DESIGN OPTIMIZATION OF PHOTOVOLTAIC SYSTEM FOR DOMESTIC CUSTOMERS

A thesis submitted in partial fulfilments of the requirements for the award of the degree of

Master of Technology

in

Electrical Engineering
(Industrial Electronics)

by

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Department of Electrical Engineering

National Institute Technology

Rourkela, Odisha

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CERTIFICATE

This is to certify that the thesis entitled "**Design optimization of Photovoltaic system for domestic customers**" submitted by **Jitendra Kumar Gouda** in partial fulfilment of the requirements for the award of Master of Technology in Electrical Engineering with specialization in Industrial Electronics, during 2014 - 2015 at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge the matter embodied in this thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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Jitendra Kumar Gouda

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Abstract

In the present work, a comparison between different population based optimization methods are applied to design optimization of standalone Photovoltaic (SPV) system. The purpose of these methodologies is to obtain optimum values of the design parameters of SPV system, such that the overall economic profit is maximized throughout the PV system lifetime operational period. Out of many design parameters available for SPV system, in the present work only few parameters are taken. The optimal design parameters chosen here are PV modules optimum tilt angle, optimum number of PV module and optimal positioning of PV modules within the provided installation area. The objective function of the proposed evolutionary optimization algorithms implemented for design optimization of the SPV system is the total profit incurred during the lifetime operational period of SPV system, which has to be maximized. Simulation results of design optimization of SPV system by using Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Differential Evolution (DE) technique are obtained. Simulation results shows that DE and PSO have similar performance and both of them had performed better compared to GA when all algorithms are computed for equal iterations and population size.

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LIST OF SYMBOLS

σ_B	total volume of concrete foundation bases (m^3)
σ_{v1}	total length of vertical rods of each side of vertical line (m)
C_{INV}	capital cost of each DC/AC converter (₹)
C_{PV}	capital cost of each PV module (₹)
c_B	per unit vol. cost of concrete foundation bases (₹)
c_l	cost of installation land per unit area (₹)
c_s	per unit length cost of metallic rods (₹)
D_1	southern dimension of actual installation area (m)
D_2	western dimension of actual installation area (m)
DIM_1	southern dimension of total available installation area (m)
DIM_2	western dimension of total available installation area (m)
α	solar radiation angle (^{0})
$FF(t,\beta)$	fill factor
r	annual inflation rate (%)
$G(t,\beta)$	global irradiance incident on PV module (W/m^2)
h_w	concrete foundation base height (m)
d	nominal annual discount rate (%)
$I_{SC,STC}$	PV module short-circuit current under STC (A)
I_M	current of PV module at maximum power point (A)
L_{PV1}	length of each PV module (m)
L_{PV2}	width of each PV module (m)
L_P	total length of each row (m)
M_{INV}	annual maintenance cost per unit of inverter (₹)
M_{PV}	annual maintenance cost per unit of PV modules (₹)
$MTBF$	mean time between failures of inverter (h)
N_{dc}	total no. of inverters
N_{rod}	total no. of intermediate vertical rods of each side of a vertical line
N_r	the no. of inverter repairs performed during lifetime operational period
N_{row}	total no. of rows
$N_{ser\min}$	no. of PV modules installed in each line
$NCOT$	nominal cell operating temperature (^{0}C)

n_v	total no. of vertical lines
n_{INV}	inverter power conversion efficiency (%)
n_{MPPT}	conversion factor of MPPT operation performed by inverter (%)
R_{pu}	repair cost of each inverter (₹)
R_p	present worth of total cost of repairing inverters (₹)
S	capital subsidization rate (%)
t_w	concrete foundation base thickness (m)
$V_{OC,STC}$	open circuit voltage under STC (V)
V_M	voltage of PV module at maximum power point (V).

CHAPTER – 1

INTRODUCTION

1.1 INTRODUCTION

The increase in energy demands and pollution facilitate the innovation and application of Green Technology. Solar Energy is more versatile than other types of renewable energy due to its abundant availability. Also Silicon, the main constituent of solar cell used to trap solar energy is the second most ample element on the earth's crust. In India, although we have approximately 300 sunny days per year and receives an average hourly radiation of 200 MW/km^2, the energy resource is under-utilized. Also electricity losses in India during transmission and distribution is about 24.7% during 2013-14. Due to shortage of electricity, power cuts are common throughout India and this has adversely affected the country's economic growth. The above cited reasons led to the investment in domestic Photovoltaic (PV) system and it is encouraged by government subsidy in initial installation cost and profit in long run.

The main challenge in installation of standalone PV system (SPV) is optimizing space requirement of PV arrays meanwhile extracting maximum energy from the PV system. Therefore in this work we have worked on optimizing the size of the PV system. Optimal sizing ratio of PV system depends on inverter operational characteristics, PV array orientation, no. of PV modules and inverters. A multi-objective optimization is proposed for optimal design of PV system taking into consideration both the technical and economic aspects. Profitability of PV system is influenced by initial capital cost, annual maintenance and repairing cost, subsidy rate, selling price of generated energy. The objective of this methodology is the maximization of system's profit while exploring optimal solutions using different optimization technique. This methodology gives optimum number of PV modules and inverters, PV modules optimum tilt angle, optimum placement of PV modules within given installation zone, maximization of overall economic benefit during system operational lifetime period.

Several optimization techniques have evolved in the past decade that mimic the biological evolution and its ability to solve problems with non-linear and non-convex dependence of design parameters. The most representative algorithms include Differential Evolution (DE) [1], [2], Genetic Algorithm (GA) [5], [6], Particle Swarm Optimization (PSO) [7], [11] . Till date different GA, PSO and DE algorithms have been applied to different problems including PV system design [8], [10], [13]. To the best of the authors knowledge no performance comparison of GA, PSO, and DE applied to design optimization of standalone PV system, has been presented previously. In this work, a comparative evaluation of GA, PSO, and DE performance to obtain optimal design size of SPV system is done with maximization of net profit during the SPV system operational period.

1.2 LITERATURE SURVEY

Optimizing the design aspects of standalone PV system is an important aspect to minimize the overall cost and space requirement for setting up SPV system. In the recent years, several research or studies were carried out on optimal sizing of both standalone and grid connected PV system which will be reviewed in this section. Also in the last decade, many population based evolutionary algorithms that mimics the biological evolution for optimization were presented, which will also be reviewed.

Arunachalam, [1] proposed Differential Evolution optimization technique as a solution methodology to optimally design the water distribution network. The objective of the model formulated is to minimize cost and this formulation is applied to two water distribution system optimization problems. In the recent years, DE has drawn the attention of many research scholars therefore many of DE variants of the basic algorithm with improved performance were presented. Das and Suganthan, [2] had given a detailed review of the basic concepts of DE and its variants and also its application to multi-objective, large scale problems and constrained problems. Das [3] had given a simple fill factor calculation for a J-V model of a solar cell. Karabanov *et al.* [4] had put forward an equation calculating the global irradiance of a particular region taking into account global horizontal irradiance and diffuse horizontal irradiance data for that particular region and also the PV module tilt angle data. Kerekes, *et al.* [5] implemented GA to minimize the cost of PV plant per watt of the nominal power installed. Thus during the operational lifetime period of the PV system, the maximization of the economic benefit that is obtained. Kornelakis and Koutroulis [6] proposed GA optimization technique to minimize the cost and hence maximized net profit and thereby obtaining optimal values of design parameters of PV Grid Connected System. Kornelakis and Marinakis, [7] devised Swarm intelligence technique to maximize net profit and obtain optimal values of design parameters for Photo Voltaic Grid Connected System. Koutroulis *et al.* [8] presented GA optimization for optimal sizing of stand-alone photovoltaic and wind-generator systems. Kumar and Alwarsamy [9] proposes DE to solve the Economic Dispatch problem (ED) of power system taking into account the transmission loss and non-linear generator constraints. The proposed method is compared with GA, PSO and Simulated Annealing (SA). Pradhan *et al.* [10] had done technical, economic and environmental study for setting up grid connected PV system. They have used Hybrid Optimization Model of Electric Renewable software to estimate system size and its performance analysis. Pourmousavi, *et al.* [11] had worked on how to manage real time energy which can be incorporated in a standalone hybrid wind micro turbine energy system. He implemented PSO technique in his work. Razali and Geraghty [12] incorporated GA to solve well known travelling sales man problem. He had highlighted different selection method used in Genetic Algorithm. Out of the various selection methods, Roulette Wheel Selection method is the noble one. In this method, population of next generation depend upon the fitness of each individual. This type of selection has disadvantage when fitness difference is more. Shrestha and Goel [13] studied on optimal sizing of standalone PV system. They have taken statistical model for insolation and load models. The reliability of the PV model is measured in terms of loss of load hours, energy loss and total cost that have been used as the parameters for evaluation of different schemes. Swider, et al., [14] had studied on the importance and the effect of various parameters on the grid connected PV system. In ccontrast with the past SPV design strategies, the strategy displayed in this work has considered important design perspectives which can highly effect the total net profit obtained from the SPV system such as cost of mounting structures for PV modules, cost of land for installation of SPV system, tilt angle of PV module. Regarding optimization, the objective function is non-linear and complex type so differential evolution method outperforms to GA and PSO. Simulation results shows that DE method is more efficient for larger non-linear system.

1.3 RESEARCH MOTIVATION

The facts which motivated for optimization of standalone PV system are few works have been reported in the design optimization of standalone PV system, performance comparison is not done using different algorithms. Also the design of highly efficient (performance and design) model with many constraint parameters within a restricted space meanwhile maximizing the profit is a challenge which need to be explored.

1.4 THESIS OBJECTIVE

The main objective of this research work is to develop standalone PV system having optimum design aspects, implementation of different optimization algorithm (DE, PSO, GA) to PV model to maximize net profit and to find optimal values of the design parameters. Also simulation results of different optimization techniques are compared.

1.5 THESIS LAYOUT

The thesis contains five chapters as follows:

Chapter 1: It gives brief introduction of the modelling of SPV system and different optimization techniques used to optimize its design aspects so to maximize the profit. It also highlights the previous works on PV system and different optimization techniques used in it.

Chapter 2: It describes the modelling of the SPV system which includes design analysis and economic analysis of the SPV system. At the end objective function is formulated for design optimization and maximization of profit earned during the SPV system operational period.

Chapter 3: It illustrates different optimization techniques (GA, PSO, DE) with its flowcharts used in the design optimization of SPV system.

Chapter 4: This chapter deals with simulation results obtained from different optimization techniques applied to SPV system. Also comparison and discussion of the obtained results were done.

Chapter 5: It concludes the thesis work and also gives the future scope of the present work.

CHAPTER – 2

MODELLING OF STANDALONE PV SYSTEM

2.1 INTRODUCTION

To meet the continuously increasing energy demand and to combat the global warming, green energy which is a clean energy has been given the top priority in energy sector in recent years. Also due to exhaust of non-renewable resources and thereby rise in oil and coal price have propelled scientists, researchers and engineers around the world, to innovate technology to extract maximum energy from renewable resources like solar, wind, tidal and geothermal, which are cleanest form of energy. Among all the renewable resources, solar energy is most reliable energy because it is available throughout the day time and also Silicon which is the fundamental element used in large scale in each PV module is second abundant element in the earth's crust after oxygen.

There are different types of PV model for different users depending upon their energy consumption. A standalone PV system is modelled for domestic purpose only whereas a grid connected PV system is modelled to cater large number of industrial and domestic users. A typical PV system consists of PV arrays, DC/AC converters, dc loads, ac loads and battery. A large number of series and parallel combination of PV modules are connected to inverters to increase the PV systems voltage and current rating. The battery is generally provided to store excess energy during day time and deliver the same during peak hour inverter are used to interface the DC output voltage of PV systems to the AC loads or to the grid. Inverters exploit maximum power point tracker (MPPT) to obtain maximum power from the PV modules. The block diagram of typical PV system is shown below.

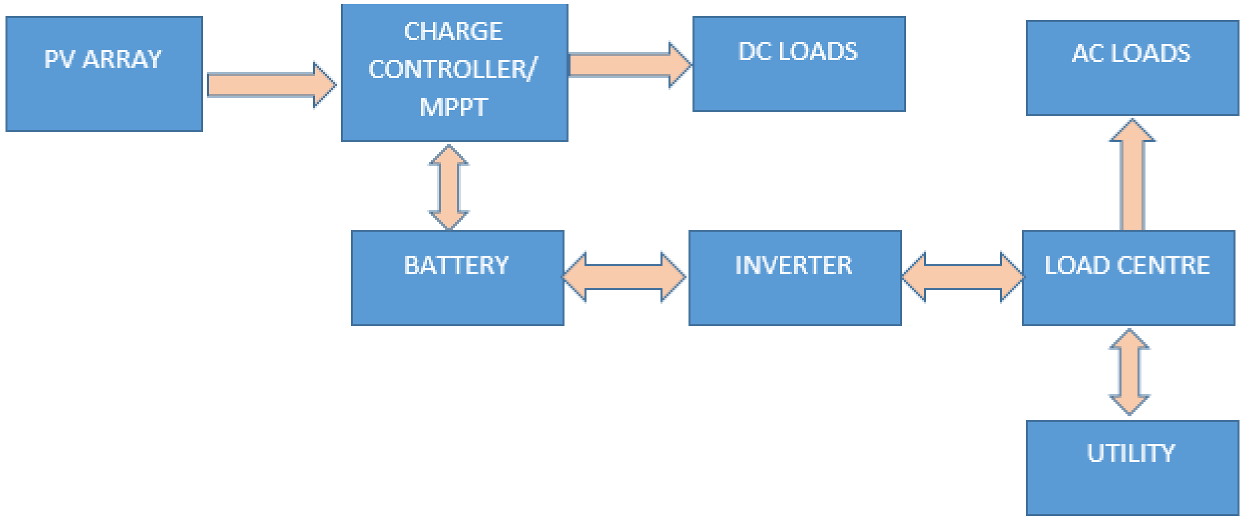

Fig. 1. Block diagram of a typical PV system.

2.2 MODELLING OF PV SYSTEM

In the standalone PV system, the PV module technical specification must satisfy the distribution of PV modules among the inverters and also the dimension limitation of available installation area. The assumption taken in this present work is the annual energy generated by PV modules is constant during total operational period of the SPV system. The PV arrays tilt angle (β) is also assumed to be constant throughout the year. The maximum output power of a PV module on each day at hour t $(1 \le t \le 24)$ under normal test conditions (solar irradiance = 1kW/m^2 and cell temperature = 25˚C) as specified by manufacturer is calculated as follows [6]:

$$P_M(t,\beta) = I_{SC}(t,\beta) V_{OC}(t) FF(t,\beta) \qquad (2.1)$$

$$I_{SC}(t,\beta) = \{K_I [T_C(t) - 25°c] + I_{SC,STC}\} \frac{G(t,\beta)}{1000 W/m^2} \qquad (2.2)$$

$$V_{OC}(t) = K_V [T_C(t) - 25°c] + V_{OC,STC} \qquad (2.3)$$

$$T_C(t) = \frac{NCOT - 20°c}{800 w/m^2} G(t,\beta) + T_A(t) \qquad (2.4)$$

where, $I_{SC}(t,\beta)$ is PV module short circuit current (A), $I_{SC,STC}$ is PV module short-circuit current under STC (A), $V_{OC}(t)$ is open circuit voltage (V), $V_{OC,STC}$ is open circuit voltage under STC (V), $G(t,\beta)$ is global irradiance (W/m^2) incident on PV module at a tilt angle β˚ [4], $FF(t,\beta)$ is fill factor [3], K_I is short circuit current temperature coefficient (A/˚C), K_V is open circuit voltage temperature coefficient (V/˚C), $T_A(t)$ is ambient temperature (˚C), *NCOT* is nominal cell operating temperature (˚C), $T_C(t)$ is the PV cell or module operating temperature (˚C).

The value of global irradiance $G(t,\beta)$ of a particular region is calculated taking into account global horizontal irradiance, diffuse horizontal irradiance data for that particular region and also the PV module tilt angle (β) data. The PV modules are organized in multiples rows in the available installation land, where each row embodies numerous lines as shown in Fig. 2.

The total no. of PV modules, N_{PV} connected to n_c number of inverters is calculated as

$$N_{PV} = n_c N_s N_p \qquad (2.5)$$

where, N_s is number of PV modules connected in series, N_p is number of PV modules connected in parallel.

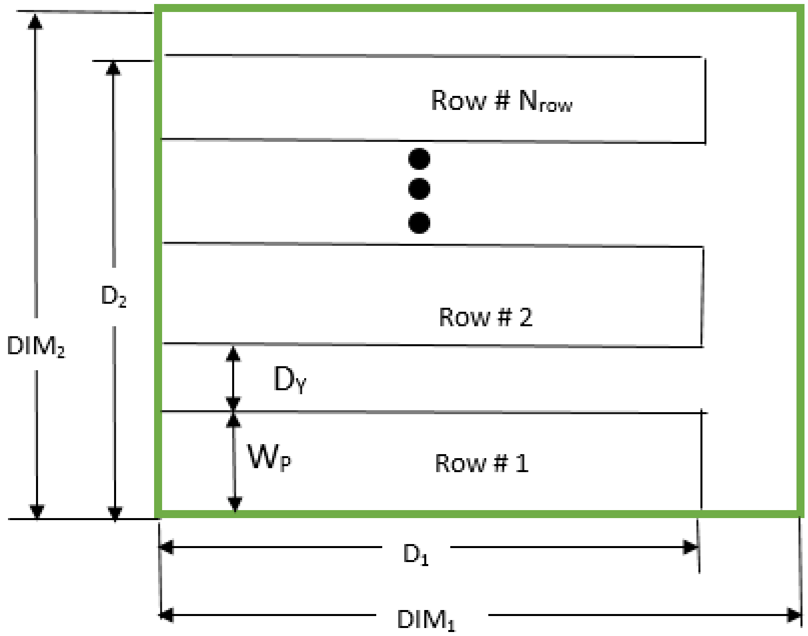

Fig. 2. Arrangement of the PV modules in rows within the available installation area.

The width, $W_P(m)$, of each PV row is calculated as

$$W_p = L_{PV2} N \cos\beta \quad (2.6)$$

where, $L_{PV2}(m)$ is width of each PV module, N is no. of lines per PV row.

The maximum height, $H_P(m)$, of each PV row is ascertained as

$$H_P = N L_{PV2} sin\beta \quad (2.7)$$

$$L_P = N L_{PV2} \quad (2.8)$$

where, $L_P(m)$ is the total length of each row.

The minimum distance between two adjacent rows, $D_y(m)$, to prevent mutual shading of corresponding PV module is calculated as

$$D_y = L_P[cos\beta + sin\beta\ cos\alpha] \quad (2.9)$$

where, α (°) is solar radiation angle and $L_P(m)$ is the total length of each row.

Southern dimension of the actual installation area, $D_1(m)$ is calculated as

$$D_1 = N_{s\,min} L_{PV1} \quad (2.10)$$

where, $N_{s\,min}$ is no. of PV modules installed in each line of a row, L_{PV1} , is length of each PV module.

Western dimension of the actual installation area, $D_2(m)$, is calculated as

$$D_2 = W_P \tag{2.11}$$

where, $W_P(m)$ width occupied by each row of PV modules.

The PV modules are supported by mounting structures which are made up of metallic rods. The intermediate vertical rods are installed at each point where the vertical height is raised to 2 m. The diagram of mounting structures where PV modules are installed is shown in Fig. 3. The total length of metallic rods, $\sigma_{tot}(m)$, required for mounting structure is calculated as follows

$$\sigma_{tot} = \sigma_v n_v \tag{2.12}$$

$$\sigma_v = [2(\sigma_{v1} + H_P + L_P) + (N_{rod} + 2)L_{PV1}]SF \tag{2.13}$$

$$\sigma_{v1} = \sum_{i=1}^{N_{rod}} 2i \tag{2.14}$$

where, $\sigma_v(m)$, is overall length of metallic rods needed to build the metallic frames of each vertical line, n_v is the total no. of vertical lines of PV system, $\sigma_{vl}(m)$ is total length of intermediate vertical rods of each side of a vertical line and SF is an over-sizing factor. A over sizing factor of 110% is considered because under practical conditions, some amount of raw material is not used during the construction of metallic frames for PV system.

The PV modules metallic mounting frames are setup on concrete foundation bases. The overall volume of concrete foundation bases needed to support the metallic mounting structures, $\sigma_B(m^3)$ is equal to total number of vertical lines in PV system multiplied by volume of concrete foundation bases of each vertical line

$$\sigma_B = (2 + N_{rod})h_w t_w L_{PV1} n_v \tag{2.15}$$

where, $h_w(m)$is the concrete foundation base height, $t_w(m)$ is concrete foundation base thickness and N_{rod} is total no. of intermediate vertical rods of each side of a vertical line.

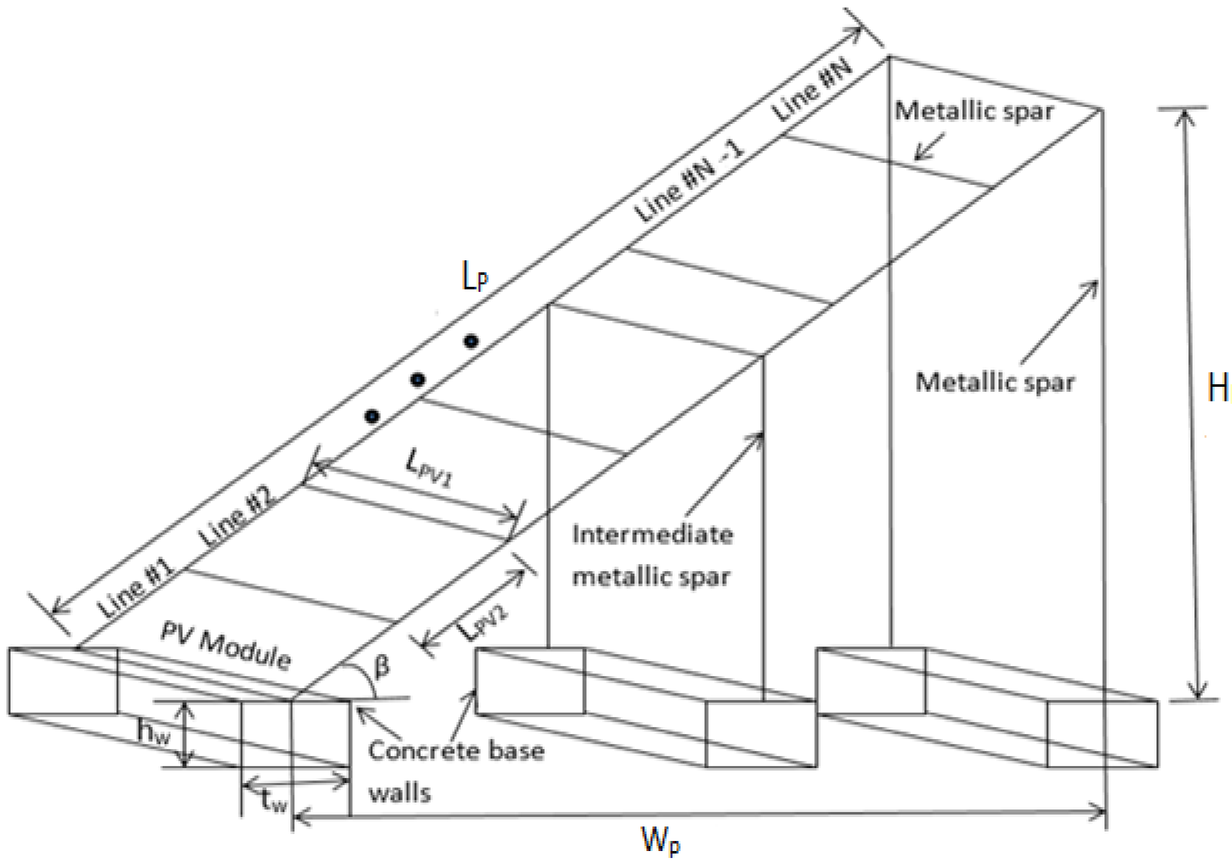

Fig. 3. The view of the mounting structures used to install the PV modules

The total manufacturing and installation cost of PV mounting structures, C_{σ}(₹), is calculated as follows

$$C_{\sigma} = \sigma_{tot} c_S + \sigma_B c_B \tag{2.16}$$

where, $\sigma_{tot}(m)$ is overall length of metallic rods used in PV installation, C_s(₹/m) is per unit length cost of metallic rods, $\sigma_B(m^3)$ is total volume of concrete foundation bases, c_B (₹/m^3) is per unit vol. cost of concrete foundation bases.

The cost of metallic rod depends upon the type of metallic rods and its thickness which rely on the weight of the PV modules and the environment conditions (salinity in air moisture causing corrosion, humidity) of that particular region where the SPV system is to be installed.

2.3 Economic Analysis

In the modelling of SPV system, the total expenditure is calculated taking into account the maintenance and capital costs of SPV system components (inverters, PV modules, and batteries), cost of land where the SPV system is to be installed, the cost of PV module metallic mounting structures and cost of the concrete foundation bases.

The total capital cost, $C_c(x)$, of SPV system is evaluated as follows

$$C_C(x) = (N_{PV}C_{PV} + N_{dc}C_{INV} + C_L + C_\sigma)(1 - s) \quad (2.17)$$

where, s (%) is the subsidy rate, C_L(₹) is the cost of the required installation area, C_{PV}(₹) is the per unit capital cost of PV module, C_{INV} (₹) is per unit capital cost of inverter and C_σ (₹) is the capital and installation cost of the PV arrays mounting structures.

The cost of the required installation area, C_L(₹), is evaluated as follows

$$C_L = D_1 D_2 c_1 \quad (2.18)$$

Where, c_1 (₹/m^2) is cost of installation land per unit area, D_1 (m) and D_2 (m) are southern and western dimension of actual installation area.

The present worth of the maintenance cost, C_m(₹) during the operational lifetime period of SPV system [6] is calculated as,

$$C_m(x) = (N_{dc}M_{INV} + N_{PV}M_{PV})(1 + r)\left[\frac{1 - [(1 + r)/(1 + d)]^n}{d - r}\right] + R_P \quad (2.19)$$

where, M_{PV}(₹) and M_{INV} (₹) are annual maintenance cost per unit of PV module and inverter respectively, r % is annual inflation rate, d % is annual discount rate, R_P(₹) is the present worth of total cost of repairing SPV inverter.

The present worth of total cost of repairing the inverter, R_P (₹), is calculated as [7]

$$R_P = N_{dc}R_{pu}\left[\sum_{\forall j=k}\frac{(1 + r)^j}{(1 + d)^j}\right] \quad (2.20)$$

where, R_{pu}(₹) is repair cost of each inverter, K is the year number that the inverter must be repaired during the operational period SPV system. The inverters are repaired only in particular years during SPV system operational period.

The value of K depends on the number of inverter repairs done during the operational lifetime period SPV system, N_r , is calculated as

$$N_r = \frac{n*365*24}{MTBF} \tag{2.21}$$

Where, MTBF (h) is the mean time between failures of the inverters, cited by the manufacturer. The DC/AC converters are repaired only for specific values of year numbers. For example if the calculated value of N_r is 10 for n = 10 years, then repairing of DC/AC converters is done for K = 10 and 20.

The present worth of total profits achieved from SPV system by reducing the consumption of energy from the distributor and utilizing more solar energy from SPV system [6], is calculated as

$$P_E(x) = C_o N_{PV} E_o \left[\frac{1-(1/(1+d))^n}{d} \right] \tag{2.22}$$

where, C_o (₹/kWh) is the cost of per unit energy fixed by distributor for domestic user, E_o (kWh) is the overall annual output energy of the PV system produced by each PV module.

The total annual output energy of the PV system generated by each PV module, E_o (kWh), is calculated as follows

$$E_o = n_{INV} n_{MPPT} \sum_{t=1}^{8760} \frac{P_M(t,\beta)}{1000} \tag{2.23}$$

where, n_{INV} is the efficiency of inverter, n_{MPPT} is the efficiency of MPPT operation accomplished by inverter.

The investment made in optimally sized SPV system is considered to be economically viable only if the Net Present Worth (NPW) is positive. The NPW of an investment is the summation of the present worth of all cash inflows and outflows made in an investment. In the present work, the SPV system NPW is equal to the total net profit function $F(x)$ which is calculated using (24). The NPW depends upon subsidy rate and cost of the installation land per unit area.

The NPW is directly proportional to subsidy rate and inversely proportional to cost of the installation land per unit area.

2.4 Objective Function

The modelling of the SPV system is done taking into account the several design parameters and economical parameters. The next thing to do is to optimize the design parameters and to maximize the profit during the SPV system operational period. Though there are lot of design parameters available for design optimization of SPV system, in the present work only three design parameters are taken for simplicity and easy to implement in optimization algorithms for less execution time. Therefore to optimize the design of SPV system and maximize the profit out of it during the operational period we need an optimization algorithm like GA, DE or PSO. The prime inputs to any optimization algorithms is the objective function of the system model and its constraints or boundary parameters. The objective function of the SPV system modelling is the net profit $F(x)$ (₹) maximization of the SPV system during its operational period is given as

$$\max\{F(x)\} = \max\{P_E(x) - C_m(x) - C_c(x)\} \tag{2.24}$$

where, x are the design variables, $P_E(x)$ is the total profit obtained during the PV system operation period, $C_c(x)$ is the total capital cost and $C_m(x)$ is the total maintenance cost of the SPV system.

The design variables for optimal sizing of SPV system are the total no. of PV modules, N_{PV} , the total no. of PV modules lines in each row, N and the PV module tilt angle, β.

The constraints of the decision variables are

$$1 \le N_{PV} \le 15 \tag{2.25}$$

$$1 \le N \le 3 \tag{2.26}$$

$$0^\circ \le \beta \le 45^\circ \tag{2.27}$$

CHAPTER – 3

OPTIMIZNG STANDALONE PV SYSTEM

3.1 OPTIMIZATION ALGORITHMS

The real world problem which are non-differentiable, non-linear, continuous and real valued can be solved to obtain global optimal solutions by these (GA, DE, PSO) modern stochastic algorithm. Hence in this work, each of these algorithm is simulated and compared for the design optimization of standalone PV system.

3.1.1 GENETIC ALGORITHM

Genetic Algorithm mimics the natural selection and survival of the fittest. GAs are a particular class of optimization algorithms that use methods inspired by biology such as selection, crossover (also called recombination) and mutation. It is a search method used in computing to find approximate solutions to optimization problems. A set of parameters to be optimized defines the individual and set of individuals comprise of population which with time evolve by the process of selection, crossover and mutation. In this algorithm, initially a random population or solutions are generated and then its fitness is evaluated. Then based on the fitness, selection is done on the individuals for reproduction. The selected individuals then undergo crossover and mutation operations to create offspring which forms the population of next generation. The above steps are repeated until maximum number of iterations or convergence is reached. The convergence speed of the algorithm depends on many factors like population size, crossover probability, mutation probability and elitism. The basic GA algorithm is shown in Figure. 4.

Every chromosome depict a possible solution of the optimization problem and many parameters. In the present work, it contains three parameters such as, $x = [N_{PV}|N|\beta]$. Before starting GA optimization process, first an initial population of 20 chromosomes or individuals is randomly generated. Secondly based on the fitness value selection is done for reproduction of best individuals. The better the fitness value, more is the chances of selection.

There are many selection methods in GA to select best individual they are as follows

- Roulette wheel selection
- Tournament selection

- Stochastic based selection
- Reward based selection

In the present work, Roulette wheel selection method is taken because in this method, chromosomes are given a probability of being chosen that is specifically corresponding to their fitness. Two chromosomes are then picked arbitrarily in light of these probabilities and produce offspring. So that, weak solutions are eliminated and strong solutions survive to the next generation. The name of the selection method is given as Roulette wheel because here each individual is assigned a part of Roulette wheel and the wheel is spanned n times to select n individuals from the population. Then the selected chromosomes undergo crossover operation. Before crossover operation, the selected chromosomes or solutions are represented in binary as strings of 0s and 1s, but other encodings are also possible. In crossover operation, segments of any two parents from the present generation are combined to create two offspring: an arbitrary subpart of the father's bit string is swapped with an arbitrary subpart of the mother's bit string. There are many types of crossover operations as listed below

- Single Point Crossover
- Multipoint Crossover
- Uniform Crossover
- Heuristic Crossover

In the present work, single point crossover is implemented for simplicity. After selection and crossover, now we have a new generation, some are directly copied, and others are produced by crossover. In order to ensure that the individuals are not all exactly the same, the next step is to allow for a small chance of mutation. In this step only a few individuals are chosen randomly from the new generation. This selection operation is done with uniform probability and not based on its fitness value. In each of the chosen chromosome, a bit is picked randomly and that bit is flipped to its complementary bit (0 or 1). Mutation operation is a more arbitrary process than crossover operation and its probability is very less. Still it is done in light of the fact that it may help to create a viable feature that is missing in the present generation. The probability of mutation is usually between 0.001 and 0.002. Finally, the new population is evaluated and the algorithm terminates when maximum number of iterations have been produced.

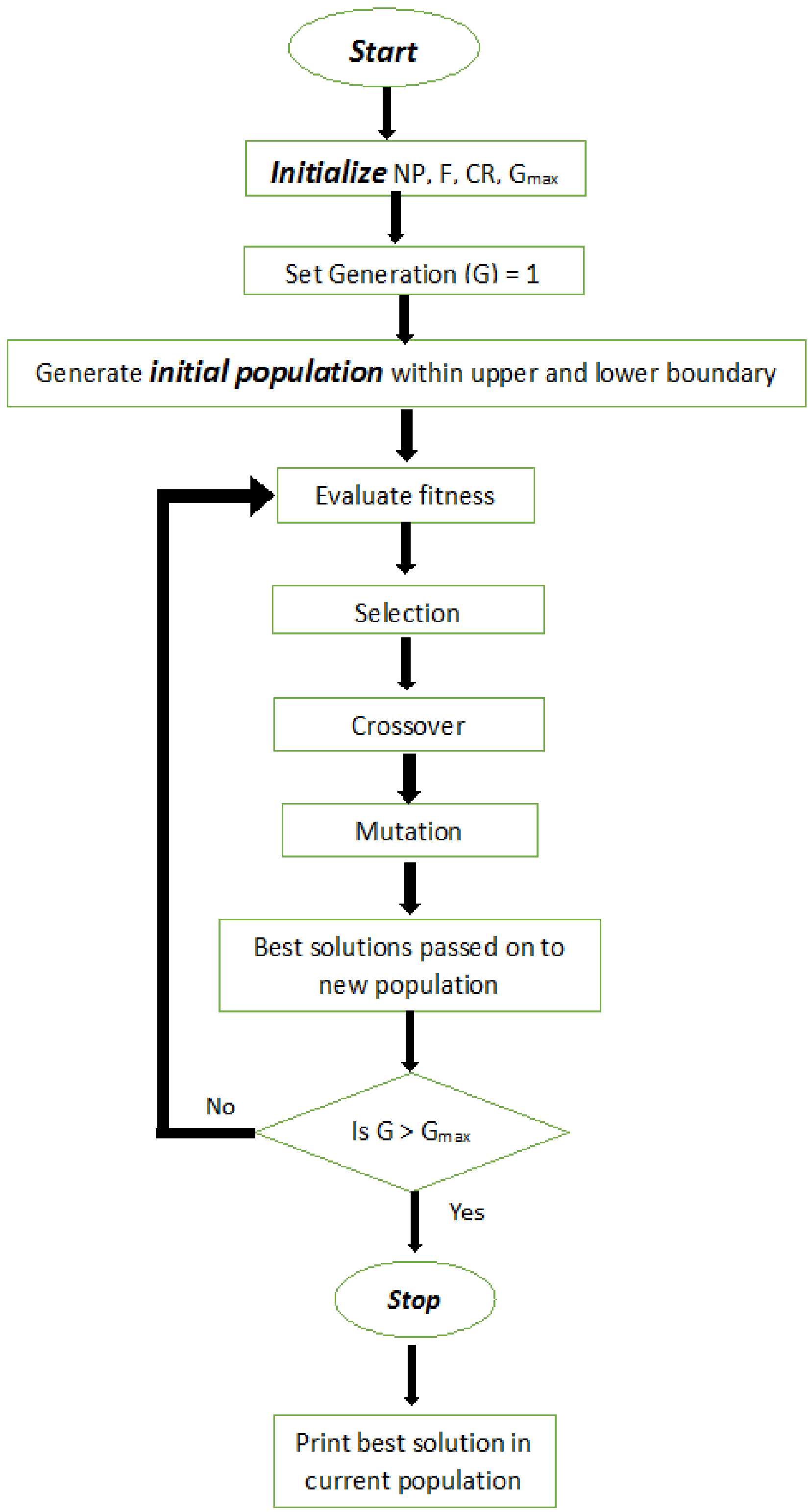

Fig. 4. Flowchart of proposed GA algorithm

3.1.2 PARTICLE SWARM OPTIMIZATION

PSO mimics the social behavior of a swarm of bees or flock of birds. In swarm intelligence, each particle moves to a new position using the velocity. Then the best position of each particle $pbest$ and the best position of the swarm of particles $gbest$ is updated. The velocity of each particle is then updated based on the experiences of the particle.

$$V(m+1) = V(m) + C_1 * rand * (pbest(m) - p(m)) + C_2 * rand * (gbest(m) - p(m)) \quad (3.1)$$

$$p(m+1) = p(m) + V(m+1) \quad (3.2)$$

where, $V(m+1)$ and $V(m)$ is velocity of particle at $(m+1)$th and mth iteration respectively, $gbest$and $pbest$ are best position of swarm and particle , C_1 and C_2 are acceleration factor related to $gbest$ and $pbest$ respectively, $rand$ is random number between 0 and 1, $p(m+1)$ and $p(m)$ are current position of particle at $(m+1)$th and m th iteration respectively.

In PSO algorithm, each particle is represented as solution and a swarm of particles is collectively known as population. The population initialization is done with a random velocity and position. Then fitness of the population is evaluated and compared with previous $pbest$ and$gbest$. Their positions are updated where needed. Hence a new swarm or population is created. The velocity and position is updated till maximum generations or convergence is reached. Some of the main advantages of PSO algorithm compared to other methods are that no calculation of derivative is required, the information of best solution is held by all particles and those particles offer data among them. The PSO algorithm can be programmed easily as it has few control parameters and also no initial solution is required. The typical PSO algorithm is shown below in Figure. 5.

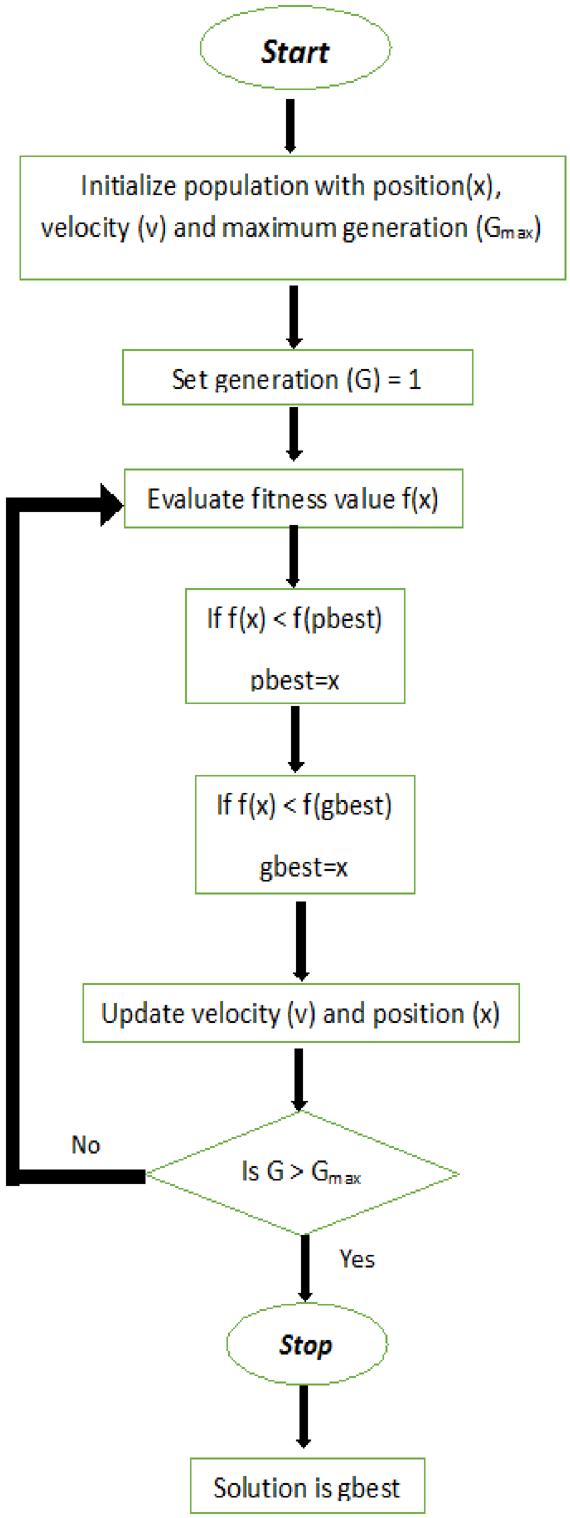

Fig. 5. Flowchart of proposed PSO algorithm

3.1.3 DIFFERENTIAL ALGORITHM

It is an Evolutionary Algorithm introduced by Rainer Storn and Kenneth Price in 1995. It is stochastic, real valued and population based optimization algorithm. The initial population is chosen randomly if no information is available about the problem. Otherwise if preliminary solution is available, the initial population is often generated by adding normally distributed random deviations to the preliminary solution. It uses mutation step as a search mechanism and selection step to lead the search toward the prospective regions. Many practical problems have objective functions that are non-linear, non-differentiable, non-continuous, noisy, multi-dimensional or have many local minima and constraints. Therefore DE is used to find exact or approximate solutions to these problems. The various steps involved in DE optimization algorithm are listed below.

Initialization: The initial population of solutions are generated randomly with constraints of each parameter are known.

$$X_k = a + (b - a) * rand(N, D) \tag{3.3}$$

Where, X_k is the initial random solutions, a is lower bound of the parameter, and b is the upper bound of the parameter, $rand(N, D)$ randomly generates population of size NXD, D is the dimension of the vector or the number of variables and N is the population size or number of solutions.

Then the fitness of the initial population is evaluated.

Mutation: It expands the search space. It adds difference vector to base vector in order to explore search space.

$$V_k = F\left(X_{3,k} - X_{2,k}\right) + X_{1,k} \tag{3.4}$$

where V_k is the donor vector, $X_{1,k}$, $X_{2,k}$, $X_{3,k}$ are randomly chosen vectors and F is the mutation constant.

Crossover: To increase the diversity of the mutated vector, crossover is done. The trial vector, U_k is developed from the crossover of the target vector, X_k and the donor vector, V_k.

$$U_k = \begin{cases} V_k & if\ rand_j \le CR\ or\ j = I_{rand} \\ X_k & if\ rand_j > CR\ and\ j \ne I_{rand} \end{cases} \tag{3.5}$$

where, CR is crossover rate, $rand_j$ is random value from [0 , 1], I_{rand} = random integer from [1, 2, ...,D]. I_{rand} ensures that $V_{k+1} \neq X_k$.

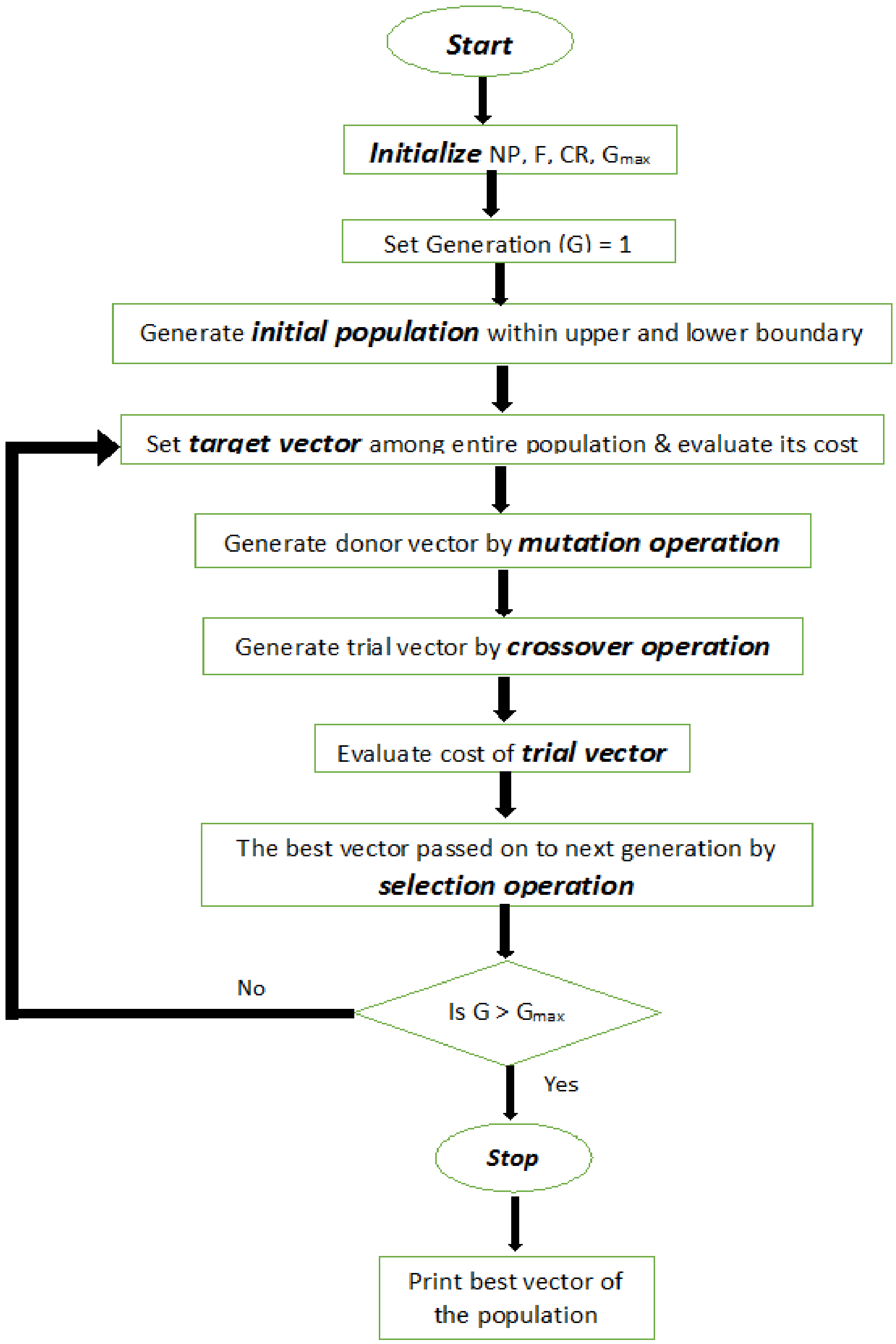

Fig. 6. Flowchart of proposed Differential Evolution algorithm

Selection: It mimics survival of the fittest. The fitness of target vector $f(X_k)$ is compared with fitness of trial vector $f(U_k)$ and the one with the better fitness value, the corresponding vector is admitted to the next generation.

$$X_{k+1} = \begin{cases} U_k & if\ f(U_k) < f(X_k) \\ X_k & else \end{cases} \quad (3.6)$$

where, X_{k+1} is next generation vector, $f(X_k)$ fitness value of target vector, $f(U_k)$ is fitness of trial vector.

The similarity between DE and GA is that both uses same evolutionary operations (mutation and crossover) to obtain the optimal solution. In GA, mutation operation occurs due to small perturbations in the genes of a chromosome whereas in DE, mutation operation occurs due to arithmetic combination of chromosomes. Mutation plays an important role in DE whereas in GA crossover plays the important role. The typical DE flowchart is shown in Figure. 6.

3.2 Optimal Sizing

The optimization algorithm has been applied for the design of SPV system of NIT, Rourkela, where significant solar irradiation is available. The annual global solar irradiation and diffused solar irradiation on horizontal plane that were recorded at NIT, Rourkela during the year 2014 is 4.752 MWh / m^2 and 2.592 MWh / m^2 respectively.

The technical specifications, capital and maintenance cost of commercially available PV module and inverter are given in Table 1 and Table 2 respectively.

Table 1. Specifications of the PV module

$V_{OC,STC}$ (V)	$I_{SC,STC}$ (A)	V_M (V)	I_M (A)	Nominal Power STC (W)	NCOT (˚C)	M_{PV} (₹/year)	C_{PV} (₹)	L_{PV1} (m)	L_{PV2} (m)	Guaranteed operational lifetime period (years)	K_V (V/˚C)
44.8	8.71	36.6	8.20	300	47±2	136.8	11400	1.984	1	25	-0.33

Table 2. Specifications of the DC/AC converter

n_{MPPT} (%)	n_{INV} (%)	P_{max} (W)	C_{INV} (₹)	MTBF (h)	V_{imin} (V)	V_{imax} (V)	M_{INV} (₹/year)	R_{pu} (₹)
100	95	3300	22000	219000	100	500	374	220

The establishment cost is also included in the capital costs. The yearly maintenance cost of the PV module and DC/AC converter is taken as 1.2% and 1.7% of their respective capital costs. As per the market prices, the per unit volume cost of foundation bases, c_B, is taken as 230 (₹/m^3) and also the per unit meter cost of the metallic poles, c_s, is taken as 33 (₹/m). The dimension of the foundation bases are set as h_w= 0.25 m and t_w=0.3 m. The current inflation rate, r, is set as 7.8% and nominal annual discount rate, d, is set as 10.74%. According to Odisha electricity regulatory commission, the per unit energy cost fixed by distributor for domestic user, C_o= 3 ₹ / kWh.

CHAPTER – 4

SIMULATION RESULTS AND DISCUSSION

The control parameter values for all the optimization algorithms are given below:

- **GA:** Binary coded, population=20, generations=100, crossover probability=0.9, mutation probability=0.001.
- **DE:** Population=20, generations=100, mutation probability = 0.7, crossover probability=0.9.
- **PSO:** Population=20, generations=100, cognitive learning factor=2, social learning factor= 2.

The application of the proposed optimization methodologies brings about convergence to the global optimum solution where the net profit function is maximized as shown in Figure 7. The optimal values of the corresponding variables such as no. of PV modules, no. of lines in each row and tilt angle are listed in the Table. 3 for different iterations. The value of optimal tilt angle $\beta(^{\circ})$ calculated using proposed optimization algorithms differ from typical angle values obtained by conventional design method for SPV system, because the objective of the tilt angle optimization is the profit maximization of the SPV system during its operational period and not the maximization of overall PV energy generated from the PV modules during the year.

As per the optimal sizing results shown in Table 3 and 4, it is inferred that the overall profit achieved in the time of SPV system operational period is dependent on the arrangement of PV modules within the given installation land, the number of PV modules connected to inverter and the tilt angle.

It is concluded from Figure .7, that the NPW of SPV system is positive which shows that the investment in the optimally sized SPV system is profitable with the subsidy rate provided by Govt. of India is 30% and cost of installation land per unit is 2200 (₹/m^2).

Based on simulation results we can infer that the standard GA performs poorly compared to recent approaches like PSO or DE. Table. 3 and 4 shows the comparison of the proposed algorithms.

Table 3. Mean value of objective function for each algorithm obtained after 30 trials.

Algorithm	Objective function mean value
DE	82926
PSO	82926
GA	81951

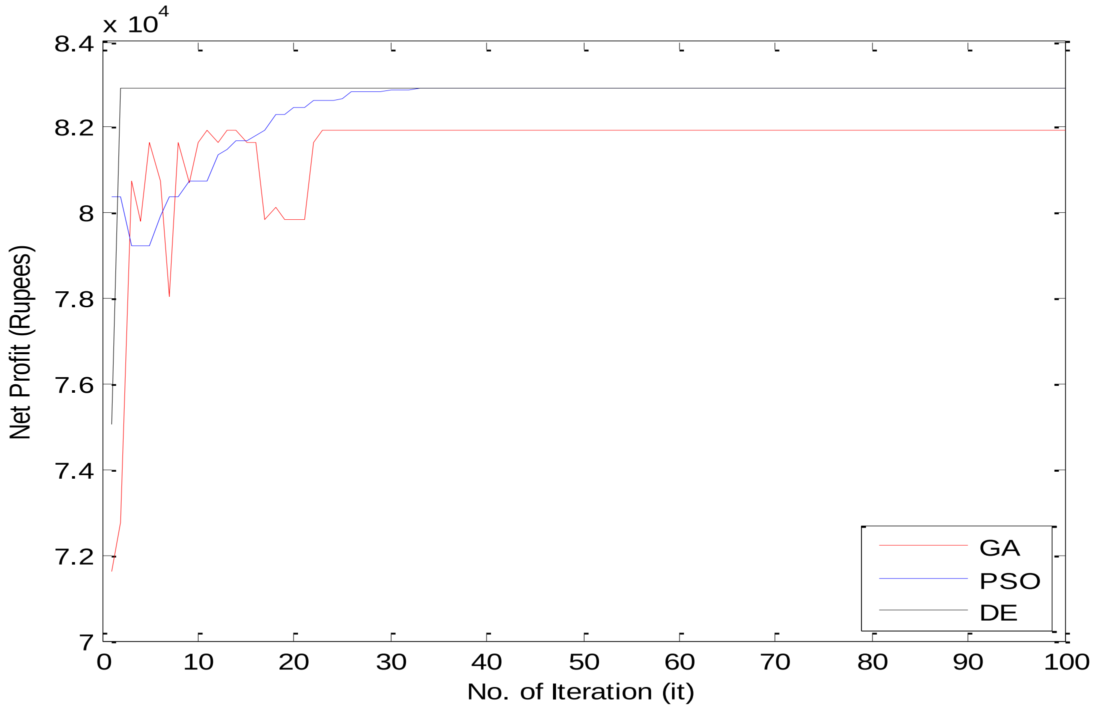

Fig. 7. Total net profit of the standalone PV system for no. of iterations using GA, DE, PSO Optimization.

Table 4. Optimal solutions of the proposed methodology

	Iterations	DE	PSO	GA
Maximum profit (Rupees), $F(x)$	30	82926	82868	81951
No. of PV modules, N_{PV}		15	15	15
No. of lines in each row, N		1	1	2
Tilt Angle (deg.), β		21.15	20.68	19.06
Maximum profit (Rupees), $F(x)$	100	82926	82926	81951
No. of PV modules, N_{PV}		15	15	15
No. of lines in each row, N		1	1	2
Tilt Angle (deg.), β		21.15	21.15	19.06
Maximum profit (Rupees), $F(x)$	150	82926	82926	81951
No. of PV modules, N_{PV}		15	15	15
No. of lines in each row, N		1	1	2
Tilt Angle (deg.), β		21.15	21.15	19.06

CHAPTER – 5

CONCLUSION

The PV systems are widely used either for small scale users like domestic PV system or for large scale users like grid connected photovoltaic system. The demerits of grid connected PV system are they are less popular due to harmonics problem on DC side and also synchronizing problem with grid. Though the PV systems have some challenges, they meet continuously increasing energy demands and also reduce pollution which are caused by thermal, diesel, nuclear power plant. Many countries provide subsidy to encourage installation and usage of PV system. So the main objective of PV system design is profit maximization during its operational period.

In this work, a methodology for design optimization and economic analysis of SPV system. The objective of the methodology is to find optimal tilt angle of PV module, optimal arrangement of PV modules in the available installation area and the optimal number of PV modules, so that the net profit incurred during the lifetime operational period of SPV system is maximized. The maximization of the economic benefit is the objective function of the proposed optimization algorithms (GA, PSO, DE). The economic viability of the SPV system is checked using NPW method. Contrasted with the past SPV design strategies, the strategy displayed in this work has considered important design perspectives which can highly effect the total net profit obtained from the SPV system such as cost of mounting structures for PV modules, cost of land for installation of SPV system, tilt angle of PV module. Also the proposed optimization algorithms (GA, PSO, DE) have the capability to find global optimum solution in case of complex problems with non-linear objective function and non-linear constraints. Additionally a comparative study of DE, PSO and GA algorithm is also done in optimal design and economic analysis of SPV system. Based on simulation results we can conclude that the standard GA performs poorly compared to recent approaches like PSO or DE.

The optimal design of standalone PV system can further be remodeled with grid integrated domestic PV system or with sun tracking facilities.

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