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Fuzzy Fractional order PI Controller for a Multilevel Inverter for Grid-Connected Photovoltaic Systems (PV)

***Abstract**. These Applications of fractional calculus are becoming more and more effective, adaptable, and have produced positive outcomes in a variety of engineering and scientific domains. In this paper, a fuzzy fractional-order PI-based control approach for grid-connected photovoltaic (PV) systems is presented. The various advantages of multi-level inverters (MLIs) in industrial and grid-connected applications have resulted to their increasing application in recent years. A five-level neutral point (NPC) inverter is used to integrate PV electricity into the electrical grid with minimal harmonic distortions and highest power capacity. The output voltage of the inverter must be maintained in order to connect to a grid, even though that the photovoltaic output voltage varies considerably with solar radiation. To achieve this, three fuzzy fractional order PI (FFOPI)controllers were used to control the inverter output voltage (Vdc), direct current (Id), and quadratic current (Iq) around a reference values. A further comparison is made with the fuzzy PI (FPI). According to research, the FFOPI controller outperforms the FPI controller in terms of performance.*

***Streszczenie.** Te zastosowania rachunku ułamkowego stają się coraz bardziej efektywne, elastyczne i dają pozytywne rezultaty w różnych dziedzinach inżynierii i nauki. W tym artykule przedstawiono podejście oparte na rozmytym ułamkowym rzędzie sterowania PI dla systemów fotowoltaicznych (PV) podłączonych do sieci. Różne zalety falowników wielopoziomowych (MLI) w zastosowaniach przemysłowych i podłączonych do sieci spowodowały ich rosnące zastosowanie w ostatnich latach. Falownik z pięciopoziomowym punktem neutralnym (NPC) służy do włączania energii elektrycznej z fotowoltaiki do sieci elektrycznej przy minimalnych zniekształceniach harmonicznych i najwyższej mocy. Napięcie wyjściowe falownika musi być utrzymywane w celu podłączenia do sieci, mimo że napięcie wyjściowe fotowoltaiki znacznie się zmienia w zależności od promieniowania słonecznego. Aby to osiągnąć, zastosowano trzy rozmyte regulatory PI ułamkowego rzędu (FFOPI) do sterowania napięciem wyjściowym falownika (Vdc), prądem stałym (Id) i prądem kwadratowym (Iq) wokół wartości odniesienia. Dalsze porównanie przeprowadza się z rozmytym PI (FPI). Według badań kontroler FFOPI przewyższa kontroler FPI pod względem wydajnoś, (**Rozmyty regulator PI rzędu ułamkowego dla wielopoziomowego falownika do systemów fotowoltaicznych podłączonych do sieci (PV**)*

Keywords: Fractional-order PI controller, Fuzzy systems, Multilevel inverter, Photovoltaics Systems.
Słowa kluczowe: Regulator PI ułamkowego rzędu, Systemy rozmyte, Falownik wielopoziomowy, Systemy fotowoltaiczne.

I. Introduction

Solar energy is becoming increasingly essential. When compared to other alternative sources, it is a renewable source that produces no fuel, emits no pollution, and emits no noise [1].

In this context, one of the solutions that improve the performance of photovoltaic systems is the use of multi-level inverters (MLI). The purpose of using MLI is to produce an almost sinusoidal voltage signal by increasing the number of inverter levels which allows for a pure sinusoidal voltage signal without the use of expensive and bulky passive filters [3].

A crucial factor to take into account is the performance of a multi-level inverter in a grid-connected PV system since it has a major impact on the effectiveness of the PV system and the caliber of the electricity generated. [2]. By adjusting the parameters of fractional-order PI controllers for DC/AC stages based on a fuzzy logic system that allows flexible injection of electrical energy into Photovoltaic generator grating without distortion or AC phase shift, the dynamic performance of grid-connected multilevel inverters will be improved [5,4].

Classical controllers and intelligent controllers are widely used in different applications. The PID controller is a classical controller the most used because it has a simple structure and is easy to assume, implement and tune [6].

The recently progress in the fractional-order systems have greatly increased the studies on the fractional-order (FO) control system [7,8].

The fractional order PID controller (FOPID or $PI^{\lambda} D^{\mu}$) is a derivation of the PID controller that includes two additional parameters, the integral order and the differential order (λ,μ) [9, 10].

The two additional parameters (λ,μ) provide more flexibility in achieving controller design specifications.

Several Studies have shown that FOPID controllers outperform other controllers in industry applications [12], including controlling greenhouse temperature [13] and bioreactor temperature [14].

Liu et al. [11] introduced a fuzzy PID control method for an industrial temperature control system in order to improve the production quality and accuracy of control models.

In this work, we present the fractional order PI controller combined with the fuzzy logic controller to improve the controller performance by adjusting the parameters (K_p,K_I,λ)

This paper investigates the dynamic behavior of a five phase multilevel inverter connected to a PV system.

The control system is made up of three control loops based on Fuzzy Factional order PI (FFOPI): the FFOPI1 is used for controlling the intermediate circuit voltage (V_{dc}), and FFOPI2, FFOPI3 for controlling the direct and quadratic currents (I_q,I_d) supplied by the multilevel inverter. The proposed controller parameters (K_p,K_I,λ) must be selected in order to increase the efficiency of the multi-level inverter while decreasing the total harmonic distortion (THD) of the output current of the inverter as well as voltage.

The aim is to have an optimal tuning of the parameters (K_p,K_I,λ) of the three FFOPI controllers in order to improve the performance of the inverter with five levels.

Consequently, a comparative study has been proposed between: fuzzy fractional order PI (FFOPI), fuzzy PI(FPI) which will be developed in the following sections. Matlab/Simulink will be used to run the simulation

This paper is organized as follows. Firstly, "The modelling of the system" introduces the studied multilevel inverter for photovoltaic, the photovoltaic generator, Buck converter DC/DC.

Secondly we present the "control design" gives the preliminaries of fractional calculus including fractional derivative, the classical PI, Fractional PI, the structure Fuzzy Fractional order PI control, where membership functions of inputs and outputs, fuzzy rules base and the design steps of Fuzzy PI controller are given. Than the simulation result is presented. Finally, we present a conclusion

II. PV model

The diagram of the studied system is illustrated in Fig.01. This figure shows the overall system. All transformers used for the PV generator. DC/DC converter DC bus line for connection with NPC multilevel converter the power injected into the grid passes through the LC filter.

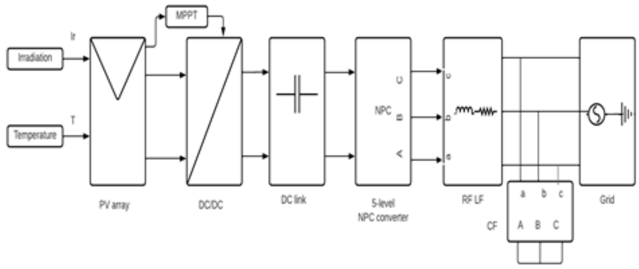

Fig.1. System's block diagram grid-connected PV.

II.1. Photovoltaic Generator

Because the power available at the terminals of a cell is very low, it is necessary to group the cells in series and parallel to obtain modules of acceptable power. These models consist of complex equations whose solution requires a number of parameters (6), the single diode model with five parameters (R_s,R_{sh},I_{ph},I_0,A) is presented in Fig.2. [15]

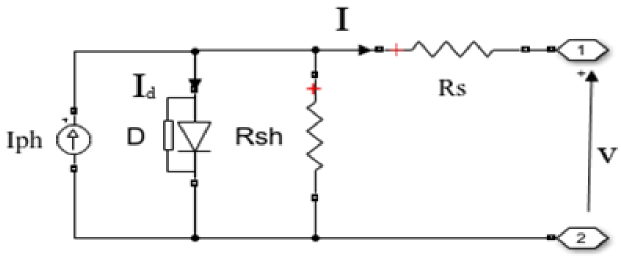

Fig 2. Equivalent diagram of a photovoltaic cell

Whereas:

$$I_{ph} - I_0\left(e^{\frac{q}{nAKT}(V+R_s\times 1)} - 1\right) - \frac{V+R_s\times 1}{R_{sh}} \tag{1}$$

I: The current delivered by the photovoltaic modulel R_{sh}: Shunt resistance; I_{sh} :Photoelectrical current; I_0 :Saturation current; R_s: Series resistance; *K:* Boltzmann factor 1.38. e^{-23} JKl; : Coefficient the diode ideality; The solar panel parameters that identify equation (1) are represented in the following equations:

$$I_{scpanel} = N_p \times I_{sc} \tag{2}$$

$$I_{opanel} = N_p I_0 \tag{3}$$

$$R_{spanel} = \frac{N_s}{N_P} R_s \tag{4}$$

$$R_{Ppanel} = \frac{N_s}{N_P} R_P \tag{5}$$

The photoelectric current (I_{ph}) depends on irradiation and temperature as shown in Eq (6).

$$I_{ph} = (I_{ph,n} + K_1 \Delta T) \times \frac{G}{G_n} \tag{6}$$

$$I_0 = \frac{(I_{scn} + K_1 \Delta T)}{\exp\left(\frac{V_{0cn} + K_v \Delta T}{AV_{th}}\right) - 1} \tag{7}$$

$$\Delta T = T - T_n \tag{7}$$

Where: I_{scn}: Short-circuit current under nominal conditions (G_n=1000W/m^2, T_n=25 °C) the cell's ambient and nominal temperatures are represented, respectively, by *T* and T_n; where the current and nominal irradiation are *G* and G_n, respectively.

The short circuit current's temperature coefficient is K_I , while the open circuit voltage's is K_v, V_{th} given in (1) is the thermal junction constant and is equal to the V_{th} =*KT/q* value. Here, where q is the electron burden (1.602. 10^{-19} C). Table1 displays the characteristics of the sol tech 1STH-215-P solar arrays parameters under standard conditions.

Table1. PV panel parameters

parameter	P_{mp}	V_{mp}	I_{mp}	V_{oc}	I_{sc}	N_s
Value	213.15	29	7.35	36.3	7.84	60cell

The solar panel array is made up of five parallel strings, each of which has 10 panels connected in series and produces 15 KW in total.

II.2. Boost Converter Dc/Dc

The boost converter is a form of DC-to-DC converter in which the output voltage magnitude is greater than the input voltage magnitude. It is a type of switched-mode power supply (SMPS) that operates with an inductor, a diode, a capacitor, and a high frequency semiconductor switch. According to Fig. 3,V_{in} is the input voltage and V_{out} is the output value [17-20].

$$V_{out} = \frac{1}{1-D} V_{in} \tag{9}$$

$$D = \frac{T_{on}}{T} \tag{10}$$

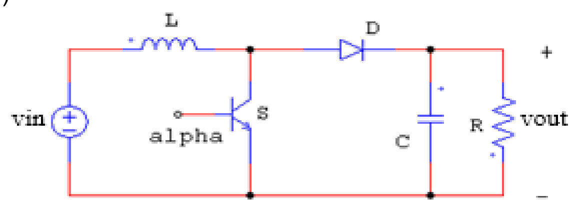

Fig 3. Circuit of the boost converter.

Table 2 Selected settings.

Parameter	C1	C2	L	f
value	1000e^{-6}F	1.3846e^{-4}F	0.0022H	10KHZ

II.3. System connected to network

Any grid-connected system's most crucial component is the inverter. The inverter transforms as much DC (direct current) power as possible from the solar array into the necessary voltage and frequency in order to supply energy (alternating current) to the grid. by using an LC filter to remove the harmonics produced by the sinusoidal signal. The filter parameter values are shown in Table 3.

Table3. Filter parameters.

Para meter	$R_f(\Omega)$	$L_f(H)$	$C_f(F)$	$U_a(V)$	f (Hz)
value	0.4312	0.0043	$1.1749e^{-6}$	380	50

II.4. Topology of the diode clamped multilevel

Multilevel inverters are being considered for an increasing number of applications due to their large power capacities together with decreased output harmonics and commutation losses. Multilevel inverters have been shown to be a successful and useful method of boosting power and lowering AC load harmonics [16].

The most popular multilevel architecture is the diode clamped inverter, in which the output voltage is modulated by clamping the dc bus voltage using a diode as the clamping device. The primary idea behind this inverter is to employ diodes to reduce the voltage stress on the power components. Each capacitor and switch is exposed to a voltage of V_{dc}[16].

The diode clamped inverter is the most commonly used multilevel topology, in which the diode is used as the clamping device to clamp the dc bus voltage in order to achieve steps in the output voltage. Thus, the main concept of this inverter is to use diodes to limit the power devices voltage stress. The voltage over each capacitor and each switch is Vdc[16]. (n-1) voltage sources, 2(n-1) switching devices, and (n-1) (n-2) diodes are required for a n level inverter. The quality of the output voltage improves as the number of voltage levels increases, and the voltage waveform approaches the sinusoidal waveform [17].

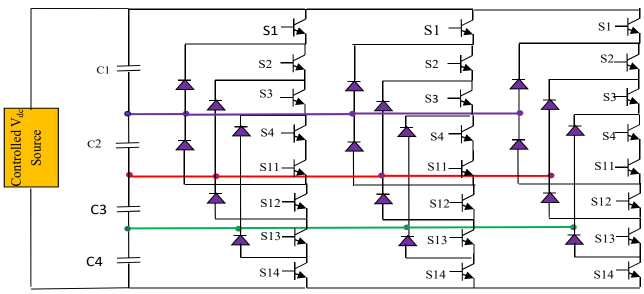

Fig. 4. The three-phase, five-level, diode-clamped inverter

Table 4. Switching state for 5-level

S_1	S_2	S_3	S_4	S_{11}	S_{12}	S_{13}	S_{14}	V_{out}
1	1	1	1	0	0	0	0	V_{dc}x0.5
0	1	1	1	1	0	0	0	V_{dc}x0.25
0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	-V_{dc}x0.25
0	0	0	0	1	1	1	1	-V_{dc}x0.5

II.5. Control system

To enable the transfer of electricity from the PV generator to the grid, a particular control system has been developed for the proposed NPC multilevel inverter. It was necessary to link a controller to accomplish this. To ensure the stability of the DC voltage buses in their reference value by using an FOPI controller. The output of this FOPI controller will define the current references, the controllers of the active currents to the network generated for the PV panels .as seen in Fig 7,8.The existing controller loops are discussed in this arrangement, First, the three phase currents *(a, b, c)* are transformed into the two phase, rotating alpha beta *(a, b, c)*, which we can't control if it is rotating, so we further convert into the two phase, stationary (dq0) , which contains the i_d and i_q currents.To produce the E_d and E_q , which are needed to obtain the three-phase reference voltages, i_d and i_q are employed.

The constant variables i^*_d and i^*_q are used to regulate grid current.The *D-Q* axes theory uses the three-phase currents to produce i_d and i_q currents.The *ED* and *EQ* outputs of the current controllers can be utilized as reference voltages to produce PWM.As shown in Fig 7,8, the *ED* and *EQ* are converted into three phase reference voltages V_{Aref}, V_{Bref} , and V_{Cref} in this process.As I mentioned before, the PLL can provide information on the grid voltage phase when the *abc/dq* transformation method is used [25].

II.6. Modulation technique

The proposed control system uses the modulation technique. This modulation technique uses the sinusoidal PWM (SPWM). A five-level voltage waveform requires four level-shifted carrier signals as shown in Fig. 5; it is the sinusoidal modulation with multiple triangles which allows it. This technique requires *(N-1)* triangular signals with the same frequency f_p and the same amplitude A_p , these triangular signals are compared, for each phase, with a reference signal of amplitude A_{ref} and frequency f_{ref}. The expressions provide the modulation rate m_a and the frequency ratio m_f, respectively [11].

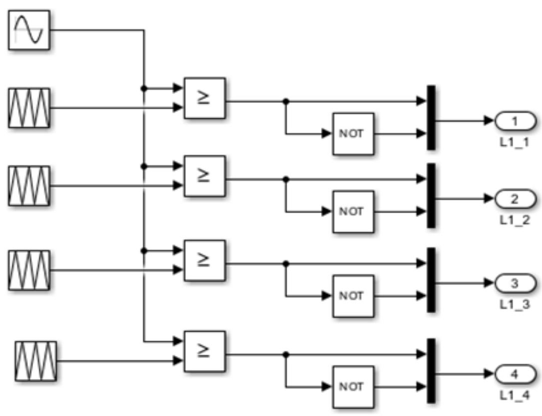

Fig.5. SPWM control strategy

$$m_a = A_{ref} / (N-1) A_p$$
$$m_f = f_p / f_{ref} \qquad)$$

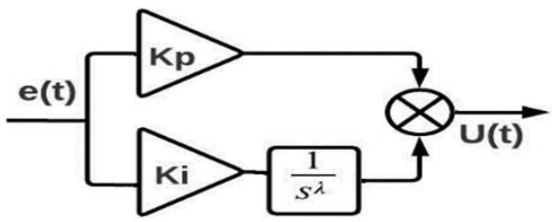

Fig. 6 Fractional order PI

III. Controller Design

Fractional calculus has attracted the attention of many engineers due to its reputation and efficiency [22,23].

The Riemann-Liouville definition, the Caputo definition, and the Grunwald-Letnikov definition are the three fundamental definitions of fractional calculus that are heavily used in the field of control systems. Due to its two additional parameters(λ,μ), which provide additional specifications and enhance the robustness of the controlled system, the fractional PID controller is a generalisation of PID controller and gives a greater flexibility [24].

III.1. Classical PI

The PI controller parameters (k_p, k_I) for the multilevel inverter for Grid-Connected Photovoltaic (PV) systems were defined using the fuzzy logic controller tuning presented in fig.7.

III.2. Fractional order PI^{λ}

The general transfer function form of the fractional PI^{λ}

(11) $$H(s)=\frac{U(s)}{E(s)}=k_p+k_i.s^{-1}$$

Where k_p, k_I are the proportional, integral gains, λ is the integration order Where : *H(s)*: The transfert function ; *E(s)*: The controller error
U(s): control

The controller structure of the proposed PI^{λ} (Fig 6) is constructed using FOMCON toolbox in Matlab described in [26,27]. The initial values of the controller parameters k_p, k_I and λ are presented in Table 5.

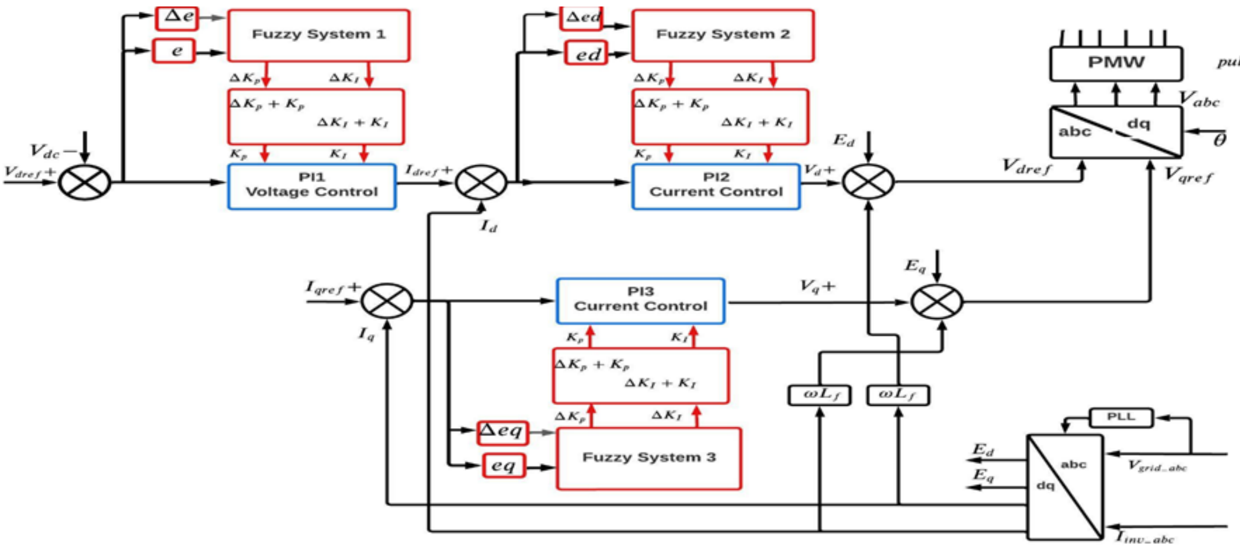

Fig 7. Bloc diagram of the fuzzy PI

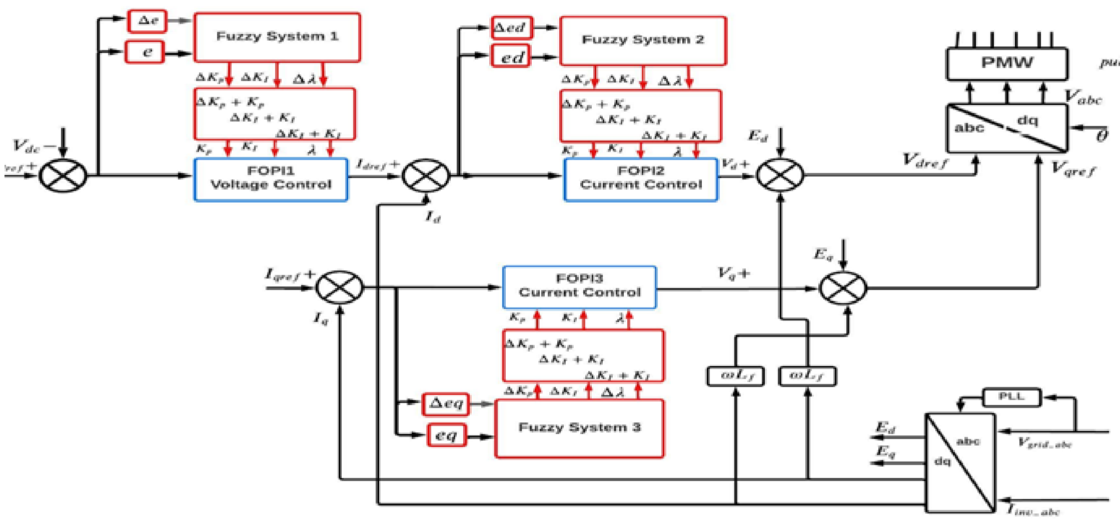

Fig 8. Bloc diagram of the Fuzzy Fractional order PI(FFOPI)

Table 5. Parameters values of the FFOPI and FPI controllers.

Parameters	FFOPI			FPI	
	k_p	k_i	λ	k_p	k_i
Voltage	0.1776	14.578	0.9763	0.15	5
Current d	400.03	25.23	2.62	50	30
Current q	400.04	25.25	2.65	50	30

III.3. Fractional order PI with fuzzy logic system

The fuzzy fractional order PI controller was proposed by Das et al [29]. The benefits of these types of controllers have been given in [30,32]. In this work, we tried to make the adjustment of the three parameters of the fractional order PI (k_p,k_I,λ) which are changed along the evolution of the system.

Fuzzy Fractional-Order PI controller (FFOPI) is a mixture of fuzzy rule base with FOPI control. Fig.8. Shows the scheme of structure of the FFOPI controller. In this control structure, the three fuzzy controllers receives a single value of the error and the error variation inputs witch are $e.\Delta e$ ($e=V_{dc}-V_{ref}$) for Voltage loop, $e_d.\Delta e_d$ ($e_d=I_d-I_{dref}$) for direct current loop and $e_q.\Delta e_q$ ($e_q=I_q-I_{qref}$) for quadratic current loop and generates 3 outputs corresponding to the parameters adjustment Δk_p, Δk_I, $\Delta\lambda$, Fig.8 shows the control system diagram of a five-level inverter for Grid-connected to a PV system.

The tuning of the FOPI regulator parameters is done according to the following steps

Step 1: according to the characteristics of the system Controlled

- choose the initial parameters (k_p,k_I,λ) of the three controllers (voltage V_{dc} , the direct current I_d and quadratic currents I_q)
- Choose the discourse universe of input variables *(e, Δe)* and output variables ($\Delta k_p,\Delta k_I,\Delta\lambda$) for the fuzzy controller
- Establish the membership functions of input variables and output variables.
- Establish the fuzzy rules base.

Step 2: Calculate the membership degrees of the inputs (e,Δe) from the membership functions presented in fig 9.

Step 3: Calculate the outputs (ΔK_p, ΔK_i,$\Delta\lambda$) From the 49 rules of table 6, 7 and from the membership functions of the outputs presented in fig.10.

The combination of FLC and FOPID controllers will ensure the process possesses good dynamic and static characteristics under various operating situations. The FFOPID controller successfully detects changes in the set point. It modifies the controller parameters (k_p,k_I,λ) appropriately, allowing the system output to reach the refference value again in a faster time than conventional controllers.

Table5 the fuzzy rules for Δk_p

e/Δe	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NM	Z	**Z**
NM	NB	NB	NM	NS	NS	Z	**PS**
NS	NM	NM	NM	NS	Z	PS	**PS**
Z	NM	NM	NS	Z	PS	PM	**PM**
PS	NS	NS	Z	PS	PS	PM	**PM**
PM	NS	Z	PS	PM	PM	PM	**PB**
PB	Z	Z	PM	PM	PM	PB	**PB**

Table6 the fuzzy rules for Δk_I, λ

e/Δe	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PS	PS	Z	**Z**
NM	PB	PB	PM	PS	PS	Z	**Z**
NS	PB	PM	PS	Z	Z	NS	**NS**
Z	PM	PM	PS	NS	NS	NM	**NM**
PS	PM	PS	Z	NS	NS	NM	**NB**
PM	Z	Z	NS	NM	NM	NB	**NB**
PB	Z	Z	NS	NM	NM	NB	**NB**

Mamdani type fuzzy inference mechanism is applied to the proposed fuzzy controller in this paper [32]. The fuzzy controller rules used to adjust the parameters of Fractional order PI controller are presented in tables 6 and 7.

The self-tuning the FOPI controller will find the fuzzy relationship between the three component of the FOPI controller. In the fuzzy controller, for choosing the variables of error (*e*) and error variation (Δ*e*), we seven memberships' functions input values presented in Fig 9 and 10.

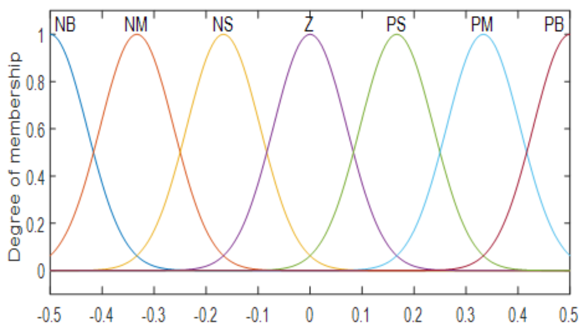

Fig. 9. Membership functions of input variable *e, Δe*

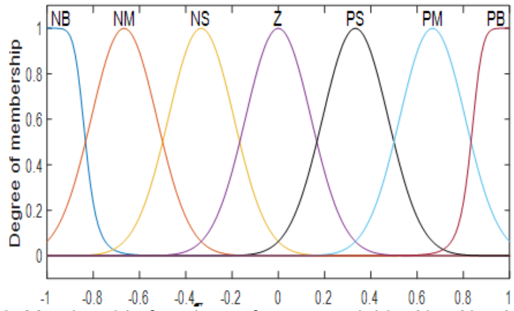

Fig. 10. Membership functions of output variable Δk_p, Δk_I , $\Delta\lambda$.

Because each input have 7 fuzzy sets (NB, NM, NSZ ,PS, PM, PB) two inputs *error, Δerror* , own 49 rules.

III.4. Multi-level inverter performance evaluation

We used three performance parameters are:

- Harmonic distortion (THD)

(12) $$THD = \frac{\sqrt{\sum_{i=2}^{N} H_i^2}}{F_1}$$

- Mean Absolute Error (MAE)

(13) $$MAE = \frac{1}{N}\sum_{i=1}^{N}|error|$$

- The root mean square error (RMSE)

(14) $$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} error^2}$$

Where error is: $e=V_{dref}$ -V_{dc} for FFOPI1; $e=I_{dref}$ -I_{ref} for FFOPI2; $e_q=I_{dref}$ -I_{ref} for FFOPI3; Hi: efficient value of the harmonic i; F1: efficient value of the fundamental component µ

IV. Simulation

Depending on the kind of multilevel PV inverter, integrating it into a grid-connected PV system necessitates the employment of a powerful controller whose dynamic reaction rapidly achieves a steady state while avoiding mistakes. To accomplish this task, this paper proposes three FFOPI controllers based on parameter adjustment (K_P,K_I, λ) These type controllers are popular because it has a simple structure, is easy to use, and provides good accuracy.

The control system is made up of three control loops based on Fuzzy Factional order PI (FFOPI): the FFOPI1 is used for controlling the intermediate circuit voltage (V_{dc}), and FFOPI2, FFOPI3 for controlling the direct and quadratic currents (I_q, I_d) supplied by the multilevel inverter.

Fig. 11 shows the three-phase voltages, three-phase currents injected into the grid, single-phase current, and voltage for the system connected to the grid.

The results with a fuzzy fractional order PI controller (FFOPI) are displayed in Figures 11 (a1-c1), while the results with a fuzzy PI controller (FPI).

We concentrate on the 0.5s instant when the irradiance has increased from 200 to 1000 W/m2 to demonstrate the effect of irradiance variation on the current and voltage. Fig 11 (b1) and (b2) show that only the current is affected by variation, but Fig 11 (a1) and (a2) show that the voltage remains constant. This is similar for both controllers.

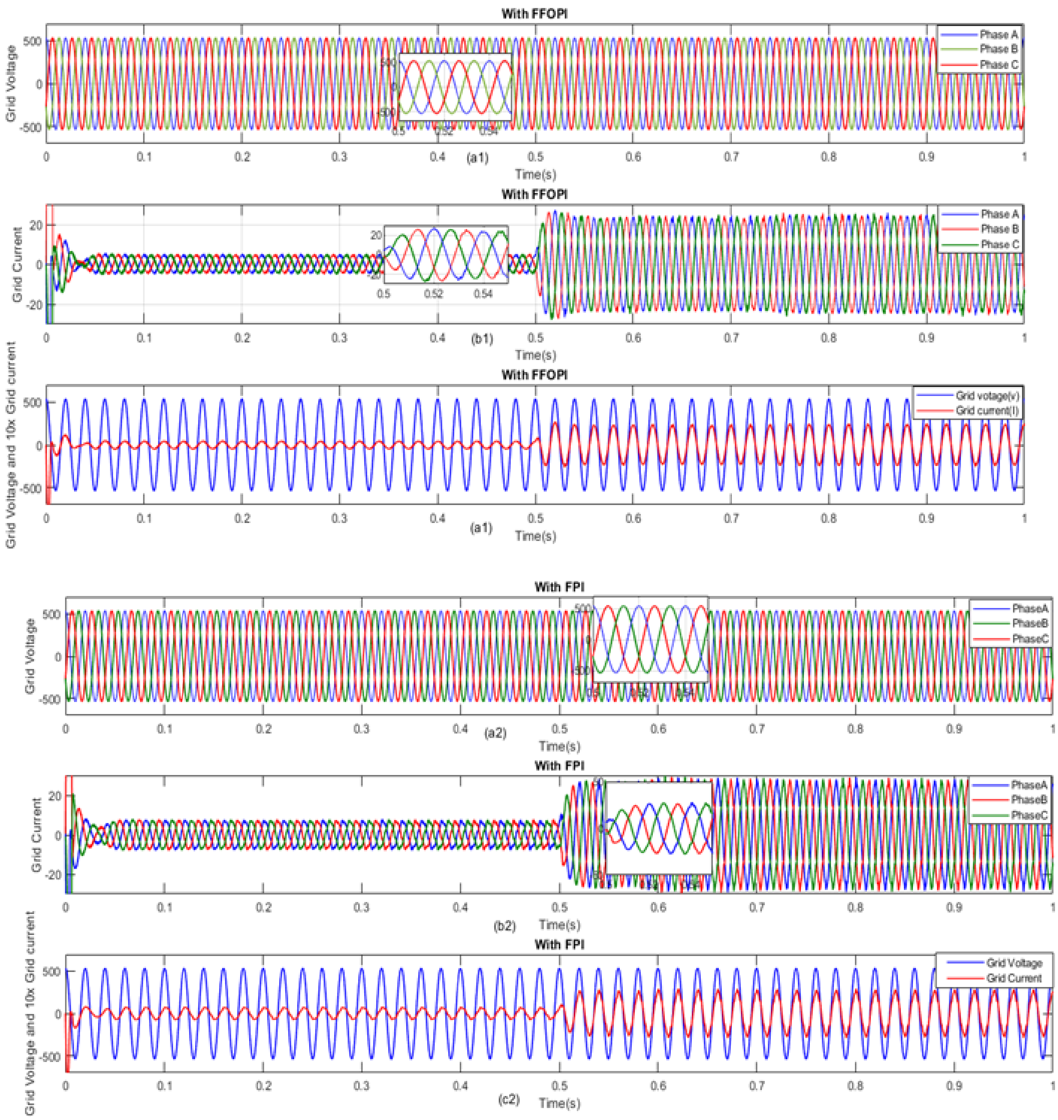

Fig. 11. (a1, a2) Three-phase voltages; (b1, b2) Three-phase Currents; (c1, c2) Single phase voltage and current of FFOPI and FPI.

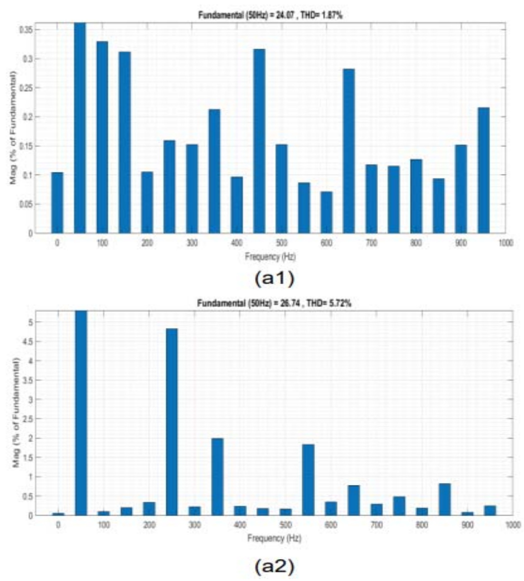

Figure 12. Current THD analysis (a1) with FFOPI (a2) with (FPI).

Figures 12 (a1) and 12 (a2) show the total harmonic distortion (THD) as a result of a spectral analysis of the current obtained using a fast Fourier transform algorithm FFT to demonstrate how the controller affects power quality. It should be noted that whereas a THD of 1.87% was produced with the FFOPI controller, a THD of 5.72% was acquired with the fuzzy PI (FPI) controller, demonstrating the efficiency of the FFOPI controller in comparison to FPI.

The goal of this work is to use fuzzy logic to adjust the three fractional order PI (FOPI) controllers' parameters in accordance with the error and its variation, including one controller for voltage loop regulation, where the error is ($e=V_{dc}-V_{ref}$) and two controllers for quadratic current I_q and direct current I_d, where the errors are ($e_q=I_q-I_{qref}$) and ($e_d=I_q-I_{dref}$) respectively.

FFOPI and FPI were compared in this study. The mean absolute error MAE, root mean square error RMSE, and total harmonic distortion of the injected alternating current are all provided in Table.7.

Table.7 shows that FFOPI provides a lower error in terms of MAE=0 .033172 and RMSE=0.14289 when compared to FPI.

The direct current (Id), quadratic (Iq), and DC voltage (VDC) of the FFOPI and FPI controllers are shown in Fig. 13. Therefore, in terms of dynamic performance and efficiency, the FFOPI is greater to the FPI.

Fig. 14 illustrates the dynamic responses of the active and reactive powers injected to the grid. The simulation results demonstrate that FFOPI is better than FPI.

Table 7. Comparison of different meta-heuristic algorithms.

	FPI	FFOPI
THD%	%5.72	1.87%
MAE	0 .097041	0 .033172
RMSE	0.368800	0.14289

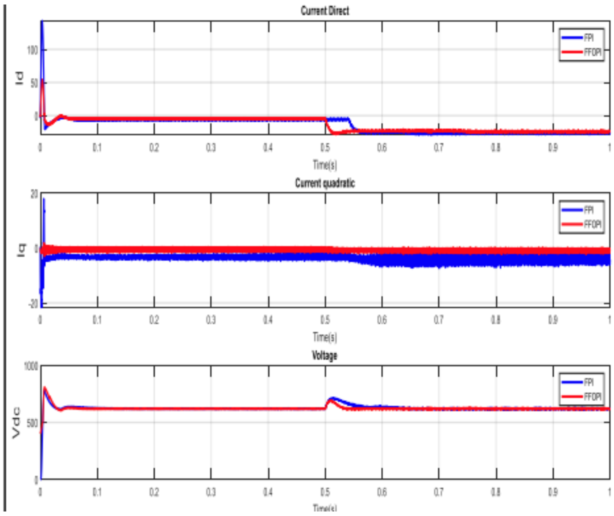

Fig. 13. Direct and quadrature currents and DC voltage.

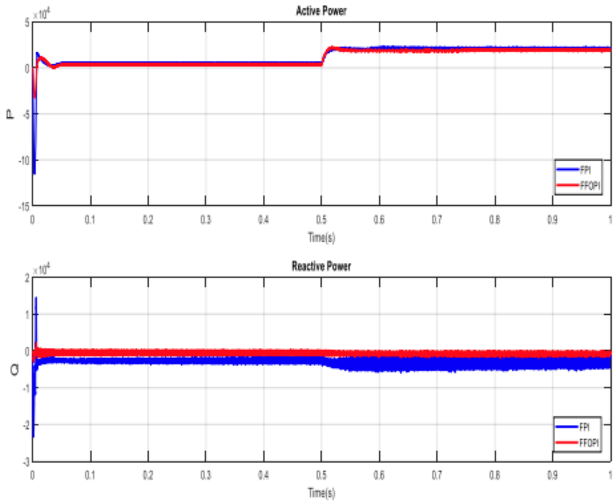

Fig. 14. Active and reactive powers dynamic behaviour of grid.

V. Conclusion

This work is based on improving the dynamic behaviour of the PV system's multilevel inverters connected to the grid. The main objective is to improve the current fed into the grid by making it more sinusoidal and having a more powerful photovoltaic system. By doing this, a DC/AC control system with one voltage loop and two current control loops performs better. straight and square. A fractional order PI (FFOPI) controller manages each of these two control loops. To enhance the dynamic behavior of the grid-connected PV system, the fuzzy logic system modifies the settings of the three controllers in accordance with the errors (e, ed, and eq). The lowest error (MAE, RMSE) and total harmonic distortion (THD) are thus to be obtained by comparing FFOPI with FPI. Consequently, in terms of effectiveness, dynamics, stability, and robustness, FFOPI surpasses FPI.

.The perspective is to combine the fractional order regulator with the artificial neural networks to have an auto-tuning of the parameters.

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