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Simulation and Real-Time Implementation of MPPT Techniques for PV System using High Precision PV Emulator and dSPACE DS1202 MicroLabBox

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Abstract— The Maximum Power Point Tracking (MPPT) is a vital element in a Photovoltaic (PV) system to harvest maximum power from solar PV system. Therefore, it is of interest to us to develop a more effective and efficient system that can transfer maximum power to the load. Implementation of the new MPPT techniques such as Artificial Neural Network (ANN), Fuzzy Logic Control (FLC) and Cuckoo Search Algorithm (CSA) is carried out to identify the most efficient system and the results are compared with conventional Perturb and Observe (P&O) and are presented in this paper. The proposed models are simulated and obtained results are analyzed and compared with the conventional method using MATLAB/Simulink, while the real-time implementation of similar prototype is carried out using a novel **dSPACE** DS1202 MicroLabBox and highly accurate PV emulator. Further this paper also comprises the comparison of steady state accuracy of D.C. link voltage of proposed techniques i.e. ANN, FLC, CSA vis-a-vis conventional P&O using MATLAB/Simulink and **dSPACE**.

***Keywords*—PV,** MPPT, **dSPACE**, CSA, FLC, ANN, P&O, AI

I. INTRODUCTION

Renewable energy has become globally the first choice to address the issue of energy crisis to solve environmental problems and to achieve sustainable development. The demand of electrical energy is increasing due to faster developments. Also, the conventional fossil-fuel energy sources have been continuously depleting and are exhausting at fast pace. Environmental concerns such as air pollution, climate change and acid deposition have continued to increase [1]. Now-a-days, alternate renewable energy sources such as Wind, Photovoltaic (PV) system, Bio mass etc. are more popular due to their advantages such as easy availability, sustainability, economic viability and reduction in pollution [2].

Solar energy is the most widely used renewable energy in the present days. The output from the PV cell is not the maximum for most of the systems; moreover the power output varies as irradiation varies. Hence, it becomes essential that the maximum power from the PV cell is to be extracted to attain the maximum output or optimized output. The main aim of Maximum Power Point Tracking (MPPT) is to satisfy the conditions such as accuracy, speed and robustness. MPPT allows us to extract maximum power from PV system and consequently, the performance of PV system depends on the efficiency of MPPT [3],[4]. There are many MPPT techniques that are in use. Some of those techniques are Incremental conductance, Short circuit current, Open circuit voltage and Ripple correlation control approaches.

The MPPT techniques have been investigated in number of ways. Mohammed et al. [5] proposed a solar PV emulator using **dSPACE** **(**Digital Signal Processing and Control Engineering**)** DS1104 for real-time implementation. Abdullah et al. [6] showed implementation of MPPT techniques using simulation and **dSPACE** hardware. MPPT tracking was performed by Perturb and Observe (P&O) method and Incremental Conductance method. The MPPT system was simulated as well as experimentally performed. The hardware implementation was done using **dSPACE** 1104. Muralidhar et al. [7] presented Perturb & Observe (P&O) MPPT for the avoidance of drift in PV system.

Shimi et al. [8] showed implementation of Artificial Intelligence (AI) based MPPT techniques using **dSPACE** DS1104. P&O, Incremental Conductance, Neural Network and Adaptive Neuro Fuzzy Inference System (ANFIS) based MPPT algorithms of PV were implemented in MATLAB/Simulink. The hardware-in-the-loop simulation of wind power system based on **dSPACE** DS1005 was shown by Hai-Hui et al. [9]. The validity of the testing platform was

confirmed by the results of off-line simulation and hardware-in-the-loop simulation.
Mohammad et al. [10] displayed a review of applications and variants of Cuckoo Search Algorithm (CSA). This paper has shown the current research on CSA and the possible future directions for the readers. Bo-Ruei et al. [11] showed a fast MPPT method for partially shaded condition. The proposed MPPT was able to improve the tracking time when it was compared to conventional P&O.

Neeraj et al. [12] implemented Genetic Algorithm (GA) based MPPT algorithm using dSPACE DS1104. GA was proposed for PV system under varying ambient conditions in real-time. Abdullah et al. [13] presented a Fuzzy Logic Control (FLC) method to track maximum power of PV module using MPPT. The system was modelled using MATLAB/Simulink. Also, dSPACE DS1104 was used for the hardware implementation of MPPT set-up.

The validation and MPPT technique of wind turbine model using MATLAB/Simulink was presented by Badreddine et al. [14], while its experimental implementation was done using dSPACE card 1104. Venkataramana et al. [15] illustrates performance of F2DTC and PIDTC of induction motor using dSPACE.
From the above literature review, the authors are motivated to work on AI based techniques available in order to get MPPT effectively in an efficient manner. Further they are also encouraged to work on dSPACE and PV emulator.
Considering the above facts, in this paper, various AI based MPPT techniques are designed such as ANN, FLC and CSA to track maximum power from PV system. A comparative analysis of different advanced MPPT techniques has been described in this paper. The performance of the methods is evaluated by MATLAB/Simulink. The proposed system is then implemented experimentally using PV emulator and **dSPACE DS1202 MicroLabBox**. The proposed emulator has following features and specifications:- 1) Flexible instrument designed to emulate the output of solar panels from different manufacturers, variations due to time of the day, effect of season and different geographical locations of installation. 2) Fast transient response with easy interfacing. 3) User can run PV emulator via any computer or Android tablet. By taking motivation from literature review, an analysis of three MPPT techniques i.e. ANN, FLC and CSA are compared with conventional Perturb and Observe (P&O). The efficiency and accuracy of all the techniques are calculated to arrive at the conclusion for better technique.

The paper is organized as follows: In section 2 system configuration is described. Section 3 shows the various proposed MPPT algorithms to track maximum power point and section 4 deals with results and discussion. In section 5 the details about results are discussed. In last section, references are placed.

II. SYSTEM CONFIGURATION

This section describes details about the Simulink and hardware modelling of PV system. PV system connected to load is shown in Fig.1; where: V_PV is the PV output voltage and I_PV is the PV output current. The output voltage of PV cell is introduced to the DC-DC boost converter to increase voltage to an appropriate required level. The boost-converter is further connected to Resistive load of 60 W. PV cells have non-linear P-V (Power-Voltage) and I-V (Current-Voltage) characteristics as given in Fig. 2. The duty cycle of boost converter is maintained to get MPP [16]. This section shows the proposed model for the implementation of various MPPT techniques. Sub-points in this section express details about the PV module, MPPT, DC-DC converter and the connected load. The proposed model is as shown in Fig.1.

II.I PV MODULE

The PV module is described in the following steps:

II.I.I GENERAL PRESENTATION OF PV CELL

The equivalent circuit of PV cell is used for modelling and simulating the PV system. Expressions (1) to (6) is used for modelling of PV system. By using Kirchhoff's Current law (KCL) in Fg.3, the PV cell current, I can be expressed as:

$$I = I_L - I_D - \frac{V+I.R_s}{R_p} \quad (1)$$

The current generated by number of series and parallel connected cells in PV model is given by:

$$I_m = n_p I_L - n_p I_D - \frac{V_m+I_m \cdot R_{s\_m}}{R_{p\_m}} \quad (2)$$

Where the diode current is given by Shockley equation as

$$I_D = I_o \left[e^{\frac{q.(V+I.R_s)}{AkTn_s}} - 1 \right] \quad (3)$$

The diode saturation current I_o depends on temperature and can be calculated from (4)

$$I_O = I_{On} \left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \quad (4)$$

$$\text{where: } I_{On} = \frac{I_{scn}}{\exp\left(\frac{V_{ocn}}{aV_{tn}}\right)-1} \quad (5)$$

The photo current I_L of PV cell is generated by the incident light falling on the PV cell. This current varies linearly with the solar insolation [17]. Current equation is in (6).

$$I_L = (I_{Ln} + K_i \Delta T) \frac{G}{G_n} \quad (6)$$

$$\text{where } \Delta T = T - T_n$$

Following are the parameters used in the mathematical modelling of PV system:

I : Photocurrent of PV module (Amp).
R_s :PV cell series resistance (Ω).
R_p : PV cell parallel resistance (Ω).
n_p : Number of parallel-connected cells.
V_m : PV model output voltage (V).
I_m : PV model output current (Amp).

R_{s_m} : PV model series resistance (Ω).
R_{p_m} : PV module parallel resistance (Ω).
I_o : Saturation current of diode (Amp).
q : Electron charge (coulomb).
A : Diode ideality constant.
K : Boltzman constant (Joules/Kelvin).
T : PV cell Actual temperature (Kelvin).
n_s : Number of series-connected cells.
I_{on} : Nominal saturation current of diode (Amp).
T_n : Nominal temperature (Kelvin).
E_g : Bandgap energy of the PV cell (eV).
I_{scn} : Nominal short-circuit current (Amp).
V_{ocn} : Nominal open-circuit voltage (V).
V_{tn} : Thermal voltage at nominal condition (V).
I_{Ln} = Nominal Photocurrent of PV model (Amp).
K_i : Temperature coefficient of Current (A/Kelvin).
G : Irradiation kW/m^2.
G_n : Nominal irradiation kW/m^2.

II.I.II Proposed PV System

The particulars about the Simulink PV model and hardware PV emulator is described in this section. Table 1 shows details about the proposed PV model parameters.

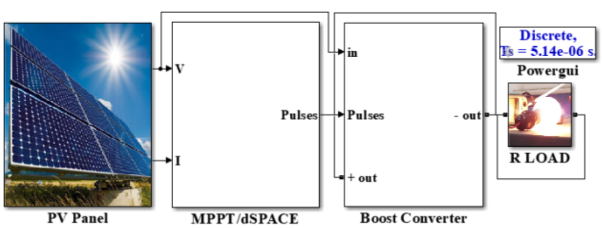


Fig.1 Proposed model of PV system with MPPT/ dSPACE

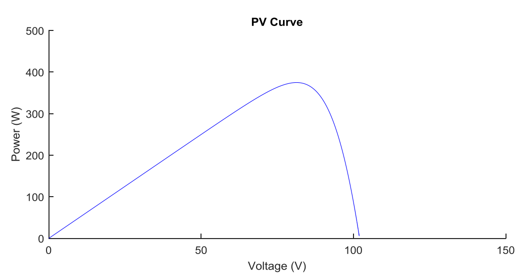


Fig.2 (a) P-V Curve of proposed PV module

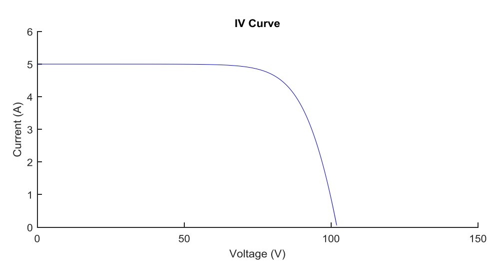


Fig.2 (b) I-V curve of proposed PV module

Table 1 Proposed PV model parameters

Parameters	**Values**
Open-circuit voltage, Voc	100 V
Short-circuit current, Isc	5 A
Number of cells in a module	170
Irradiance	1000 W/m^2
Device simulation temperature	25 degC
Measurement temperature	25 degC

SIMULINK PV MODEL:
The PV module is proposed according to the requirement for the efficient and effective implementation of MPPT. The proposed PV module consists of an assembly of 170 solar cells. The output of the PV model i.e. voltage and current are given to the DC-DC converter and also to the MPPT's blocks as inputs. Fig.3 shows MATLAB/Simulink diagram of PV model.

HARDWARE PV EMULATOR:
Ecosense**:** Set up with the aim of promoting education in the field of Renewable Energy Sources, Ecosense Sustainable Solutions Pvt. Ltd. was established by a team of IIT alumni in the year 2010. We have used PV emulator of ecosense having model no. IGE-PV4C400-002. PV emulator is a programmable power supply designed to emulate solar panel as shown in Fig.4. It is a user controlled, cost effective way to test response of PV system for wide range of solar panels. It simulates the I-V curve under varying environmental condition. Actual measured meteorological data of earth is used to simulate I-V curve and can also verify different parameters like MPPT tracking efficiency, overall efficiency etc. It consists of four channels with 0-50 V at 8A. Channels can be used independently or in series/parallel.
There are three mode of operation in PV emulator:

i. ***Fixed mode***: In fixed mode user is prompted to enter operating voltage and limiting current.
ii. ***Table mode***: Table mode offers users a way to test their PV systems for variations in solar radiation throughout the day.
iii. ***Simulated mode***: Simulated mode uses pre-simulated I-V tables stored on the device to emulate the typical output of the solar panels.

The specifications of proposed PV emulator are given in Table 2.

II.II About dSPACE DS1202 MicroLabBox

MicroLabBox is an all-in-one development system that helps in optimizing and testing controllers and it also combines compact size and low system costs with high performance and versatility. **MicroLabBox** includes **DS1202** base board as shown in Fig.5. **DS1202** houses the main real-time, dual core processor, and a separate co-processor that manages host PC communications. The control desk view of dSPACE is shown in Fig.6

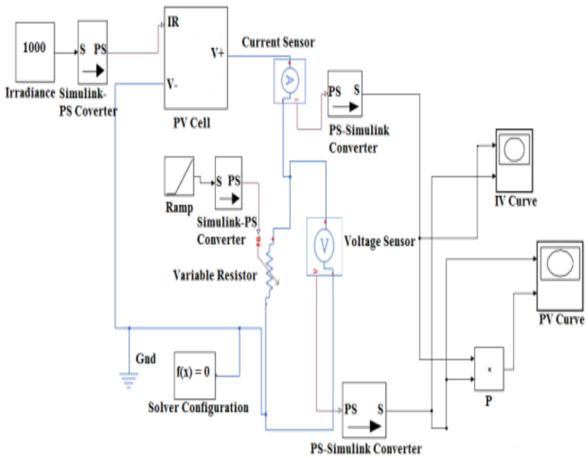


Fig.3 MATLAB/Simulink diagram of PV model

Fig.4 Four channel solar PV emulator (Ecosense)

Table 2 Proposed PV emulator specifications

S.No	Components	Sub Components		
1	No. of channels	4		
2	Connection type: Series/parallel	Series		
3	Mode of operation	Fixed mode		
		Channel	Voltage (V)	Current (A)
		CH0	25	1
		CH1	25	2
		CH2	25	1
		CH3	25	1

.

Fig.5 ***dSPACE*** **DS1202 MicroLabBox**

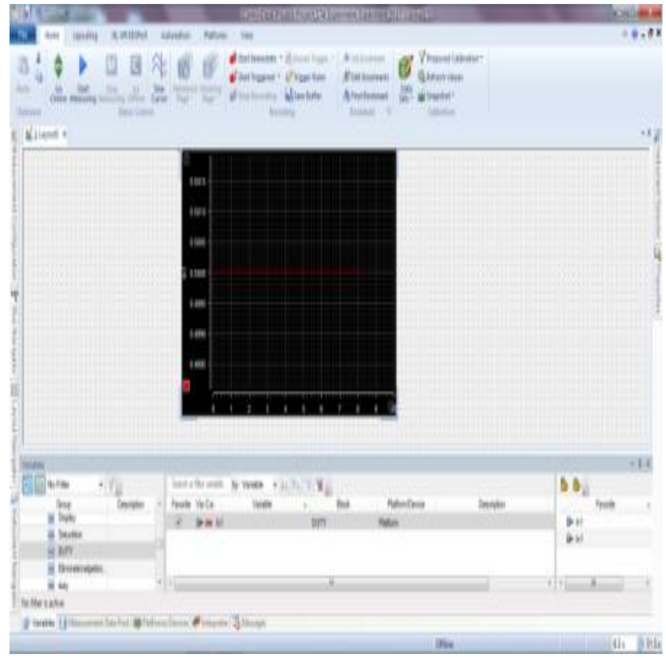


Fig.6 Control desk screenshot

II.III MPPT

MPPT is an important part of the PV system as it ensures that system operates at maximum power. The operation of MPPT cannot be fulfilled until there is some tuneable control parameter. This tuneable parameter is used for tuning of the system for maximum power extraction and is represented as duty ratio (δ). According to the principle of maximum power transfer when the internal impedance of source matches with the impedance of load then the power delivered to the load is maximum. The following relation can be written as:

$$Z_S = Z_L^* \quad (7)$$

where: Z_S = Internal impedance of source;
Z_L^* = Impedance of Load.

Thus, the impedance seen from the converter side i.e. load impedance needs to be similar to the internal impedance of the PV array i.e. source internal impedance [18].

Various MPPT techniques based on ANN, FLC, CSA are designed and implemented which are then compared with conventional technique i.e. P&O. The detailed description about various models of MPPT's is given later in section 3.

SOFTWARE MPPT IMPLEMENTATION

The Simulink implementation is done as shown in Fig.1 which includes PV module, MPPT, DC-DC converter and load. Fig.7 shows the Open circuit voltage, Voc of PV model. Various MPPT techniques are implemented and the duty cycle is generated which is used to drive MOSFET with 30 kHz switching frequency. In order to verify the tracking behaviour of MPPT techniques, maximum power generated by these techniques at the load is compared.

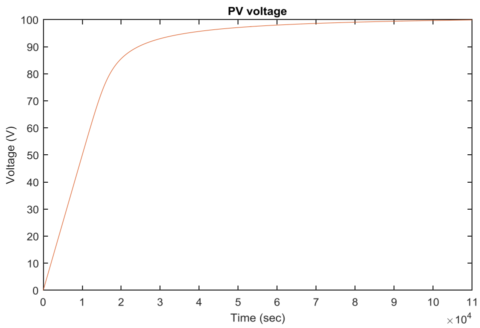


Fig.7 PV Open circuit voltage, Voc

HARDWARE MPPT IMPLEMENTATION

The hardware implementation of MPPT is done using dSPACE real time control as shown in Fig.5. The hardware set up of the solar system is shown in Fig.8. The implementation of MPPT and data acquisition is done using dSPACE **DS1202 MicroLabBox.** The initial PV voltage and PV current of proposed emulator is measured by the in-built sensor in the hardware and can be realised in the control desk view. Fig.9 and Fig.10 shows control desk view of acquired PV voltage and PV current measured from emulator respectively with noise.

The analog PV voltage and PV current are fed to the ADC (Analog-to-digital converter) block of dSPACE so that it can be used in Simulink MPPT block. Fig. 13 shows the MPPT model implemented using dSPACE. PV voltage and PV current are further filtered in order to remove high frequency noise or switching noise that appeared in signal. Further, the voltage and current are calibrated in MATLAB/dSPACE as shown in Fig.11 to get required PV voltage and PV current as shown in Fig.12 and Fig.13 respectively. The PV voltage and PV current are then applied to the MPPT algorithm to acquire desired duty cycle. The output signal of MPPT model is the applied to DIO (Digital Input Output) block which produces required switching signal to drive the MOSFET (Range of switching frequency from 10kHz - 60 kHz). This is further connected to boost converter which gives the boosted output voltage and is connected to resistive load.

Fig.8 Hardware set up of MPPT system

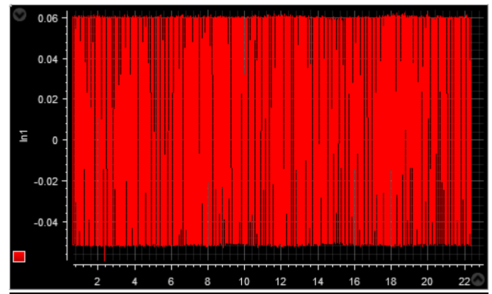


Fig.9 Control desk view of PV voltage

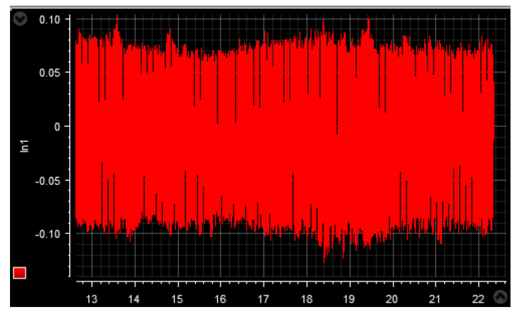


Fig.10 Control desk view of PV current

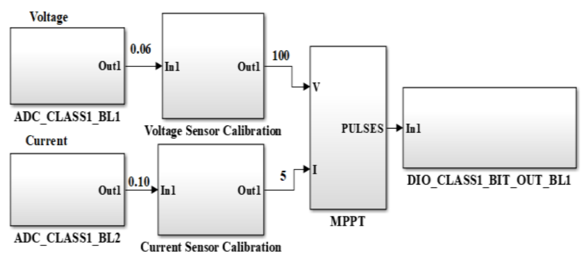


Fig.11 MPPT model implemented in dSPACE

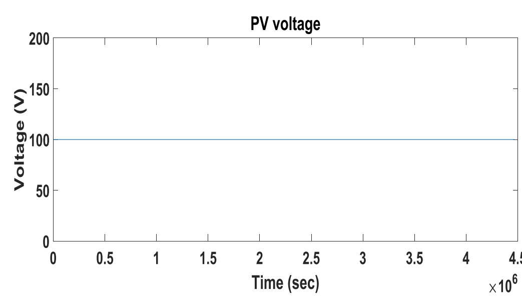


Fig.12 Calibrated PV output voltage

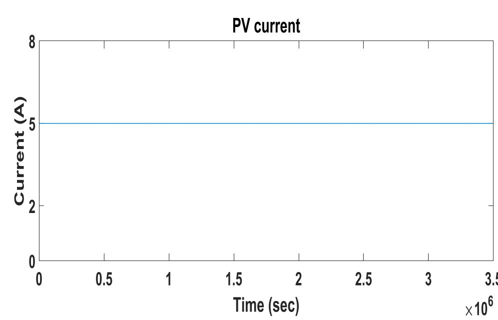


Fig.13 Calibrated PV output current

II.IV DC-DC Converter with connected D.C.Load

The DC/DC converter acts as an interface between the PV panel and the load, allowing the generation of the maximum power point (MPP) in PV systems. Average output voltage can be obtained using DC-DC converters. DC-DC converter used in this work is boost converter [19]. Boost converter is connected to D.C load. The values of inductor (L) and capacitor (C) for the boost converter can be calculated from the equations given in [20].

A representation diagram of boost converter is given in Fig.14; where: V_{in} :input voltage, V_{out} :output voltage, L:inductor, C:capacitor, D:Diode, S:Switch. Various parameters of boost converter used are given in Table 3. A resistive load of 60 W is used at the output of D.C-D.C converter in the proposed work. Fig.15 shows resistive load used. Table 4 shows parameters of load.

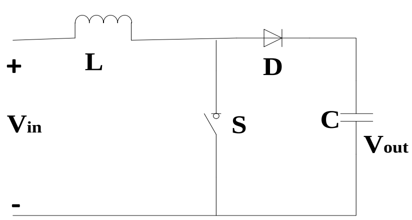


Fig.14 Representation diagram of Boost Converter

Fig.15 Resistive load

Table 3 Parameters of Boost Converter

Parameters	Values
Inductor, L	0.003 H
Capacitor, C	0.00047 F
Switching frequency	30 kHz
Diode voltage drop	0.7 V
Ron of MOSFET	0.118 Ω

Table 4 Parameters of Resistive load

Parameters	Values
Power	60 W
Nominal voltage	230 V
Nominal frequency	60Hz

III. MPPT TECHNIQUES (P&O, ANN, FLC, CSA)

In this section, various MPPT techniques are explained to obtain maximum power from PV module. The duty cycle is obtained from various MPPT techniques to trigger the boost converter.

III.I Hardware implementation of Conventional Perturb and Observe Algorithm (P&O)

The conventional P&O algorithm is made on the PV characteristics of PV module where the slope $\left(\frac{dP}{dV}\right)$ is varied [21]. MPPT algorithm for P&O technique is applied with inputs from PV voltage and PV current/sensors and the resultant output is taken as duty cycle and is applied to DIO block. P&O is an illustration of hill climbing method. The code for P&O algorithm is implemented using dSPACE in order to get duty cycle to be applied to converter through DIO channel obtain maximum power all the time. Fig.16 shows P&O optimization algorithm flowchart.

III.II Hardware implementation of Artificial Neural Network (ANN)

Artificial Intelligence (AI) based back-propagation technique is used to track MPPT. A multilayer feedforward network with hidden layers is used in this work [22]. In this section the proposed hardware based ANN algorithm is shown which is one of the efficient method being used now-a-days. The simulation of ANN is performed using MATLAB/dSPACE. The maximum power from PV module is obtained by training the neural network and then applying the output duty

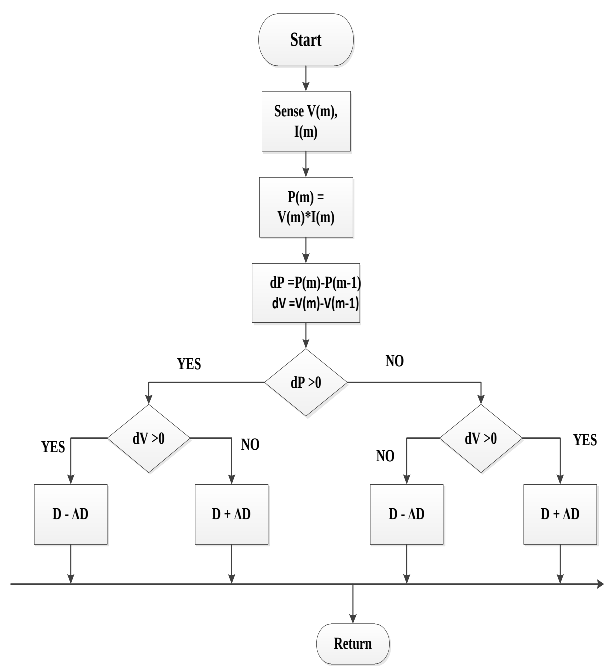


Fig.16 Flow chart of conventional P&O Algorithm

cycle to DIO block. The neural network based MPPT and back- propagation neural network are trained using 60 set of data points obtained from improved neural model. Fig.17 shows proposed model of ANN with two inputs, one output and one hidden layer.

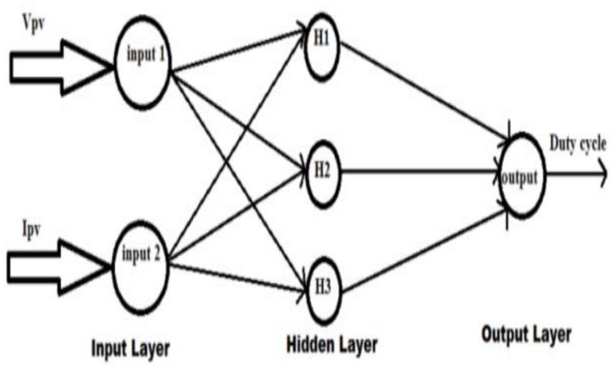


Fig.17 ANN proposed model

The inputs PV voltage (V_{pv}), PV current (I_{pv}) are given to ADC block and the duty cycle obtained as output is given to DIO block of dSPACE. The Levenberg-Marquardt backpropagation (trainlm) training method is used for ANN. This training method is used with an optimization gradient descent method. Parameters of the ANN are shown in Table 5.

III.III Hardware implementation of Fuzzy Logic Control (FLC)

In fuzzy logic rules are written with prior knowledge of the system. The controller has two inputs as error E and change in error CE at sample time m, given by equations (8) and (9), and one output:

$$E(m) = \frac{P(m)-P(m-1)}{V(m)-V(m-1)} \quad (8)$$

$$CE(m) = E(m) - E(m-1) \quad (9)$$

Four stages of fuzzy are: fuzzification, fuzzy inference, rule-base and defuzzification. In this process of fuzzification crisp input is converted into linguistic variable. Such conversion depends on membership functions. The inputs E and CE are converted into linguistic variables and then the resultant output is generated by looking up to rule base table. The FLC tracks the output based on rule: If A and B, then C. Fuzzy output is determined by fuzzy inference system. The most frequently used inference method is Mamdani. The output of fuzzy is converted back to crisp output from linguistic value using defuzzification [23]. Fig.18 shows various stages of FLC.

Table 5 Parameters for ANN

Parameters	**Values**
Number of sample data	60
Inputs	2
Outputs	1
Hidden layers	1
Weights	60
Training function	Levenberg-Marquardt backpropagation (trainlm)
Transfer function	Sigmoid
Epoch	5

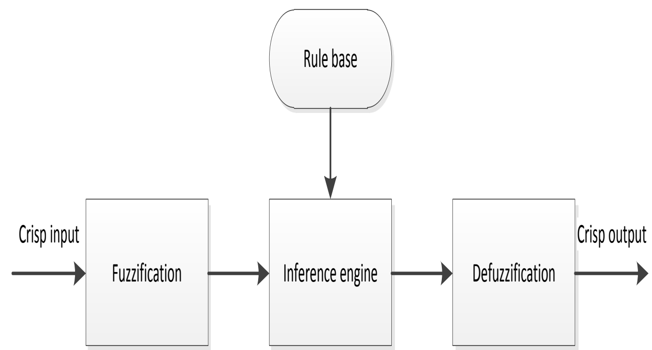


Fig.18 Stages of FLC

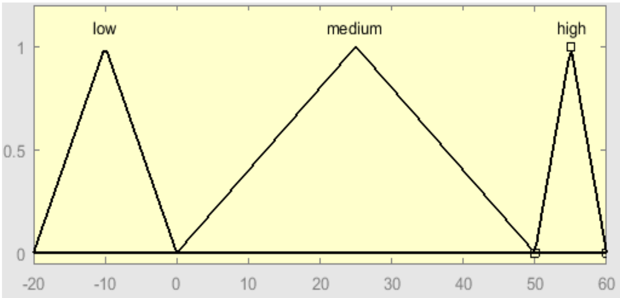
In the proposed work of FLC, PV voltage and PV current are taken as inputs with triangular Membership Functions (M.F's) and the output is the duty cycle. Mamdani Fuzzy Inference System (FIS) [23] is used in this model which maps inputs to that of outputs. The number of rules is given by formula: 2^n, where n is the number of inputs. Hence, one rule is defined for the proposed algorithm. The M.F's are presented in Fig.19 (a), (b), (c). The surface view of the proposed FLC is also shown in Fig.20.

III.IV Hardware implementation of Cuckoo Search Algorithm (CSA)

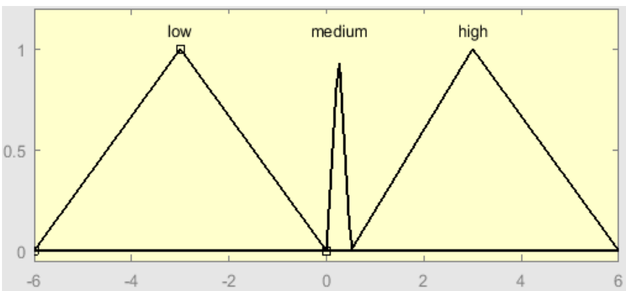
This evolutionary algorithm was developed by Yang and Deb in 2009 and has undergone a substantial development [24]. CSA is based on the destructive reproduction strategy of the cuckoo's bird behaviour. Three important components required essentially for CSA are: selection of the best nest; search pattern using Levy's flight for replacing the host eggs with the new solutions; and discovery of some cuckoo eggs by the host birds and replacing those eggs according to the quality of the local random walks. [24], [25], [26].

Levy ~ u = $t^{-\lambda}$, $(1 < \lambda \leq 3)$ (10)

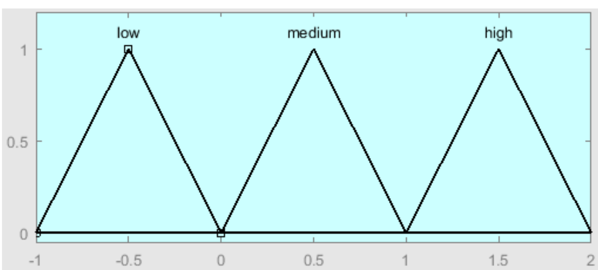
where: $\lambda > 0$ is a parameter which is the mean or expectation of the occurrence of the event during a unit interval, t = step length. CSA flow chart can be seen from [26].



(a) Voltage M.F (Input)



(b) Current M.F (Input)



(b) Duty cycle M.F (Output)

Fig.19 (a), (b), (c) Membership functions (M.F's) for FLC

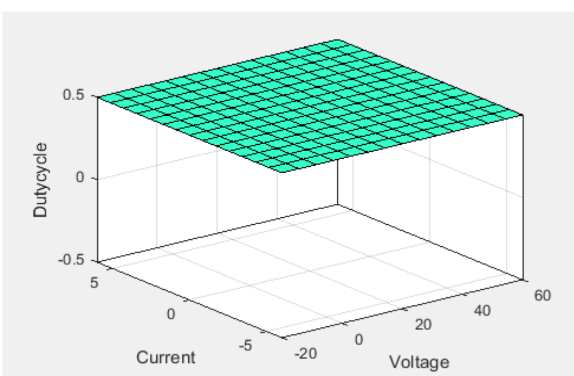


Fig. 20 Surface view of FLC

For the proposed algorithm the number of inputs is PV voltage and PV current and the resultant output is the duty cycle. The objective function is as shown in section 3.4.1. The proposed CSA is shown in Fig.21. Also, an analogy between natural system and artificial system is shown in Table 6.

Table 6 Analogy between Natural system and Artificial system

Natural system	**Artificial system**
Number of eggs	Voltage, Current
Nests	Power
Best output values	Maximum Power
Stopping criteria	Maximum Iteration

III.IV.I OBJECTIVE FUNCTION

An equation, to be optimized with given certain constraints and variables that need to be minimized or maximized using non-linear programming techniques is referred to as objective function. In the proposed work the objective function for the CSA is taken as power (P). Mathematically, optimization problems can be written in generic form as given in [24].

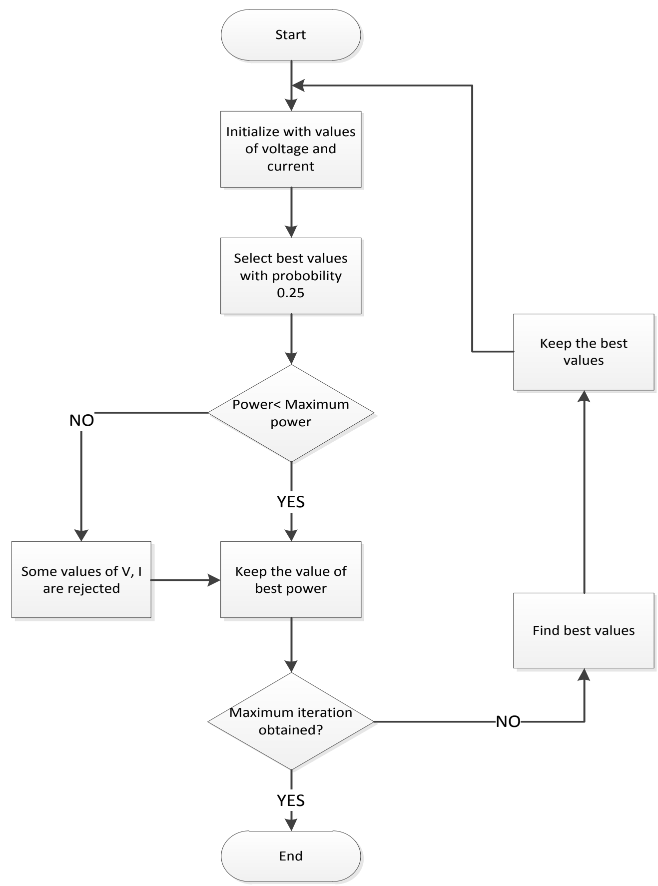
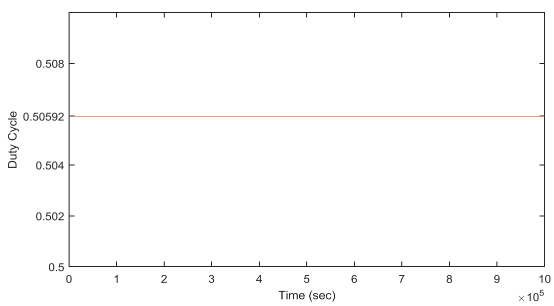


Fig.21 Proposed CSA

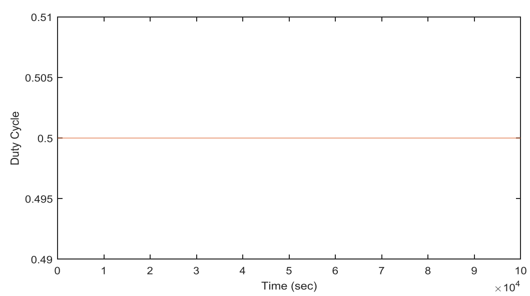
IV. RESULTS AND DISCUSSIONS

The results of the proposed MPPT methods i.e. ANN, FLC & CSA based along with P&O based are presented by using MATLAB/Simulink and **dSPACE** in this section. The performance of these algorithms are investigated under constant 1000 W/m^2 irradiance condition. The model is first realized in MATLAB/Simulink and the duty cycle obtained is presented in Fig.22. Then the hardware implementation of all algorithms is performed using **dSPACE** and results of the duty cycle are shown in Fig. 23.

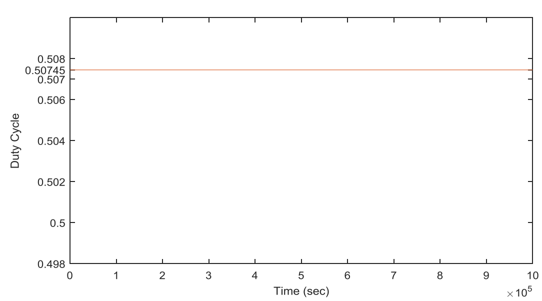
The D.C link is in a parallel connection with rectifier and load. The D.C.link consists of a capacitor known as D.C link capacitor. The use of this capacitor is to reduce ripples and noise from load side to make output voltage constant. The D.C.link voltages are recorded for the comparison in both software and hardware implementation as shown in Fig. 24 and Fig.25 respectively. The set point of D.C link voltage is fixed as 200 V. The ANN D.C.link voltage is 201.5 V, FLC D.C.link voltage is 199 V, CSA D.C.link voltage is 207 V & P&O D.C.link voltage is 254 V in software implementation and in hardware implementation these are 161 V, 129 V, 200 V, 156 V for ANN, FLC, CSA, P&O methods respectively.



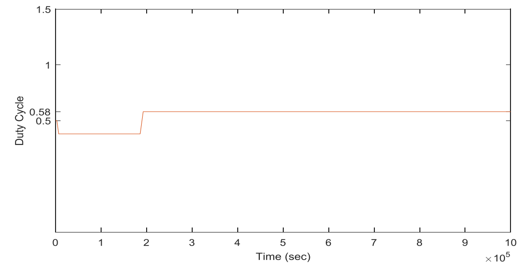
(a) Duty cycle for ANN, D=0.50592



(b) Duty cycle for FLC, D=0.50

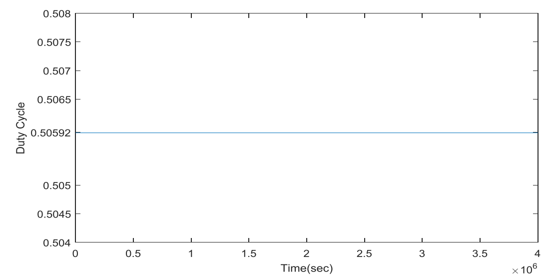


(c) Duty cycle for CSA, D=0.50745

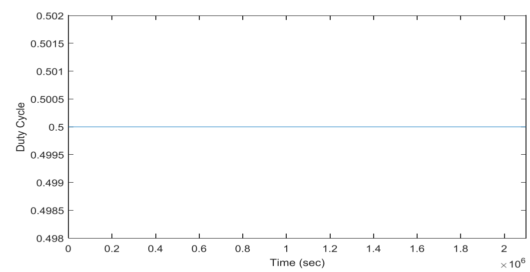


(d) Duty cycle for P&O, D=0.58

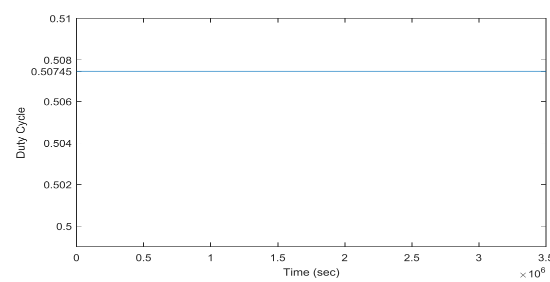
Fig.22 Duty cycle for software (a) ANN (b) FLC (c) CSA (d) P&O



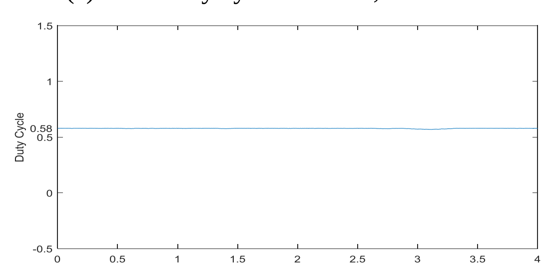
(a) Duty cycle for ANN, D=0.50592



(b) Duty cycle for FLC, D=0.50



(c) Duty cycle for CSA, D=0.50745



(d) Duty cycle for P&O, D=0.58

Fig. 23 Duty cycle for hardware (a) ANN (b) FLC (c) CSA (d) P&O

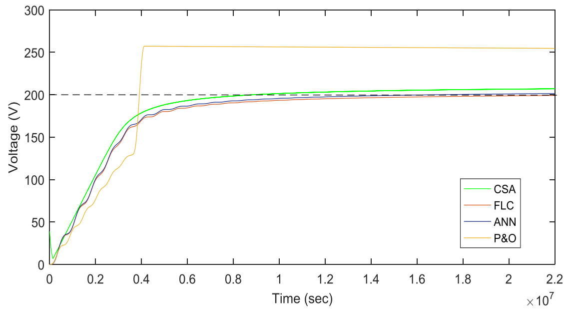
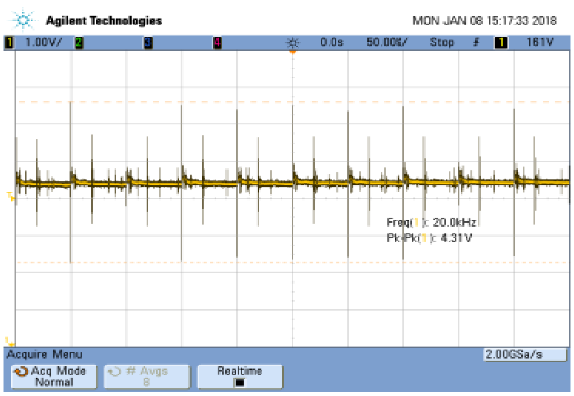


Fig. 24 D.C.link voltage for software

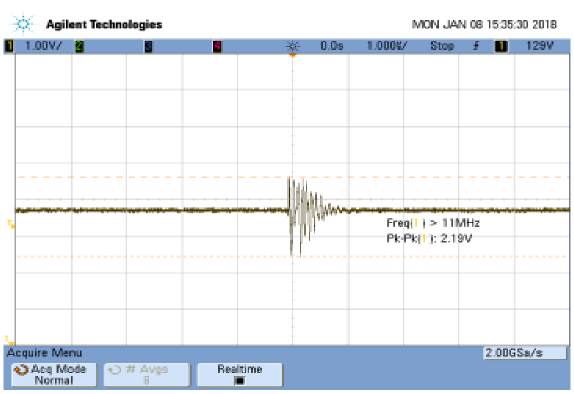
Steady state tracking accuracy of D.C. Link voltages is also shown in Table 7. Tracking accuracy of D.C.Link is calculated by dividing the acquired D.C.link value with the D.C.link set point value [27], [28], [29], [30], [31], [32], [33].

$$\text{Accuracy } \% = \frac{\text{Obtained D.C.link value}}{\text{D.C.link set point value}} * 100 \qquad (11)$$

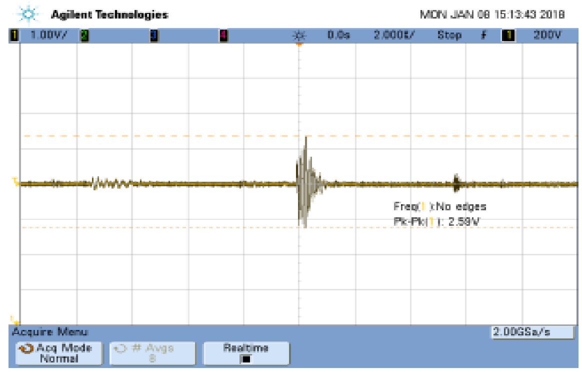
In software implementation FLC gives the better accuracy of 99.5 % a other techniques as shown in Table 7. While in hardware implementati gives 100 % of accuracy whereas, FLC gives 65 % of accuracy. Maxir tracking efficiency primarily depends upon the tracking accuracy of ha hardware tracking accuracy of CSA is highest among all the MPPT techniques.



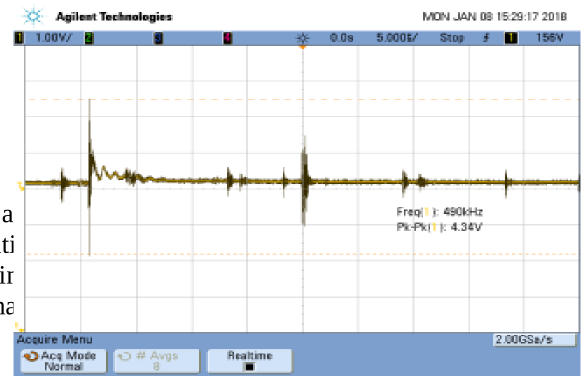
(a) ANN D.C.link voltage, 161 V



(b) FLC D.C.link voltage, 129 V



(c) CSA D.C.link voltage, 200 V



(d) P&O D.C.link voltage, 156 V

Fig. 25 D.C.link voltage for hardware

However, there is marginally lower value of software accuracy in CSA as compared to ANN & FLC. The reason can be that CSA is simple and fast converging algorithm and guarantees global convergence properties and FLC is a complex method, has more rules and each iterations takes time and ANN is lengthy and has space and time complexity also it gives local minima. In software matching sample time with the duty cycle can be managed hence, FLC and ANN are running smoothly. But in case of hardware sample time with the duty cycle is to be matched carefully therefore, FLC and ANN are not giving better results. We have compared all results with same sample time. CSA is performing well in both hardware and software implementation.

Table 7 also shows the comparison of overshoot voltages of Fig. 25. The CSA and FLC have comparable overshoot voltage and ANN, P&O have overshoot of 4.31 and 4.34 respectively.

Fig.22 and Fig.23 shows comparison of duty cycle for software as well as hardware implementation. The output voltage depends upon the duty cycle. The desirable output is kept 200V. For this output ANN gives 0.50592 duty cycle, FLC gives 0.50 duty cycle, CSA gives 0.50745 duty cycle and P&O gives 0.58 duty cycle. Hence, CSA has shown better duty cycle output therefore, it will perform better.

From the output power values of hardware given in Table 8, it is evident that the output power value of 40 obtained through CSA technique is the highest as compared to ANN, FLC, P&O with values 32.2, 25.8 and 31.2 respectively. From the output power values of software it appears that the values in three MPPT techniques i.e ANN (40.3), FLC (39.8), CSA (41.4) marginally differ with each other except P&O with a value of 50.8. From the above results it can be understood that the output power of CSA technique is almost similar in software as well as hardware implementation due to the fact that CSA iteration takes less time. As hardware and software results of CSA are same hence, we can test simulation of CSA also to ensure the possible outcome with hardware.

Table 7 Comparison of tracking Accuracy of D.C. Link Voltages and Overshoot Voltages

MPPT Algorithms	**Accuracy (%) (Software)**	**Accuracy (%) (Hardware)**	**Overshoot Voltages (V)**
ANN	99.2	80.5	4.31
FLC	99.5	64.5	2.19
CSA	96.6	**100**	2.59
P&O	78.7	78	4.34

So, it can be concluded that CSA based tracking algorithm is more accurate and it takes less time to tune parameters as compared to other MPPT techniques. ANN and FLC are complex methods and consume more time. Testing of any system controlled using CSA can be done online as this algorithm is fast to implement and gives same results in software and hardware. It will save time and cost. ANN, FLC and P&O have the problem in hardware implementation where complexity of the algorithm does not allow the data flow in feedback loop at the same speed as desired in iteration. Hence, they give different results in software and hardware implementation.

Table 8 Comparison of Output Power

MPPT Algorithms	**Power (W) (Hardware)**
ANN	32.2
FLC	25.8
CSA	40
P&O	31.2

Hence, it can be concluded that proposed CSA based technique in this study have shown better results in software and hardware implementation and can be effectively used in power generation using PV system and other similar complex system.

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