Nonlinear robust integral backstepping based MPPT control for stand-alone photovoltaic system

Kamran Ali1, Qudrat Khan2, Shafaat Ullah1, Ilyas Khan3*, Laiq Khan1

1 Department of Electrical and Computer Engineering, COMSATS University Islamabad, Abbottabad Campus, Abbottabad, KP, Pakistan, 2 Center for Advance Studies in Telecommunication (CAST), COMSATS University Islamabad, Islamabad, Pakistan, 3 Faculty of Mathematics and Statistics, Ton Duc Thang University, Ho Chi Minh City, Vietnam

* ilyaskhan@tdtu.edu.vn

Abstract

PV (Photovoltaic) cells have nonlinear current-voltage \( (I-V) \) and power-voltage \( (P-V) \) characteristics with a distinct maximum power point (MPP) that entirely depends on the ambient meteorological conditions (i.e. solar irradiance and temperature). Hence, to continuously extract and deliver the maximum possible power from the PV system, under given meteorological conditions, the maximum power point tracking (MPPT) control strategy needs to be formulated that continuously operates the PV system at its MPP. To achieve this goal, a hybrid nonlinear, very fast and efficient MPPT control strategy, based on the robust integral backstepping (RIB) control, is formulated in this research article. The simulation testbed comprises a standalone PV array, a non-inverting buck-boost (NIBB) DC-DC power converter, a purely resistive and a dynamic load (sound system). The proposed MPPT control scheme consists of two loops, where the first loop generates the real-time offline reference peak power voltage through an adaptive neuro-fuzzy inference system (ANFIS) network, which is then utilized in the second loop as a set-point value for generating a control signal and then forcing the PV system to be operated at this set-point by continuously adjusting the duty ratio of the power converter. This control strategy exhibits no overshoot, fast convergence, good transient response, fast rising and settling times and minimum output tracking error. The MATLAB/Simulink platform is used to test the performance of the proposed MPPT strategy against varying meteorological conditions, plant current and voltage faults and plant parametric uncertainties. To validate the superiority of the proposed control strategy, a comparative analysis of the proposed control strategy is presented with the nonlinear backstepping (B), integral backstepping controller (IB) and conventional PID and P&O based MPPT controllers.

1 Introduction

Recently, worldwide energy demand has increased exponentially. More than 70% of the globally generated electricity is supplied by the fossil fuels (namely natural gas, coal and petroleum) [1]. Unfortunately, the available supply of these resources is shrinking abruptly, resulting in a
challenging future for the energy production. Furthermore, the fossil fuels based power generation gives rise to greenhouse effect and global warming. In order to decrease the dependence on the fossil fuels for energy production in the world, it is essential to exploit renewable energy sources, including solar energy, wind energy, tidal energy, geothermal energy etc. Among these aforementioned energy resources, photovoltaic (PV) based energy production is a good choice owing to the fact that it is universally available, environment friendly, free of charge and has less operational and maintenance costs [2]. The need for PV based energy generation has increased both for grid-connected and standalone systems. However, solar panels have a nonlinear electrical characteristics \((I - V)\) and \((P - V)\), with a unique maximum power point (MPP), under uniform solar irradiance and temperature [3]. But, under the partial shading condition (PSC), the PV modules belonging to the same string experience different or nonuniform solar irradiance. Consequently, the solar array \(P - V\) curve deviates from its standard form and exhibits multiple local MPPs (LMPPs) [4, 5]. This condition may be caused by the movement of clouds or some obstacle (e.g. nearby trees or buildings, long-lasting dust etc.) causing a shade or shadow over the solar array. The PSC hinders an efficient MPPT operation. When a local instead of the global MPP (GMPP) is tracked, the result is the energy loss that can be significant (up to 70%), leading to the degradation of the overall system performance and efficiency. So, to uninterruptedly extract and deliver the maximum possible power from the PV system, it needs to be operated at its MPP, despite variations in the meteorological conditions.

The key objective of this research article is to carry out the optimum operation of the PV system based on the maximum power point tracking (MPPT) control strategy under uniform solar irradiance and temperature within a specific time interval. In the literature [6], numerous techniques on MPPT have been developed such as offline or indirect, online or direct and hybrid techniques.

Offline MPPT strategies, such as short circuit current (SCC) strategy [7, 8], open circuit voltage (OCV) strategy [9, 10], basically require some PV values to produce the control signal essential for operating the PV system at its MPP. Since, these techniques are simple and inexpensive, therefore, they have been frequently employed in the PV systems. However, the disadvantage of these MPPT control strategies is that they generally fail under varying meteorological conditions and are incapable of operating under PSC. Because, they are restricted to local search for the MPP, and can identify only a single MPP, but not the GMPP with the highest power output [11, 12].

Several MPPT regarding articles have been reported to have focused on the online techniques, such as extremely seeking control (ESC) method [13–15], perturb and observe (P&O) strategy [16–18] and incremental conductance (IC) method [19, 20]. These control schemes usually use PV current and voltage in real-time to achieve the MPP. The major drawback of these methods is oscillations around the MPP [21].

Hybrid MPPT control strategies [22–24] are basically the combination of both online and offline control strategies. For tracking the MPP, these techniques use two loops. In the first loop, an offline strategy is employed to estimate the real-time reference peak power voltage \((V_{MPP})\) for the PV system. In the second loop, the estimated reference peak power voltage is used as a set-point for generating the control signal, \(u\), and then forcing the PV system to be operated at this set-point by continuously adjusting the duty ratio, \(d\), of the power electronic interface (power converter).

Typically, for a PV system, MPPT control strategy is a highly nonlinear control problem. Several MPPT based nonlinear control strategies have been reported in the literature for both grid-connected and stand-alone PV systems [25, 26]. In [27, 28], two loops hybrid nonlinear backstepping and integral backstepping MPPT controllers, respectively, have been proposed.
for a PV system with a purely resistive load. In the first loop, regression plane has been used to estimate the real-time offline MPP for the PV system. While in the second loop, nonlinear backstepping and integral backstepping based MPPT controllers have been formulated to force the PV system to be operated at their estimated MPPs. Both the control strategies have been found very faithful in achieving the MPPT either under varying temperature alone, or varying irradiance alone. Their performances have been found to be superior to the traditional P&O based MPPT technique. However, a substantial steady-state error and overshoot have been observed in the backstepping (B) and integral backstepping (IB) techniques, respectively. Also, the robustness of these techniques have not been tested for certain plant parametric uncertainties, plant voltage and current faults and dynamic load. Moreover, these techniques need to be further evaluated under simultaneous variation of temperature and solar irradiance.

The backstepping is a nonlinear recursive control design technique. The principal idea behind its application is the stabilization of the virtual control state [29, 30]. It is based on designing an MPPT controller recursively by choosing some of the system state variables as the virtual controllers, and then designing intermediate control laws for each of the selected virtual controller. This approach is well-suitable for boundary control problems. While the control is acting only from the boundary, its main feature is the capability of canceling out all the destabilizing effects (i.e. forces or terms) appearing throughout the domain. Its attractive features include: fast dynamic response, robustness to system parametric uncertainties, good performance against unmodeled system dynamics and external disturbance rejection [31, 32].

To mitigate the stated problems of the recently proposed backstepping and integral backstepping techniques [27, 28], a hybrid nonlinear robust integral backstepping (RIB) based MPPT control strategy is formulated in this research work. The proposed technique is tested on a PV system comprising a standalone PV array, a non-inverting buck-boost (NIBB) DC-DC power converter, a resistive load (comprising DC lighting) and a dynamic load (comprising sound system used in military parade grounds, large religious gatherings and holy worship places). The proposed control strategy contains two loops. The first loop estimates the real-time offline MPP, \( V_{MPP} \), through an adaptive neuro-fuzzy inference system (ANFIS). The second loop uses the estimated value of the MPP as a set-point for the robust integral backstepping strategy to generate the control signal, \( u \), and then forcing the PV system to be operated at this set-point by continuously adjusting the duty ratio, \( d \), of the NIBB DC-DC power electronic converter.

1.1 Significant contributions

The major contributions made by this research article are as follows:

1. A nonlinear hybrid RIB based MPPT scheme is formulated for a standalone PV system connected to a dynamic load, using ANFIS for real-time offline estimation of the MPP during the PV system operation.

2. The stability of the formulated MPPT scheme is guaranteed through the Lyapunov stability theory and MPPT is ensured under varying meteorological conditions subject to certain plant voltage and current faults and plant parametric uncertainties.

3. The proposed control scheme has been figured out in such a way that it should be simple to understand and easy to implement.
4. Through RIB controller, the MPPT is guaranteed with a superior performance to the benchmarks backstepping (B), integral backstepping (IB) and conventional PID and P&O based MPPT techniques.

The present research article is organized in the following manner: The reference peak power voltage estimation is covered in Section 2. The mathematical modeling of the overall PV system comprising the PV array, DC-DC converter and load is discussed in Section 3. Section 4 is about the proposed RIB based MPPT control strategy design. Performance validation and superiority of the proposed control scheme is validated through Matlab simulations in Section 5. Finally, Section 6 presents concluding remarks and future research recommendations.

2 Reference peak power voltage estimation through Adaptive Neuro-Fuzzy Inference System (ANFIS)

In this work, ANFIS based on Takagi–Sugeno–Kang (TSK) is used for generating the reference peak power voltage, $V_{MPP}$ or $v_{r_{pv}}$, of the PV array. The ANFIS network has temperature, $T(˚C)$, and irradiance, $G(W/m^2)$, as two input variables and $V_{MPP}$ as an output variable. The input layer is the fuzzification layer, having three Gaussian membership functions (GMFs) for each input variable. The output layer consists of a linear equation for each rule. The 3D–surface, illustrated in Fig 1, represents the estimated $V_{MPP}$ of the PV array through the ANFIS, under varying irradiance and temperature.

For ANFIS based $V_{MPP}$ estimation, the $V_{MPP}$ related input–output data is recorded by entering the user-defined PV array specifications, expressed in Table 1, in Matlab/Simulink. During this procedure, the temperature is perturbed from 20˚C to 85˚C in uniform steps of 1˚C. On the other hand, the solar irradiance is perturbed from 600 W/m$^2$ to 1,000 W/m$^2$, in uniform steps of 1 W/m$^2$. As a result, about 26,500 input–output data points are recorded. This data set is then used to obtain an ANFIS based trained model.

The flowchart for working of ANFIS based $V_{MPP}$ estimation is illustrated in Fig 2. The trained ANFIS based model is then exported to Simulink for estimating the real-time offline $V_{MPP}$ of the PV array during simulation, for any combination of input temperature and irradiance levels, which is then tracked by the MPPT controller.
Overall PV system mathematical modeling

The block diagram of the overall proposed control system used in this study is depicted in Fig 3 that comprises a standalone PV array, a NIBB DC-DC power converter, a resistive load (comprising DC lighting), a dynamic load (comprising sound system used in military parade grounds, large religious gatherings and holy worship places) and an RIB based MPPT controller.

3.1 Standalone PV array mathematical modeling

The PV cell contains a PN–junction just like an ordinary diode that generates electricity (DC) using photons. In order to get a better physical insight into a PV cell operation and its characteristics, equivalent circuit models are used. Depending on their complexity and accuracy, a PV cell can be represented by several different equivalent circuit models, such as: single-diode model (SDM), two-diode model (TwDM) and three-diode model (ThDM) [33]. The SDM is the simplest equivalent circuit model of a PV cell having reasonable accuracy, as illustrated in Fig 4. A practical model of PV cell, based on SDM, consists of a series resistance, \( R_s \), a shunt resistance, \( R_p \), a light-dependent current source, \( I_{ph} \), and an anti-parallel diode, \( D \). Generally, \( R_s \ll R_p \), where \( R_s \) exists due to the metallic leads resistances, while \( R_p \) due to the leakage current of the PN–junction. Furthermore, \( I_p, I_o, i_c \) and \( v_c \) are the diode current, current through the shunt-resistance, cell output current and cell output voltage, respectively.

| Type         | Name of Parameters                      | Symbols | Magnitude          |
|--------------|-----------------------------------------|---------|--------------------|
| PV Array     | Maximum power per PV module            | \( P_{max} \) | 1555 W            |
|              | Number of Cells per module              | \( N_s \) | 72                 |
|              | Number of module per PV array           | –       | 16                 |
|              | Module voltage at maximum power         | \( V_{MPP} \) | 102.6 V          |
|              | Module open circuit voltage             | \( V_{oc} \) | 165.8 V          |
|              | Module short circuit current            | \( I_{sc} \) | 17.56 A           |
|              | Module current at maximum power         | \( I_{MPP} \) | 151.16 A          |
| Converter    | Input Capacitor                         | \( C_1 \) | \( 1 \times 10^{-3} \) F |
|              | Inductor                                | \( L \) | \( 20 \times 10^{-3} \) H |
|              | Output capacitor                        | \( C_2 \) | \( 48 \times 10^{-6} \) F |
|              | Load resistance                         | \( R_L \) | 50 \( \Omega \) |
|              | IGBT switching frequency                | \( f_s \) | 5000 Hz           |
| Sound System | Back emf constant                       | \( K_b \) | \( 15 \) V/(m/s) |
|              | Speaker resistance                      | \( R_s \) | 10 \( \Omega \)  |
|              | Speaker inductance                      | \( L_s \) | \( 10^{-3} \) H  |
|              | Proportional constant                   | \( K_f \) | 15 \( \) N/A |
|              | Spring constant                         | \( k \) | \( 5 \times 10^5 \) N/m |
|              | Spring and diaphragm mass               | \( m \) | 0.001 kg          |
| Controller   | Constant                                | \( k_1 \) | 60                |
|              | Constant                                | \( k_2 \) | 9000              |
|              | Constant                                | \( k_3 \) | 2000              |
|              | Constant                                | \( k_4 \) | 10                |
|              | Constant                                | \( \lambda \) | 29              |

https://doi.org/10.1371/journal.pone.0231749.t001
Fig 2. Computational flowchart for ANFIS based V\textsubscript{MPP} learning.

https://doi.org/10.1371/journal.pone.0231749.g002
Mathematically, the PV cell output current, $i_c$, can be obtained by applying Kirchhoff’s current law at the junction in Fig 4, as follows:

$$i_c = I_{ph} - I_o e^{\frac{q}{k} \left( \frac{V_c + i_c R_c}{R_p} \right)} - 1 - \frac{V_c + i_c R_p}{R_p}$$

(1)

In Eq (1), $I_D$ denotes the Shockley diode equation, $I_o$ represents the diode leakage (or reverse saturation) current, $q$ equals the electron charge ($1.6 \times 10^{-19} C$), $k$ is the Boltzmann
constant \((1.38 \times 10^{-23} \text{ J/K})\), \(T\) represents the PN–junction temperature \((\text{K})\) and \(A\) denotes the diode ideality factor (or constant), where usually: \(1 \leq A \leq 1.50\).

For practical use, many PV cells are joined in series and parallel combination to obtain higher voltages and currents, respectively. Let, \(N_p\) and \(N_s\) represent the number of parallel-connected PV modules and series-connected PV cells, respectively. Then, the mathematical equation between the PV array output current, \(i_{pv}\), and output voltage, \(v_{pv}\), can be written as follows [34]:

\[
i_{pv} = N_p I_{ph} - N_p A \left[ \exp \left( \frac{q (v_{pv}/N_s)}{k T} \right) - 1 \right] - \frac{N_p}{R_p} \left( \frac{v_{pv}}{N_s} + \frac{i_{pv} R_p}{N_p} \right)
\]

(2)

A user–define standalone PV array has been considered in this work. It consists of 16 PV modules, each of 1, 555 W, where 4 PV modules are connected in series in each string and then 4 such strings are connected in parallel to constitute the complete PV array with a total power output of 24, 880 W. Table 1 describes different parameters of the PV array, under standard test conditions (STC), i.e. 25°C and 1, 000 W/m². Furthermore, the PV array electrical characteristics \((I – V\) and \(P – V\)), are illustrated in Fig 5.
3.2 Sound system (dynamic load) mathematical modeling

The main component of the sound system is as a speaker. It belongs to the class of electromechanical devices known as electro-acoustic. It is a dynamic load that is analogous to a permanent magnet DC (PMDC) motor. Its working principle is as follows: generally a stereo (or radio amplifier) produces a current in a coil that is attached to a diaphragm in the speaker cone. This causes the coil and diaphragm to move relative to the permanent magnet (PM). The motion of the diaphragm generates air pressure waves or sound [35].

The simplified model of the mechanical subsystem of the speaker is illustrated in Fig 6. Applying Newton’s law of motion to the mechanical subsystem of the speaker, it yields:

\[
m \frac{d^2x}{dt^2} = K_f i_s - kx
\]

where \(m\) represents the combined mass of the speaker coil and diaphragm (kg), \(x\) denotes the diaphragm displacement, \(\frac{d^2x}{dt^2} = a\) represents the diaphragm acceleration, \(K_f\) indicates the
magnetic force constant \( (N/A) \), \( i_s \) represents the speaker current \( (A) \), \( F \) denotes the magnetic force \( (N) \) and \( k \) represents the spring constant \( (N/m) \).

Similarly, the simplified model of the electrical subsystem of the speaker is illustrated in Figs 7 and 8. Applying Kirchhoff’s voltage law to the electrical subsystem of the speaker, it yields:

\[
v_o = L_s \frac{di_s}{dt} + R_s i_s + K_b \frac{dx}{dt}
\]

where \( v_o \) is the applied voltage \( (V) \), \( R_s \) and \( L_s \) are the resistance \( (\Omega) \) and inductance \( (H) \) of the speaker coil, respectively, \( v_b \) is the back emf \( (V) \), \( K_b \) is the back emf constant \( (V/(m/s)) \) and \( \frac{dx}{dt} = \dot{x} = \omega \) is the velocity of the diaphragm.

Eqs (3) and (4) constitute the dynamic model of the speaker. In state-space representation, the speaker dynamic model can be expressed as follows:

\[
\begin{aligned}
\frac{dx}{dt} &= \omega \\
\frac{dx^2}{dt^2} &= \frac{d\omega}{dt} = \frac{1}{m} (K_b i_s - kx) \\
\frac{di_s}{dt} &= \frac{1}{L_s} (v_o - K_b \omega - R_s i_s)
\end{aligned}
\]

Fig 7. Electrical subsystem of speaker.

https://doi.org/10.1371/journal.pone.0231749.g007

Fig 8. Equivalent circuit diagram of the NIBB DC-DC converter with source (standalone PV array) and dynamic load.

https://doi.org/10.1371/journal.pone.0231749.g008
3.3 Non-inverting DC-DC buck-boost converter state-space average modeling

DC-DC converter serves as a power electronic interface for delivering power from the PV array to the load. For this purpose, several well-known variants of the converter have been used, such as, Cuk converter, boost converter, buck converter or conventional buck-boost converter. However, all these stated converters are prone to high switching stresses, and therefore reduced efficiency. Moreover, the polarity of the output voltage is reversed with respect to the polarity of the input voltage, especially in case of the Cuk converter and conventional buck-boost converter. These problems are solved by employing a NIBB DC-DC converter [36]. Therefore, in this research work, a NIBB power converter is employed as a power electronic interface between the DC source (standalone PV array) and the dynamic load, as illustrated in Fig 8. It has two diodes ($D_1$ and $D_2$) and two IGBT based controllable switches ($S_1$ and $S_2$), an input and output capacitor ($C_1$ and $C_2$, respectively) and an inductor $L$. This converter is a cascaded combination of two other converters (i.e. a buck converter and a boost converter). Moreover, it is capable of being operated in three separate operating modes, that is, a buck mode (with $S_1$: ON, while $S_2$: OFF), a boost mode (with $S_1$: OFF, while $S_2$: ON) and a buck-boost mode (with both $S_1$ and $S_2$: ON, concurrently). In this research article, the NIBB converter is operated in the buck-boost mode.

Throughout this research work, it is assumed that the converter operates in the continuous conduction mode (CCM). Furthermore, there are two different switching modes of operation for the stated converter in the buck-boost mode. Mode 1: $S_1$ and $S_2$ are ON, while diodes $D_1$ and $D_2$ remain OFF. Mode 2: $D_1$ and $D_2$ are ON, while $S_1$ and $S_2$ remain OFF.

Generally, linearized state-space average modeling technique is used to study a converter behavior and performance in different operating modes. For operation in Mode 1 of the NIBB converter, the corresponding, state-space equations in compact vector-matrix form are given as follows [37]:

\[
\begin{align*}
\frac{dv_{pv}}{dt} &= \begin{bmatrix} 0 & -\frac{1}{C_1} & 0 & 0 & 0 & 0 \\ \frac{1}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{R_1C_2} & -\frac{1}{C_2} & 0 & 0 \\ 0 & 0 & -\frac{1}{L_s} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{K_f}{m} & 0 & -\frac{k}{m} \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_{pv} \\ i_t \\ v_o \\ i_s \\ \omega \\ x \end{bmatrix} \\
\frac{id}{dt} &= \frac{i_{pv}}{C_1} \\
\frac{dv}{dt} &= \begin{bmatrix} \frac{1}{L} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{L_s} & -\frac{R}{L_s} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{L_s} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{K_f}{m} & 0 & -\frac{k}{m} \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_{pv} \\ i_t \\ v_o \\ i_s \\ \omega \\ x \end{bmatrix} \\
\frac{dx}{dt} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{pv} \\ i_t \\ v_o \\ i_s \\ \omega \\ x \end{bmatrix}
\end{align*}
\]
Similarly, for operation in Mode 2 of the NIBB converter, the corresponding state-space equations in compact vector-matrix form are given as follows:

\[
\begin{bmatrix}
\frac{dv_{pv}}{dt} \\
\frac{di_l}{dt} \\
\frac{dv}{dt} \\
\frac{di}{dt} \\
\frac{d\omega}{dt} \\
\frac{dx}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & -\frac{1}{L} & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{R_1C_2} & -\frac{1}{C_2} & 0 & 0 \\
0 & 0 & 1 & -\frac{R_i}{L_i} & 0 & 0 \\
0 & 0 & 0 & \frac{K_f}{m} & 0 & -\frac{k}{m} \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
v_{pv} \\
i_l \\
v \\
i \\
\omega \\
x
\end{bmatrix} +
\begin{bmatrix}
i_{pv} \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]  

(7)

Now, the overall average state-space model of the NIBB converter, based on inductor volt-second balance and capacitor charge-balance principles, over one switching period, \( T_s \), in compact vector-matrix form is given as follows:

\[
\begin{bmatrix}
\frac{dv_{pv}}{dt} \\
\frac{di_l}{dt} \\
\frac{dv}{dt} \\
\frac{di}{dt} \\
\frac{d\omega}{dt} \\
\frac{dx}{dt}
\end{bmatrix} =
\begin{bmatrix}
0 & -\frac{d}{C_1} & 0 & 0 & 0 & 0 \\
0 & 0 & d - \frac{1}{L} & 0 & 0 & 0 \\
0 & 0 & -\frac{1}{R_1C_2} & -\frac{1}{C_2} & 0 & 0 \\
0 & 0 & \frac{1}{L_i} & -\frac{R_i}{L_i} & 0 & 0 \\
0 & 0 & 0 & \frac{K_f}{m} & 0 & -\frac{k}{m} \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
v_{pv} \\
i_l \\
v \\
i \\
\omega \\
x
\end{bmatrix} +
\begin{bmatrix}
i_{pv} \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\]  

(8)

where in Eq (8), \( d \) is the duty ratio, \( \bar{v}_{pv}, \bar{i}_l, \bar{v}, \bar{i}, \bar{\omega} \) and \( \bar{x} \) are the average values of \( v_{pv}, i_l, v, i, \omega \) and \( x \), respectively. All the significant parameters of the NIBB DC-DC converter are expressed in Table 1.

4 Robust integral backstepping MPPT controller design

In this section, a nonlinear hybrid two-loop RIB based MPPT controller is designed that regulates the PV array output voltage, \( v_{pv} \), for maximum power extraction. The schematic of the
The overall control scheme is depicted in Fig. 3. The ANFIS block estimates the real-time offline reference peak power voltage, \( V_{MPP} \) or \( v_{r pv} \), for any combination of the input temperature, \( T \), and irradiance, \( G \). The MPPT controller block (RIB controller) utilizes the estimated value of \( V_{MPP} \) as a set-point to generate a control signal, \( u \), for adjusting the duty ratio, \( d \), of the converter switches (\( S_1 \) and \( S_2 \)) and forces the PV array output voltage (or converter input voltage), \( v_{pv} \), to track the \( V_{MPP} \).

To proceed with the proposed control system design, first of all, some assumptions are made as follows:

\[
\begin{align*}
\v_{pv} &= x_1 \\
\i_{L} &= x_2 \\
\v_{o} &= x_3 \\
\o &= x_4 \\
\x &= x_5 \\
\d &= u
\end{align*}
\]  

Now, a PV array output voltage error, \( \v_1 \), is defined as follows:

\[
\v_1 = v_{pv} - v_{pv}^* = x_1 - x_{1 ref}
\]  

Differentiating Eq (10) with respect to time, and substituting value of \( \dot{v}_{pv} = \dot{x}_1 \) from Eq (8), it becomes as follows:

\[
\dot{\v}_1 = \dot{x}_1 - \dot{x}_{1 ref} = \left( \frac{i_{pv}}{C_1} - u \frac{x_2}{C_1} - \dot{x}_{1 ref} \right)
\]  

Since, the key design objective is to provide a robust MPPT performance with almost zero steady-state error, therefore, an integral action, \( \zeta \), is introduced into Eq (10), as follows:

\[
\v_1 = \v_1 + \lambda \zeta
\]

where \( \lambda \) is a positive design constant. Moreover, \( \zeta \) is defined as follows:

\[
\zeta = \int_0^t \v_1 \, dt
\]

As, the goal is to converge the error \( \v_1 \) asymptotically to the origin, \( O \), (equilibrium point), for this purpose, defining a Lyapunov candidate function, \( V_1 \). In order to ensure the asymptotic stability of the system, \( V_1 \) must satisfy these three conditions, (i). \( V_1 \) must be positive definite, (ii). \( V_1 \) must be radially unbounded, and (iii). \( V_1 \) must have a negative-definite time derivative.

The selected Lyapunov function candidate, \( V_1 \), is defined as follows:

\[
V_1 = \frac{1}{2} \v_1^2 + \frac{\lambda}{2} \zeta^2
\]
Now, differentiating Eq (14) with respect to time and substituting values of $\dot{e}_1$ from Eq (11), and $\dot{\zeta}$ from Eq (13), one comes up with:

$$
\dot{V}_1 = e_1 \dot{e}_1 + \lambda \dot{\zeta} e_1 = e_1 \left( \frac{i_p}{C_1} - u \frac{x_2}{C_1} - \dot{x}_{1\text{ref}} + \lambda \zeta e_1 \right)
$$

(15)

For the time derivative of the Lyapunov candidate function, $\dot{V}_1$, to be negative-definite, let

$$
\left( \frac{i_p}{C_1} - u \frac{x_2}{C_1} - \dot{x}_{1\text{ref}} + \lambda \zeta \right) = -k_1 e_1 - k_2 \text{sign} (e_1)
$$

(16)

where $k_1$ and $k_2$ are positive designed constants.

Rearranging Eq (16) yields

$$
x_2 = \left( \frac{i_p}{C_1} - \dot{x}_{1\text{ref}} + \lambda \zeta + k_1 e_1 + k_2 \text{sign} (e_1) \right) \frac{C_1}{u}
$$

(17)

Substituting Eq (16) into Eq (15), it takes the following form:

$$
\dot{V}_1 = -k_1 e_1^2 - k_2 e_1 \text{sign} (e_1)
$$

(18)

Now, treating the inductor current, $i_L = x_2 = x_{2\text{ref}}$ in Eq (17) as a virtual control input that acts as a stabilization function (i.e. reference or desired current) for the actual inductor current, $i_L = x_2$. Consequently, one has the following new reference:

$$
x_{2\text{ref}} = \left( \frac{i_p}{C_1} - \dot{x}_{1\text{ref}} + \lambda \zeta + k_1 e_1 + k_2 \text{sign} (e_1) \right) \frac{C_1}{u}
$$

(19)

Now, to track $x_2$ to its set-point or reference, $x_{2\text{ref}}$, another error, $e_2$, is defined as follows:

$$
e_2 = x_2 - x_{2\text{ref}} \quad \text{or} \quad x_2 = e_2 + x_{2\text{ref}}
$$

(20)

Substituting $x_2$ from Eq (20) into Eq (11), it yields:

$$
\dot{e}_1 = \frac{i_p}{C_1} - u \frac{x_{2\text{ref}}}{C_1} - u \frac{e_2}{C_1} - \dot{x}_{1\text{ref}}
$$

(21)

Substituting $x_{2\text{ref}}$ from Eq (19) into Eq (21), it yields:

$$
\dot{e}_1 = -k_1 e_1^2 - k_2 e_1 \text{sign} (e_1) - \lambda \zeta - u \frac{e_2}{C_1}
$$

(22)

Substituting Eq (22) into Eq (15), it yields:

$$
\dot{V}_1 = -k_1 e_1^2 - k_2 e_1 \text{sign} (e_1) - u \frac{e_1 e_2}{C_1}
$$

(23)

The inequality expressed above can also be written as:

$$
\dot{V}_1 = -2k_1 V_1 - \sqrt{2}k_2 \sqrt{V_1} - u \frac{e_1 e_2}{C_1}
$$

(24)

The details about this differential inequality will be presented at the end of this section. Taking the derivative of Eq (20), it yields

$$
\dot{e}_2 = \dot{x}_2 - \dot{x}_{2\text{ref}}
$$

(25)
Now, taking the derivative of Eq (19) w.r.t time, by applying the quotient rule of derivatives, it becomes as follows:

$$\dot{x}_{2\text{ref}} = \frac{1}{u} \left[ (u) \left( i_{pv} - C_1 \ddot{x}_{1\text{ref}} + \lambda C_1 \dot{\zeta} + k_i C_i \dot{e}_1 \right) 
- (i_{pv} - C_1 \ddot{x}_{1\text{ref}} + \lambda C_1 \dot{\zeta} + k_i C_i e_1 + k_2 C_i \text{sign}(e_1))(\dot{u}) \right]$$

(26)

Substituting the value of $\dot{e}_1$ from Eq (22), $x_{2\text{ref}}$ from Eq (19) and $\dot{\zeta}$ from Eq (13), it yields:

$$\dot{x}_{2\text{ref}} = \frac{1}{u} \left[ i_{pv} - C_1 \ddot{x}_{1\text{ref}} + \lambda C_1 e_1 - C_1 k_1 k_2 \text{sign}(e_1) - C_1 k_1 \dot{\zeta} - k_i ue_2 \right]$$

$$- \frac{x_{2\text{ref}}}{u} \dot{u}$$

(27)

Substituting the value of $\dot{x}_{2\text{ref}}$ from Eq (27) into Eq (25), $\dot{e}_2$ becomes as follows:

$$\dot{e}_2 = \dot{x}_2 - \frac{1}{u} \left[ i_{pv} - C_1 \ddot{x}_{1\text{ref}} + \lambda C_1 e_1 - C_1 k_1 k_2 \text{sign}(e_1) - C_1 k_1 \dot{\zeta} + k_i e_2 \right]$$

$$+ \frac{x_{2\text{ref}}}{u} \dot{u}$$

(28)

Now, to ensure the asymptotic stability in the closed-loop and the convergence of both the error signals, $e_1$ and $e_2$, to the equilibrium point, a new composite Lyapunov candidate function, $V_2$, is selected under the same assumptions as those made for $V_1$, as follows:

$$V_2 = V_1 + \frac{1}{2} e_2^2$$

(29)

Differentiating Eq (29) w.r.t time and substituting $\dot{V}_1$ from Eq (23), it becomes as follows:

$$\dot{V}_2 = \dot{V}_1 + e_2 \dot{e}_2 = -k_i e_1^2 - k_2 e_1 \text{sign}(e_1) + e_2 \left( \dot{e}_2 - u \frac{e_1}{C_i} \right)$$

(30)

For the second Lyapunov candidate function, $\dot{V}_2$, to be negative-definite, let

$$\left( \dot{e}_2 - u \frac{e_1}{C_i} \right) = -k_3 e_2 - k_4 \text{sign}(e_2)$$

(31)

where $k_3$ and $k_4$ are positive design constants.

Comparing Eqs (30) and (31), it yields:

$$\dot{V}_2 = -k_i e_1^2 - k_2 e_1 \text{sign}(e_1) - k_3 e_2^2 - k_4 e_2 \text{sign}(e_2)$$

(32)

Now, substituting $\dot{e}_2$ from Eq (28) and $\dot{x}_2$ from Eq (8) into Eq (31), it gives:

$$-k_i e_2 - k_4 \text{sign}(e_2) = \frac{ux_1}{L} + \frac{(u - 1)x_1}{L} \left[ i_{pv} - C_1 \ddot{x}_{1\text{ref}} + \lambda C_1 e_1 - C_1 k_1 \dot{\zeta} \right]$$

$$- C_1 k_1 k_2 \text{sign}(e_1) - C_1 k_1 \dot{\zeta} + k_i e_2 + \frac{x_{2\text{ref}} \dot{u}}{u} - u \frac{e_1}{C_i}$$

(33)
Nonlinear robust integral backstepping based MPPT control for stand-alone photovoltaic system

Now, rearranging and solving Eq (33) for \( \dot{u} \), the proposed complete RIB based MPPT control law becomes as follows:

\[
\dot{u} = \frac{u}{x_{2ref}} \left[ -k_2 e_2 - k_4 \text{sign}(e_2) + u \frac{e_1}{C_1} - k_6 \frac{\dot{x}_2}{u} \right] - \frac{u}{x_{2ref}} \frac{ux_4}{L} + \frac{u}{L} (u - 1) x_3 \tag{34}
\]

This choice of the dynamic control input, \( \dot{u} \), reduces Eq (32) to the following differential inequality:

\[
\dot{V}_2 \leq -2\tilde{k}_1 V_2 - \sqrt{2} \tilde{k}_2 \sqrt{V_2} \tag{35}
\]

where \( \tilde{k}_1 = \min(k_1, k_2) \) and \( \tilde{k}_2 = \min(k_3, k_4) \). The differential equation Eq (35) looks very similar to the fast terminal attractor [38]. This confirms that \( V_2 \to 0 \) with finite settling time:

\[
t_s = \frac{1}{\tilde{k}_1} \ln \left( \frac{2\tilde{k}_1 \sqrt{V_2(0) + \sqrt{2} \tilde{k}_2}}{\sqrt{V_2}} \right) \]

In other words, \( e_2 = x_2 - x_{2ref} \to 0 \) in finite-time which confirms high precision in reference tracking as well as in errors and states regulation problems. As \( e_2 \to 0 \) in finite-time, the last term in the differential equation Eq (24) vanishes. Consequently, a terminal attractor in terms of \( V_1 \) is obtained which, once again, confirms the fast finite-time convergence of \( e_1 \) to zero. This convergence of \( e_1 \) is estimated to be:

\[
t_1 \leq \frac{1}{\tilde{k}_1} \ln \left( \frac{2\tilde{k}_1 \sqrt{V_2(0) + \sqrt{2} \tilde{k}_2}}{\sqrt{V_2}} \right) \]

Hence, the proposed control law Eq (34), along with the virtual control law, Eq (19) regulates the respective error dynamics to zero in finite-time with high precision. Consequently, the reference tracking is achieved which will provide maximum power at each time instant.

Now, at this state, it is necessary to discuss the stability of the zero dynamics.

4.1 Stability of zero dynamics

Since, a two step integral backstepping based MPPT law is designed, therefore, the following dynamic equations, expressed in Eq (8), are straight-a-way the internal dynamics of this proposed PV system:

\[
\begin{align*}
\ddot{x}_3 &= \left(1 - u\right) \frac{x_3}{C_2} - \frac{\dot{x}_3}{R_c C_2} - \frac{\ddot{x}_2}{C_2} \\
\ddot{x}_4 &= \frac{\ddot{x}_3}{L_s} - \frac{R_s \ddot{x}_4}{L_s} - \frac{v_b}{L_s} \\
\ddot{x}_5 &= \frac{K_i x_4}{m} - \frac{k \ddot{x}_6}{m} \\
\ddot{x}_6 &= \ddot{\omega}
\end{align*}
\tag{36}
\]

According to the nonlinear control theory [39], the zero dynamics can be obtained by substituting the the applied control input, \( u \), and the control driven states, \( x_1 \) and \( x_2 \), equal to
zero into the internal dynamics, Eq (36). Thus, one has the following zero dynamics:

\[
\begin{bmatrix}
\dot{x}_3 \\
\dot{x}_4 \\
\dot{x}_5 \\
\dot{x}_6
\end{bmatrix} =
\begin{bmatrix}
-\frac{1}{R_2C_2} & \frac{1}{C_2} & 0 & 0 \\
\frac{1}{L_3} & -\frac{R_3}{L_3} & 0 & 0 \\
0 & \frac{K_f}{m} & 0 & -\frac{k}{m} \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
x_3 \\
x_4 \\
x_5 \\
x_6
\end{bmatrix} +
\begin{bmatrix}
0 \\
-v_c \\
0 \\
0
\end{bmatrix}
\]

(37)

This is a linear time invariant (LTI) non-homogeneous system that can be represented, in general form, as follows:

\[
\dot{x} = \bar{A}x + \bar{B}
\]

(38)

where \(x = [x_3, x_4, x_5, x_6]^T\) represents zero dynamics state vector, \(\bar{A}\) is the respective system distribution matrix, and \(\bar{B}\) is a vector of time varying non-vanishing disturbances, which depend on the speaker back emf, \(v_c\). This system has general solution of the following form:

\[
x(t) = e^{\bar{A}t}x(0) + e^{\bar{A}t} \int_0^t e^{-\bar{A}r} \bar{B} dr
\]

(39)

Since, all the typical plant parameters are positive, therefore, the system Eq (37) of zero dynamics has two poles on the \(jw - axis\) i.e. at \(\pm j - \frac{k}{m}\) and two poles in the left-half plan (LHP) at \(-\frac{R_fL_2^2 + L_2}{2RL_2C_2} \pm \frac{1}{2} \sqrt{\left(\frac{R_fL_2^2 + L_2}{2RL_2C_2}\right)^2 - 8 \frac{R_f}{R_LC_2}}\). Note that, as long as the discriminant in the square root remains negative, it will give rise to conjugate poles with negative real parts. Thus, the exponential term \(e^{\bar{A}t}\), which can be calculated via Caylay-Hamilton approach on the spectrum of the above defined LHP poles, has two oscillatory modes and two modes with decaying oscillations. Based on the information of the poles, the overall response of the zero dynamics will initially observe decaying oscillatory response to the vicinity of the origin, and then all the states will remain ultimately bounded. In other words, this also confirms that initially the zero dynamics will show a minimum phase nature, and as the effects of the exponential terms die out, the over all zero dynamics will stay bounded in a small neighborhood. This confirms the practical asymptotic convergence of the zero dynamics. Hence, the control will effectively track the reference in the presence of the practical asymptotic convergence of the internal dynamics.

5 Simulation results and discussion

The Matlab/Simulink platform is used to test and validate the superiority of the proposed RIB based MPPT technique. The specifications of the MPPT controller, PV array, NIBB DC-DC power converter and sound system used in this research are given in Table 1. The irradiance and temperature profiles are shown in Fig 9. The proposed technique is evaluated and
compared with the backstepping [27] and integral backstepping [28] based MPPT controllers under the following three different operating conditions:

Case 1: Performance test against varying meteorological conditions.

Case 2: Performance test against plant faults under varying meteorological conditions.

Case 3: Performance test against plant parametric uncertainties under varying meteorological conditions.

Finally, comparison with other conventional PID and P&O based MPPT techniques, under the stated three conditions, is also conducted.
5.4.1 Performance test against varying meteorological conditions

In this case study, the performance of the proposed MPPT control strategy is analyzed under varying meteorological conditions and then compared with the backstepping (B) and integral backstepping (IB) based MPPT control strategies.

The comparative plot for the PV array output voltages, under case 1 is depicted in Fig 10. It can be seen from the zoomed-in view of Fig 10 that the proposed MPPT control strategy starts tracking the reference voltage ($V_{MPP}$) in around 0.01 s, outperforming the other two MPPT techniques. This shows that the proposed control strategy has the lesser rising time, for achieving the MPPT, compared to the backstepping and integral backstepping techniques. Similarly, after abrupt change in meteorological conditions at 0.1 s and 0.2 s, the proposed technique performs very well by converging and settling earlier than the other two MPPT candidates. Throughout the simulation, the backstepping controller suffers from steady-state error, as shown in the zoomed-in view of Fig 10. Moreover, Fig 11 indicates the PV array output current. It is evident that the proposed control strategy extracts much smoother current from the PV array than its contenders.

Fig 12 depicts the comparative plot for the PV array output powers under case 1. Again, the proposed technique is robust and better than the other two MPPT techniques, in terms of lesser rising time, faster convergence, and offering almost negligible chattering, as shown in the zoomed-in view of Fig 12. Moreover, the proposed technique renders the minimum PV array output voltage tracking error ($|V_{pv} - V_{MPP}|$), as illustrated in Fig 13, thus guaranteeing the accurate MPPT.

The three MPPT candidates are also compared on the basis of the well-known performance indices ($ISE$, $ITSE$, $IAE$ and $ITAE$), as depicted in Fig 14. It can be seen that the proposed paradigm renders the minimum accumulative error and the flattest error profile. It means that the proposed strategy is superior to both the backstepping and integral backstepping techniques. Furthermore, the proposed technique successfully delivers the maximum power from the PV array to the load with more than 98% efficiency, which is the maximum efficiency as compared to the other two techniques, as depicted in Fig 15.
5.4.2 Performance test against faults under varying meteorological conditions

During practical operation, the PV system is prone to certain faults that degrades its overall performance. This case study tests and compares the performance of the proposed control strategy with backstepping and integral backstepping strategies under case 2. For this purpose, a time varying sinusoidal fault $x_{3f} = 30 \sin(t)/C_1$ is injected into the output capacitor voltage, $x_3$, during the time interval $0.06 - 0.08 \text{ s}$, which resulted in $\Delta x_3 = x_3 + x_{3f}$. Similarly, another time varying sinusoidal fault $x_{2f} = 0.5 \sin(t)/C_1$, is injected into the inductor current, $x_2$, during the time interval $0.16 - 0.18 \text{ s}$, which resulted in $\Delta x_2 = x_2 + x_{2f}$.

The comparative plot for the PV array output voltages under case 2 is shown in Fig 16. It is evident that all the MPPT controllers deviates from the $V_{MMP}$ thereby losing tracking at the onset of faults in the plant. However, the proposed RIB control strategy deviates the minimum,
thus offering more robustness against faults, as compared to the backstepping and integral backstepping strategy. Again, the backstepping controller suffers from steady-state error, as depicted in the zoomed-in view of Fig 16. Moreover, Fig 17 indicates the PV array output current. It is evident that the proposed control strategy extracts much smoother current from the PV array than its contenders. Similarly, the comparative plot for the PV array output powers under case 2 is illustrated in Fig 18. It can be seen that the proposed control scheme recovers...
and reaches the steady-state earlier than the other two MPPT candidates, once the faults are over.

Fig 19 depicts the PV array output voltage tracking error, whereas Fig 20 illustrates various performance indices under case 2. Again the proposed strategy achieves the MPPT with the minimum error, thus making it the best MPPT candidate under case 2. Similarly, Fig 21 compares the efficiencies of the three MPPT candidates, where it can be seen that the proposed strategy renders the highest efficiency of around 98%.

5.4.3 Performance test against parametric uncertainties under varying meteorological conditions

In this case study, the superiority of the proposed controller is tested and validated against plant parametric uncertainties and then compared with the backstepping and integral
backstepping based MPPT controllers under case 3. This is carried out by introducing uncertainties into the converter inductor, $L$, and output capacitor, $C_2$. Such that, from 0.06 − 0.08 s, $L$ is increased by $\Delta L = 200 \text{ mH}$, which resulted in $L_{\text{new}} = L + \Delta L$. Similarly, $C_2$ is increased by $\Delta C = 0.48 \text{ \mu F}$ from 0.16 − 0.18 s, which resulted in $C_{\text{new}} = C_2 + \Delta C$.

Fig 22 illustrates the comparative plot for the PV array output voltages under case 3. It can be observed from the zoomed-in view that both the capacitive and inductive uncertainties deviates the backstepping and integral backstepping control strategies from $V_{\text{MPP}}$, however,
the proposed RIB control strategy shows more robustness against plant uncertainties and remains unaffected. Moreover, Fig 23 illustrates the PV array output current. It is evident that the proposed control strategy extracts much smoother current from the PV array than its contenders.

Similarly, Fig 24 depicts the comparative plot for the PV array output powers under case 3. It can be observed that both the backstepping and integral backstepping controllers has the worst performance under plant parametric uncertainties. However, the proposed RIB control
technique remains unaffected, achieves steady-state faster and offers a superior tracking performance. Moreover, the proposed technique renders the minimum tracking error as compared to the other two MPPT candidates as depicted in Figs 25 and 26. Similarly, Fig 27 shows that the proposed RIB based MPPT strategy has the highest efficiency than its competitors.

5.4 Comparison with conventional MPPT techniques

A comparative analysis between the proposed RIB control based MPPT scheme and the well-known conventional PID and P&O based MPPT techniques is presented in this section.

5.4.1 Performance test against varying meteorological conditions. In this case study, a comparative analysis is presented between the proposed RIB based MPPT strategy and the traditional PID and P&O based MPPT techniques under the same scenario as discussed in case 1.
Fig 28 depicts the comparative plot for the PV array output powers. It can be seen that both the PID and P&O based MPPT techniques suffer from a lot of oscillations around the $V_{MPP}$ under their steady-states. This is practically undesirable. However, the proposed RIB control technique performs the best with negligible steady-state error, thus, outperforming both the PID and P&O control techniques.

5.4.2 Performance test against faults under varying meteorological conditions. In this case study, the proposed technique is further tested and validated by comparing its MPPT performance with the PID and P&O based MPPT control techniques under the same conditions as discussed in case 2.

It is evident from Fig 29, that both the conventional PID and P&O based MPPT control techniques deviate from $P_{MPP}$ upon the occurrence of faults in the plant, while the proposed MPPT technique exhibits more robustness against plant faults with negligible deviation.
5.4.3 Performance test against uncertainties under varying meteorological conditions. Finally, in this case study, a comparative analysis between the proposed RIB based MPPT control strategy and the conventional PID and P&O based MPPT control techniques is presented under the same conditions as discussed in case 3.

Fig 30 depicts the comparative plot for the PV array output powers. It can be observed that the proposed RIB control technique delivers the maximum power with the minimum chattering as compared to the PID and P&O based control techniques. It means, that the proposed technique is more robust to plant parametric uncertainties than the conventional MPPT candidates.
Fig 28. PV array comparative powers under varying meteorological conditions.
https://doi.org/10.1371/journal.pone.0231749.g028

Fig 29. PV array comparative powers under faults and varying meteorological conditions.
https://doi.org/10.1371/journal.pone.0231749.g029

Fig 30. PV array comparative powers under uncertainties and varying meteorological conditions.
https://doi.org/10.1371/journal.pone.0231749.g030
6 Conclusions and future research recommendations

This research paper presents a nonlinear, hybrid, very fast and efficient robust integral backstepping based MPPT control approach for a stand-alone PV system, consisting of a PV array, a non-inverting DC-DC buck-boost power converter, a purely resistive and an dynamic load. The DC-DC buck-boost converter is employed as a power electronic interface between the PV array and the load. The proposed MPPT control scheme consists of two loops, where the first loop generates the real-time offline reference peak power voltage through an ANFIS network, which is then utilized in the second loop as a set-point value for generating a control signal and then forcing the PV system to be operated at this set-point by continuously adjusting the duty ratio of the power converter. The superiority of the proposed MPPT approach is validated through Matlab simulations carried out under time varying plant faults, plant parametric uncertainties and varying meteorological conditions. The comparative analysis depicts that the proposed MPPT control strategy exhibits a superior tracking performance with no overshoot, fast dynamic response, less rising and settling times and minimum output tracking error as compared to the existing backstepping, integral backstepping and conventional PID and P&O based MPPT control schemes.

The proposed MPPT control paradigm successfully achieved the desired objectives under a standalone PV system. The authors are working to test and validate its effectiveness under grid-connected system and under partial shading conditions. Hopefully, it will be submitted separately for a review in near future.

Author Contributions

Conceptualization: Kamran Ali.
Investigation: Kamran Ali.
Project administration: Qudrat Khan.
Software: Kamran Ali.
Supervision: Qudrat Khan.
Writing – original draft: Kamran Ali.
Writing – review & editing: Shafaat Ullah, Ilyas Khan, Laiq Khan.

References

1. (2012-01-27). World Proved Reserves of Oil and Natural Gas, Most Recent Estimates. Available: http://www.eia.gov/beta/international/
2. Reisi AR, Moradi MH, Jamaab S. Classification and comparison of maximum power point tracking techniques for photovoltaic system: A review. Renewable and sustainable energy reviews. 2013 Mar 1; 19:433–43. https://doi.org/10.1016/j.rser.2012.11.052
3. Enrique JM, Andújar JM, Bohorquez MA. A reliable, fast and low cost maximum power point tracker for photovoltaic applications. Solar Energy. 2010 Jan 1; 84(1):79–89. https://doi.org/10.1016/j.solener.2009.10.011
4. Tey KS, Mekhilef S, Seyedmahmoudian M, Horan B, Oo AT, Stojcevski A. Improved differential evolution–based MPPT algorithm using SEPIC for PV systems under partial shading conditions and load variation. IEEE Transactions on Industrial Informatics. 2018 Jan 15; 14(10):4322–33. https://doi.org/10.1109/TII.2018.2793210
5. Paraskevadaki EV, Papathanassiou SA. Evaluation of MPP voltage and power of mc-Si PV modules in partial shading conditions. IEEE Transactions on Energy Conversion. 2011 Apr 21; 26(3):923–32. https://doi.org/10.1109/TEC.2011.2126021
6. Bhatnagar P, Nema RK. Maximum power point tracking control techniques: State-of-the-art in photovoltaic applications. Renewable and Sustainable Energy Reviews. 2013 Jul 1; 23:224–41. https://doi.org/10.1016/j.rser.2013.02.011

7. Alghwaimem SM. Matching of a dc motor to a photovoltaic generator using a step-up converter with a current-locked loop. IEEE Transactions on Energy Conversion. 1994 Mar; 9(1):192–8. https://doi.org/10.1109/60.282492

8. Mosam MA, Dehbonei H, Fuchs EF. Theoretical and experimental analyses of photovoltaic systems with voltage and current-based maximum power-point tracking. IEEE Transactions on energy conversion. 2002 Dec; 17(4):514–22. https://doi.org/10.1109/TEC.2002.805205

9. Enslin JH, Wolf MS, Snyman DB, Swiegers W. Integrated photovoltaic maximum power point tracking converter. IEEE Transactions on industrial electronics. 1997 Dec; 44(6):769–73. https://doi.org/10.1109/41.649937

10. Salameh ZM, Dagher F, Lynch WA. Step-down maximum power point tracker for photovoltaic systems. Solar Energy. 1991 Jan 1; 46(5):279–82. https://doi.org/10.1016/0038-092X(91)90095-E

11. Jiang LL, Maskell DL, Patra JC. A novel ant colony optimization based maximum power point tracking for photovoltaic systems under partially shaded conditions. Energy and Buildings. 2013 Mar 1; 58:227–36. https://doi.org/10.1016/j.enbuild.2012.12.001

12. Mohanty M, Selvakumar S, Koodalsamy C, Simon SP. Global maximum operating point tracking in photovoltaic system using best convergence firefly algorithm. Turkish Journal of Electrical Engineering and Computer Science. 2019 Nov 27; 27(6):4640–58.

13. Heydari-doostabad H, Keypour R, Khalghani MR, Khooban MH. A new approach in MPPT for photovoltaic array based on extremum seeking control under uniform and non-uniform irradiances. Solar Energy. 2013 Aug 1; 94:28–36. https://doi.org/10.1016/j.solener.2013.04.025

14. Yau HT, Wu CH. Comparison of extremum-seeking control techniques for maximum power point tracking in photovoltaic systems. Energies. 2011 Dec; 4(12):2180–95. https://doi.org/10.3390/en4122180

15. Zazo H, Del Castillo E, Reynaud JF, Leyva R. MPPT for photovoltaic modules via newton-like extremum seeking control. Energies. 2012 Aug; 5(8):2652–66. https://doi.org/10.3390/en5082652

16. Bendib B, Belmili H, Krim F. A survey of the most used MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems. Renewable and Sustainable Energy Reviews. 2015 May 1; 45:637–48. https://doi.org/10.1016/j.rser.2015.02.009

17. Ishaque K, Salam Z, & Lauss G. (2014). The performance of perturb and observe and incremental conductance maximum power point tracking method under dynamic weather conditions. Applied Energy, 119, 228–236. https://doi.org/10.1016/j.apenergy.2013.12.054

18. Ishaque K, Salam Z, Lauss G. The performance of perturb and observe and incremental conductance maximum power point tracking method under dynamic weather conditions. Applied Energy. 2014 Apr 15; 119:228–36. https://doi.org/10.1016/j.apenergy.2013.12.054

19. Sivakumar P, Kader AA, Kaliavaradhan Y, Arutchelvi M. Analysis and enhancement of PV efficiency with incremental conductance MPPT technique under non-linear loading conditions. Renewable Energy. 2015 Sep 1; 81:543–50. https://doi.org/10.1016/j.renene.2015.03.062

20. Tey KS, Mekhilef S. Modified incremental conductance MPPT algorithm to mitigate inaccurate responses under fast-changing solar irradiation level. Solar Energy. 2014 Mar 1; 101:333–42. https://doi.org/10.1016/j.solener.2014.01.003

21. Mohammed SS, Devaraj D, Ahamed TI. A novel hybrid maximum power point tracking technique using perturb & observe algorithm & learning automata for solar PV system. Energy. 2016 Oct 1; 112:1096–106. https://doi.org/10.1016/j.energy.2016.07.024

22. Moradi MH, Reisi AR. A hybrid maximum power point tracking method for photovoltaic systems. Solar Energy. 2011 Nov 1; 85(11):2965–76. https://doi.org/10.1016/j.solener.2011.08.036

23. Moradi MH, Tousi SR, Nemat M, Basir NS, Shalavi N. A robust hybrid method for maximum power point tracking in photovoltaic systems. Solar Energy. 2013 Aug 1; 94:266–76. https://doi.org/10.1016/j.solener.2013.05.016

24. Zhang F, Thanapalans K, Procter A, Carr S, Maddy J. Adaptive hybrid maximum power point tracking method for a photovoltaic system. IEEE Transactions on Energy Conversion. 2013 Apr 26; 28(2):353–60. https://doi.org/10.1109/TEC.2013.2255292

25. Mumtaz S, Ahmad S, Khan L, Ali S, Kamal T, Hassan S. Adaptive Feedback Linearization Based NeuroFuzzy Maximum Power Point Tracking for a Photovoltaic System. Energies. 2018 Mar; 11(3):606. https://doi.org/10.3390/en11030606

26. Dahech K, Allouche M, Damak T, Tadeo F. Backstepping sliding mode control for maximum power point tracking of a photovoltaic system. Electric Power Systems Research. 2017 Feb 1; 143:182–8. https://doi.org/10.1016/j.epsr.2016.10.043
27. Armghan H, Ahmad I, Armghan A, Khan S, Arsalan M. Backstepping based non-linear control for maximum power point tracking in photovoltaic system. Solar Energy. 2018 Jan 1; 159:134–41. https://doi.org/10.1016/j.solener.2017.10.062

28. Arsalan M, Iftikhar R, Ahmad I, Hasan A, Sabahat K, Javeria A. MPPT for photovoltaic system using nonlinear backstepping controller with integral action. Solar Energy. 2018 Aug 1; 170:192–200. https://doi.org/10.1016/j.solener.2018.04.061

29. Wang J, Bo D, Ma X, Zhang Y, Li Z, Miao Q. Adaptive back-stepping control for a permanent magnet synchronous generator wind energy conversion system. International Journal of Hydrogen Energy. 2019 Jan 28; 44(5):3240–9. https://doi.org/10.1016/j.ijhydene.2018.12.023

30. Krstić M, Kanellakopoulos I, Kokotović PV. Nonlinear and adaptive control design. John Wiley & Sons Inc.; 1995.

31. Errami Y, Obbadi A, Sahnoun S, Benhmida M, Ouassaid M, Maaroufi M. Design of a nonlinear back-stepping control strategy of grid interconnected wind power system based PMSG. InAIP Conference Proceedings 2016 Jul 25 (Vol. 1758, No. 1, p. 030053). AIP Publishing LLC.

32. Krstić M, Smyshlyaev A. Boundary control of PDEs: A course on backstepping designs. SIAM (Society for Industrial and Applied Mathematics); 2008.

33. Villalva MG, Gazoli JR, Ruppert Filho E. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Transactions on power electronics. 2009 Mar 27; 24(5):1198–208. https://doi.org/10.1109/TPEL.2009.2013862

34. Kim IS. Robust maximum power point tracker using sliding mode controller for the three-phase grid-connected photovoltaic system. Solar Energy. 2007 Mar 1; 81(3):405–14. https://doi.org/10.1016/j.solener.2006.04.005

35. Palm WJ. System dynamics. McGraw-Hill Higher Education; 2005.

36. Almasi ON, Fereshtehpour V, Khooban MH, Blaabjerg F. Analysis, control and design of a non-inverting buck-boost converter: A bump-less two-level T–S fuzzy PI control. ISA transactions. 2017 Mar 1; 67:515–27. https://doi.org/10.1016/j.isatra.2016.11.009

37. Erickson RW, Maksimovic D. Fundamentals of power electronics. Springer Science & Business Media; 2007 May 8.

38. Yu S, Yu X, Shirinzadeh B, Man Z. Continuous finite-time control for robotic manipulators with terminal sliding mode. Automatica. 2005 Nov 1; 41(11):1957–64. https://doi.org/10.1016/j.automatica.2005.07.001

39. Isidori A. Nonlinear control systems. Springer Science & Business Media; 2013 Apr 17.