ORIGINAL RESEARCH

Design and validation of a single-phase buck–boost inverter with Grey Wolf optimization algorithm under partial shaded conditions

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Abstract The key intention of this research article is to design and validate a single-phase buck–boost inverter which can be utilized to modify DC power from solar panel to AC power without the need of a DC-DC converter. The proposed topology is designed to perform Maximum Power Point Tracking (MPPT) directly and the output from the inverter can be used for standalone load or can be integrated with grid. In this paper, a Global Maximum Power Point Tracking (GMPPT) is executed to gain maximum power under the Partial Shading Conditions (PSC) of solar panel. GMPPT is tracked instantaneously using Grey Wolf Optimization (GWO) technique. The proposed work is successfully carried out using MATLAB software and a prototype model is developed to validate the simulation results.

Keywords GMPPT · GWO · PSC · Single phase buck–boost inverter · Solar PV

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1 Introduction

The requirement of electrical power is drastically growing day-by-day due to technology advancement and population growth. The ever-increasing demand could not be met with conventional energy sources. This leads to invent a lot of alternate energy sources and in which the renewable energy sources are most promising for future generations. The present scenario is to increase the energy generation using renewable sources such as solar or wind along with conventional generating systems. Moreover, large usage of non-renewable energy resources has significantly affected the environment by depleting the biosphere and cumulatively adding to global warming. Replacing the fossil fuels with renewable sources like solar and wind will lead to clean the atmosphere and reduce global warming. The performance of solar Photovoltaic (PV) based energy generation for standalone and grid connected inverter applications under various partial shading conditions was evaluated in this paper.

The necessity of high performance, reliable and low-cost solar PV panels for standalone and grid connected systems are increasing rapidly. A simple single stage buck–boost inverters with Maximum Power Point Tracking (MPPT) algorithms are preferred for converting the DC output from solar panels to required AC supply especially in small and medium level applications under partial shading conditions [1–3]. Because of instantaneous changes in solar output a buck–boost converter with duty cycle controlling algorithm is required in DC applications. Also, MPPT tracking is essential to get maximum output from solar panel. The performance of various single stage buck–boost inverter is improved much better in last 25 years [4]. Mostly, Current Source Inverters (CSI) are not widely used in industry and domestic purpose because of numerous

problems like control complexity, practically inefficient current sources, high cost etc., The mathematical analysis of grid connected inverters also need to be considered to design an appropriate inverter for particular application [5].

A modified Perturb & Observe (P&O) for any shading configuration, irradiation is formulated and solved the low irradiation tracking problem of conventional P&O algorithm. P&O based MPPT method for photovoltaic system [6–8] gives efficient output, but the circuit complexity and implementation difficulty reduce its performance. Modified variable step incremental conductance method [9] was implemented to get maximum power output by automatically tracking the next step size. In sliding mode based MPPT control algorithm for cuk converter, each PV module is provided with separate MPPT controller and power converter circuit which complicates the practical implementation and makes the circuit bulkier [10]. The idea behind the proposed method was to provide accurate and fast convergence to the global Maximum Power Point (MPP) during different weather conditions. Analysis of simple and hybrid MPPT methods with partially shaded solar PV systems becomes necessary to understand the implementation difficulties in stand-alone and grid connected applications [11–13]. The above mentioned existing MPPT methods has many problems such as less duty cycle ratio, circuit complexity etc., so, investigation about different MPPT techniques under partial shading condition is required to choose a best optimization technique [14, 15].

In this research work a new Grey-Wolf based optimization algorithm was selected to track Maximum Power Point. The key objective of this method is to get accurate results compared to conventional algorithms. The GWO algorithm is widely used in many applications such as Wireless Sensor Networks (WSN), Hydro power generation, wind speed forecasting etc., [16–18] especially for MPPT selection it gives a better performance among other conventional control algorithms. The implementation of GWO MPPT algorithm for solar PV system helps to obtain maximum output power than other conventional algorithms [19].

The novelty of this research work is to maintain the constant AC output voltage during partial shading conditions in stand-alone or grid connected systems. Irrespective of input voltage (lower or higher than the required output voltage) the output voltage has to be maintained. In buck–boost inverters the duty cycle plays the major role in output voltage. If the duty cycle is varied up to its maximum level (0 to 1) then the output voltage can be maintained even though high fluctuations in input side. Duty cycle optimization ensures the accurate output voltage in buck–boost converters under various input and load conditions [20]. In existing buck–boost converter and zeta converter using incremental conductance MPPT algorithm, the maximum

duty cycle obtained was 68.96% [21]. Also, in novel drift P&O M-MPPT algorithm for boost converter, the maximum duty cycle obtained was below 80% [22]. An GWO MPPT algorithm for Brushless Direct Current (BLDC) motor has designed with 84% of duty cycle [23]. The proposed system aims to obtain maximum duty cycle of up to 95% to maintain the constant AC output voltage.

By the above analysis there is a need to design a single-phase buck–boost inverter using Grey Wolf Optimization algorithm for stand-alone and grid connected applications. The simulation results suggest that this optimization method will be better for all type of solar PV applications. In this paper, the Chap. 2 discusses the proposed block diagram. The Chap. 3 is focussing on mathematical modelling of a solar panel. In Chap. 4 Grey Wolf Optimization based GMPPT algorithm is discussed. In Chap. 5, overall simulation results with resistive load are presented and discussed. Chapter 6 discusses its hardware implementation and Chap. 7 concludes.

2 Proposed block diagram

The solar PV panels may experience numerous power hikes under partial shading conditions. The conventional MPPT methods are inefficient to track GMPP. The proposed arrangement has four solar panels connected in series which can delivered with different irradiance levels. The output of solar panels further connected via buck–boost inverter to standard 230 V, 50 Hz AC supply.

The block diagram of the proposed system is shown in Fig. 1. Here the analysis is made with solar PV under partial shaded condition and under normal irradiance. The unregulated solar PV output is given to four switch buck–boost inverter. This buck–boost inverter directly converts unregulated DC to regulated single phase AC supply. This will operate in both DC-DC conversion mode and DC-AC inversion mode. The output from GWO GMPPT algorithm ensures the input for accurate PWM pulse generation.

3 Mathematical modelling of solar panel

The mathematical design analysis of solar PV panel is obtained starting from the equation of diode current as shown below:

The module photo current (I_{ph}) is given by

$$I_{ph} = [I_{sc} + k_i(T - 298)] * \lambda/1000, \tag{1}$$

where I_{ph} = module photo current (A)

K_i = Short circuit current temperature coefficient.
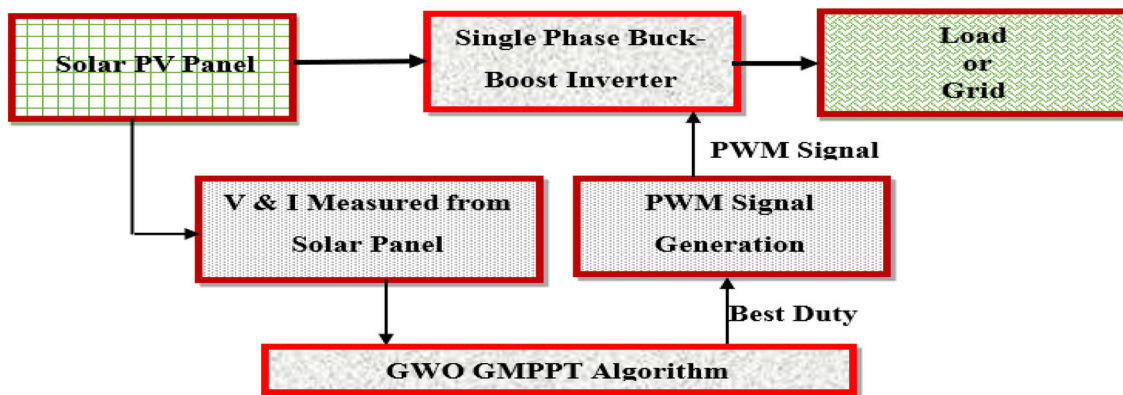
T = working temperature of module in K.

Fig. 1 Block Diagram of PSC PV fed four Switches inverter with GWO

λ = illumination of PV module (1000 W/m^2).

I_{sc} = short circuit current of PV module (A) and.

The expression for I_{sc} at any temperature and irradiance is given by

$$I_{sc} = I_{sc,ref}\left[1 + \alpha\left(T - T_{ref}\right)\right]\frac{S}{S_{ref}}, \qquad (2)$$

$I_{sc,ref}$ = short circuit current under STC (ampere).

I_{sc} = short circuit current (A).

T = PV module temperature in Kelvin.

T_{ref} = PV array temperature under STC in K.

S = Solar irradiance (W/m^2).

S_{ref} = Irradiance under STC (W/m^2).

α = Temperature coefficient of I_{SC} (/̊C).

Module reverse saturation current is given by

$$I_{rs} = I_{sc}/\left[exp(qV_{oc}/N_s kAT) - 1\right], \qquad (3)$$

V_{oc} = open circuit voltage (V).

q = charge in a electron in C.

K = Boltzmann's constant.

A = Ideality factor of diode.

N_s = total cells connected in series.

T = PV module temperature in Kelvin.

The module saturation current I_o is given by

$$I_o = I_{rs}\left(\frac{T}{T_r}\right)^3 exp\left(\frac{q \times E_{go}}{Bk}\left\{\frac{1}{T_r} - \frac{1}{T}\right\}\right), \qquad (4)$$

T_r = Reference Temperature (^{o}C).

E_{go} = Band gap energy of semiconductor (for silicon = 1.1 ev).

B = Ideality factor of diode.

The output current from the PV module (I_{pv}) is given by [24]

$$I_{pv} = N_p * I_{ph} - N_p * I_o\left[exp\left\{\frac{q * \left(V_{pv} + I_{pv}R_s\right)}{N_s AKT}\right\} - 1\right], \qquad (5)$$

I_{ph} = Photo current (A).

I_o = Saturation current (A).

I_{pv} = Total output current (A).

N_s, N_p = No. of cells connected in series and parallel respectively.

Rs = series resistance of solar panel (Ω).

q = charge of an electron, C.

K = Boltzmann's constant.

A = Ideality factor of diode.

$V_{pv} = V_{oc}$ = open circuit voltage (V) and the equation to calculate open circuit voltage is given by

$$V_{oc} = V_{oc,ref}\left[1 + aln\left(\frac{S}{S_{ref}}\right) + \beta\left(T - T_{ref}\right)\right], \qquad (6)$$

where,

$V_{oc, ref}$ = V_{oc} under STC (Standard Test Conditions) in V.

β is Temperature coefficient of V_{oc} (/°C).

a is Irradiance correction factor of V_{oc}.

Using the Eqs. (1) to (6), it is decided to employ four panels connected in series with each panel having four modules in parallel. The partial shading condition is incorporated by means of different irradiance level. A simple resistive load is considered as load to measure the output from the solar panels. Each panel is connected in parallel with a diode and small capacitor to avoid the circulating current among solar panels and to reduce voltage fluctuations at output. The specifications of the PV panels

Table 1 Specifications of a single PV panel

Power rating	100 × 4 W
Maximum power (P$_m$)	60 × 4 W
Open circuit voltage (V$_{oc}$)	20 V
Voltage at maximum power point (V$_{mp}$)	15 V
Short circuit current (I$_{sc}$)	5 × 4 A
Current at maximum power point (I$_{mp}$)	4 × 4 A

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are as shown in Table 1. The temperature value of each panel is commonly fixed as 25 °C.

The simulation circuit for partial shaded condition are shown in Fig. 2. Using the above SIMULINK model of Fig. 2, Power-Voltage and Current-Voltage characteristics of PV panel under partial shaded condition is analyzed for four different shading patterns. Partial shaded condition has been achieved by varying irradiance levels of PV panels.

Irradiance levels for four panels for four different shading patterns are,

- Pattern-1: 500, 600, 700 and 900 W/m^2.
- Pattern-2: 400, 500, 600 and 800 W/m^2.
- Pattern-3: 300, 400, 500 and 700 W/m^2.
- Pattern-4: 200, 300, 400 and 500 W/m^2.

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The characteristics of the series connected PV panel are obtained for non-uniform irradiations representing partial shaded condition. The voltage and current of a PV panel
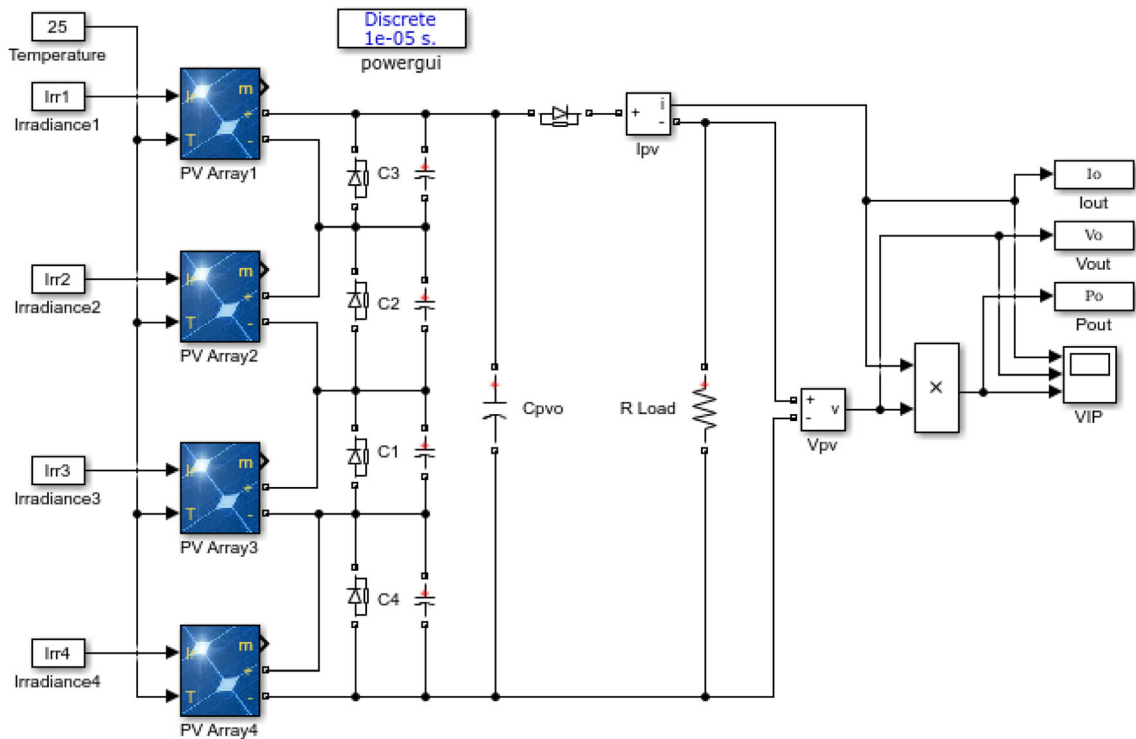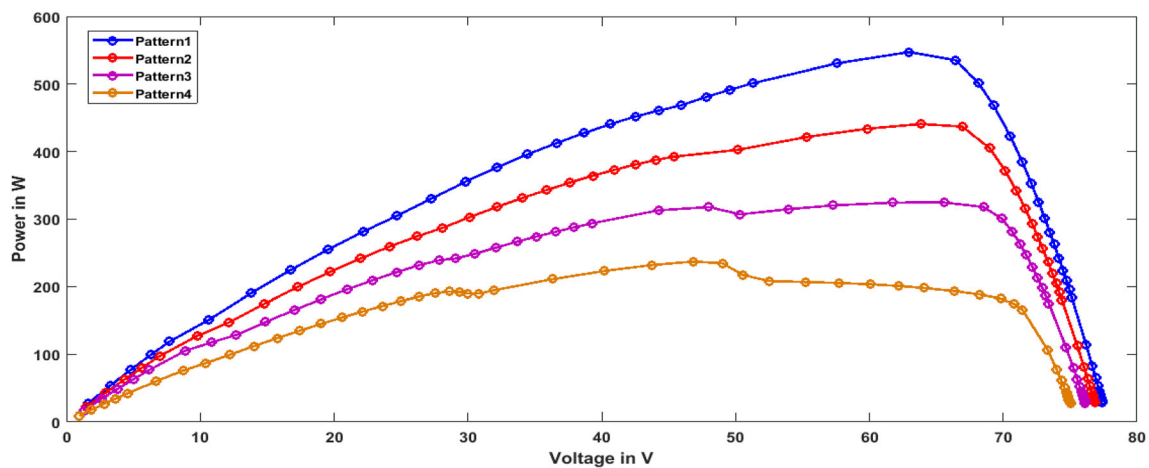

Fig. 2 SIMULINK model for PV characteristics under PSC
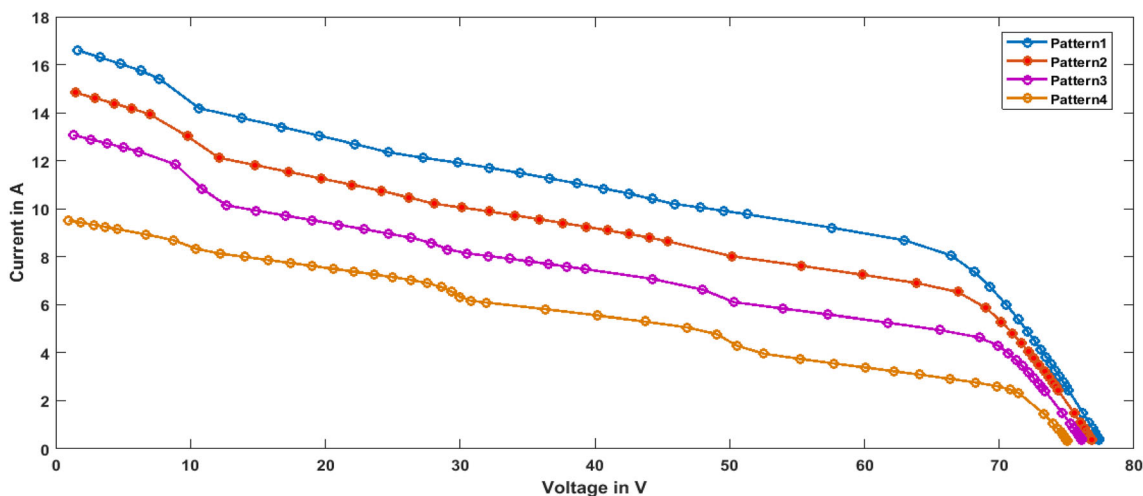

Fig. 3 P-V characteristics with different PSC
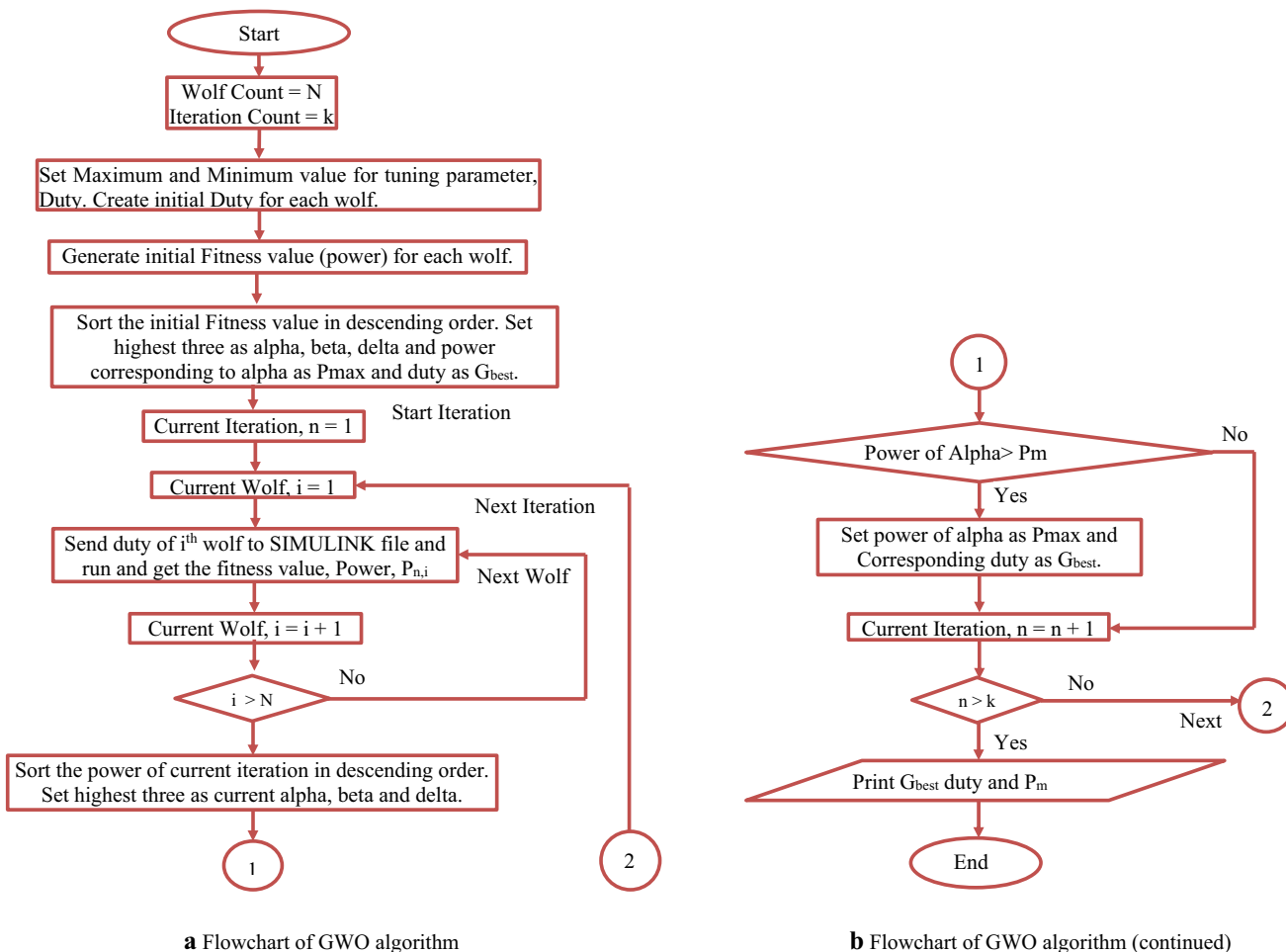
Fig. 4 I-V characteristics with different PSC

a Flowchart of GWO algorithm   **b** Flowchart of GWO algorithm (continued)

Fig. 5 a Flowchart of GWO algorithm. **b** Flowchart of GWO algorithm

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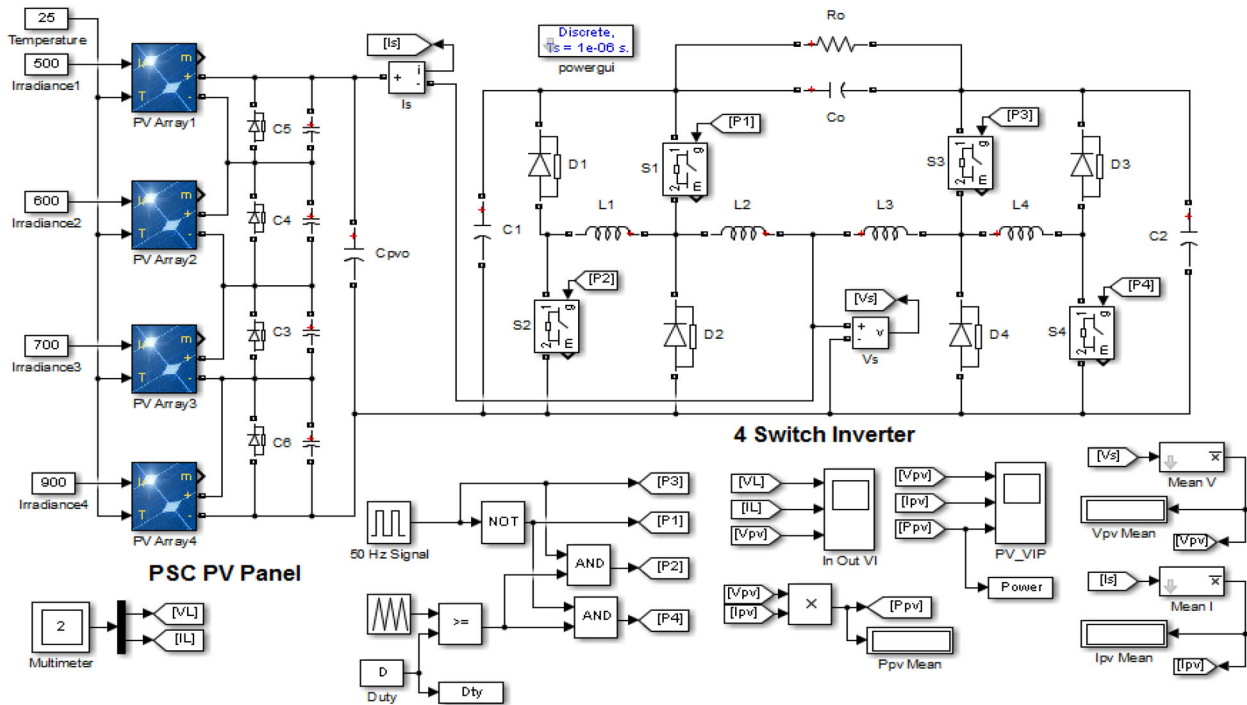
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Fig. 6 Proposed overall Simulation diagram
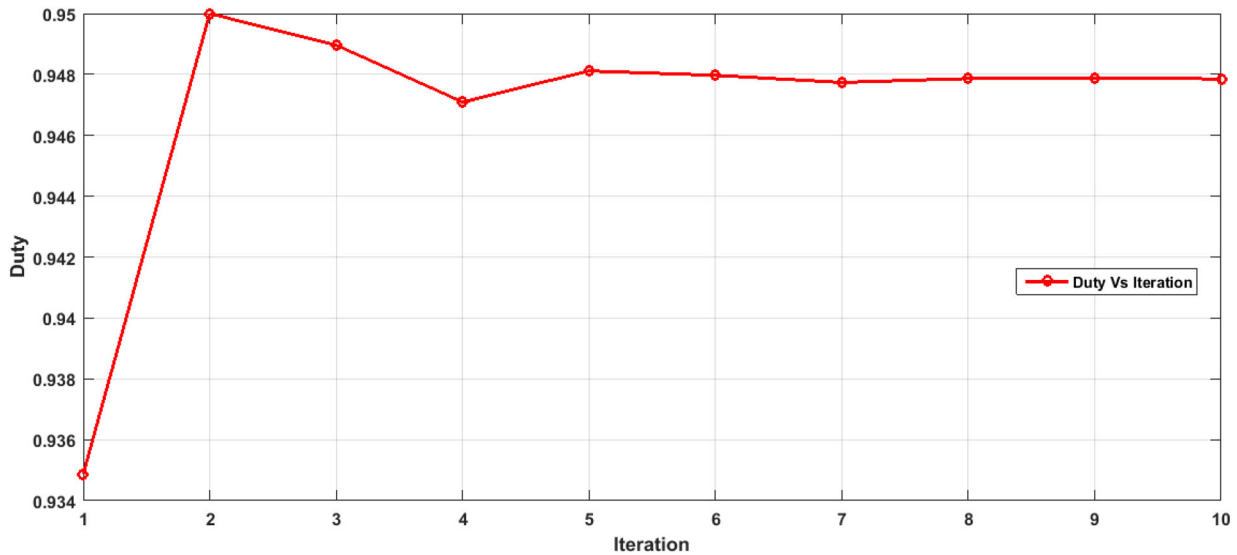
Fig. 7 GWO Convergence Curve

changes with respect to the irradiance and temperature. Hence, while modelling the PV panel the effect of temperature and irradiation must be taken into consideration. Power-Voltage and Current-Voltage characteristics of four series connected PV panel with non-uniform irradiance levels are shown in Figs. 3 and 4 respectively.

From the P-V and I-V characteristics, it is observed that multiple power peaks occur under partial shaded condition. Also, it is observed that the power is a maximum only at a particular peak called global peak and the power at other peaks are less than global peak and so they are called local peaks.
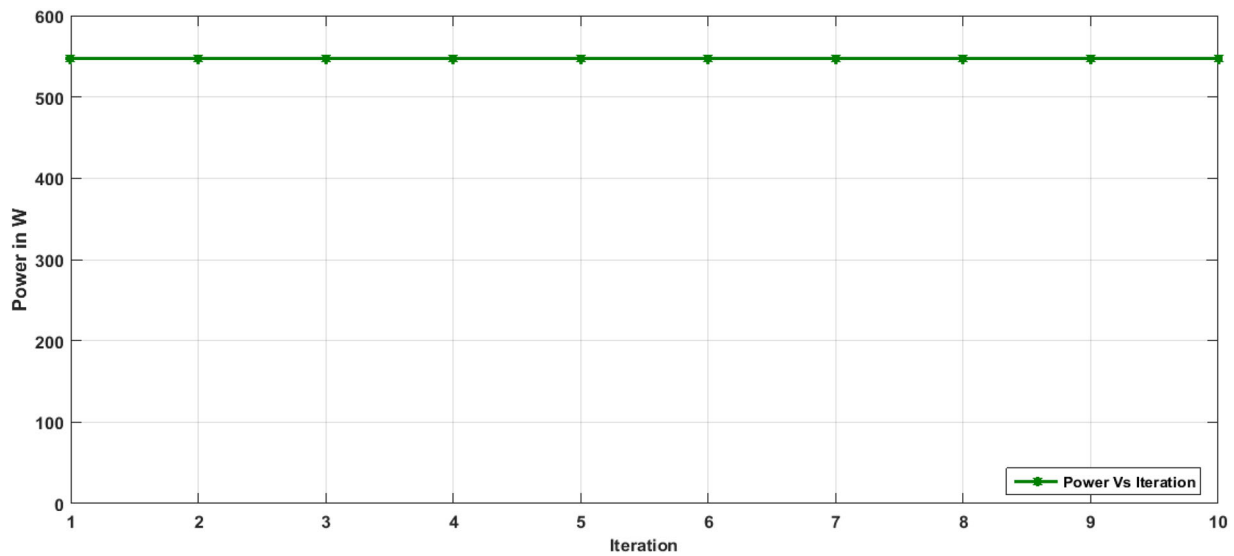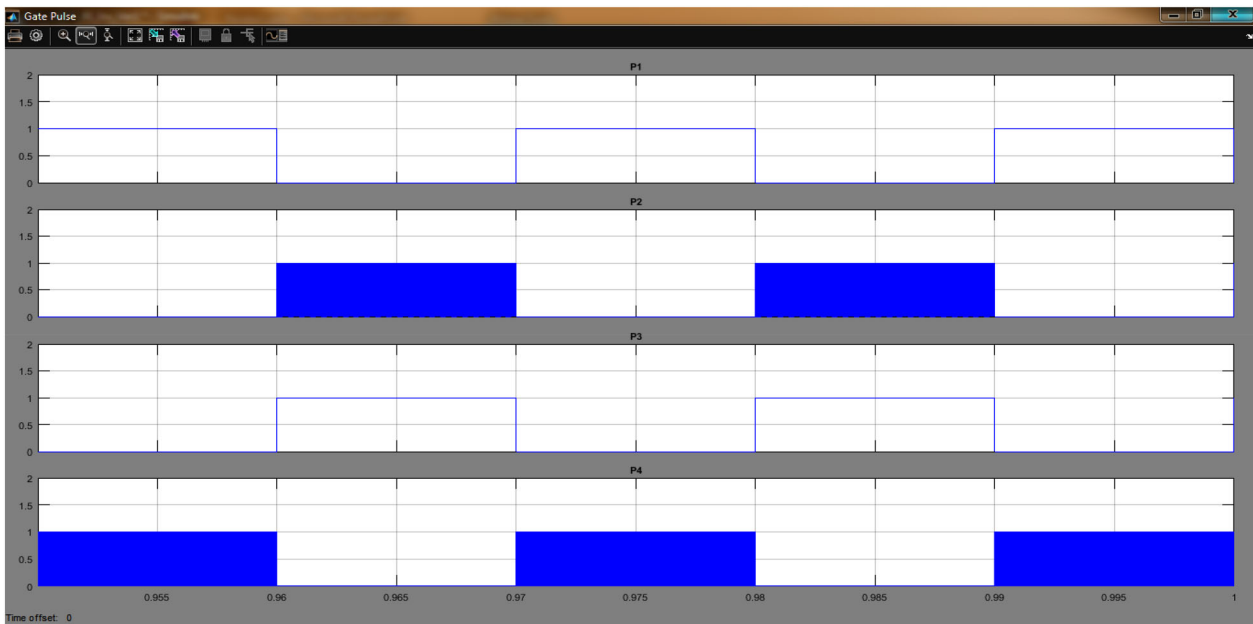
Fig. 8 GWO Fitness Curve

Fig. 9 Generated gate pulses for the inverter switches

4 GWO algorithm implementation

The various steps of GWO algorithm are represented by a flowchart shown in Fig. 5a, b. The main objective of using GWO algorithm is to obtain the best duty cycle for the single-phase v inverter. By obtaining the best duty cycle, it is possible to extract the maximum possible output power from the solar PV panels. The procedure of GWO algorithm is not discussed in this paper because of it is existing in many research articles.

5 GWO tuning of PV based buck–boost inverter

The complete simulation model of the proposed topology is shown in Fig. 6. A simple resistive load is connected at the output side of inverter. As explained in block diagram, the unregulated PV output is given to buck–boost inverter through filter capacitors. The gate pulses for MOSFET switches are generated based on the output of GWO based GMPPT algorithm. According to the output voltage and current from solar panels, the algorithm will change its duty cycle to ensure the sinusoidal output.
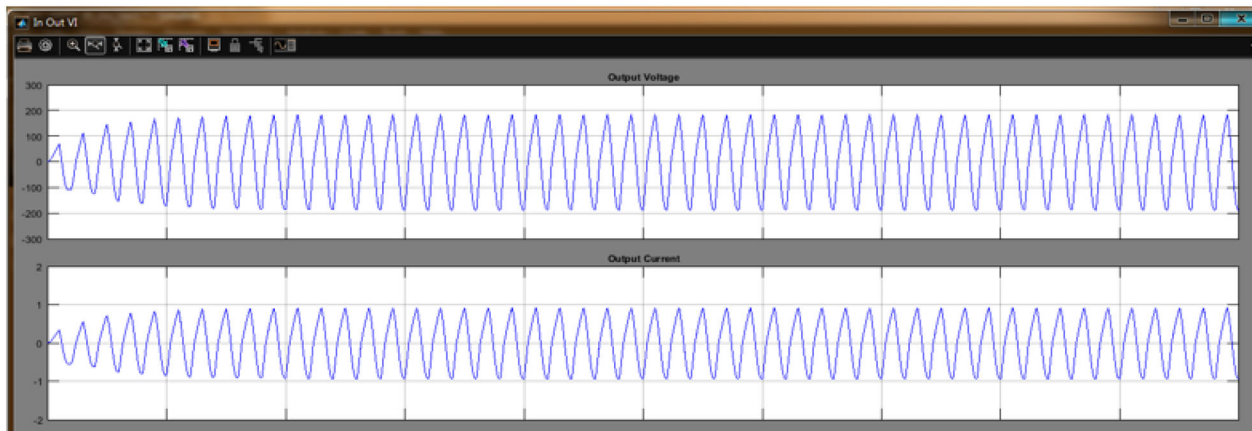
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Fig. 10 Output voltage and current waveforms of the proposed circuit
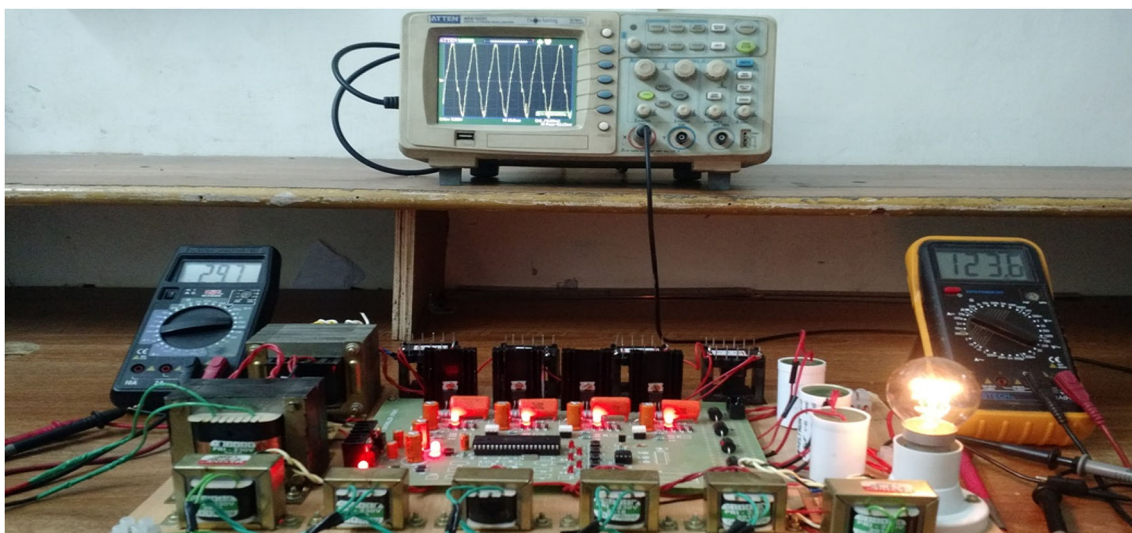

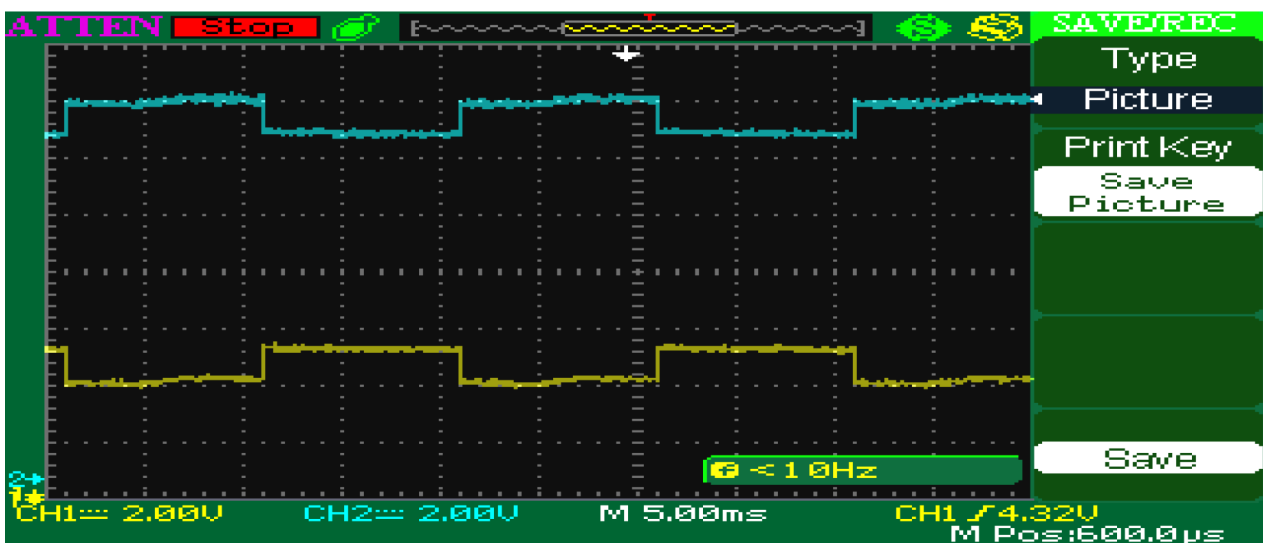**Fig. 11** Hardware set up of the proposed model
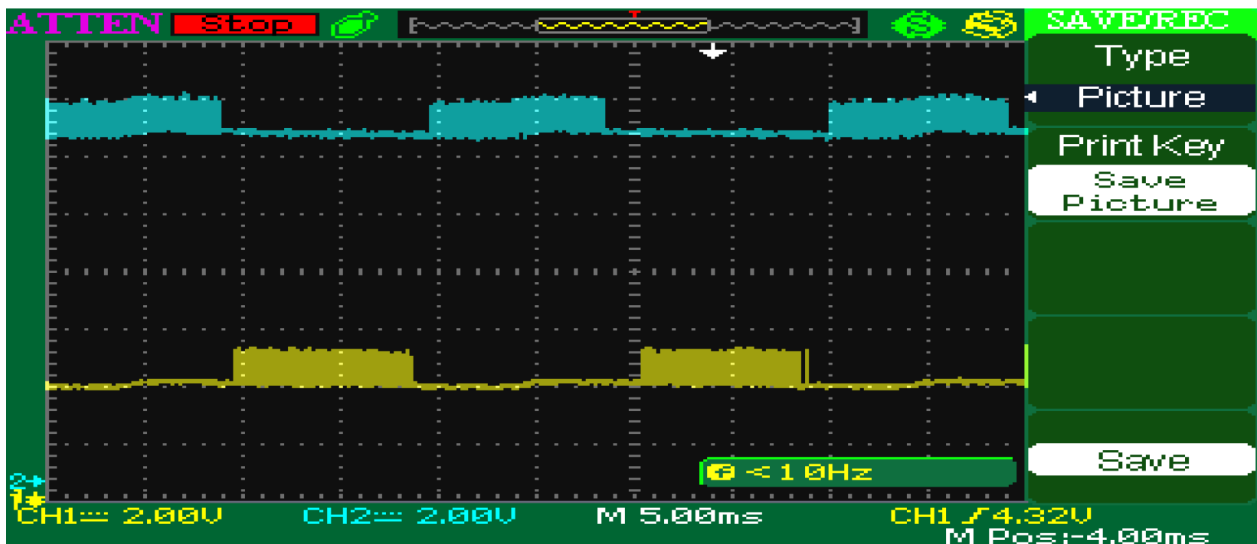

Fig. 12 Un-modulated Gate Pulses

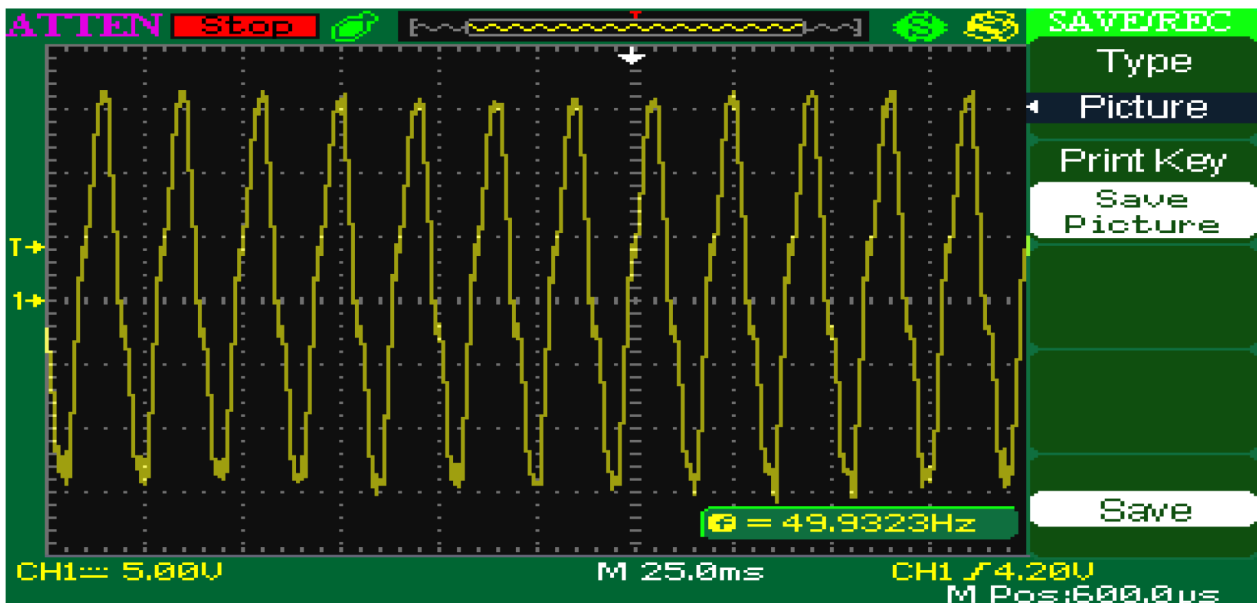**Fig. 13** Modulated Gate Pulses by GWO algorithm

Fig. 14 Inverter Output Voltage

The GWO convergence and the generated fitness waveforms are shown in Figs. 7 and 8 respectively. The Grey Wolf Optimization is performed by selecting 10 iterations and with 5 wolfs in all iteration.

GWO Optimized best duty = 0.95.
Maximum Power in GWO Optimization = 547.2 W.

The pulse waveforms generated using GWO algorithm is shown in Fig. 9. The proposed simulation circuit is designed to generate 120 V AC RMS output voltage. The generated output voltage and current waveforms are shown in Fig. 10.

6 Hardware implementation of the proposed model

The hardware prototype of the proposed model is shown in Fig. 11. The PV fed inverter for standalone load is developed using PIC16F877A microcontroller as the CPU (Central Processing Unit). The four-switch inverter is

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constructed using MOSFET Power switches IRFP460A. The PIC16F877A microcontroller is a popular microcontroller used in industries. It is an ideal microcontroller to implement the control logic of GWO based MPPT for PV fed 4 Switch inverter. The GWO MPPT algorithm is implemented using microcontroller PIC16F877A. It has all devices (memory, ADC, PWM unit) internally to develop a single chip embedded system to control the inverter. The PWM pulses to control MOSFET switches are produced by the internal PWM generator in PIC16F877A microcontroller.

The microcontroller reads the PV panel voltage through internal ADC. The microcontroller is programmed to produce 50 Hz pulses for PWM signals generation, so that the output frequency will be maintained as 50 Hz. The Turn-on time of MOSFET switches is determined by GWO algorithm in order to maintain MPPT. 50 Hz pulses are modulated by the PWM pulses externally using AND gate and these pulses are applied to MOSFET gate through optocoupler based driver circuits. The optocoupler provides electrical isolation between control and power circuit. Also, it amplifies the 5 V PWM pulses to 12 V PWM pulses because the MOSFET needs 10 to 20 V pulses for turn ON. The prototype is designed to generate 120 V RMS AC voltage with 50 Hz for the input of 30 V DC from solar panels.

The PSC is manually created so that the performance of PSC with GWO can be practically verified. At load side one 60 W incandescent lamp is connected. The generated un-modulated and modulated gate pulses are shown in Figs. 12 and 13 correspondingly. Figure 14 shows the inverter output voltage waveform. The frequency of sinusoidal waveform obtained at the output side of this inverter is 49.93 Hz.

7 Conclusion

The simulation of MPPT in PSC PV panel with Grey Wolf Optimization (GWO) technique is examined with fixed resistive load and grid connected via buck–boost inverter. Here four different patterns are implemented in PV panel to examine the performance of the proposed topology. From simulation and hardware output, it is clearly visible that GMPPT will be an effective technique to determine the extreme output power which can be extracted from solar panel. On the other hand, the hardware requirements also can be reduced by integrating the DC-DC boost converter and inverter into single buck–boost inverter which results

further reduction in hardware cost and complexity. The simulation outputs have been verified through a hardware prototype model. The inverter output voltage, pulses generated by using GWO technique is measured and displayed using DSO. A small 60 W lamp is connected at load side and the performance of the proposed methodology was verified. The proposed single-phase buck–boost inverter is especially designed to operate along with solar input under partial shading conditions. In future, it can be converted into three phase inverter for medium and high power applications. Also, the proposed inverter only concentrates to obtain maximum duty cycle which ensures the constant voltage output irrespective of input voltage and load demand. Further investigations can be made in this research such as power quality-based analysis, Selective Harmonic Elimination (SHE), performance analysis based on load demand etc., The performance of the proposed topology can be further enhanced with other multi-level inverter or hybrid MPPT algorithms for any other applications.

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