A NOVEL PARTICLE SWARM OPTIMIZATION ALGORITHM FOR MAXIMUM POWER POINT TRACKING BASED PHOTOVOLTAIC SYSTEM

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Abstract: *In recent years, solar energy is effectively utilized as an alternate energy source for generating electricity. Maximum Power Point Tracking(MPPT) is applied to the photovoltaic (PV) system to extract maximum power (MP). Numerous algorithms are developed and implemented to extract the MP under varying environmental conditions. One such algorithm is the Particle Swarm Optimization algorithm(PSO).This article introduces a novel PSO algorithm with Cauchy distribution to track MP from the PV system. It is designed to overcome the drawback of slow convergence rate of conventional PSO. Parameters required for conventional PSO are inertial weight, acceleration coefficients, and a number of particles. In case of Cauchy PSO(CPSO), tuning parameter is the number of particles. In order to increase the convergence speed, Cauchy distribution is used instead of normal distribution function to generate the random numbers. The advantage of this algorithm is that it provides the global best-optimized result at a faster convergence speed. It has the ability to track the MP in extreme climatic conditions with varying loads. The proposed method outperforms the standard PSO and some of the existing methods in terms of quick convergence and also has a simplified structure.*

Keywords: *Photovoltaic(PV) system, Maximum Power Point Tracking (MPPT), Particle Swarm Optimization (PSO) Algorithm, Cauchy PSO (CPSO).*

1. Introduction

These days increased demand for electricity consumption and negative effects on the environment are the major issues [1]. These are due to depleting of fossil fuels at a faster rate. To overcome these issues continuous research is being conducted to seek efficient alternate sources of energy for power generation [2]. Therefore attention is being given to the utilization of Renewable Energy Sources (RES). RES are solar, hydropower, biomass, wind, geothermal energy etc. RES are economical and they also reduce the environmental issues caused by power generation from non-renewable energy sources such as fossil fuels. Because of the merits of RES, these are utilized as best alternate for generation of electrical energy. Nowadays, the generated electricity from various sources is distributed via the centralized grid. Various resources are referred to as Distributed Energy Resources (DER)[3].

Among the RES solar energy and wind energy are currently widely deployed. Compared to solar energy, wind energy has some limitations. The rotatary motion of wind turbine is used to produce electricity. Following are some of the important practical difficulties. Wind turbines are very large machines. It occupies larger area and also wind turbine blades make more noise. Another important fact is that the wind mills are installed near shores, and on high mountain. Site selection also plays a crucial role in several aspects. Financial returns from the project, ease of construction, maintenance and overall safety are the factors that decide the overall design and implementation of wind power generation systems[4].Therefore solar energy has become widely essential to compensate the energy demand. Its environmental friendly nature, abundance presence on the earth's surface, it being totally free from pollution, low operational cost and also renewable and sustainable characteristics are the merits of solar energy [5]. Although the operational cost is low for the solar energy , the cost of solar modules are high .Still the grid connected PV power generation systems are being commercialized in many countries because of its long term benefits. Further more generous financial schemes for example the feed in tariff and subsidized policies are introduced in various countries resulting in rapid growth of the industry [5].Recently the power generation systems designed using integration of solar and wind energy. The reason is to generate interminable power depend upon the environmental conditions [6].

Conversion of photon energy to electrical energy is called Photovoltaic (PV) effect. PV cells are the smallest element used to produce power. Integration of large number of PV cells produces PV module, large number of series and parallel connected modules produce PV arrays. Nowadays PV arrays are constructed pyramidal like shapes used to upgrade the radiation intensity falling on solar panels.[7]. To extract the MP solar panels are to be operated at Maximum Power Point (MPP). Because of the dynamic environmental conditions such as temperature and irradiance, PV characteristic varies nonlinearly. It is difficult to locate the MPP. Another common issue is Partial Shading Condition (PSC) due to surrounding buildings, trees, passing clouds in the sky etc. Under PSC the PV curve exhibits multiple MPPs with one global and several local peaks [8]. To overcome these issues MPPT controllers are integrated with DC-DC converters.

Conventional MPPT algorithms are Perturb and Observe (P&O), Incremental conductance (INC) and Hill climbing (HC). These are very common MPPT techniques. P&O compares PV array voltage (or current) to the constant reference voltage (or current) at the MPP under specific atmospheric condition. The difference of voltage (or current) is used to decide the direction of tracking. Simply this method perturbs the operating voltage (or current)[9,10]. In INC output conductance is taken for reference. At MPP its magnitude is zero. On either side of MPP, its magnitude has negative and positive increments [9-11]. It is developed to increase the convergence time of tracker. HC approach uses the PV array output current. Change in current is measured before and after a change in duty cycle. Therefore this method perturbs the duty cycle of the converter.

Traditional MPPT techniques have two major difficulties. Under PSC it tracks only the first local MPP.It is unable to track the global MPP and they also suffer from steady state oscillations [12-14].This means after capturing MPP, the operating point oscillates back and forth around MPP. This limits maximum power generation.

Fuzzy based controllers and neural network are another type of controllers. The fuzzy controller uses an ad-hoc technique to handle nonlinearity problems. Its execution is complex with a process of fuzziffication, rule based storage, inference and defuzziffication operations. Implementation requires more knowledge for both user and designer [15]. Neural Network is an Artificial Intelligence (AI) based technique and its implementation process is much complicated. It uses a large amount of data, for tuning. Because of the varying weather conditions, real time implementation needs intelligence processors for better performance [15].

Evolutionary Algorithms (EA) such as PSO , Genetic Algorithm (GA), Ant Colony Algorithm (ACO), Evolutionary Programming (EP), Simulated Annealing (SA) etc. are introduced to improve the performance of MPPT under dynamic atmospheric conditions. In SA, setting of control parameters is a difficult task and convergence speed is slow when applied to a real system. Though the GA techniques have been employed successfully to solve complex optimization problems, its efficiency is degraded due to its premature convergence. EP seems to be good choice to solve multimodal optimization problem. But it takes long simulation time to obtain the optimum solution for this kind of problems [16]. The word optimization broadly refers to locating either the maxima or minima of real functions. It uses a systematic approach to choose real or an integer variable from within the allowed set is called search space.

Among these PSO shows outstanding performance in attaining optimized solutions. The most suitable and attractive approach to obtain MP from PV array is the PSO algorithm. Merits of PSO are its ability to track the MPP location quickly and accurately irrespective of the climatic conditions. It eliminates the steady state oscillations and produces more stable output unlike the conventional methods [17]. It doesn't require the gradient of the objective function and uses only the values of the objective function. It eliminates complex computational procedures. It also has a simple structure with fast computational ability. Characteristics of Conventional PSO are, it converges quickly and has good search accuracy. Convergence is defined when the particles stop at the desired operating point to provide global optimal result [18, 19]. In practice, the algorithm stuck at local maxima is called premature convergence and it requires larger search space.

To tackle the issue of slow convergence of PSO and Gaussian PSO, CPSO is proposed and implemented. It is an improved version of Gaussian PSO [GPSO] [20] with enhanced convergence speed. Other advantages are reduction in the number of tuning parameters, speedy convergence rate and faster output settling time.

Remainder of this article is organized as follows. Section 2 explains the related work to CPSO Method. Section 3 presents the concepts in conventional PSO. Functional blocks of the proposed method, configuration and implementation of CPSO algorithm are discussed in section 4. In section 5 functional modules are validated through simulation results. Section 6 presents the merits of the proposed method as compared with other techniques and concluding remark on future scope of this work.

2. Related work

Several solutions are dealt in the literature to overcome the PSO convergence issue. These are as follows:

- Introducing variable parameters
- Use of different swarm topologies
- Changing the velocity update formula with the enhancements applied in the inertial weight [21].
- Modifying the particle position and velocity through the mutation operator.
- Modifying the position and velocity update rules, outside the equations, and so on [22,23].

Changes in velocity formula is implemented in improved PSO–MPPT algorithm. Vanxay Phimmasone et al.[24] introduced the fourth term which is called as repulsive term. The repulsive term is given by $c_3 r_3 (cent^k - S_i^k)/(\left|cent^k - S_i^k\right| + d)^3$. Where, $c_3 r_3$ term is same as those used in conventional PSO. Where, cent is the center of all particles. The term'd' is small constant added to avoid divide by zero error for the values of ($cent^k - S_i^k$).

Qing Zhang et al. [25] presented a modified PSO with both mutation and crossover functions to increase the convergence speed and to avoid the trapping of PSO into local maxima. Authors introduced Cauchy random number in velocity and position update expressions.

Venkatesh Kumar et al.[16] introduced the Cauchy mutation in the position update equation of PSO to optimize the results of economic dispatch problems.

Hui wang et al.[26] proposed a hybrid PSO with Cauchy mutation. The inertial weight is modified with the help of Cauchy random number. It is used to enhance the position of best particle to achieve faster convergence.

The difference between the above mentioned methods and the proposed method is faster convergence is achieved using minimum number of tuning parameters.

3. Conventional PSO

PSO is a population based optimization algorithm. It is one of the metaheuristic methods and it follows the random search techniques. Tuning parameters required for the execution of the conventional PSO algorithm are acceleration coefficients (c_1,c_2), inertial weight(ω) and maximum velocity as given by equations(1) and (2) [17,27]. Equation (1) is the velocity update equation and (2) is the positions update equation.

$$v_i(k+1) = \omega v_i(k) + c1\,r1((p_{best,i} - x_i(k) + c2\,r2(g_{best} - x_i(k))$$

(1)

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (2)$$

Where r_1, r_2 are uniformly distributed random numbers, p_{best} and g_{best} are particles individual and global best positions respectively from the target position and k is number of iterations.

4. Proposed Cauchy PSO method

Existing methods have complex computational structure. Proposed method has less complex computational structure with faster convergence.

In the proposed method the velocity update formula is modified. Velocity equation is constructed by without inertial weight, maximum velocity and acceleration coefficients (cognitive and social parameters) to achieve the convergence. Gaussian and Cauchy probability distributions are very effective for updating the velocity equation.

Cauchy PSO is also stochastic, population based swarm intelligence evolutionary algorithm. Equations (3) and (4) present the velocity and position updates of the proposed PSO.

$$v_i(k+1) = v_i(k) + r1((p_{best,i} - x_i(k) + r2(g_{best} - x_i(k)) \quad (3)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (4)$$

Here r_1 and r_2 are the Cauchy distributed random numbers. Cauchy random numbers possesses the long jump ability. It enhances the velocity of the particles. Also this property helps the particles to get best position [3]. Another useful property is that, it is capable of providing huge search space for the particles. This is due to its tail decay very slowly. This yields better result for the search.

The proposed method and the conventional PSO are similar except that the initialization of the tuning parameters. Importance of tuning parameters in PSO is that, it greatly influences the algorithm performance. It is often referred to as exploration and exploitation tradeoff. Exploration is the ability to check the test space and provide global optimal results. Exploitation is the ability to concentrate on the optimization precision.

Important property of Cauchy distribution is that it has heavier tail [28]. This means its probability distributions are not exponentially bounded. That is, its distribution is greater than exponential distribution. Some of the other properties of this distribution is it has no expected value and other moments also. Its median and mode are equal. Probability Density Function (PDF) of Cauchy distribution is given in equation (5) [29].

$$f(x; x_0, \gamma) = \frac{1}{\pi\gamma\left[1 + \left(\frac{x - x_o}{\gamma}\right)^2\right]} \quad (5)$$

x_0 - Location parameter specifies the location of the peak of distribution. γ - Scale parameter or probable error. Its value is half the width of PDF at the half maximum height. Amplitude of Cauchy PDF is $\frac{1}{\pi\gamma}$ located at $x = x_0$. γ=1, x_0=0, the Standard Cauchy distribution with PDF[30] ,

$$f(x;0,1) = \frac{1}{\pi(1+x^2)} \quad (6)$$

In this work , the random numbers are characterized by standard Cauchy distribution. It is a special case of the student's t-distribution. Student's t-distribution is looks almost identical to normal distribution but it possess heavier tail like Cauchy distribution [31].

PDF of student's t- distribution is given in equation (7).

$$f(x) = \frac{\Gamma\left(\frac{n+1}{2}\right)}{\sqrt{n\pi}\,\Gamma\left(\frac{n}{2}\right)\left(\frac{x^2}{n} + 1\right)^{\frac{(n\pi)}{2}}} \quad -\infty < x < \infty; \quad (7)$$

Where, 'n' is called degrees of freedom. If Student's t-distribution has degree of freedom as 1 its PDF is same as that of the standard Cauchy distribution. It is presented in equation (8).

$$f(x) = \frac{1}{\pi(1+x^2)} \quad -\infty < x < \infty \text{; for n=1.} \quad (8)$$

Now it is seen that the Equations (8) and (5) are the same.

Figure 1 shows the flowchart of the proposed method. The implementation starts with three different duty cycles. These are referred to as the particles, di, (i=1, 2, 3). Selection of initial duty cycles are based on the MP output of the system. First duty cycle value (d_1) is chosen such that the duty cycle value required generating 80% of the MP of the system. The subsequent duty cycles (d_2, d_3) are 65% and 50% of MP outputs respectively [13]. In the first iteration these are considered to be the personal best (P_{best}) values of the algorithm. For each duty cycle, the current and voltage are sensed and the corresponding power is calculated. This power is the objective function of the system [32]. Its mathematical relationship is given in equation (9). It is compared for different duty cycles. Depending on the received power, the P_{best} value is modified. It is presented in the flow chart.

$$P\left(\begin{matrix}k\\di\end{matrix}\right) > P\left(\begin{matrix}k-1\\di\end{matrix}\right) \quad (9)$$

$P\left(\begin{matrix}k\\di\end{matrix}\right)$-New power and $P\left(\begin{matrix}k-1\\di\end{matrix}\right)$-Old power

The G_{best} value is computed based on the maximum output power. The value of P_{best} corresponds to the maximum output power is taken as G_{best}. The duty cycle corresponding to the MP is applied to the power converter for each cycle.

Efficiency of the system is computed using equation (10). Where, P_o is the output power and P_{in} is the input power of the system.

$$\text{Tracking efficiency: } \eta = \frac{P_o}{P_{in}} \times 100\,\% \quad (10)$$

4.1 Block diagram of the proposed system

PV system consists of PV array, controller unit and load called Power Conditioning System [5]. Figure 2 shows the block diagram of the proposed system. Buck-Boost converter is designed to transfer the regulated DC output to the load. The output voltage and current of PV array are the inputs of the digital controller to perform iterative tracking for the MPP. The controller decides the operating voltage for the PV array by adjusting the duty cycle of the buck boost (BB) converter.

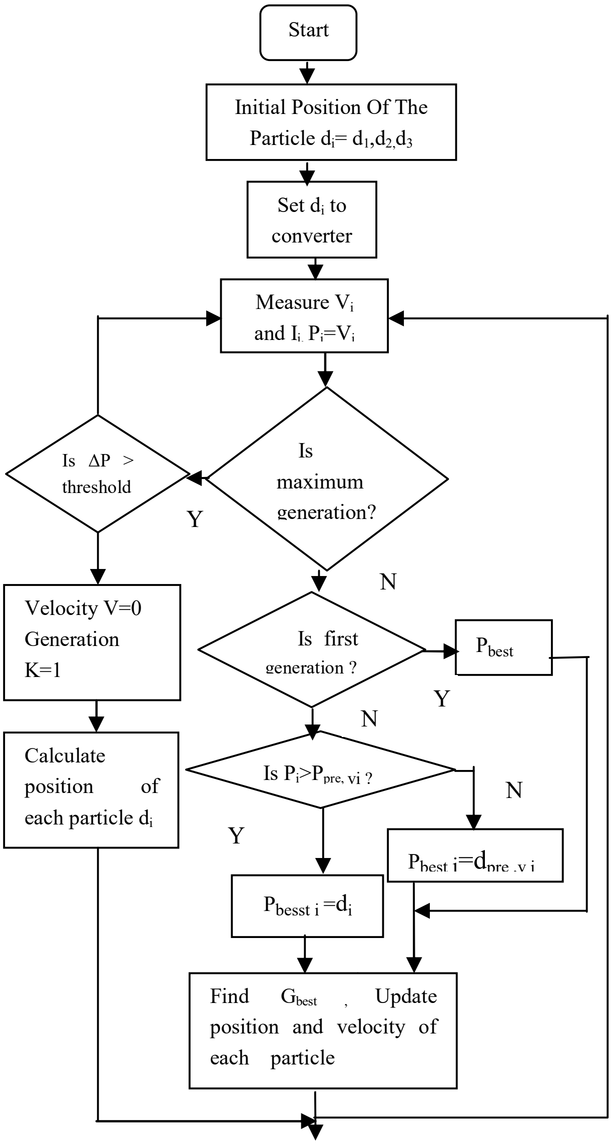

Fig.1.Flow chart of CPSO algorithm [33].

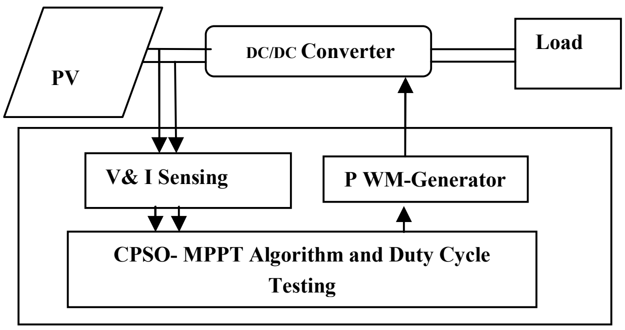

Fig.2. Block diagram of MPPT based PV system [11]

A. System Configuration and Implementation using CPSO

Figure 3 shows the MATLAB/SIMULINK simulation model for the PV system used in this discussion. As per the block diagram the simulation model consists of PV panel, converter and the MPPT control circuitry. PV array consists of series connection of 44 solar cells. Each cell has open circuit voltage, V_{oc} = 0.6V and short circuit current I_{sc} = 2.1 A. The sampling period (or time interval) for sensing voltage and current from the PV panel is 0.01 seconds to obtain the input power. Input power is the objective function. The next important block is a CPSO function block. Inputs are panel voltage and current. Based on the power product, the algorithm computes duty cycle for the converter to obtain the MP. Third section is converter section and the system is implemented with a BB converter.

Table 1 shows the specifications of solar panel at 25°C, temperature and insolation of 1000 W/m2.

Table 1 Parameters of PVpanel

Peak Power(W)	P_{MPP}	42.7
Peak power voltage(V)	V_{MMP}	21.7
Peak power current(A)	I_{MMP}	1.97
Open circuit voltage(V)	V_{oc}	26.4
Short circuit current(A)	I_{sc}	2.1
Number of series cells	Ns	44

Table 2 shows the specifications of the BB converter. It is designed with the help of BB converter design equations [34].

Table 2 Specifications of BB Converter.

Input Inductor	5mH
Output capacitor	25µF
Output ripple voltage	0.05 V
Output ripple current	0.1A
Switching frequency	25kHz

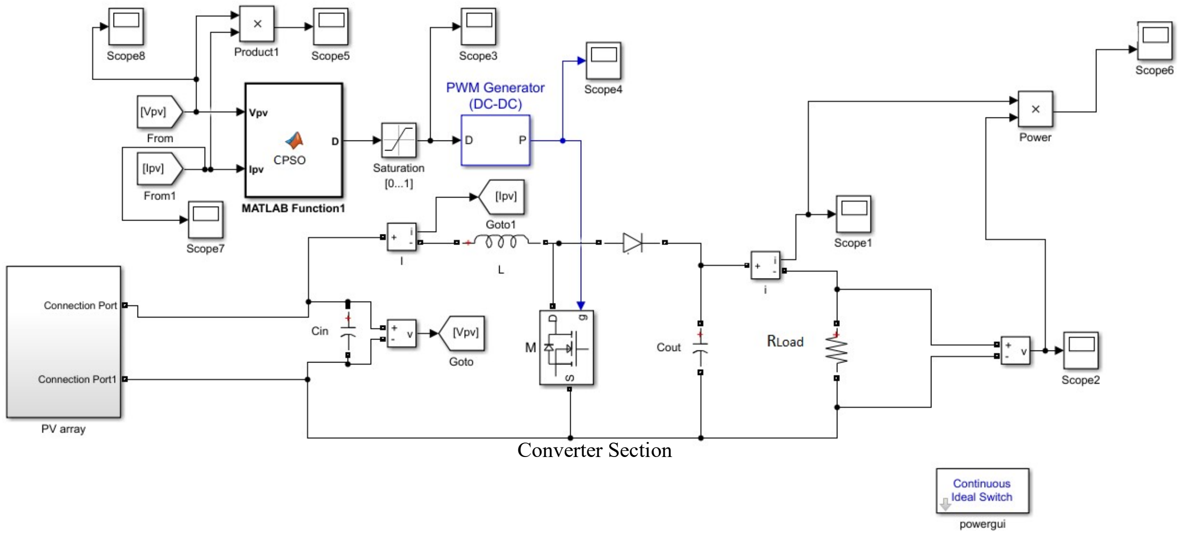

Fig.3.Simulation circuit for CPSO based MPPT system

5. Results and Discussion

In order to evaluate the effectiveness of the algorithm and to validate the results of the proposed method, two different existing algorithms "conventional PSO and Deterministic PSO (DPSO)[17]" are implemented and analyzed. The following parameters of the proposed method are compared,

- Output settling time and
- Convergence time of particles.

Apart from that the system response is analyzed for,

- Varying load conditions
- Varying irradiance conditions.

5.1 Output settling time

The output settling time of conventional PSO is presented in Figure 4 .The settling time is around 1.2s. Figure 5 shows output of DPSO. Output settling time is nearly 0.35s and Figure 6 is output wave form of CPSO. It shows the output settling time as 0.25s.

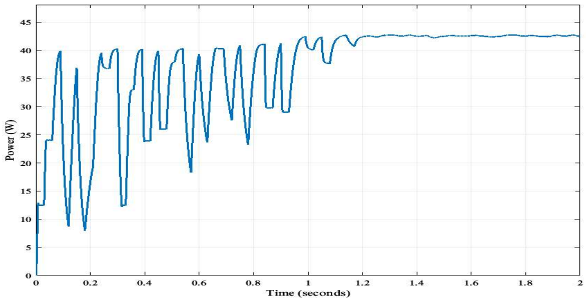

Fig. 4. PSO_Output

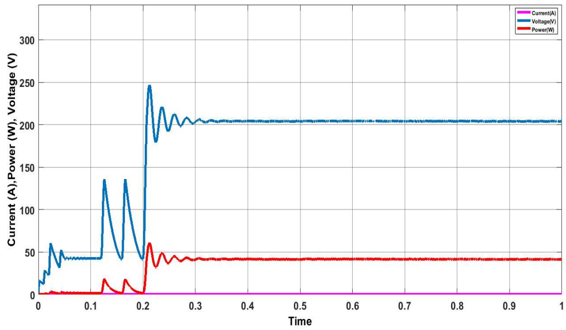

Fig. 5.DPSO_Output

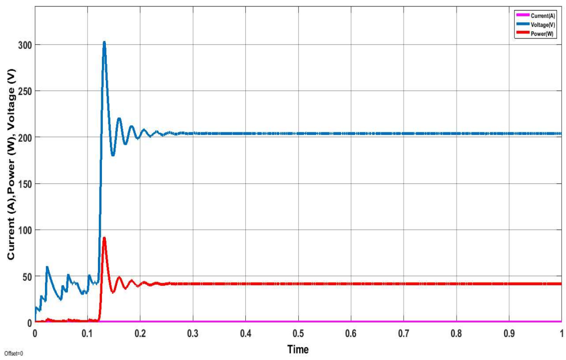

Fig. 6. CPSO_Output

Figure 7 is the comparison chart between the output settling time of all the different implemented versions of PSO discussed in this work. Ratio between the output settling time of PSO ,DPSO and CPSO are analyzed. From the figure CPSO is 4.8 times faster than PSO and 1.4 times faster than DPSO. Therefore from the results it is seen that the proposed method has the fastest settling time.

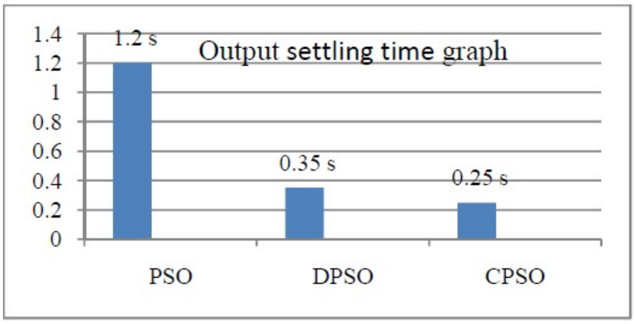

Fig. 7. Comparison chart for output setting time

5.2 Particles converging time of PSOs

Figure 8 shows the duty cycle exploration of standard PSO for 0.2s. All the particles are converged around 0.65s. Figure 9 is for DPSO algorithm. Particles converged at nearly 0.2s. Figure 10 is duty cycle exploration of CPSO. Convergence of particles takes just 0.12s.Among these algorithms DPSO technique doesn't use any random numbers to avoid randomness of PSO. It is designed such that the particles follow deterministic behavior to speed up the operation. Though the proposed method uses the random numbers it still converges earlier than DPSO.

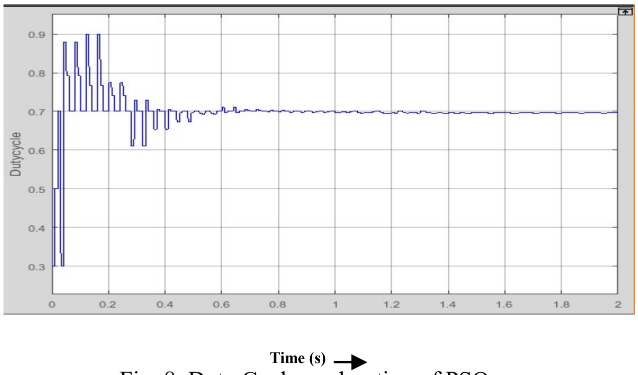

Fig. 8. Duty Cycle exploration of PSO

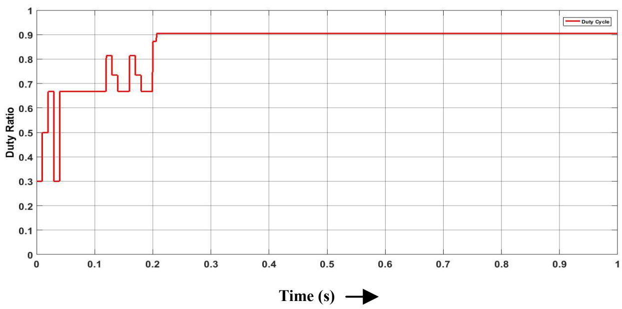

Fig. 9.Duty cycle exploration of DPSO

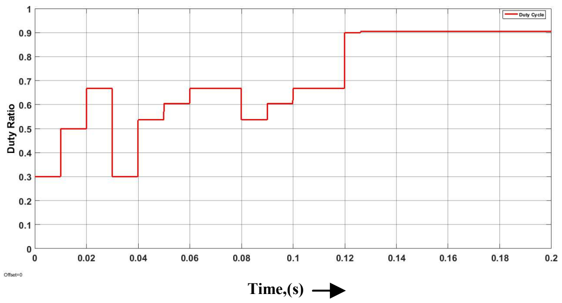

Fig. 10.CPSO duty cycle exploration

Figure 11 shows the converging time of all different PSOs. From this chart it is seen that the in CPSO algorithm particles converged quickly. It is 5.41 times faster than PSO and 1.66 times faster than DPSO.

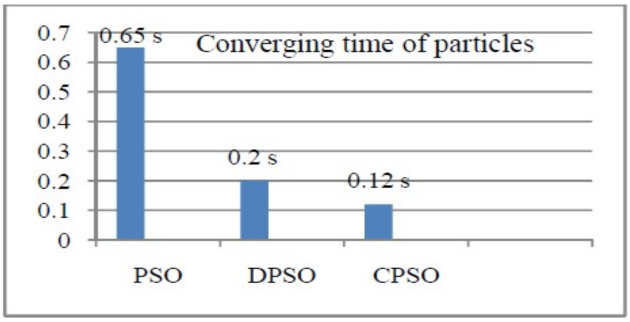

Fig.11. Comparison chart for particles converging time

5.3 Response to load resistance variations

Figure 12 and 13 are plot between load resistance and output power of the proposed system. The output power of the BB converter using CPSO algorithm is recorded for various loads. It provides maximum output power irrespective of load variations.Output power fluctuates approximately by only 1W from minimum load value to maximum load.

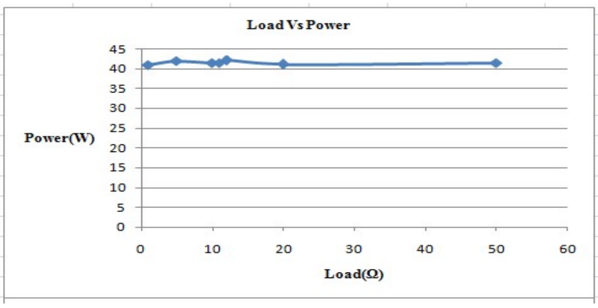

Fig. 12.Load resistor and CPSO P_out for low range of loads

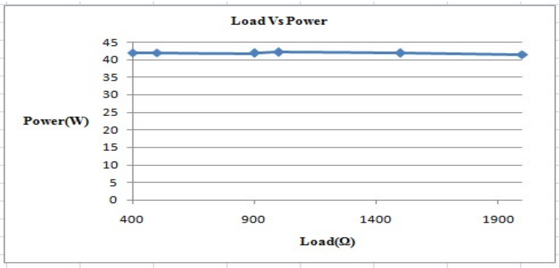

Figure13.Load resistor and CPSO P_out for high range of loads

Figure 14 shows the load versus duty cycle (duty ratio) curve for the proposed method. For the load fluctuations, the algorithm gradually expand the duty cycle to track the maximum panel power.

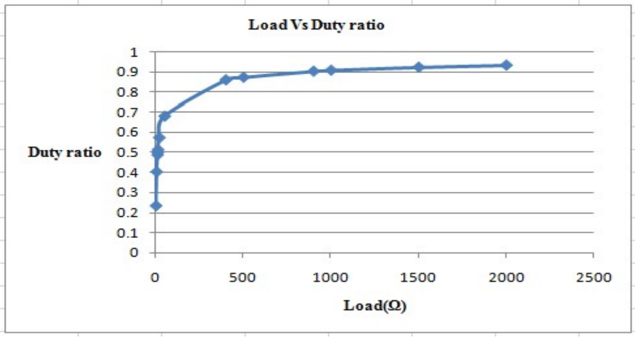

Fig. 14. load resistance Vs Duty cycle of CPSO

5.4 Respose to Irradiance changes

Figure 15 is the plot between irradiance versus power. As we know these two quantities are directly propotional with each other, for lower irradiance(Irs) the power output is low and is increases linerly.

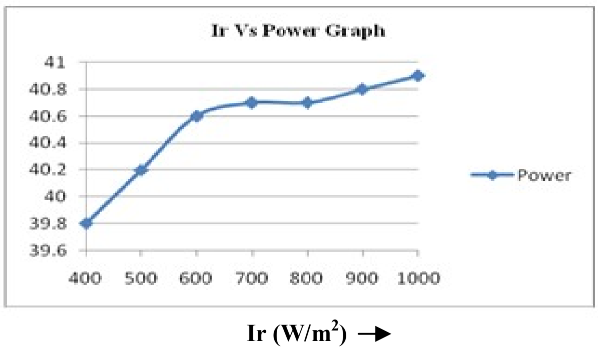

Fig.15.IrradianceVs P_out of CPSO

Figure 16. is a plot between duty cycle versus power for the proposed method.This duty ratio

variations are obtained for various load resistances of the system. Due to the load variations duty ratio is expanded with the help of the proposed PSO method.The system provides the almost constant output power with very slight variations.

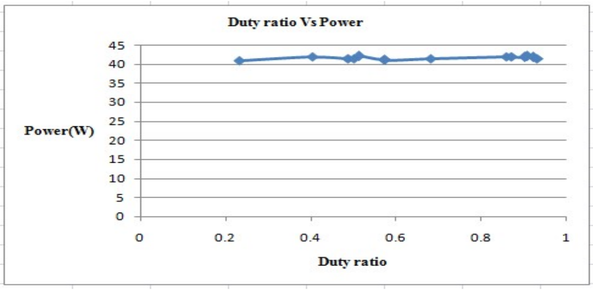

Fig.16.Duty cycle Vs P_out of CPSO

Simulation results illustrate the proposed method outperforms the existing methods in terms of convergence speed and output settling time. Merits of CPSO are (i) It converges quickly than other PSOs (ii) It requires only the number of particles and no other tuning parameters.

6. Conclusion

In this article, a novel Cauchy PSO based MPPT technique is implemented for PV system. The proposed method is designed to overcome the drawback seen in conventional PSO. The enhanced feature of the proposed Cauchy PSO is its less susceptibility of getting stuck at local optima. This is achieved with the help of its long jump ability. It provides rapid convergence rate with high convergence precision. The positive trait of the algorithm is its fast convergence. It is a good thing because it helps to find faster solutions. Hence it can be applied for time critical applications. Though the efficiency of all PSOs are same, CPSO's major advantage is its simplified control structure due to the reduced number of tuning parameters. Therefore the system is economical and less complex. Compared to other algorithms it possess fast convergence rate. The results proved that this algorithm performs better and extracts the maximum power irrespective of load fluctuations. It delivers a wide range of duty cycle output for a low and high range of loads. It provides global maximum power even for uneven insolation.

In future, the proposed system can be used in the hybrid MPPT systems. The hybrid system uses more than one renewable energy sources, combination of wind energy and solar energy. Furthermore it is useful for supplying uninterrupted power to the commercial buildings and industries.

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