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Tuning proportional integral controller to enhance the photovoltaic system performance

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ABSTRACT

This paper presented a closed loop buck-boost converter controlled by using proportional and integral controller (PIC) for photovoltaic (PV) applications. The mathematical equations of design the solar panel type KC200GT and buck–boost converter is illustrated. The electrical behaviors of solar panel are examined at 1,000 light radiation and room temperature (25 °C) situation. A PIC tuning is difficult with conventional methods such as graphs and mathematical analysis, so for that reason two approaches are used for tuning and optimization of PIC, particle swarm optimization (PSO), and Zeigler–Nichols (ZN). The suggested closed loop application through the converter preserves the constant voltage in the output spite of alterations to the input voltage, decreases settling time, overshoot and ripple voltage to minimum value that enhancement the efficiency of the converter. The results show that the PSO approach is improved than the ZN approach. The proposed model is constructed by using SimPower system tool box in MATLAB package.

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1. INTRODUCTION

Currently, photovoltaic (PV) panels are a popular transducer for converting solar energy into electricity. Optimum operating point is influenced by environmental factors including sun radiation and cell temperature. The intensity of light depends on the weather condition, and the irregularity of the light intensity causes the output or load voltage (V_o) of the solar panels to shift. By using DC–DC switching converters with given DC input voltage, a stabilized output voltage can be acquired through using buck–boost construction that increases the efficiency of converter DC–DC compared with linear regulators. In case of variations in load and input power source, the load voltage is obtained as stable value when using a proportional integral derivative (PID) controller [1]. Sivamani *et al.* [2] introduced a self-excited induction generator controller for a buck-boost converter helped by a regulatory genetic algorithm that works with wind energy translation system. The design of a solar panel converter type buck–boost fed by an input voltage in the interval (10–50) V is presented by Dinniyah *et al.* [1]. PID controller in the design of the system with Proteus software for simulation is used. Blange *et al.* [3] applied a system based a buck-boost DC-DC converter fuzzy logic controllers (FLCs) to control the load voltage (V_o). MATLAB/Simulink program using SimPower system and fuzzy tool is a tool for system design and simulation. The simulation shows the controller technique (fuzzy logic) offers well performance than PID controller technique. Al–Dmour [4] designed on–line for converters that use buck, boost, and buck-boost of particle swarm optimization (PSO) controller. In order to support the PSO for controlling tasks, the performance of a PSO controller is compared to that of a PID controller. Shyma *et al.* [5] presented the design of the converters type buck–boost in solar energy battery system and analyzed the performance of the system by employing a hybrid-fuzzy controller. For proportional-integral (PI) and PID controllers, a hybrid approach based on fuzzy logic is described. Mühürcü *et al.* [6] proposed a buck converter concept that enhanced a discrete time PI controller. By enhancing the PSO algorithm's integral gain (K_i) and proportional gain (K_p), the control procedure efficiency is maintained at an acceptable level. Kose and Muhurcu [7] illustrated the behavior of the control process in a nonlinear system through applying particle swarm and genetic depending on optimization processes. Musyafa *et al.* [8] provided buck-boost converter system modeling and design using PI and PID control for horizontal wind turbine generation by using Ziegler–Nichols (ZN) method. The analysis, design, and modeling of a DC to DC buck-boost converter type for PV applications are the main topics of this work. PSO and ZN methods are used to tune the proportional and integral controller (PIC) for improving the system response. The electrical characteristics and the behavior of solar panel are examined at (standard test conditions) STC conditions. The expressions are derived for buck–boost converter and solar power system. The suggested system is modelled using MATLAB and Simulink.

2. SYSTEM DESIGN

A buck-boost converter is seen in Figure 1 connected to a PIC. An error signal is generated when the load voltage (V_o) and the reference voltage (Vref) are coupled (e). By using PIC as a helper tool the error signal is produced to identify the duty cycle of the switching signal. The saw tooth signal is used as a benchmark for comparing the switching signal generated by the PIC to create the necessary signal for pulse width modulation (PWM), which is applied to a transistor (M) metal oxide semiconductor field effect transistor (MOSFET) to control the system's load voltage (V_o). The converter type buck–boost is investigated as switching time (ON/OFF) that is termed as duty cycle ratio (D).

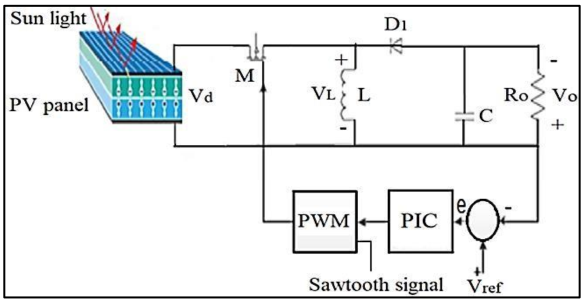


Figure 1. PI controller with buck–boost converter

3. PHOTOVOLTAIC CELL/ARRAY PRINCIPLE

A PV cell is the PV module's primary component. Depending on the cells that make up the module, there are various types of PV modules. In this research, silicon single-diode PV cells are useful to simulate. According to Figure 2 [9], a photocurrent source, series resistance, a nonlinear diode, and shunt resistance make up the PV model.

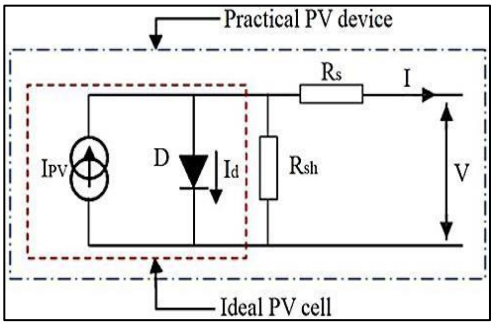


Figure 2. PV cell design

Efficiency (η), maximum power point (Pmax), short circuit current (Isc), open circuit voltage (Voc) are the four primary parameters that define each of a PV panel. Mathematics equation for the voltage and current are characterized as in (1) [9]:

$$I = I_{Ph} - I_s \left[e^{\left\{\frac{q\,(v+IR_S)}{AKT}\right\}} - 1 \right] - \left[\frac{V+IR_S}{R_{sh}} \right] \tag{1}$$

where I_{ph} stands for the photocurrent, is (1.602*10-19 C) for the diode saturation current, and q for the electron charge. A stand for the PN junction factor, K for the Boltzmann's constant (1.381*10-23), and T for the cell temperature (in Kelvin). The photocurrent (I_{ph}) can be defined as in (2):

$$I_{ph} = [G/G_{ref}][I_{Ph.ref} - C_T(T_{ref} - T)] \tag{2}$$

where G represents the real solar radiation (W/m^2); G_{ref}, T_{ref}, I_{ph}, and ref stand for solar radiation, cell's absolute temperature, and photocurrent in STC, respectively. and the term C_T presents temperature coefficient.
Cell temperature affects the diode saturation current as in (3):

$$I_s = I_{s.ref} \times \left(\frac{T}{T_{ref}}\right)^3 \times exp\left[\frac{q\times E_g}{A\times K} \times \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{3}$$

where $I_{s,\,ref}$ is the diode saturation current (A), and E_g is the band gap of a semiconductor cell (eV).

Cells are connected in parallel and series to make up the PV panel. As shown in Figure 3 [9], the analogous circuit of a PV array can be explained.

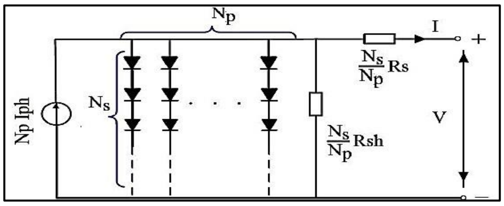


Figure 3. PV model

The characteristic equation of current, based on a PV module's circuit, is displayed [9]:

$$I = N_p I_{ph} - N_p \times I_s \times \left[exp\left(\frac{q}{A*K*T} \left(\frac{V}{N_s} + \frac{1\times R_s}{N_p} \right) \right) - 1 \right] - \frac{N_p}{R_{sh}} \left(\frac{V}{N_s} + \frac{1\times R_s}{N_p} \right) \tag{4}$$

where I_s N and N_p, respectively, stand for series and parallel cell numbers.

As is clear from Figure 4, MATLAB/Simulink software is utilized to realize and carry out the mathematical in (4). Table 1 [10] is a list of all Simulink's necessary parameters.

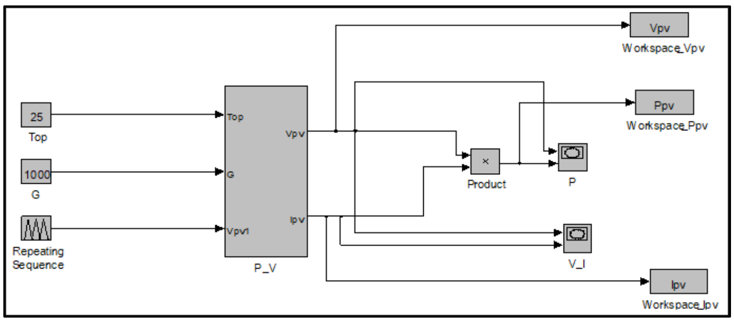


Figure 4. PV cell Simulink model in MATLAB

Table 1. Solar module characteristics for KC200GT at 1,000 W/m^2 at ambient temperature

Parameter	Value	Parameter	Value
Gref	1 KW/m^3	Tref	298 K
N_s, N_p	24	Isc	8.210 A
V_{oc}	32.9 V	I_m, V_m	7.610 A, 26.30 V
K_i	0.00090 A/K	K_v	-0.1230 V/K
E_g	1.2370 eV	R_s	0.2210 Ω
R_{sh}	415.30 Ω	A	1.350

4. MODELING OF BUCK-BOOST CONVERTER IN STATE SPACE AVERAGING

Figure 5 shows the converter (buck-boost) circuit. The (buck-boost) converter's output related to an input has been formed as fixed frequency PWM cycle. In case of a duty cycle (D) is less than a half, the load voltage (V_o) is less than the input voltage, V_d. But, if D is greater than a half, the load voltage (V_o) is greater than V_d [11]. In conclusion, modeling a buck-boost converter in state-space averaging involves choosing the state variables, writing the equations, averaging them over a switching cycle, linearizing the equations, and obtaining the transfer function. This technique simplifies the analysis of the converter and is commonly utilized for creating DC-DC converters.

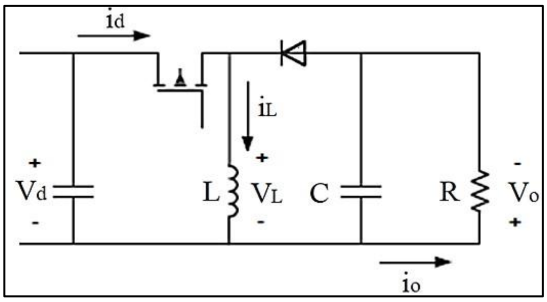


Figure 5. Circuit for a buck-boost converter

A PWM is a technique used to regulate the signal width. The signal width is characterized for single period. The amplitude and frequency of a PWM signal are constant, but it varies in width of pulse (τ). In a PWM method, a switching time as pulses (ON and OFF) has been established. The duty cycle function is performed by ON pulses. The voltage output, Vo, is known when determining the duty cycle [1]. Figure 6 shows the principle operation of buck-boost converter circuit.

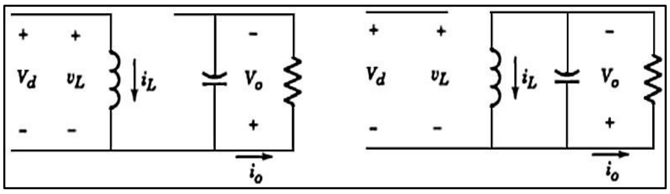


Figure 6. OFF and ON state of the buck-boost converter [12]

When M turns on, the diode becomes reverse biased since the inductor (L) is connected to the source voltage (V_d) (not conducting). As a result, Sreedevi and David [11] is reported as the inductor voltage in the ON condition.

$$V_L = V_d = L\frac{di_l}{d_t} \tag{5}$$

where V_L is the inductance voltage, V_d is the input voltage, i_L is the inductance current. From in (5), the inductance current is [11]:

$$\Delta i_{L(close)} = \frac{V_d}{L} DT \tag{6}$$

When M goes OFF, the diode becomes forward biased, conducts the signal, and creates a route for current to flow through the inductor. Therefore, the inductor voltage (V_L) during OFF case is same to the output voltage (V_o) and is given as [11].

$$V_L = V_o = L \frac{d_{iL}}{d_t} \tag{7}$$

From in (7), inductance current variation is:

$$\Delta i_{L(open)} = \frac{-V_o}{L}(1 - D)T \tag{8}$$

At steady state, the output voltage (average value) is determined as (9)-(11) [11]:

$$\Delta_{(open)} + \Delta i_{L(close)} = 0 \tag{9}$$

$$\frac{V_d}{L} DT + \frac{V_o}{L}(1 - D)T = 0 \tag{10}$$

$$V_o = -V_d \frac{D}{1-D} \tag{11}$$

The timing diagram is displayed in Figure 7 [13]:

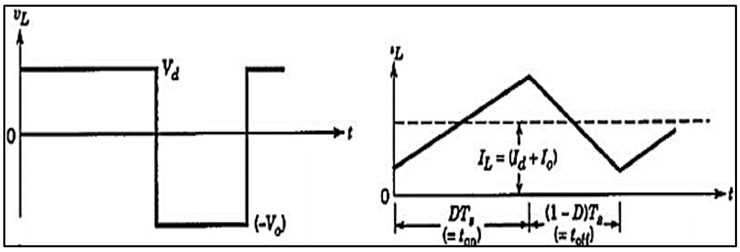


Figure 7. Timing diagram of V_L and L

The minimum values of inductor (L) at *D=0.5* and capacitor (C) are [3]:

$$L = \frac{R(1-D)^2}{2f_s} \tag{12}$$

where, f_s is switching frequency.

$$C = \frac{DT_S V_O}{\Delta V_O R} \tag{13}$$

To enhance the buck-boost converter's dynamic model and the state–space case is used. Where, D'=1−D [11]

$$X = AX + BU \tag{14}$$

$$Y = CX \tag{15}$$

So that:

$$X = \begin{pmatrix} i_L \\ V_c \end{pmatrix}, U = V_L, Y = V_o, A = \begin{bmatrix} 0 & \frac{D'}{L} \\ \frac{-D'}{C} & \frac{-1}{RC} \end{bmatrix}, B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{16}$$

The transfer function, G(S) of the converter in continuous system is (17) [11]:

$$G(s) = \frac{-\dot{D}R}{LRCS^2 + L_s + D^2R} \quad (17)$$

5. PROPORTIONAL INTEGRAL CONTROLLER

The methods for tuning controller settings are widely employed across a wide range of industries. The PID controller voltage's settings are adjusted in three steps. The PID controller consists of three terms K_p, K_i, and K_d. The proportional gain (K_p) can be regulated in between zero and value able to make the output or load voltage (V_o) close to value up to 80% of the specific V_o. The integral gain (K_i) can be regulated to some values without reason of oscillation in the V_o. After then, the differential gain (K_d) is adjusted between zero and a speeding-up value [13]. Another type of control can be used without D mode when the system fast response is not necessary with a large transfer system delay. Similarly, wide upsets and noises existing through operation of the system. PICs are widely used in industries, specifically when response speed is not important. PIC can remove force oscillation and steady state error [14]. Figure 8 presents the block diagram of PIC which generates an output signal that has two intervals, the first interval relates to the actuation signal, while the second interval relates to its integral. The output signal of controller in this case becomes (18) [15]:

$$u(t) = K_p\, e(t) + K_i \int e(t)\, dt \quad (18)$$

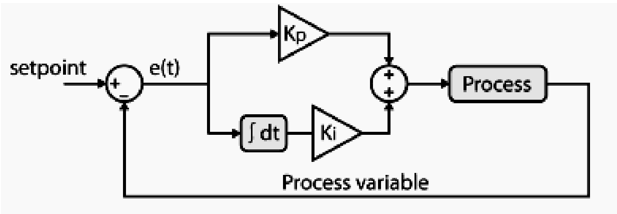


Figure 8. Block diagram of PIC [16]

6. TUNING METHOD

6.1. Particle swarm optimization

The PSO algorithm starts with a collection of random particles with random velocities and random distributions. The particles move as a swarm through the search space, updating their positions during the generations in search of the optimal solution. Each particle adjusts its velocity and moves within the consideration area in the direction of the desired setting (fitness) [17]. For evaluating particle performance, the fitness function is utilized to identify the ideal arrangement. To reduce the errors threshold, all feasible sets of controller parameter values are adjusted. The PI controller needs to be calibrated properly to ensure that the PV system performs effectively and consistently. The most popular index parameters are [18]:

$$Integral\ of\ the\ Absolute\ Error\ (IAE) = \int_0^\infty |e(t)|\, dt \quad (19)$$

$$Integral\ of\ the\ Square\ Error\ (ISE) = \int_0^\infty e^2(t)\, dt \quad (20)$$

$$Integral\ of\ the\ Time\text{–}Weighted\ Absolute\ Error\ (ITAE) = \int_0^\infty t\, |e(t)|\, dt \quad (21)$$

$$Mean\ Square\ Error\ (MSE) = \int_0^\infty t\, e^2(t)\, dt \quad (22)$$

where (t) denotes the response's inaccuracy with respect to the desired set point.

6.2. Ziegler–Nichols methods

ZN is one of a tuning method of PID controller. It provides guidelines for calculating gains for proportional (K_p), integral (K_i), and derivative (K_d) functions based on the characteristics of the plant's transient response [16]. The tuning process involves selecting the optimal (K_p) and (K_i) values based on the system's characteristics and the grid's operating conditions. The (K_p) value determines the system's response speed, while the (K_i) value controls the steady-state error as illuminate in Table 2. If the plant does not have integrators and mostly complex conjugate poles, the ZN method's unit step response curve may appear S-shaped, as shown in Figure 9 [18].

Table 2. The first method of ZN [19]

PID type	K_P	$T_i=K_P/K_i$	$T_d=K_d/K_P$
P	T/L	∞	0
PI	0.90 T/L	L/0.30	0
PID	1.20 T/L	2L	0.5L

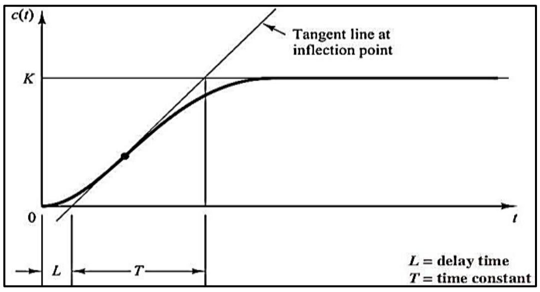


Figure 9. Response curve for ZN (S–shaped curve) [18]

It should be noted that the response curve in Figure 10 represents a typical over damped second order system [12], [19]. This curve (S–shaped) described by two constant of time factors; the time constant (T) and time delay (L), that is displaying a line tangent to the S-shaped curve at the sag point to specify as shown in Figure 9. On the other side the genetic algorithms, Fuzzy logic and other techniques are explained in many papers [20], [21]. Overall, tuning a PI controller to optimize the current output of a PV system requires careful consideration of the system's characteristics and operating conditions [22], [23]. By the PI controller can successfully control the current output by altering the proportional and integral gains, even as the source frequency changes, to ensure that the PV system operates efficiently and reliably [24], [25].

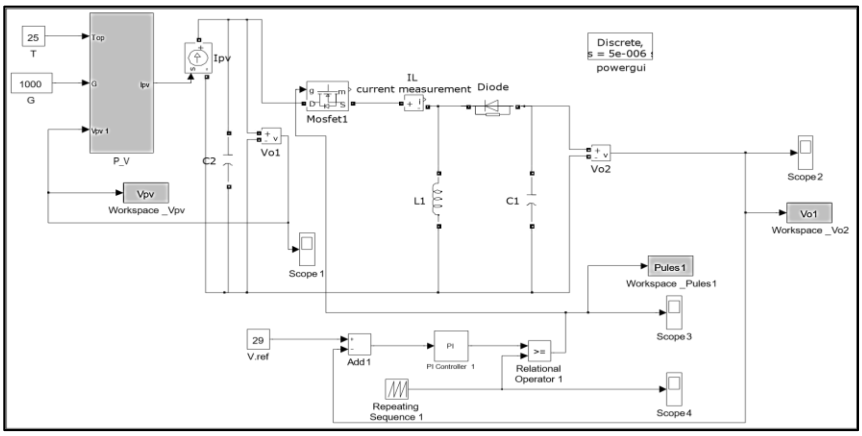


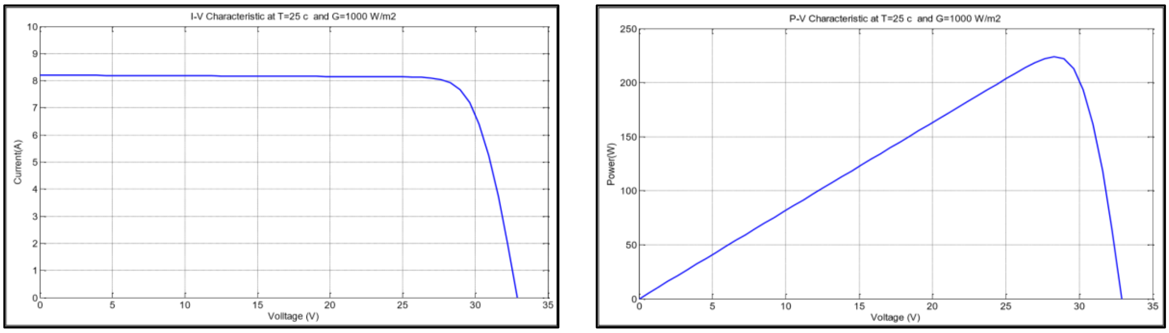
Figure 10. MATLAB/Simulink of control system

7. SIMULINK OF CONTROL SYSTEM

The PV panel, denoted by P-V in Figure 10, the system's core Simulink components are the DC-DC buck-boost converter and PIC. The static MOSFET transistor switch, inductor (L1), diode (D), and capacitor are all components of the DC-DC converter model (C1). The K_p and K_i values are changed during tuning, and the system's reaction to various setpoint changes is monitored. Finding the ideal settings that reduce the system's overshoot, settling time, and steady-state inaccuracy is the goal.

8. RESULTS AND DISCUSSION

Using MATLAB/Simulink, the system may be tested. Figure 11 depicts the results of a simulation of the electric properties of a PV module under temperature conditions and 1000 W/m^2 of radiation. The simulation's component values are $Rs = 0.221$ and $Rsh = 415.3$. The results are =8.2, Pm=220 W. When tuning a PI controller to improve a (PV) system's performance, it is important to consider the effect of the source frequency on the current output as shown in Figure 11(a). Typically, as the source frequency increases, the current output of the PV system will increase up to a certain point, and after which it will start to decrease as shown in Figure 11(b). The PV voltage is shown in Figure 12. The PV voltage equals 30 V and it is remaining stable after 0.2 sec.



(a) (b)

Figure 11. Electrical behaviors of PV module; (a) I-V and (b) P-V

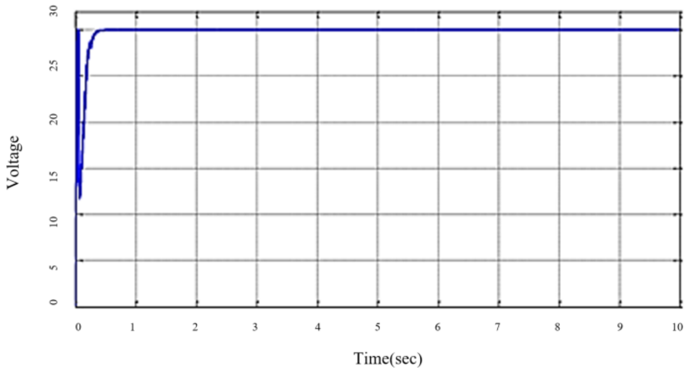


Figure 12. Vpv for PV panel

When a PI controller-controlled DC-DC boost converter is used to connect a PV panel, the distortion between 0 and 0.2 seconds can be decreased. Examination of the boost converter is carried out using switching at 1 KHz functioning mode that is continuous. The buck-boost converter's operation is controlled by a switching pulse produced by the PI controller. The values of the parameter in converter design are listed in Table 3 overall, tuning a PI controller is crucial for optimizing the performance of a PV system when the grid is joined. It can support ensuring the PV system runs effectively and reliably, while also helping to stabilize the grid and improve its overall performance.

Table 3. Parameters and its design values of converter

Parameters	Design values
Vd	14 V
Vo	21 V
L	11.0 µH
C	10.0 µF
R	14.0 Ω
fs	400 KHz

The PSO method is used to tune the PIC that is a scheme for nonlinear control. It is employed to regulate the output voltage (V_o) by controlling the duty cycle of the system. By controlling the PWM, the setting of Vo is carried out by altering the switch's duty cycle, and then the operating frequency is preserved constant. Duty cycle assigned the period ratio in which the semiconductor power is saved ON to the cycle period. The duty cycle calculated from Figure 13 is equal to 0.21.

Table 4 is a list of the PSO algorithm's input parameters. The parameters Kp and Ki are finded and equal to 0.0134 and 5.439, respectively. Figure 14 shows the output response of the system by using PSO–PI controller. By using ZN method, the step function is applied to the system when the parameters L=0.045=0.075 are found. These values are used to find K_p=1.5 and K_i=10. Figure 15 displays the system's output response. Table 5 shows the boost converter's dynamic performance analysis with several types of controllers. It is obvious that the PSO-PI algorithm has an advantage over the ZN-PI approach in that it reduces the settling time, rising time, and oscillation.

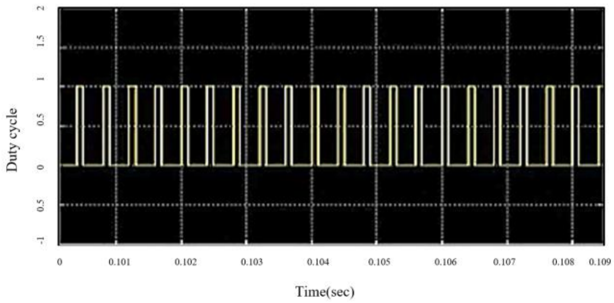


Figure 13. PWM signal

Table 4. PSO variables

Parameters	Values
Populace size	49
Count of iterations	50
Weight of inertia (W)	0.9
Ratio of cognitive ability (C_1)	0.9
Social coefficient (C_2)	0.12

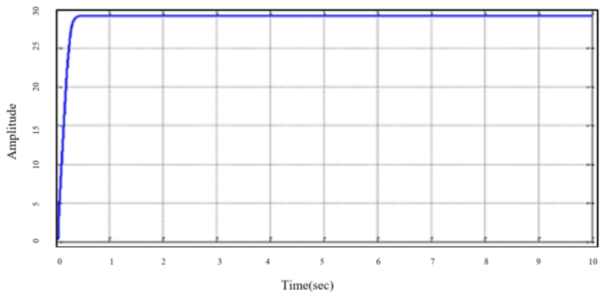


Figure 14. Output response of system using PSO–PI controller

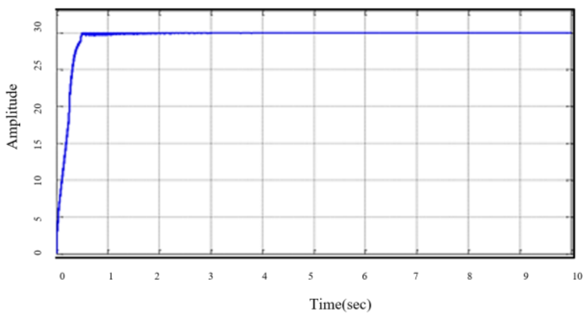


Figure 15. Output response of system using ZN method

Table 5. Dynamic performance analysis

Specification	PSO - PI	ZN - PI
Rising time(s)	0.083	0.107
Settling time(s)	0.415	0.5
Overshoot	0	0
Kp	0.0134	1.5
Ki	5.439	10
ISE	0.04482	0.006302
IATE	0.008652	0.009944
IAE	0.09192	0.05003
Oscillation	0	0.5

9. CONCLUSION

PV modules and closed-loop buck-boost converters controlled by PIC are carried in full MATLAB/Simulink form. With the KC200GT solar module, P-V and I-V curves which represent electrical properties are obtained. The extreme power, Pm, of a PV voltage, Vo, equals 30 V, and the module is equivalent to 220 W. The output voltage oscillation of a DC-DC converter is reduced by using a PIC as feedback. PIC is often tuned using ZN and PSO techniques. In terms of responsiveness, PSO outperforms ZN approach because overshoot, settling time, and rising time issues are lessened. The steady state error and minimum values of indices parameters under various variations of the operating conditions, when PSO is using, gives good regulation in the output voltage, so the system is reliable, stable, and simple to operate. To enhance the system response, one of the sophisticated control strategies that may be used with buck-boost DC-DC converters is the PSO controller.

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