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RESEARCH ARTICLE

# Inverter Controlling with Fuzzy Logic Controller for Solar Photovoltaic Based Grid Connected System

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## Abstract

**Background/Objectives:** The integration of solar photovoltaic with the AC microgrid causes improper variation in voltage and power in the system. This study presents the integration of solar photovoltaic(SPV) with AC grid via boost converter and inverter. **Methods:** The controlling of the boost converter has been done with the maximum power point (MPP) extraction from the perturb and observe (P&O) based method. Further, the controlling of the inverter has been done with a fuzzy logic controller (FLC). The P&O method is used for MPP and for switching the boost converter. FLC and vector control are used for controlling the inverter. **Findings:** The integration causes deviations in voltage and larger THD at the AC grid terminals. The deviation in voltage (≈3.6%) and total harmonic distortion(THD), (≈6.1%) are found to be least with FLC in contrast to vector control under variable solar irradiations. **Novelty:** The existing methods are unable to resolve the power quality issue or harmonics. After the implementation of the given methods, it is found that the least voltage deviation and minimum harmonics are found with FLC when compared to vector control.

**Keywords:** Solar Photovoltaic; Boost Converter; Inverter; FLC; Vector Control; THD

## 1 Introduction

Over the past few years, solar photovoltaic systems have gained popularity worldwide as a very efficient energy source for power generation. The amazing daily energy potential of the Earth can be easily harnessed by using photovoltaic (PV) panels to generate electricity. However, before a solar plant is established, it is necessary to understand its efficacy and efficiency. The design of maximum power point tracking (MPPT) controllers is also essential for maximizing the utilization of solar energy and producing electricity using PV panels. Module parameters must be extracted as quickly, simply, and precisely as possible for both of these applications.

Renewable energy sources have become increasingly popular as a result of the devaluation of traditional fossil fuel sources. Among all renewable energy sources, photovoltaics (PV) has attracted a lot of interest due to its environmental friendliness, security, safety, lightweight nature, and lack of cost. However, with further study and widespread application, the high setup and manufacturing costs of today will eventually drop. The amount of power that is taken from the PV module is determined by environmental factors that monitor power variations under varying operating situations. Therefore, incorporating auxiliary power sources like batteries, diesel generators, and fuel cells is essential. Batteries and diesel generators have limitations in terms of providing backup power for all load needs and for certain durations, respectively[(1)].

- The current study is improving the power quality issues of solar photo- voltaic based grid connected system. The power quality issues like harmonics and voltage deviations are serious concern which was not resolved properly by existing methods like vector control which are the research gap of the scheme.
- By design the set of rules in fuzzy logic controller and implement in proposed model, then power quality issues can be resolved.
- The design of rules of the fuzzy logic controller is the greatest challenge of the proposed model.
- The fuzzy logic controller itself is the intelligent technique helps to mitigate the power quality issues of grid connected system is the novelty and original contribution of scheme with simple mathematics.

To address shortcomings, this research suggests a hybrid paradigm for forecasting the power generation of several renewable energy sources. The Attention-based Long Short-Term Memory (A-LSTM) network is designed to capture the nonlinear time-series data features of weather and individual power, the Convolutional Neural Network (CNN) is designed to extract the local correlations among multiple energy sources, and the Auto-Regression model is used to extract the linear time-series traits of each energy source[(2)]. The suggested method's correctness and applicability are confirmed using a renewable energy system as an example. The findings demonstrate that the hybrid framework outperforms other cutting-edge models like decision trees and artificial neural networks in terms of accuracy[(3)].

The standard efficiency of PV would be reduced by the impact of irradiance and temperature increases on the PV module's back surface. Newton Raphson's (iterative) techniques and the observed findings of the solar module (ORSM) have been proposed in this study to address this issue. In order to compute irradiance and different operating circumstances, this article contrasts ORSM with iterative techniques of altering the specifications of a single diode model (SDM) taken from a PV module under standard test conditions (STC)[(4)]. The precise value of each diode parameter on the STC is necessary in order to perform this comparison. Iterative methods and recognized algebraic values are used to accomplish these. It has been established that Newton Raphson's method is the most accurate way to locate these parameters in STC[(5)].

This study employs MATLAB/Simulink software to model multi-junction solar cells (MJSCs) in order to increase conversion efficiency. Research is being done to determine how well the multi-junction photovoltaic (PV) cell performs in comparison to the traditional silicon PV cell. Results from MATLAB/Simulink modeling demonstrate that, in comparison to traditional PV cells, tandem cells may deliver about three times the maximum power[(6)]. Additionally, maximum power point tracking (MPPT) has been used to increase the PV systems' conversion efficiency. The MPPT can help the PV cells generate more power more effectively and supply the grid with electricity[(7)].

In order to achieve the best and most effective energy management for a Grid-Connected Hybrid Power Plant, this study offers a comprehensive sophisticated control structure. Subject to limitations and process requirements, this control scheme, which consists of layers for process oversight and oversight, may be able to improve industrial processes' energy consumption. The suggested structure combines an optimal finite-state machine decision system, a Model-Based Predictive Controller developed within the Chance Constraints framework to handle stochastic disturbances (renewable sources, such as solar irradiance), and the application of disturbance estimate methods to renewable source prediction. Nonlinear Auto-Regressive Neural Networks with time delays are used to obtain feedforward correction of estimated future disturbances, which is then used by the predictive controller[(8)]. Choosing which energy system to employ and where to store energy from several storage alternatives are the two main tasks of the suggested controller. Due to contract regulations, this must always be done while optimizing energy generation and using as much renewable energy as possible. A case study of energy generation at a sugar cane power plant using dispatchable renewable sources (like biomass and biogas) and non-dispatchable renewable sources (like photovoltaic and wind power generation) is used to illustrate the suggested approach. This hybrid power system must meet rigorous contract requirements with a local distribution network operator in order to generate steam at various pressures, meet internal demands, and generate and maintain a certain amount of electricity each month[(9)].

The efficiency of the suggested model is assessed across various climates and time periods. The findings show that the performance of the suggested model is not significantly affected by climate when it comes to wind speed forecasting. However, we found that the error reductions for solar irradiance forecast varied depending on the climate[(10)]. This disparity is undoubtedly caused by the processes by which clouds arise, which vary greatly depending on the location and temperature. Furthermore, by incorporating DERs into the microgrid, the suggested framework will assist the smart community in achieving an annual reduction in electricity bills of up to 38%, according to a thorough analysis of the generation estimation and electricity bill reduction [11].

In [12], a new hybrid fuzzy logic MPPT controller creation and evaluation for solar PV systems under partial shadowing conditions is presented.

In [13], a smart solar connected to the grid inverter simulator system with fuzzy PI control was reported.

In [14], a fuzzy-logic MPPT controller for connected to the grid photovoltaic systems is implemented.

Photovoltaic system's optimum FLC-based PSO was introduced in [15].

Using the Finite Control set model prediction controllers introduced in [16], MPPT efficiency of a connected to the grid solar PV system is increased.

In [17], the topic of adaptive fuzzy logic control for hybrid photovoltaic and wind coupled to microgrids was covered.

## 2 Methodology

The complete research is carried out on MATLAB/Simulation environment. The various parameters like solar module, open circuit voltage(Voc), short circuit current(Isc), no, of panel, no. of series and parallel connection, power rating, inductance and capacitance of boost converter, inverter power rating, operating frequency, fundamental frequency. The dataset of the proposed model is given in Table 1. [18]

**Table 1. Dataset of the proposed model**

| Module | Parameter | Value |
|---|---|---|
| Solar Module | Overall Power Rating Power Rating per Panel Voc Isc No. of Panel Series Parallel Combination | 1.8kW 320W 43V 8.9 8 4 4 |
| Boost Converter | Power Rating Inductance Capacitor Oper. frequency | 1.2kW 5mH 6$\mu$F 10kHz |
| Inverter | Operating Frequency Fundamental Frequency | 15kHz 50Hz |

The comparison of work of existing literature for the estimation of voltage deviation and THD(%) is shown in Table 2.

**Table 2. Voltage deviation and THD(%) estimation with various methods**

| References | THD(%) | Voltage deviation |
|---|---|---|
| Ref. [1] | High | Medium |
| Ref. [2] | Medium | High |
| Ref. [3] | Very high | High |
| Ref. [4] | Medium | High |
| Ref. [5] | High | Very high |
| Ref. [6] | Medium | Very high |

After doing the exhaustive literature review, it is observed that there are lot of concerns related to power quality issues like THD and voltage deviation exist with the existing literature specially to the integrated system. In order to address such problems, Fuzzy logic controller has been applied in the integrated system so that power quality issues could be resolved.

## 3 Boost converter controlling with P&O method

The DC-DC booster's structure is depicted in Figure 1. A DC-DC boost converter is used to increase the output voltage by an additional 142 V. The output voltage(Vo) of boost converter is given in Equation (1).

$$V_o = \frac{V_i}{1-\alpha} \tag{1}$$

The terms in Equation (1) are arranged which gives Equation (2)

$$\alpha = 1 - \frac{V_i}{V_o} \tag{2}$$

The design specifications for the DC-DC boost converter are shown in Equation (3).

$$L_b = \frac{Vpv * D}{2 * \Delta i * fsw} \tag{3}$$

where duty cycle (D) = 1-(Vin/V b) is represented by D. The output capacitor $C_{dc}$ for this DC-DC boost converter which is given in Equation (4).

$$Cdc = \frac{I_{ob} * D}{\Delta v * f_{sw}} \tag{4}$$

given that the output current is $I_{ob}$=($P_{ob}$ / $V_b$). $P_{ob}$ is the DC-DC boost converter's power output, and apparent oscillation is its highest voltage output. 3% Vb is the output voltage, and 31.25 A is the measured consequent current, Iob. Vb is the voltage that emerges. The output condenser value (Cdc) that was measured is 700$\mu$F.

The minimum dc bus voltage should be twice as high as the system's phase voltage given as in Equation (5)

$$V_{dc=} \frac{2\sqrt{2}}{\sqrt{3}} * V_{in} \tag{5}$$

The inductance ($L_f$) of VSC is given in Equation (6)

$$L_f = \frac{\sqrt{3}\mathrm{m}{*}\mathrm{V}_{\mathrm{dc}}}{\Delta \mathrm{i}{*}12{*}\mathrm{h}{*}\mathrm{f}_{\mathrm{s}}} \tag{6}$$

If the ripple is a current value with a value of 5%, the bus's voltage is 10 kHz (V dc) DC, its v dc voltage is 700 V, and its ripple frequency is switching. The Lf is 4.97 mH was measured. One form of hill climbing strategy is the Perturb and Observe (P&O) algorithm. The DC connection voltage in P&O interferes with the converter's duty cycle, the voltage at the PV-panel output, and the voltage at the converter's standard terminals.

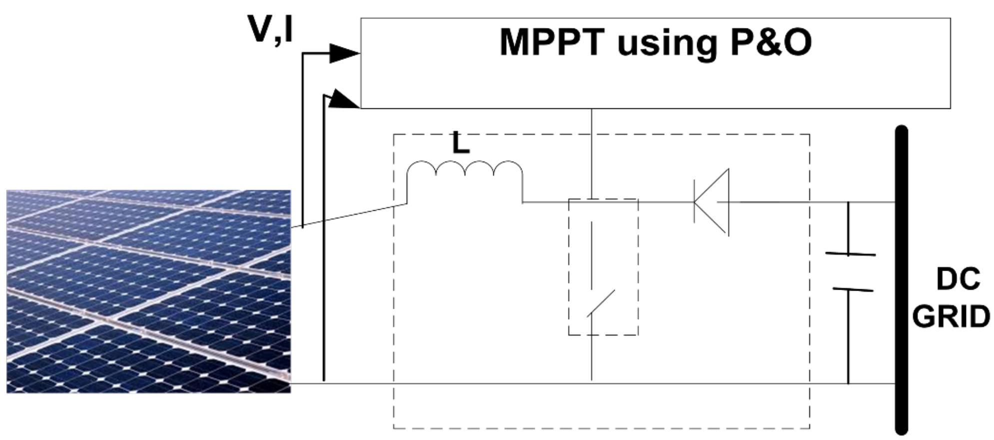


**Fig 1. MPPT based boost converter**

In this procedure, the present interruption is evaluated using the increments and signs of the previous disruption. The disruption's trajectory needs to be changed to give the appearance that it is coming from a decrease in energy, but when the pull from the previous disturbance increases, the interruption should rise. Until the MPPT is reached, the disruptions persist. Throughout the disruption and monitoring process, power is evaluated using voltage and current sensors. Limits are presented and the voltage is determined using the Nth instant. The voltage and current data are assessed at the (N+1)th instant by gradually raising the duty cycle numbers. The energy cost will be shown between the Nth and the (N+1)th. The method will be used again soon because the duty cycle has been marginally improved. The technique follows the negative path after peak energy if the voltage intensity is low. If this happens, the settings for the subsequent operation have been altered and the service cycle is shortened. Case I: $\frac{dP}{dV}$ = 0, Case II: $\frac{dP}{dV}$ > 0, Case III: $\frac{dP}{dV}$ < 0

## 4 Inverter controlling with FLC and vector control

The two methods of inverter controlling are FLC and vector control which are discussed one by one. The general structure of inverter controlling is shown in Figure 2.

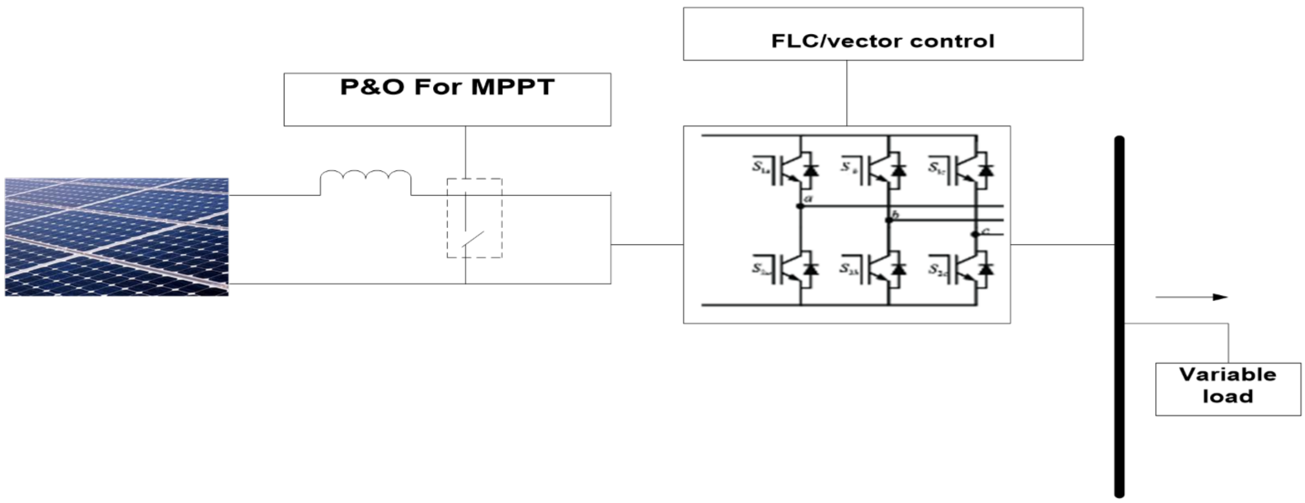


**Fig 2. Inverter controlling with FLC and vector control**

### 4.1 Vector control

After measuring the 3-ph voltage from the AC terminal, it was converted into stationary coordinates ("$\alpha$-$\beta$") using the Clarke transformation, as demonstrated in Equation (7) and Equation (8). These stationary coordinates were then converted into a rotating reference frame (d-q) using the Park transformation, as demonstrated in Equation (9) and Equation (10).

$$V_\alpha = \frac{2\mathrm{V}_a}{3} - \frac{V_b - \mathrm{V}_c}{3} \tag{7}$$

$$V_\beta = \frac{2(V_b - \mathrm{V}_c)}{\sqrt{3}} \tag{8}$$

$$V_d = \mathrm{V}_\alpha cos(\theta) + V_\beta Sin(\theta) \tag{9}$$

$$V_q = -\mathrm{V}_\alpha sin(\theta) + V_\beta cos(\theta) \tag{10}$$

Similarly, the three phase current will transformed into two phase coordinates using Clarke and park transformation from $I_{\text{abc}}$ to $I_{\text{dq}}$.

As indicated by Equation (11), the reference value of the direct axis current (Idref) is produced by the direct axis voltage (Vd) passing through the PID controller.

$$V_d\left(k_p + \frac{k_i}{s} + \mathrm{s}k_d\right) = \mathrm{i}_{\text{dref}} \tag{11}$$

Before going through a PID controller that generated error (e1), the reference value of the direct axis current will be checked with its measured direct axis current, as specified in Equation (12).

$$(i_d - i_{dref})\left(k_{p1} + \frac{k_{i1}}{s} + sk_{d1}\right) = e_1 \tag{12}$$

The error ($e_1$) passes through the PID controller and provides reference values of quadrature axis current($i_{qref}$) as mentioned in Equation (13).

$$e_1\left(k_2 + \frac{k_{i2}}{s} + sk_{d2}\right) = I_{qref} \tag{13}$$

After passing through a PID controller, the modified component of the d-axis voltage (Vd) is obtained by comparing the reference values of the quadrature axis current (iqref) with the measured value of the q-axis current (iq), as indicated in Equation (14).

$$(I_{qref} - I_q)(k_{p3} + \frac{k_{i3}}{s} + sk_{d3}) = V_d \tag{14}$$

Now q-axis will pass through the PID controller as mentioned in Equation (15).

$$V_q(k_{p4} + \frac{k_{i4}}{s} + sk_{d4}) = V_{qref} \tag{15}$$

Additionally, the reference q-axis voltage value will be compared to its DC voltage before passing via a PID controller to get the changed q-axis voltage value as indicated by Equation (16).

$$(V_{qref} - V_{dc})(k_{p5} + \frac{k_{i5}}{s} + sk_{d5}) = V_q \tag{16}$$

Now, using the inverse Park and Clark transformation, the modified value of the dq voltage (Vdq) is converted into a three-phase voltage (Vabc). Additionally, the reference voltage, also known as the three phase voltage (Vabc), will be sent through a PWM converter and compared to the career voltage, which produces the pulses needed to switch the inverter.

## 4.2 Fuzzy logic controller

The FLC-based inverter control procedure is somewhat similar to vector control. Once more, the three-phase voltage (Vabc) is measured, and this is then converted into the two-axis coordinate voltage of voltage (Vdq). The fuzzy logic control's architecture and mathematical modeling for the converter controlling have not changed from what was previously shown. The two inputs used for the FLC-based inverter control are error (e1) and error (e2). While error (e2) is expressed as the difference between the measured and reference value of the q-axis voltage, as demonstrated in Equation (17), error (e1) has already been measured from Equations (5) and (6).

$$(V_{\mathrm{qref}}\text{-}\mathrm{V}_q)=\mathrm{e}_2 \tag{17}$$

The FLC's two inputs are e1 and e2, and its output is direct axis voltage (Vd). As demonstrated in Equation (18), the rules between two inputs are created using Cramer's rule of intersection.

$$A \cap \mathrm{B}=\min(\mathrm{A,B}) \tag{18}$$

7x7 rules and triangle membership are created to ensure accuracy, as indicated in Table 3. The FLC surface is displayed in Figure 3.

**Table 3. Fuzzy rules between two inputs**

| e1/e2 | NB | NS | NM | ZS | PM | PS | PB |
|---|---|---|---|---|---|---|---|
| NB | NM | NB | NB | ZS | PB | PS | PS |
| NS | NM | NB | NS | ZS | PM | PM | PS |
| NM | NB | NS | NM | ZS | PB | PS | PM |
| ZS | ZS | ZS | ZS | ZS | ZS | ZS | ZS |
| PM | PM | PM | PB | ZS | NB | NB | NM |
| PS | PS | PS | PM | ZS | NM | NM | NS |
| PB | PM | PM | PS | ZS | PB | PS | NS |

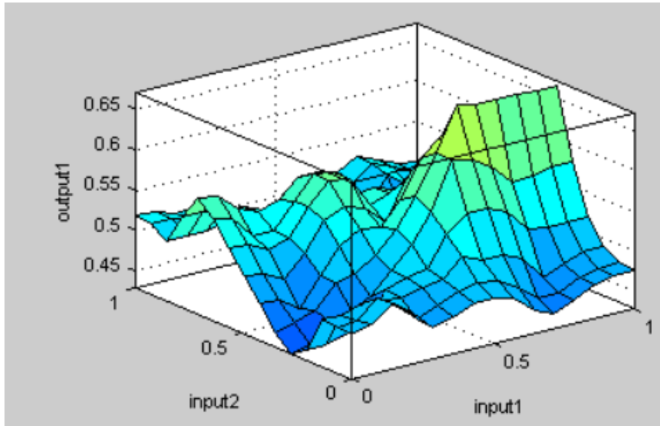


**Fig 3. Surface view of fuzzy rules between inputs and output**

## 5 Results and Discussion

The various characteristics of current and power for single module are shown in Figure 4. The deviations of voltage and THD(%) for various irradiations are shown in Table 4 and Table 5 which shows that the least deviation in voltage and THD have been attained with FLC in contrast to existing method (vector control) under variable loading conditions. The various loading conditions like no load, half load, and full load have been considered for the performance analysis of the proposed system.

Upon employing the recommended procedures, FLC demonstrates the lowest total harmonic distortion (THD) at approximately 6.1% and the minimal voltage deviation at around 3.6% in comparison to vector control.

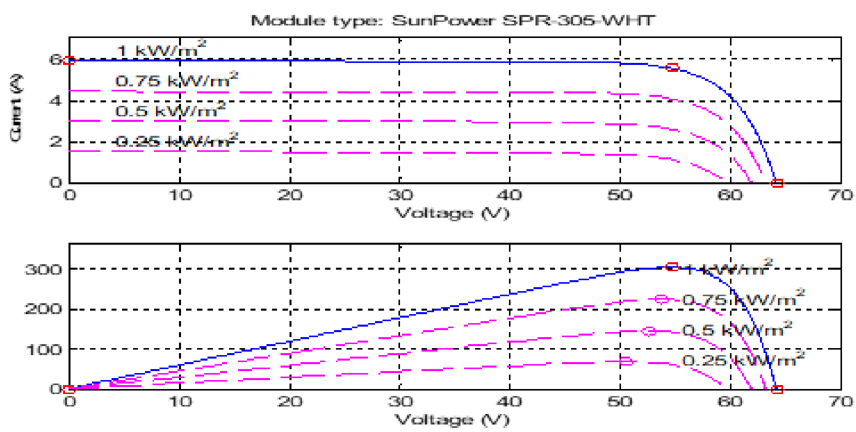


**Fig 4. Current voltage and power voltage characteristics of a single module of solar PV array**

**Table 4. Comparison of THD(%) of voltage with FLC and vector under different loading conditions**

| THD (%) | FLC | Vector control [18] |
|---|---|---|
| No load | 5.6 | 7.9 |
| Half load | 6.8 | 9.1 |
| Full load | 7.7 | 9.8 |

The comparative analysis for the estimation of THD(%) and voltage deviation under different loading conditions are shown in Table.4 and Table.5. The finding of the research gives least voltage deviation and minimum THD(%) with FLC in contrast to the previous method i.e vector control [18]. The improvement of these performance parameters in the grid integrated system with the support of solar photovoltaic cell is the novelty of the research.

**Table 5. Comparison of voltage deviation with FLC and vector under different loading conditions**

| Voltage deviation (%) | FLC | Vector control [18] |
|---|---|---|
| No load | 2.6 | 7.8 |
| Half load | 3.8 | 6.9 |
| Full load | 1.9 | 5.6 |

## 6 Conclusion

This study describes how to integrate solar photovoltaics (SPV) with the AC grid using an inverter and boost converter. The maximum power point (MPP) extraction from perturb and observe (P&O) based method has been used to control the boost converter. Additionally, a fuzzy logic controller (FLC) has been used to operate the inverter. At the AC grid terminals, the integration results in greater THD and voltage variations. Following the use of the suggested techniques, FLC is shown to have the lowest THD($\approx$6.1%) and the least voltage deviation($\approx$3.6%) when compared to vector control.

There is a scope of improvement in the performance parameters like voltage deviation and THD of the integrated system. Such enhancement could be possible with the advanced intelligent techniques.

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