Adaptive Fractional-Order Fuzzy Logic Control of Grid-Tied Photovoltaic Inverter

Hamedalneel Babiker Aboh

Indian Institute of Technology Roorkee, Electrical Engineering Department, Roorkee, Uttarakhand 247667, India

Abstract: Photovoltaic (PV) energy source has gained more interest in recent decades, due to the environmental concerns and depletion in the conventional energy resources reserve such as fossil fuel. Furthermore, this type of energy source has more advantages such as free of pollution, reliability, availability, no mechanical moving part, little maintenances, has long life time, and quietness. In future more, photovoltaic energy source is anticipated to be interfaced with a grid. Beside the low efficiency of a photovoltaic energy source, a controllability of grid-tied based photovoltaic system is its main challenge. As the result, interfacing photovoltaic energy source to grid can derived to grid instability, if the system is not appropriately designed. Therefore, the control techniques applied to grid-tied photovoltaic energy source becomes of high interest and always important for the sake of accomplish excellent power quality and highest reliability. Those goals can be accomplished by advanced control methods which includes two stages: The first stage is MPPT controller based on the fractional-order fuzzy logic controller (FOFLC) to accomplish the objective of maximizing the output power of photovoltaic array during regular and irregular atmospheric conditions. A second stage is the control of H-bridge VSI with unipolar sinusoidal pulse width modulation (SPWM) technique. A control technique of the H-bridge VSI consists of two cascaded loops, where an external loop voltage regulator is employed to stabilize voltage of dc link to a required level, this can be achieved by the means of MPPT algorithm, while an internal loop current regulator is employed to maintain the unity power factor operation. It has been found that from many research studies have been done concerning to the grid-tied photovoltaic energy source which mainly focuses on the internal control loop with less attention to external control loop and lacking of stability analysis. This paper presents the complete control techniques of single-phase grid-tied photovoltaic energy source considering the nonlinear dynamic behavior of photovoltaic energy source. For the validation of an effectiveness, efficiency, and validity of the proposed model the simulation results have accomplished through MATLAB/ Simulink simscope power system.

Keywords: Photovoltaic (PV), grid-tied PV system; FOFLC MPPT, current/voltage controller, phase locked loop (PLL).

1. Introduction

Recently the renewable energy source has gained more interest, due to the environmental concerns and depletion in the conventional energy resources reserve such as fossil fuel [1], [2]. Among all renewable energy source photovoltaic energy is preferred. This type of energy source has more advantages such as free of pollution, reliability, availability, no mechanical moving part, little maintenances, has long life time, and quietness [3]. The photovoltaic system exhibits nonlinear dynamic characteristics of (voltage, current), and change with atmospheric conditions (irradiance and temperature). Consequently, a MPPT algorithm technique is employed to ensure that the photovoltaic array is operating at MPP to match the current atmospheric variations [4]. MPPT technique is a real-time control algorithm, which applied to energy converter placed between photovoltaic module and photovoltaic inverter to amplify the photovoltaic module output power. Numerous MPPTs algorithm techniques have studied and industrialized in recent decades to increase the efficiency operation of the photovoltaic module during varying atmospheric conditions [4], [5]. In this study fractional order fuzzy logic controller based MPPT techniques is integrated to the system to maintain the photovoltaic array operation at MPP regardless of the atmospheric conditions. The advantages of this technique are: fast dynamic response; control imprecise system; robustness; needless of exact mathematical expression [6]. Moreover, this technique has ability to precisely track the MPP with minimum oscillation under rapidly atmospheric conditions compare to the classical MPPT algorithms such as free of pollution, reliability, availability, no mechanical moving part, little maintenances, has long life time, and quietness. In future more, photovoltaic energy source is anticipated to be interfaced with a grid. Beside the low efficiency of a photovoltaic energy source, a controllability of grid-tied based photovoltaic system is its main challenge. As the result, interfacing photovoltaic energy source to grid can derived to grid instability, if the system is not appropriately designed. Therefore, the control techniques applied to grid-tied photovoltaic energy source becomes of high interest and always important for the sake of accomplish excellent power quality and highest reliability. Those goals can be accomplished by advanced control methods which includes two stages: The first stage is MPPT controller based on the fractional-order fuzzy logic controller (FOFLC) to accomplish the objective of maximizing the output power of photovoltaic array during regular and irregular atmospheric conditions. A second stage is the control of H-bridge VSI with unipolar sinusoidal pulse width modulation (SPWM) technique. A control technique of the H-bridge VSI consists of two cascaded loops, where an external loop voltage regulator is employed to stabilize voltage of dc link to a required level, this can be achieved by the means of MPPT algorithm, while an internal loop current regulator is employed to maintain the unity power factor operation. It has been found that from many research studies have been done concerning to the grid-tied photovoltaic energy source which mainly focuses on the internal control loop with less attention to external control loop and lacking of stability analysis. This paper presents the complete control techniques of single-phase grid-tied photovoltaic energy source considering the nonlinear dynamic behavior of photovoltaic energy source. For the validation of an effectiveness, efficiency, and validity of the proposed model the simulation results have accomplished through MATLAB/ Simulink simscope power system.

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Keywords: Photovoltaic (PV), grid-tied PV system; FOFLC MPPT, current/voltage controller, phase locked loop (PLL).
2. System Configuration

A Schematic representation of the proposed dual-stage grid-tied single-phase PV system is illustrated in Fig. 1, which consists of PV array, the dc-dc boost converter, the MPPT based on Fractional order fuzzy logic controller, H-bridge unipolar SPWM VSI inverter, single-phase LCL filter, and grid synchronization algorithm based on the phase locked loop (PLL).

3. FOFLC Based on MPPT

The main goal of a FOFLC based on MPPT technique in a PV energy source is to regulate constantly operation of PV module at MPP irrespective of the variations of the atmospheric conditions [9]. The FOFLC-based MPPT offers adaptive variations of the duty ratio based on the position of the operating point regrading to maximum power point. Hence, this can decrease the steady-state oscillation and power functioning problems under quick variations in atmospheric conditions. Nevertheless, although the excellent performance of FLC technique in tracking an MPP, but also it has some limitations such as fixed on fuzzy field [13], deep experience of the system operation, and requires large memory size with high-speed microcontroller ability with large memory size. Fractional order-FLC (FOFLC) is proposed to enhance the tracking in case of the varying atmospheric conditions, by comprehend the precision of a FLC with robustness the of an FO. As the result the FOFLC fast-tracks the MPP and prevents deviating from the MPP. A FLC has two input variables error E(j) and change in error ΔE(j) described as in (1) and one output is change in the duty ratio Δd(j) of power converter (boost converter).

\[
E(j) = \frac{P(j) - P(j-1)}{V(j) - V(j-1)}
\]

\[
ΔE(j) = E(j) - E(j-1)
\]

The fraction derivatives of the Grunwald–Letnikov (GL) and Riemann–Liouville definition are commonly used in an FO system. Based on the GL equation which is documented in [14].

\[
\frac{d^α P(V)}{dV^α} = \lim_{ΔV→0} \frac{1}{ΔV^α} \sum_{j=0}^{n} \binom{α}{j+1} P(V - jΔV)
\]

Where P(j) indicates as the PV array output power at sample time (j), and V(j) indicates as an output voltage PV array when α > 0. (2) can be modified as in (3) by take into account the only first two terms.

\[
\frac{d^α P(V)}{dV^α} = \frac{P(V) - αP(V - V)}{ΔV^α}
\]

Variations of a voltage and power describe the fair calculation in fractional order calculus. The power (P) and the voltage (V) are at current step. The FO incremental variations of a P and a V are approximated as dP ≈ PαP0 and dVα = ΔVα = VαV0 respectively. Therefore, the (1) can be written as in (4).

\[
E(j) = \frac{P(j) - P(j-1)}{V(j) - V(j-1)} = \frac{P - αP_0}{V - V_0}
\]

\[
ΔE(j) = E(j) - E(j-1)
\]

Here 0 < α ≤ 1, Once α = 1, represents a FLC. Once 0 < α < 1, signifies a FOFLC [15]. Fig 2 illustrate the geometric estimation of ΔV to the αth derivative, the vertical-axis presents the output power while a horizontal-axis indicates as an output voltage, the third line is α. The fractional order variation of the output power equal to P(αV)-αP(V-ΔV). A fractional order variation of an output voltage equal to (αth) differentiate of (ΔV).

![Figure 2: Geometric interpretation of FO differentiation.](image-url)
By using these membership functions and division of fuzzy subsets, handling efforts to obtain the output control can be diminished drastically, though the steady state oscillation is kept small. Once an input values of FLC E(j) and CE(j) are transformed to the linguistic variables, fuzzy logic output ΔD(j) can be look up in rule base table. The rule base is framed using fuzzy inference system (FIS) as given in Table 1.

$$\Delta D = \frac{\sum \mu(D_j)D_j}{\sum \mu(D_j)}$$

The output of FOFLC offers an analog signal that is control through PWM which gives ΔD to step up power converter

### 4. An external Voltage Regulator

The main goal of an external regulator is to adjust the voltage of dc link to a desired level. Generally, dc-link voltage with voltage ripple of 1-5% of the dc-link rated voltage is allowed. Fig 4 illustrates a block diagram of an external loop voltage regulator.

Here the reference dc-link voltage compares to actual value of dc-link voltage, and their difference (error) is passed through PI controller to minimize the steady state oscillation [16]. The PI controller for an external loop voltage regulator is expressed by

$$G_{PI}(s) = \frac{K_p + K_i}{s}$$

Where $K_p$ indicates as proportional gain; $K_i$ indicates as integral gain of PI controller. The PI controller for external loop is properly designed for a low crossover frequency (5-20Hz) using Ziglar-Nicholes technique with $(K_p = 0.01, K_i = 0.5)$ in order to attenuate the value of (100Hz) that is feedback from dc link. The mathematical expression between the mean voltage of dc-link and the differences in the fundamental grid current magnitude can be determined by means of peak power balance concepts, by neglecting the losses of the converter. The mathematical derivation of the plant transfer function is documented in [17] and repeated here for the purpose of the completeness.

$$G_{plus}(s) = \frac{V_n(s)}{I_p(s)} = -\frac{1}{2sC_{dc}}$$

### 5. An Internal Current Regulator

Typically, the current regulator is applied to achieve high power quality, stability, which are very significant matters for responding with the standards. Usually, the dynamic response of an internal current regulator is faster than the dynamic response of an external voltage regulator. The proportional plus resonant controller (PR) and PI controller with feedforward grid voltage are commonly used in an inner loop current regulator for photovoltaic inverters. However, the PR controller has superiority over PI controller when adjusting the sinusoidal signals. The former controller has ability to remove phase angle steady-state oscillation with needless the voltage feedforward, as well it has capability of disturbance rejection [18], [19]. Due to the harmonic rejection capability and fast dynamic response of PR controller is considered in this study. Fig 5 represents a block illustration of non-ideal PR controller and its transfer function is given in (8).

$$G_{pr}(s) = \frac{2K_p\omega ps^2 + 2K_p\omega ps + \omega_p}{s^2 + 2\omega ps + \omega_o^2}$$

Where the $K_p$ indicates as proportional, and $K_o$ indicates as resonant gain of PR controller, is (Ω) frequency, and is grid frequency.
6. Single-Phase Grid Synchronize algorithm

Grid synchronization algorithm presents an essential role in the control of a grid-tied photovoltaic system inverters. Moreover, the parameters of utility grid voltage e.g. (frequency, phase, and amplitude) can be calculated to observe the differences of grid voltage. Various number of the synchronization algorithms such as (park transformation, transport delay T/4, inverse park transformation, and Hilbert Transformation) have been studied and developed in literature [20], [21], [22]. Nevertheless, all these PLL techniques have some drawbacks (i.e. nonlinearity, frequency dependency, complexity) as specified in the [21]. Therefore, in this study PLL technique e based on second order generalized integrator (SOGI) for OSG is used as a substitutional solution to mitigate the abovementioned disadvantages of a conventional PLL techniques. Fig 7 shows a schematic representation of the PLL based on a SOGI-OSG. The SOGI transfer functions are given by

\[ G_{SOGI}(s) = \frac{\omega s}{s^2 + \omega^2} \]  
\[ G_p(s) = \frac{V_p(s)}{s^2 + k\omega s + \omega^2} \]  
\[ G_q(s) = \frac{qV_q(s)}{s^2 + k\omega s + \omega^2} \]

Form (9-11) it is clear that the bandwidth of SOGI is the closed loop gain (K) function, and it does not depend on center frequency \( \omega_c \), which makes this technique appropriate for variable frequency operations. In this study the value of K was set equal to 0.7

7. Single-Phase LCL Filter

Generally, the LCL filter is interfaced at the PV inverter output to mitigate the switching harmonics injected into the utility grid [23], [24]. An equivalent electrical circuit configuration of the single-phase LCL filter is illustrated in Fig. 9, which consist of \( L_p \) is the inductor of the inverter side \( L_p \), is the inductor of the grid side, and \( C_i \) is filter capacitor. By considering the inverter as harmonics generator and grid as short circuit the current harmonics attenuation can be calculated. The design procedures of LCL filter values use a line frequency, inverter power rating, and switching frequency as inputs parameters [24]. The LCL values are stated as percentage of the base values.
an LCL-filter transfer function includes damping resistance is
given by

\[ G_{LCL}(s) = \frac{1}{(L_i + C_i s + L_f) R_j s^2 + (L_i + L_f)s} \]  

(12)
The base capacitor and base impedance can be calculated as
in (13)

\[ Z_n = \frac{V_i}{P_i}, C_b = \frac{1}{\omega_r z} Z_n \]  

(13)
Where \( V_i \) is rated voltage (RMS), \( P_i \) is rated power (W), and \( \omega_r \) is grid frequency. Since the unipolar SPWM is used; hence the inverter side induc-tor is given by

\[ L_i = \frac{V_{dc}}{8 \times \Delta i_{r,\text{max}} \times f_s} \]  

(14)
Where \( f_s \) is switching frequency , \( \Delta i_{r} \) is currnt ripple. The desired ripple current is given by

\[ \Delta i_{r,\text{max}} = \text{ripples\%} \times \frac{P_i \sqrt{2}}{V_i} \]  

(15)
The filter capacitor can be calculated as given in (19)

\[ C_f = x C_b \]  

(16)
Where \( x \) represents the percentage of the reactive power required by \( C_f \) (in this paper \( x \) is taken 5%). The grid side inductor can be calculated using resonant frequency \( (\omega_r = 2 \pi f_s) \).

\[ \frac{f_s}{2} > f_r > \frac{f_s}{4} \]  

(17)
\[ L_{LCL} = \frac{L_{L}}{\omega^2 r_s L_{L} x C_f - 1} \]  

(18)
An LCL filter design procedures mentioned above has been applied to system with rated power \( P_2 = 2.7 \text{Kw} \), switching frequency \( f_s = 10 \text{KHz} \), rated voltage \( V_i = 230 \text{V (RMS)} \), and dc-link voltage \( V_{dc} = 400 \text{V} \) gives the LCL filter values as given in TABLE 2.

8. Simulation Results and Discussion

For the validation of reliability, accuracy, adequacy, and the efficiency of a proposed system, simulations outcomes are
obtained. Moreover, to verify an efficiency and reliability of a proposed MPPT algorithm based FOCFLC technique and
test control techniques of a single-phase grid-interface VSI, have
been carried out by means of MATLAB/Simulink Simscape power
system under three different atmospheric conditions.

8.1 Case one: at standard test condition (STC) 1000
W/m² and 25°C.

Fig 8 illustrates the simulation results of the dual-stage system at STC (1000W/m², 250C). The dc-link voltage
regulator adjusts the voltage of a dc link in a short period (t =
0.09 sec) with minimum steady state oscillation as given in
Fig 8 (a). It can be noticed that as its given in Fig 8 (b) and
(c) an output sinusoidal waveforms of output voltage and
current, where both are in-phase. The average active and
reactive powers generated by PV system at STC (1000W/m²,
25°C) are about 2.7 kW and 0 Var as shown in Fig 8 (d). In
this situation the inverter is injecting an active power into
grid by controlling the d-axis current, and the current of
the q-axis is made to be zero at similar time to maintain
the reactive power at zero value.

Figure 9: (a) dc link voltage (b) grid voltage (c) grid current
(d) Active/ Reactive power.

Fig 10 illustrates an LCL-filter impacts on of a PV inverter
output current and output voltage. The FFT plot of a
harmonic spectrum and grid current THD is illustrated in Fig
11. Its shows lower harmonic content for inverter output
current which is satisfy the IEEE standards. Therefore, the
proposed system successfully injected the maximum power
into utility grid with nearly unity power factor and high
efficiency.

Figure 10: Inverter output (a) voltage (b) current before and
after LCL filter.
8.2 Case two: at irregular solar irradiance and constant temperature 25°C.

In this situation the simulation results have carried out under irregular solar irradiance and constant temperature. At the beginning the surface temperature was kept constant at 25°C and the initial solar irradiance is considered as 1000W/m² the corresponding active and reactive power is 2.7 kW and 0 Var respectively. At \( t = 0.4 \) sec, solar irradiance is ramped down from 1000W/m² to 500W/m² the corresponding decrease in output current and active power equal 1.3 kW but reactive power is kept equal zero as shown in Fig 12 (a), (g). Regardless of change in the solar irradiance the dc link voltage is rapidly stabilized at its desired level of 400 V, which confirms the efficiency and reliability of an external voltage regulator and MPPT algorithm as depicted in Fig 12 (b). At \( t = 0.8 \) sec the solar irradiance starts increasing from 500W/m² to 1000W/m² corresponding increase in the output current, voltage, and active power (2.7 kw), but the reactive power is remaining constant zero. An external voltage regulator is appropriately track the d-q axis references current as given in Fig 12 (h). An inverter output voltage and current waveforms that injected into utility grid are given in Fig 12 (c), (d), (e). the injected voltage into grid was pure sinusoidal with frequency of 50 Hz and amplitude of 330 V as depicted in Fig 12 (f).

![Figure 11: Harmonic spectrum and THD of grid current.](image)

![Figure 12: System responses for the variations of solar irradiance](image)

The grid current and voltage both are in-phase. Therefore, the THD of an inverter output current is less than 5%, which is satisfy the IEEE-519 standards as shown in Fig 13.

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**Figure 11:** Harmonic spectrum and THD of grid current.

**Figure 12:** System responses for the variations of solar irradiance (a) solar irradiance change level (W/m²), (b) dc link voltage (V), (c) grid voltage (V), (d) grid voltage at \( t = 0.4 \) sec-0.6 sec, and (e) grid current (A) (f) grid frequency (g) active/reactive power (w/var) (h) d-q axis current (pu).
8.3 Case three: at irregular solar irradiance and surface temperature variations

In this case the simulation results have carried out under solar irradiance level variations and surface temperature variations of the PV array. Initially the solar irradiance is set to 1000 W/m² and surface temperature is considered as 25°C as represented in Fig 14 (a), (b) it easily to be observed that, the voltage at dc link stabilized at desired level 400 V as shown in Fig 14 (c). At the t = 0.4 sec the PV array is subjected to the lower temperature (25°C) and lower solar irradiance (500 W/m²), it can be noticed from Fig 14 (c) an external voltage regulator adjusts the voltage at desired level with the help of the FOFLC MPPT algorithm. PV array surface temperatures increase linearly from 25°C to 35°C during the period of 0.7 to 0.8 sec as in Fig 14 (a), (b), also it is easy to notice that the voltage of dc link is still stable as given in Fig 14 (c) which demonstrate which confirms the effectiveness and accuracy of proposed MPPT controller and an external dc link voltage regulator. An inverter output current and voltage injected into grid is illustrated in Fig 14 (d), (e).

9. Conclusion

In this paper a dual-stage grid-tied PV system generation and its control schemes have been proposed. The control schemes of the proposed system involve of MPPT algorithm, dc link voltage controller, and current controller. The MPPT technique based on the FOFLC is applied to the PV array for extraction the maximum power, while an external voltage controller is used to adjust the dc link voltage at a desired value. Evaluation of MPPT based FOFLC, voltage and current controller, and grid-side filter for different operation modes have been discussed. From above discussion and simulation results of a proposed system, it has been demonstrated that the control techniques offer better performance with nearly unity power factor under standard test condition (1000W/m², 25°C) and changing atmospheric conditions.

References


**Author Profile**

Hamedalneel Babiker received the B.Sc. degree in electrical and electronic engine-ring (Power system) from university of Nyala, Nyala, Sudan, in 2014, and the M-tech from Indian Institute of Technology Roorkee, Roorkee, UK, India, in 2018. In 2014 he joined the University of Nyala, electrical engineering department, as teaching assistance and then he became a lecturer in 2018. He has authored three technical papers in referred journal and conferences. His research interests include control of grid interfaced photovoltaic (PV) system, power electronics, power quality, control system, FACTS devices, power system protection, and distributed generation.

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