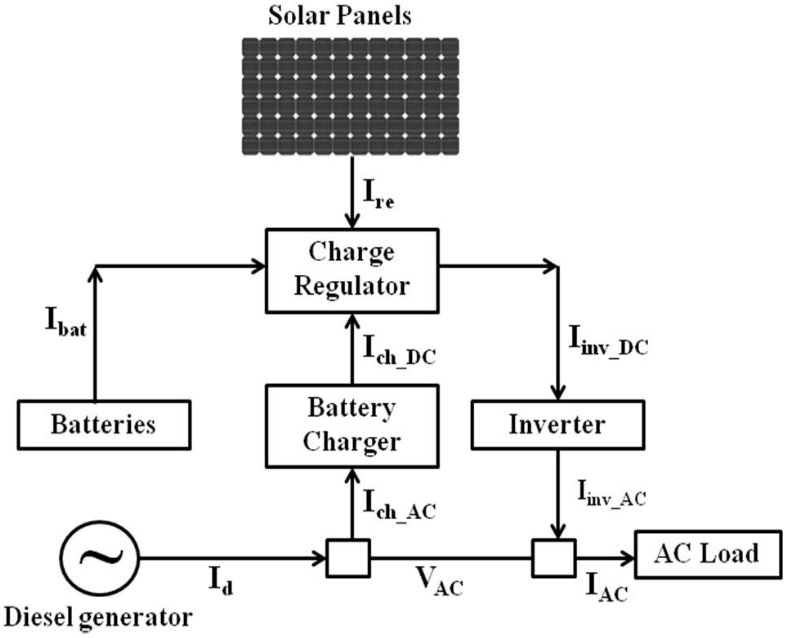

Fig.1: PV-Diesel System with AC Load

TABLE I
TYPES OF PV PANELS

PV Panel Type	Nominal voltage (V)	Peak Power (Wp)	Acquisition cost(€)	Lifespan (Years)
1	12	10	47	25
2	12	20	109	25
3	12	22	80	25
4	12	50	154.9	25
5	12	60	200	25
6	12	66	216	25
7	12	95	245	25
8	12	130	478	25
9	12	135	277	25
10	12	135	354	25

B. Diesel Generator

Suitable diesel generator that can supply the load demand has been selected, based on the peak load characteristics. The specifications of the diesel generator are as given in Table II. A linear model has been assumed for the fuel consumption rate (F) in litres/ hour of operation by the diesel generator [10], given by-

$$F = (0.246 \text{ x } P_{out}) + (0.08415 \text{ x } P_{Ngen}) \text{ litres/hour} \quad (2)$$

Where, P_{out} = Operating output power (kW)
P_{Ngen} = Rated power of diesel generator (kW).
The fuel cost C_{fuel} can then be calculated using the formula

$$C_{fuel} = C_{diesel} * F \text{ (Rs.)} \quad (3)$$

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

C. Battery

Battery banks serve as backup storage, and are charged either by the PV generator or the diesel generator depending on availability and discharge strategy adopted. Ten 12V battery models have been considered, the model being a variable in the optimization. Four batteries are connected in series to make up the DC voltage, while the number of batteries in parallel is a variable. The types of battery models considered are as shown in Table III. The minimum state of charge of the batteries is taken as 40% of their capacity, while the efficiency taken is 80%.

TABLE III
DIESEL GENERATOR SPECIFICATIONS

Rated Power (KVA)	**Minimum Power (kVA)**	**Acquisition Cost (€)**	**O&M Cost (€/h)**	**Lifespan (hours)**
4	1.2	1050	0.17	10000

III.SYSTEM MODEL - CALCULATION OF SYSTEM CURRENTS

A. Battery state Of Charge

The time step taken for system analysis is denoted by Δt=1 hour. For every hour, the maximum current that the battery is capable of providing, $I_{bat,max}(t)$ is calculated using the state of charge of the battery in the previous time step, hence at t+Δt , the maximum battery current [1] is given by the equation-

$$I_{bat,max}(t+\Delta t)=\max[0,\min[I_{max},(\frac{c}{\Delta t}.(SOC_{max}-SOC(t))+(SOC(t)-SOC_{min}).\frac{1-c}{\Delta t})]] \qquad (4)$$

where,

I_{max} = Current supplied by PV generator for irradiance of 1 kWh/m^2

c = Binary variable, where c=0 for discharging and c=1 for charging

The state of charge of the battery for the next step can be calculated as

$$SOC(t+\Delta t)=SOC(t).(1-\delta)+I_{bat}(t).\Delta t.\eta \qquad (5)$$

where, δ is the self discharge coefficient of the battery.

TABLE IIIII
BATTERY MODELS

Battery Panel Type	**Voltage (V)**	**Nominal Capacity (Ah)**	**Acquisition cost (€)**	**Lifespan (Years)**
1	12	68	166	25
2	12	78	254.9	25
3	12	97	150	25
4	12	106	194.9	25
5	12	120	160	25
6	12	134	154	25
7	12	170	464	25
8	12	189	174	25
9	12	190	562	25
10	12	296	961	25

B. System Currents

The dispatch strategy adopted for the system is shown in the flow diagram in Fig. 5. In every time step, the load unmet by the PV generator, I_{net_DC} in DC is calculated according as

$$I_{net\_DC}=I_{AC}.\frac{V_{AC}}{V_{DC}.\eta_{inv}}-I_{re} \qquad (6)$$

where I_{AC} is the AC load current. If the value of I_{net_DC} is negative, the PV panels generate excess energy, hence the remaining current is used to charge the batteries after checking their SOC. The charging current of the battery is given by

$$I_{bat}=\max(I_{bat,max},|I_{net\_DC}|) \qquad (7)$$

If I_{net_DC} is positive, the PV generator is unable to meet the load. Here, two cases arise:

(a) If the batteries are able to supply I_{net_DC}, the batteries discharge and the Diesel generator is off.

$$I_{bat}=I_{net\_DC} \qquad (8)$$

(b) If the batteries are not able to supply Inet_DC, the diesel generator is switched on to full power. The load is met, and the batteries are charged with remaining current from the diesel generator, if any. The current from Diesel generator in this case is given by

$$I_d = \max\left[\frac{P_{Ngen}}{V_{AC}}, \left(I_{bat}\frac{V_{DC}}{V_{AC}\cdot\eta_{ch}} + I_{net\_DC}\frac{V_{DC}\cdot\eta_{inv}}{V_{AC}}\right)\right] \quad (9)$$

where, η_{ch} and η_{inv} are the charger and inverter efficiencies respectively. The current with which the batteries will be charged is given by

$$I_{bat} = \min[\, I_{bat,max}, (P_{Ngen}/V_{AC} - I_{AC} + I_{re}.V_{DC}.\eta_{inv}/V_{AC}).V_{AC}.\eta_{ch}/V_{DC}] \quad (10)$$

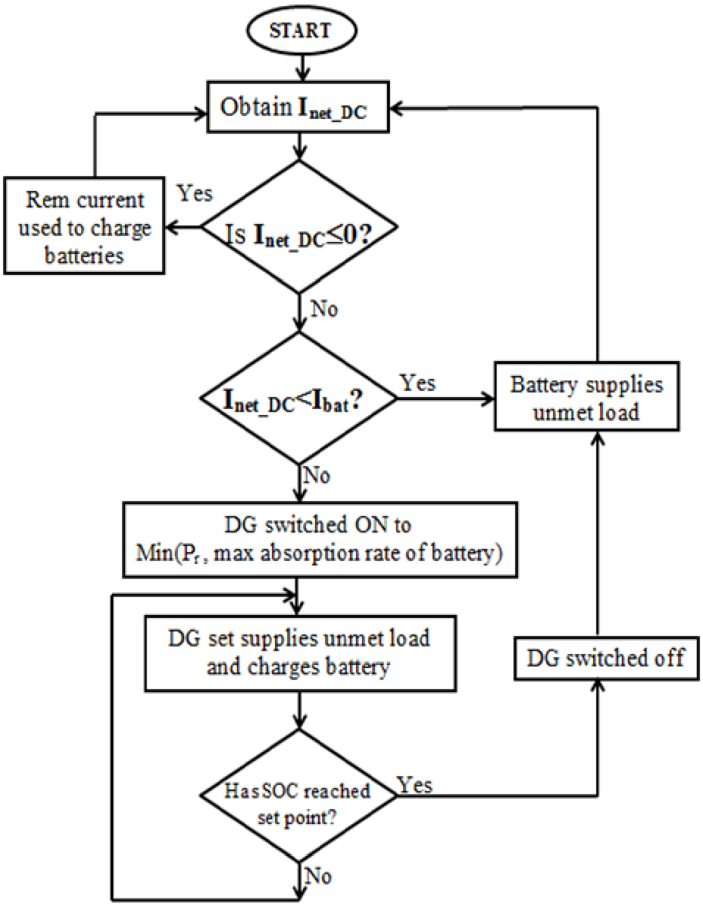

Fig.2: Dispatch Strategy

IV. OPTIMIZATION ALGORITHM

Elitist Multi-Objective Genetic Algorithm using the Non-Dominating Sorting procedure for populations (NSGA-II) was used for optimizing the system programmed using MATLAB. The number of variables considered was 4 and the number of objective functions optimized was 2. Optimization was carried out for the system using insolation data and fuel prices in two regions, namely Zaragoza, Spain and Chennai, India.

A. NSGA-II

Elitist Non-Dominated Sorting Algorithm (NSGA-II) [7][8][11] sorts the initial and successive populations by non-domination based on fitness and rank, into different fronts. The best front is numbered 1 and the subsequent fronts that are dominated by these members are numbered thereafter. Members of the same front are differentiated by their crowding distance. The diversity among non-dominated solutions in a front is introduced by crowding distance comparison. In every generation, selection to the following generation is done after clubbing the parent population with the current population to generate offspring using binary tournament operator, simulated binary crossover and polynomial mutation functions.

(1) Non-dominated Sort:

For each individual p in main population P ,

- Initialize Sp =ϕ. S_p contains all the individuals that p dominates
- Initialize np = 0. np stores the number of individuals that dominate p.
- For each individual q in P
  -if p dominates q , add q to Sp i.e. Sp = Sp∪ {q}
  -else if q dominates p, increment the domination counter for p i.e. np = np + 1
  - if np = 0 i.e. no individuals dominate p then p belongs to front 1, and rank of p, p_{rank} = 1.

Update the front set by adding p to front 1 i.e F1 = F1∪{fp}.

- Initialize the front counter to one. i = 1
- While (i^{th} front $F_i \neq \phi$) non empty set

- Q = ϕ. The set for storing the individuals for $(i + 1)^{th}$ front.
- For each individual p in front F_i for each individual q in Sp
 *nq = nq-1, decrement the domination count for individual q.
 *if nq = 0 then none of the individuals in the subsequent fronts would dominate q. Hence set qrank = i + 1.

Update the set Q with individual q i.e. Q = Q∪ q.

- Increment the front counter by one.
- Now the set *Q* is the next front and hence $F_i = Q$.

(2) Crowding Distance:

The crowing distance is calculated as below-

- For each front *Fi*, *n* is the number of individuals.
  - initialize the distance to be zero for all the individuals i.e. *Fi*(*dj*) = 0,

Where *j* corresponds to the j^{th} individual in front *Fi*.

-for each objective function m

*Sort the individuals in front *Fi* based on objective *m* i.e. *I* =*sort* (*Fi;m*).

* Assign infinite distance to boundary values for each individual in *Fi* i.e. *I*(*d*1) = *1* and *I*(*dn*) = *1*

*for *k* = 2 to (*n*- 1)

$$I(d_k) = I(d_k) + \frac{1(k+1).m - 1(k-1).m}{f_m^{max} - f_m^{min}} \qquad (11)$$

(3) Binary Tournament Selection

Once the individuals are sorted based on non-domination, and crowding distances are assigned, the selection is carried out using a crowded-comparison-operator (<*n*). The comparison is carried out as below based on

(a) Non-domination rank *prank* i.e. individuals in front *Fi* will have their rank as Prank = i.

(b) Crowding distance Fi(dj)

*p <q if

- Prank < Qrank

-or if p and q belong to the same front Fi then

Fi(dp) > Fi(dq) i.e. the crowing distance should be more. The individuals are selected by using a *binary tournament selection* with crowed-Comparison-operator.

(4) Simulated Binary Crossover

Simulated binary crossover simulates the bi-nary crossover observed in nature and is give as below.

$$C_{1,k} = \frac{1}{2}[(1 - \beta_k)p_{1,k} + (1 + \beta_k)p_{2,k}] \qquad (12)$$

$$C_{2,k} = \frac{1}{2}[(1 + \beta_k)p_{1,k} + (1 - \beta_k)p_{2,k}] \qquad (13)$$

where ci,k is the ith child with kth component, Pi,k is the selected parent and βk (≥ 0) is a sample from a random number generated having the density.

$$p(\beta) = \frac{1}{2}(\eta_c + 1)\beta^{\eta} \ , \ \text{if } 0 \leq \beta \leq 1 \qquad (14)$$

$$p(\beta) = \frac{1}{2}(\eta_c + 1)\frac{1}{\beta^{\eta c+2}} \ , \ \text{if } \beta > 1 \qquad (15)$$

This distribution can be obtained from a uniformly sampled random number *u* between (0, 1) ηc is the distribution index for crossover.

(5) Polynomial Mutation

$$C_k = p_k + (p_k^u - p_k^l)\delta_k \qquad (16)$$

where ck is the child and Pk is the parent with Pu/k being the upper bound on the parent component, Pl/k is the lower bound and ±k is small variation which is calculated from a polynomial distribution by using

$$\delta_k = (2r_k)^{\frac{1}{\eta_m+1}} - 1 \text{ , if } r_k < 0.5 \qquad (17)$$

r_k is an uniformly sampled random number between (0,1) and η_m is mutation distribution index.

B. Problem Statement

The problem statement is to optimize the system to achieve two objectives- minimize total net present value of the system after one year and the pollutant emissions in kg of CO_2 emitted. These are described below:

(1) **Cost Function**

The cost function consists of the following components:

- *Acquisition cost*: PV Panels(C_{ACQ_PV}), batteries(C_{ACQ_B}), inverter(C_{ACQ_INV}), charge regulator(C_{ACQ_REG}), Diesel generator(C_{ACQ_GEN}).
- *O&M Cost*: PV panels($C_{O\&M\_PV}$) and battery($C_{O\&M\_B}$) ,Diesel generator($C_{O\&M\_GEN}$)
- *Fuel Cost*: Cost of fuel consumed throughout system life.
- *Replacement Costs*: Cost of replacing components throughout the life of the system. Diesel generator (C_{REP_GEN}), Charge regulator(C_{REP_REG}), Inverter (C_{REP_INV}) , Battery (C_{REP_B}), Battery charger (C_{REP_BCH})

The net present cost [13] is then calculated as follows-

$$\text{NPC} = \sum_{i=1}^{L} N_i(CC_i + RC_i * K_i + MC_i * P(ir,R)) \qquad (11)$$

Here,
L = No. of renewable resources
N = No. of units in each source
CC =Capital Cost
RC =Replacement cost
MC =Maintenance cost
ir = interest rate
R =Lifetime of total system
Ki = Replacement cost factor

$$= \sum_{n=1}^{l1} \frac{1}{(1+ir)\verb|^|(n*l2)}$$

P(ir,R) = Present worth value

$$= \frac{(1+ir)^R - 1}{ir(1+ir)^R}$$

B. Pollutant Emissions

The pollutant emissions in kg. Of CO_2, which are a function of the fuel consumption F, is given by

$$\text{Emissions} = (\text{Emission factor})*F \qquad (12)$$

The emission factor [12] is considered between 2.4-2.8 kg of CO_2 per litre of fuel consumed.
Thus the two fitness functions taken for optimization are-

$$f1 = NPC + L*(\text{Load current} - \text{Generation Current}) \qquad (13)$$
$$f2 = \text{Emissions} \qquad (14)$$

V. RESULTS

In this paper, hourly insolation for a year, Chennai, India (Fig. 3) have been used for simulation. Average monthly irradiation values for these regions were obtained using the NASA Metereological website and hourly values were generated using Graham's model (Graham and Hollands, 1990).

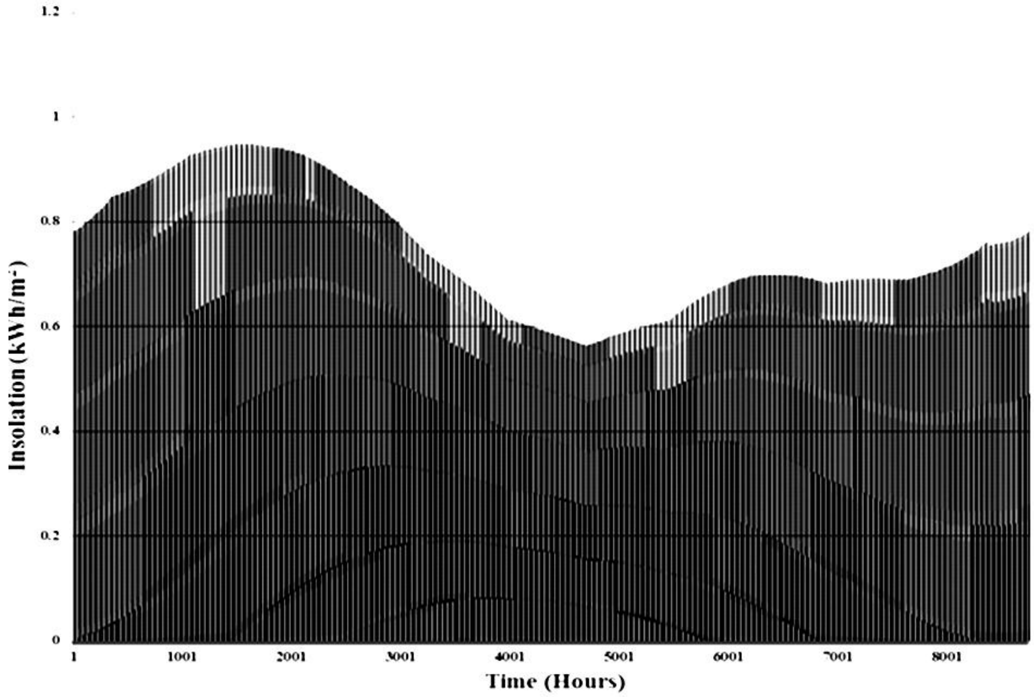

Fig. 3: Annual Solar Insolation Chennai, India

System load for 24 hours has been extended to generate hourly load profile for a period of one year, i.e. 8760 hours. The load profile is as shown in Fig. 4.

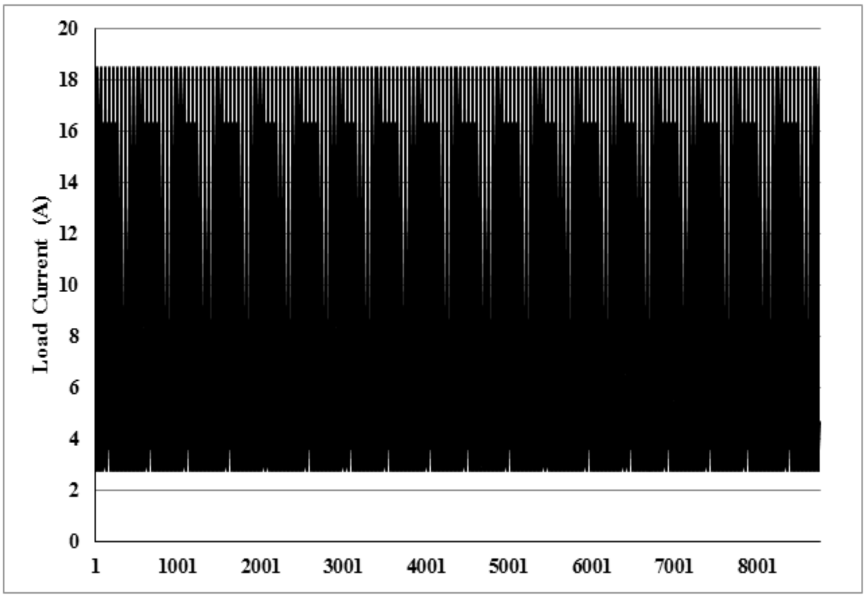

Fig. 4: Load Profile

Fig. 5 shows battery state of charge for 8760 hours for Chennai India. In this case input data has been considered for a period of 8760 hrs. i.e. 365 days. The program optimizes four variables namely- the type of PV panels, no. of PV Panels in parallel, the type of battery, as well as the no. of batteries in parallel. The Net present cost of the plant and the emission of CO_2 has been minimized and the most effective configuration for the plant has been obtained. The following are the parameters for the system.

1. No. of variables = 4

2.	Type of PV Panel	(1-10)
3.	No. of PV panels in parallel	(1-25)
4.	Type of battery	(1-10)
5.	No. of batteries in parallel	(1-10)

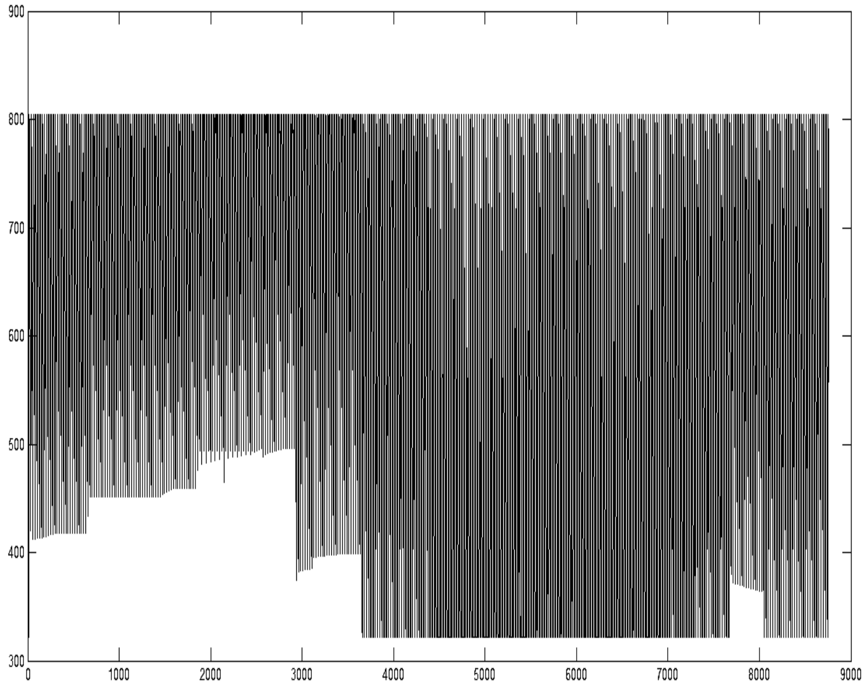

Fig. 5: Battery State of Charge – Chennai, India

Tables IV enlists the optimal results obtained on simulating the system for Chennai. The state of charge plot shows that the charge-recharge cycles are high, indicating that inclusion of the battery pack substantially reduces runtime of the diesel generator, and thereby the fuel costs. The population size taken is 60. The tournament size is 2. The crossover fraction is 0.8. Pareto front population fraction is 0.35. The algorithm stops when the weighted average change in the fitness function value over stall generations is less than Function tolerance.

TABLE IV
RESULTS OF OPTIMIZATION – CHENNAI, INDIA

PV Panel Type	10
No. of PV modules in parallel	24
Battery Type	6
No. of batteries in parallel	6
Diesel Generator Runtime	838 hours
Fuel Consumed	1106.7 litres
Fuel Cost	Rs.57,303
Net Present Cost	Rs.35,18,700

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VI. CONCLUSION

Renewable energy sources can be tapped effectively to transcend conventional sources to meet the growing energy demands. Hybrid systems, which are a combination of two or more different sources, have proven to be efficient in this endeavour. For the system considered in this paper, addition of few more renewables like wind, fuel cells, biomass units can add to the diversity of energy production and reduce the contribution of any one source to meet the load. The dispatch strategies could be multiple, and could also be one of the factors that are optimized. More variable parameters including, different ratings for diesel generators, and other components suitable to the system can be optimized. The design and operation of such a hybrid system in integration with the grid can also be considered. This project considers pollutant emissions only during the operation of the diesel generator. In reality however, pollutant emissions occur during the manufacture, transport and installation of different components in the system. These factors could be considered in evaluating and minimizing overall emissions in planning, commissioning and running a hybrid system of substantial size.

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