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OPTIMIZATION OF FRACTIONAL ORDER PI CONTROLLER USING META-HEURISTICS ALGORITHMS APPLIED TO MULTILEVEL INVERTER FOR GRID-CONNECTED PV

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Abstract

Due to its multiple advantages in industrial and grid-connected applications, Multi-Level Inverters (MLIs) have increased in popularity in recent years. To improve the efficiency of a grid-connected PV system's integrated multi-level inverter fractional order PI (FOPI) controllers are used to describe the control process. The control system is made up of three control loops based on FOPI controllers: one for controlling the intermediate circuit voltage (Vdc) and the other two for controlling the direct and quadratic currents (Id, Iq) 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. For this we used three meta-heuristic algorithms (PSO, ABC, GWO). The performance of the three controllers PSO-FOPI, ABC-FOPI and GWO-FOPI controller is compared. The findings showed that GWO-FOPI performs better than the other PSO-FOPI and ABC-FOPI in accuracy and total harmonic distortion THD term. The simulation will be conducted using Matlab/Simulink.

Keywords: MLI inverter, Fractional Order PI, Meta-heuristic, PSO, ABC, GWO, THD.

1. INTRODUCTION

Solar energy (SE) generation systems are an increasingly popular source of electricity that use a variety of inverters, such as A Multilevel inverters (MLIs) who represent a new technology for high power requirements [1]. The goal of (MLIs) is to produce a near-sinusoidal voltage waveform. By increasing the level of the output waveform, a pure sinusoidal voltage can be reached and the cost and size of passive filters can be reduced [2].

The performance of multilevel inverters used in grid-connected PV systems is an important parameter to consider because it has a major impact on the quality of electrical energy produced and, thus, the efficiency of the PV system [3]. This work aims to improve the dynamic performance of PV grid-connected multilevel inverters by optimizing the fractional order PI controllers of the DC/AC stage, which enables flexible injection of energy from the PV generator into the electrical grid without distortion or phase shift of the AC current [4,5]. Classical control and intelligent control are two widely used control methods in a variety of fields. The PID controller is one of the most widely used classic control methods. It has the advantage of having a simple structure that is very 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 (FOPID or $PI^{\lambda}D^{\mu}$) controller is a PID controller extension that comprises two additional tuning parameters: integral order and differential order(λ, μ) [9,10].

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

Numerous studies have demonstrated that FOPID controllers perform effectively than other controllers in industrial processes [11-12] including greenhouse [13] and bioreactor temperature [14].

In this work we present The Fractional order PI controller combined with meta-heuristic algorithms for guarantee optimum performance and fine-tuning of the parameters (K_p, K_I, λ). This paper investigates the dynamic behaviour of a five-phase multilevel inverter connected to a PV system.

The goal is to optimize the parameters (K_p, K_I, λ) of Fractional order PI controller by using meta-heuristics algorithms (PSO, ABC, GWO) for the three FOPI one for voltage loop control and two for quadratic and direct current loop to improve the performance of the multilevel inverter. As a result, a

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comparative study of a three controllers has been proposed: PSO-FOPI, ABC-FOPI, and GWO-FOPI, 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 modeling of the system" introduces the studied multilevel inverter for photovoltaic, the photovoltaic generator, Boost converter DC/DC. Secondly we present the Fractional order PI control method. Than the meta-heuristics algorithms are presented. We discussed the simulation result with a comparative study of three meta-heuristics in terms of mean absolute error (MAE), Root Mean Squared Error (RMSE), and the total harmonic distortion (THD).

2. THE MODELING SYSTEM

The proposed diagram of the system is shown in fig.01. This figure shows the complete system. All transformers used for PV generator. DC/DC converter DC bus line for connection with NPC multilevel converter the power injected into the network passes through the LC filter.

2.1. Photovoltaic generator

The power available at the terminals of a cell is very low, it is therefore necessary to combine such cells in series and in parallel to obtain power modules considering, this model consists of complex equations whose solution requires many (6 parameter) of parameter, another name for model with a single diode with five parameters $(Rs, Rsh, Iph, I0, A)$[15] presented in fig. 2.

Whereas:

$$I = I_{Ph} - I_0\left(e^{\frac{1}{V_T}(V+R_S\times I)}\right) - \frac{V+R_S\times I}{R_{sh}} \quad (1)$$

$$V_{th} = \frac{n\,K\,T}{q} \quad (2)$$

I: The current delivered by the photovoltaic module.
R_{sh}: Shunt resistance.
I_{ph}: Photoelectrical current.
I_0: Saturation current.
R_s: Series resistance.
K: Boltzmannfactor$1.38 \times e^{-23} JK$.
n: Coefficient the diode ideality.
q: the electron burden $(1.602 \times 10^{-19} C)$.

The parameters of the solar array that identify equation (1) as following relate to the solar panel parameters:

$$I_{scpanel} = N_p \times I_{sc} \quad (3)$$

$$I_{0panel} = N_p I_0 \quad (4)$$

$$R_{Spanel} = \frac{N_S}{N_P} R_S \quad (5)$$

$$R_{Ppanel} = \frac{N_S}{N_P} R_P \quad (6)$$

The photoelectric current (I_{ph}) depends on the irradiation and the temperature as shown in Eq (7).

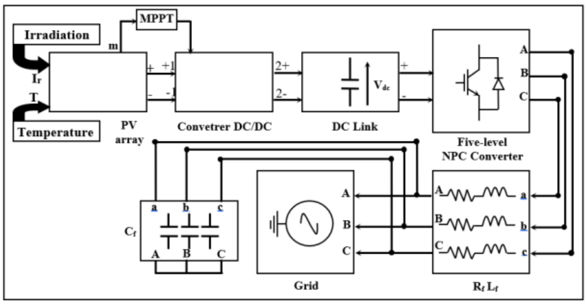

Fig. 1. System's block diagram grid-connected to PV

PV array: solar panels,
DC-DC converter: Boost converter,
DC Link:direct current bus.
Five-level NPC Converter: 5-level NPC topology multilevel inverter,
R_f, L_f, C_f: passive filter (LC).

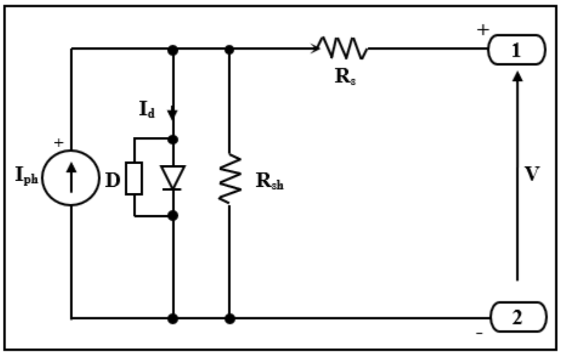

Fig. 2. Equivalent diagram of a photovoltaic cell

$$I_{ph} = \left(I_{ph,n} + K_I \Delta T\right) \times \frac{G}{G_n} \quad (7)$$

$$I_0 = \frac{(I_{scn} + K_I \Delta T)}{exp\left(\frac{V_{ocn} + K_v \Delta T}{AV_{th}}\right) - 1} \quad (8)$$

$$\Delta T = T - T_n \quad (9)$$

Here, I_{scn} short-circuit current under nominal conditions $(G_n = 1000\, W/m^2, Tn = 25^oC)$ 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. Here, where Table1 displays the sol-tech 1STH-215-P solar arrays parameters under standard operating conditions. 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.

Table 1. PV panel parameters

Parameter	R_f	L_f	C_f	U_a	f
value	0.4312 Ω	0.0043 H	1.1749 e^{-5} F	380 V	50 Hz

2.2. Boost converter DC/DC

A boost converter increases the value of the input DC voltage to the necessary output voltage level because the DC output voltage of the PV module has a low value that needs to be converted to AC compatible with the grid voltage and frequency. A boost converter is also known as a step up converter because it uses an inductor, a diode, a capacitor, and a high frequency semiconductor switch to operate. According to Fig. 3, V_{in} is the input voltage and V_{out} is the output value [16-17].

$$V_{out} = \frac{1}{1-\propto} V_{in} \tag{10}$$

$$\propto = \frac{T_{on}}{T} \tag{11}$$

α: Cyclical report

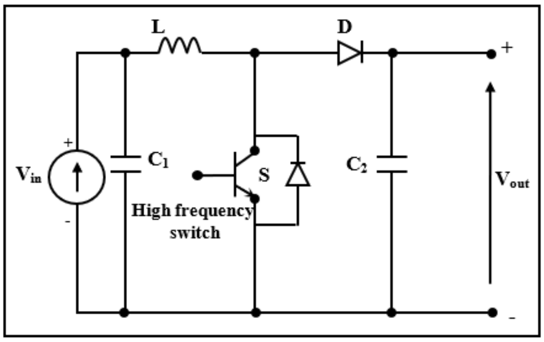

Fig. 3. Circuit of the boost converter

Table 2. Selected settings

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

Due to its ability to synthesize an output voltage greater than the voltage rating of each switching device, multilevel inverters have several benefits for medium and high power systems [18-20].

2.3. System connected to network

The inverter is the component of any grid-connected system that matters the most. In order to deliver electricity (alternating current) to the grid, the inverter converts as much DC (direct current) power as possible from the photovoltaic array into the appropriate voltage and frequency. Via an LC filter in order to eliminate the harmonics generated in the sinusoidal signal. Table 3 represents the values filter parameters.

Table 3. Filter 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

2.4. Diode-clamped multi-level inverter

In 1981, Nabae, Takahaski, and Akagi have successfully offered the neutral point converter for a variety of applications [21]. A multi-level inverter structure was used in high and intermediate voltage conditions.

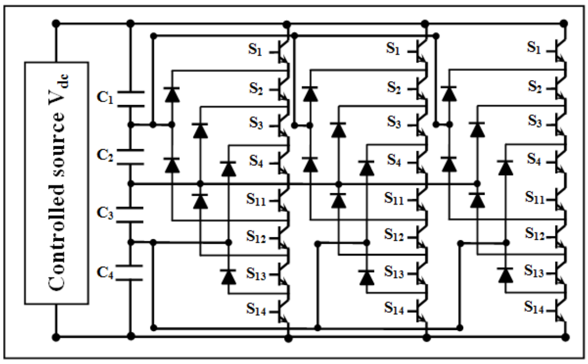

Fig 4.The three-phase, five-level, diode-clamped inverter

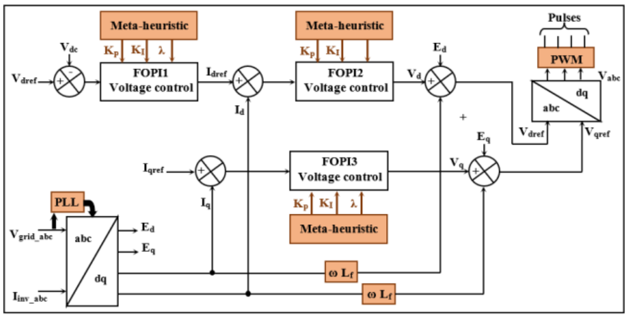

Fig 5. Control diagram

Figure 4, basic architecture for this inverter was addressed [22-23]. NPC inverters are one of the most widely used photovoltaic systems. The system has significant advantages. The $(n-1)$ capacitors required on the DC bus are part of the multilevel inverter, the required number of switches for each phase is $2 \times (n-1)$ Moreover, and thereare diodes in each phase $2 \times (n-2)$ [24].

Table 3. 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	$V_{dc}/2$
0	1	1	1	1	0	0	0	$V_{dc}/4$
0	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	$-V_{dc}/4$
0	0	0	0	1	1	1	1	$-V_{dc}/2$

2.5. 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 5.

The existing controller loops are discussed in this arrangement, First, the three phase currents (a, b, c) are transformed into the two phase (d, q), which we can't control if it is rotating, so we further convert into the two phase, stationary (dq), 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 $E_d$andE_q outputs of the current controllers can be utilized as reference voltages to produce PWM as shown in Fig 5.

The E_d and E_q are converted into three phase reference voltagesV_{Aref}, V_{Bref}, and V_{Cref} in this process.

The phase-locked loop(PLL) can provide information on the grid voltage phase when the abc/dq transformation method is used [25].

2.6. 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 6; 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 amplitudeA_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].

$$m_a = A_{ref}/(N-1)A_p \tag{9}$$

$$m_f = f_p/f_{ref} \tag{10}$$

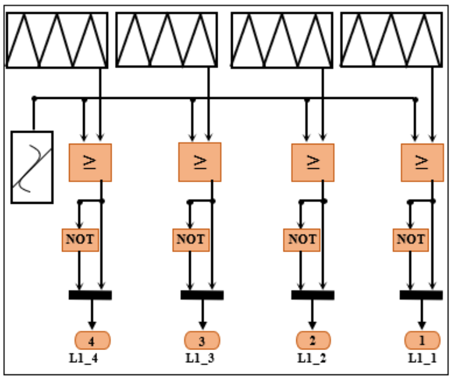

Fig. 6. SPWM control strategy

3. FRACTIONAL ORDER PID CONTROLLER

The FOPID control system has advanced rapidly in recent years. Many studies have been conducted to determine how to tune the FOPID controller for improved control performance. The FOPID controller is a fractional expansion of the PID controller, rather than using integers as tuning parameters. It improves system performance by increasing flexibility and efficiency. The FOPID controller parameters are the fractional orders for the integral (λ) and derivative (μ) as well as the gain coefficients for the proportional(K_p), integral(K_I), and derivative(K_d) parameters.

It is a stable controller with few tuning parameters [26-27]. Nowadays, more methods rely on FOPID controllers in industrial and control applications. Fig.7 shows a schematic representation of the FOPID controller.

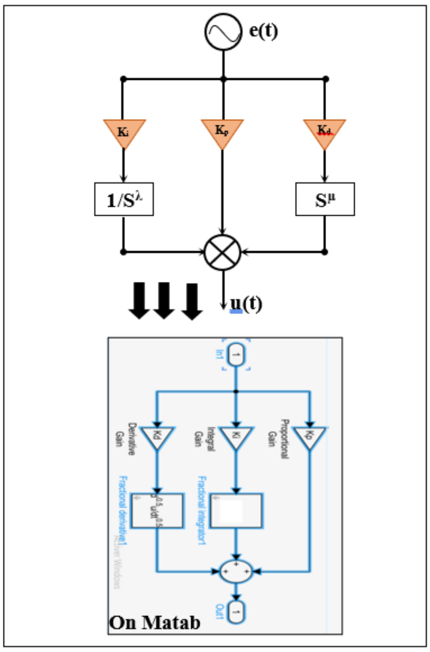

Fig 7. FOPID Diagram

To tune the parameters of FOPID $(K_p, K_I, K_d, \lambda, \mu)$ meta-heuristic algorithms $(PSO, ABC. GWO)$ are used in this paper.

4. META-HEURISTIC ALGORITHM

Glover (1986) first used the term meta-heuristic, which combines the prefix meta-(which means "beyond," in a higher level) with heuristic ("to find"). The precise, ideal solution is discovered using traditional optimization techniques in a finite amount of time [28]. A better trade-off between the accuracy and computing time is provided by meta-heuristic methods, which aim to find a solution that is "good enough" in a computing time that is "small enough" [29].

In the current study, three well-known meta-heuristics algorithms particle swarm optimization (PSO), artificial bee colony (ABC) optimization, and grey wolf optimization (GWO) are used to optimize the parameters of a fractional order PI controller. These algorithms will be briefly described below.

4.1. Particle swarm optimization (PSO)

Kennedy and Eberhart first proposed particle swarm optimization in 1995. It was motivated by the movement and intelligence of swarms, as its name suggests. Initialized with a population of randomly chosen potential solutions (particles) to the optimization problem, a particle swarm optimizer moves each particle through the search space, which contains all potential solutions. The algorithm monitors the best positions for each individual and the overall fitness, iteratively performing operations until a stopping criterion is met. [30-31]. Figure 8 illustrates the PSO organization chart.

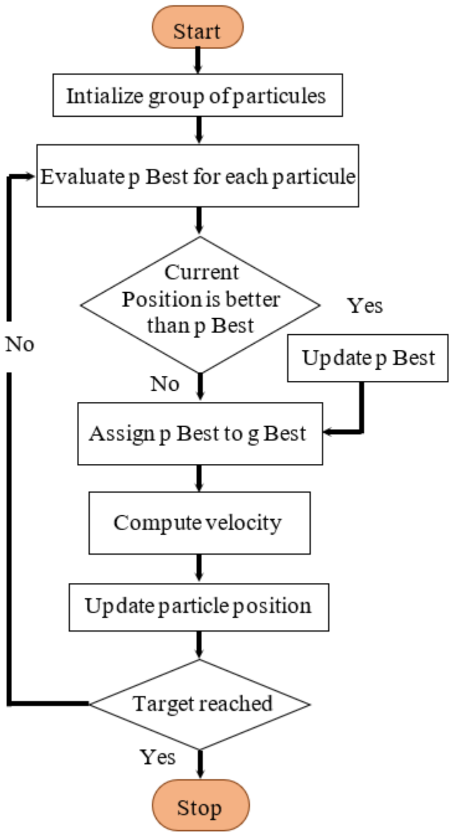

Fig 8. Flowchart of PSO Algorithm

4.2. Artificial bee colony (ABC)

ABC algorithm, one of the meta-heuristic optimization methods, is inspired by the honey bees [32].Developed in 2005, algorithm is a population-based optimization algorithm. The algorithm was created using as its model the swarm intelligence of bees as they searched for food. The artificial bee colony contains two different kinds of bees. The first kinds of bees are called worker bees. Unemployed bees are another species of bee. Bees that observe are bees without a job. Some assumptions are made by the ABC algorithm. The first is that each resource's nectar is only taken by one bee. As a result, the total number of food sources and the number of bees employed are equal. Another presumption is that the number of bees working and the number of bees watching are equal [33-35].

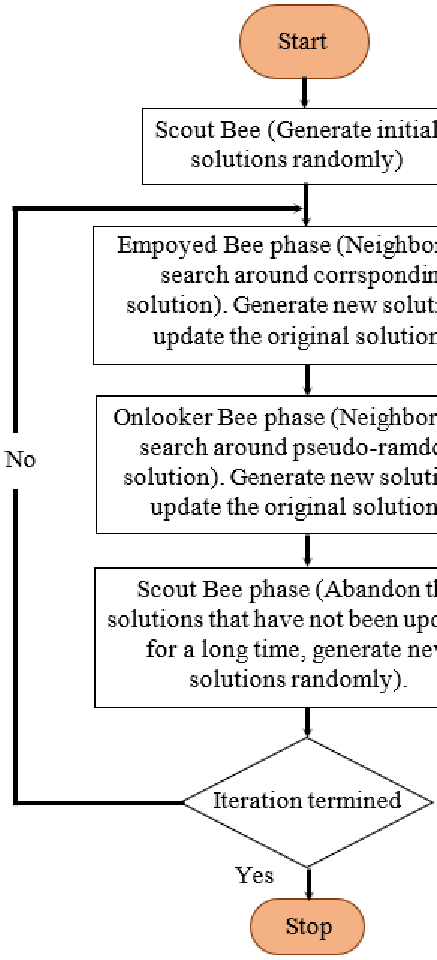

Fig 9. ABC organization chart

4.3. Grey wolf optimization (GWO)

A swarm intelligent optimization algorithm called Grey Wolf Optimizer (GWO) simulates the social structure and leadership of grey wolves while hunting [36]. The wolves in GWO are divided into three categories based on their level of leadership: the wolf, wolf, and ordinary wolf. In the course of the optimization process, the wolves,, and lead the other wolves to update their positions. In the fig10 an organization chart to the GWO.

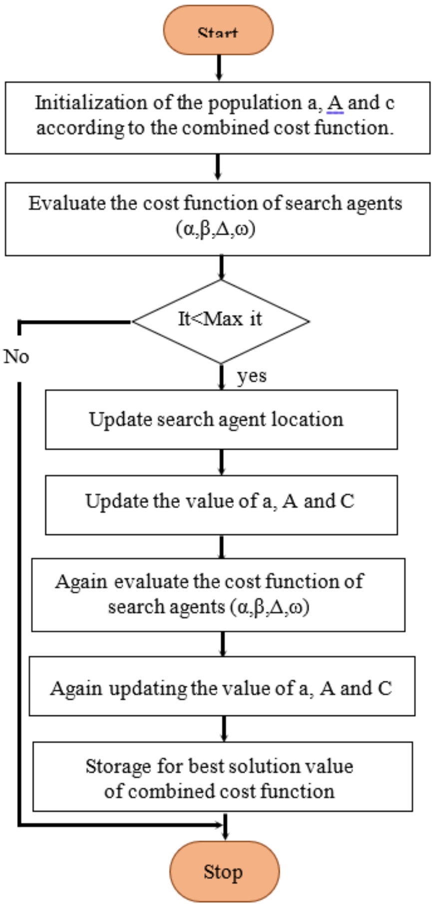

Fig 10. Flowchart of GWO algorithm

4.4. Performance indexes

In the optimization algorithm, several objective functions based on the error performance index are used. The performance index is calculated over a period of time. A comparison of FOPI controller dynamic performances is achieved based on the fitness function that depends on the two commonly used performance measures to define the best meta-heuristic that gives the best parameter tuning. These indices are mean absolute error (MAE) and Root Mean Squared Error (RMSE), and the total harmonic distortion (THD) as shown in Equations (11),(12),(13).

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|e| \tag{11}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e^2} \tag{12}$$

$$THD = \frac{\sqrt{\sum_{i=2}^{N} H_i^2}}{F_1} \tag{13}$$

Where:

$e = V_{dref} - V_{dc}$

Hi: efficient value of the harmonic i.

F1: efficient value of the fundamental component

5. SIMULATION AND RESULTS

Due to the nature of the PV multilevel inverter, its integration into a PV system connected to the grid necessitates the use of a high-performance controller whose dynamic response quickly reaches the steady-state while minimizing error. To accomplish this task, the paper proposes a fractional order PI based on meta-heuristic algorithms.

In the first stage, the meta-heuristics are used to optimize the FOPI parameters $(K_{pv}, K_{iv}, \lambda_v)$that are used to control the voltage loop, which acts on the DC voltage error to generate reference currents (Id ref) as shown in Fig. 5, the meta-heuristics are used in a second stage to optimize the parameters $(K_{pc}, K_{ic}, \lambda_c)$of the FOPI of a quadratic and direct current loops injected into the grid.

The FOPI current control loop injects alternating current in phase with a low THD term.

The goal of this work is to present optimization algorithms that will help to improve the characteristics of FOPI controllers. The optimal parameters are assigned to the FOPIs of the two control loops by these meta-heuristic algorithms. Table 5 presents the control parameters of the three meta-heuristics (PSO, ABC, and GWO) as well as the parameter variation intervals to be optimized.

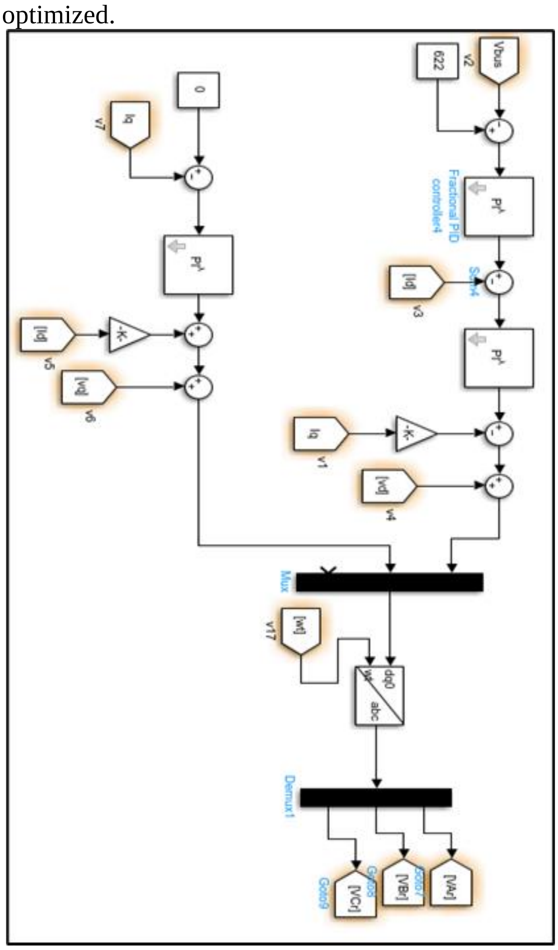

Fig 11. Matlab/Simulink model

To evaluate the effectiveness of the employed controllers, a simulation was run under various irradiance conditions at constant ambient temperature (25°C) .The applied irradiance was changed in steps of 0.5 seconds and ranged from 200 to1000 W/m^2.

Table 5. Meta-heuristic algorithm parameters and interval Variation parameters of FOPI controllers

	ABC	PSO	GWO
THD%	7.81%	6.64%	1.72%
MAE	0.45220	0.37578	0.04529
RMSE	0.56862	0.48852	0.3103

Table 6. The optimal values of FOPI controllers provide at the end of meta-heuristic optimization

	PSO	ABC	GWO
Control parameters	c1=1.5, c2=2,w=1	$a = 1$	
Search agent	10	10	10
Max Iterar	20	20	20
K_{pv}	[0.02 0.9]	[0.02 0.9]	[0.02 0.9]
K_{Iv}	[0.1 20]	[0.01 20]	[0.01 20]
λ_v	[0.5 3]	[0.5 3]	[0.5 3]
K_{pc}	[30 400]	[30 400]	[30 400]
K_{Ic}	[5 20]	[5 20]	[5 20]
λ_c	[0.5 3]	[0.5 3]	[0.5 3]

Table 7. Comparison of different meta-heuristic algorithms

	Parameters Voltage FOPI			Parameters Current FOPI		
Approach	K_P	K_I	λ	K_P	K_I	λ
PSO	0.1255	11.8601	0.9943	41.9831	20	1.2
ABC	0.1601	19.9776	1.1008	35.3040	13.7149	0.9628
GWO	0.1660	13.9812	0.9620	400	18.73	2.4595

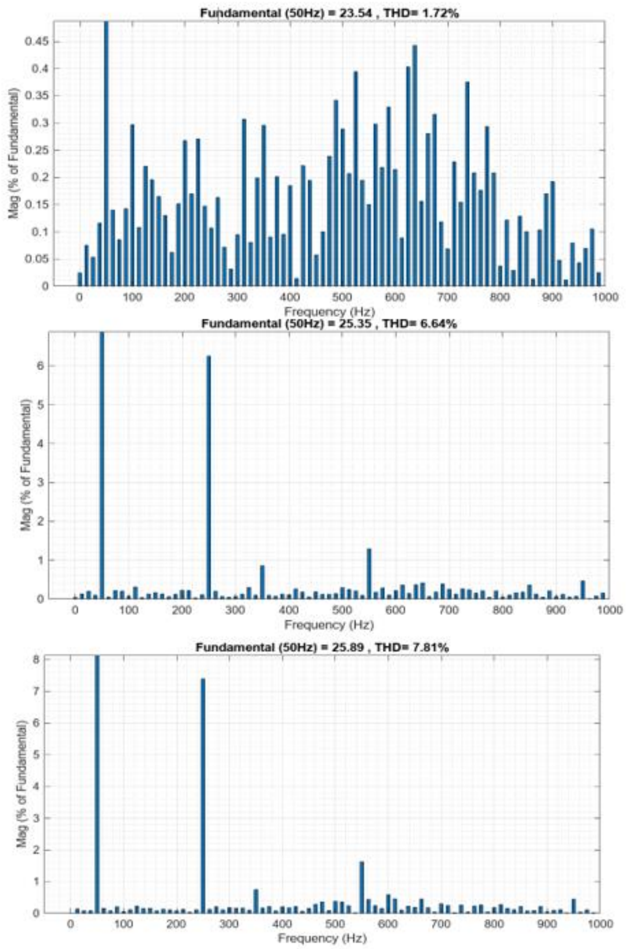

Fig 12. FFT analysis of PV grid current of the PSO-FOPI, ABC-FOPI, GWO-FOPI

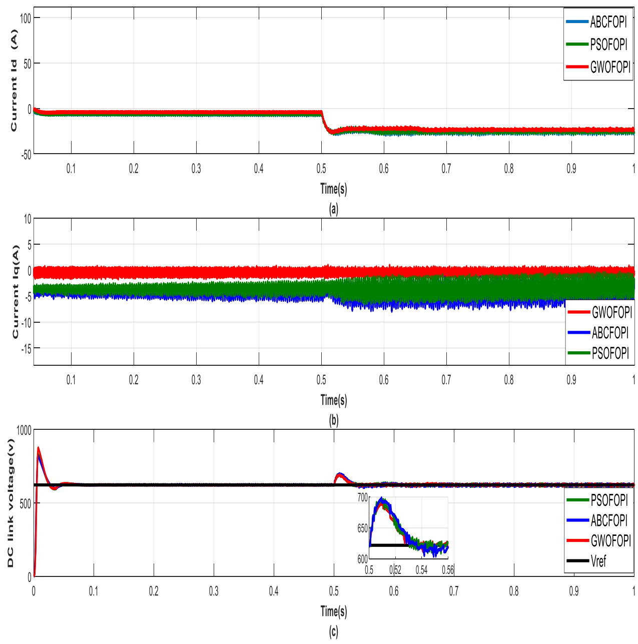

Fig 13. Dynamic response of direct (a) and quadratic Currents (b) and DC link voltage (c) of the PSO-FOPI, ABC-FOPI, GWO-FOPI controllers

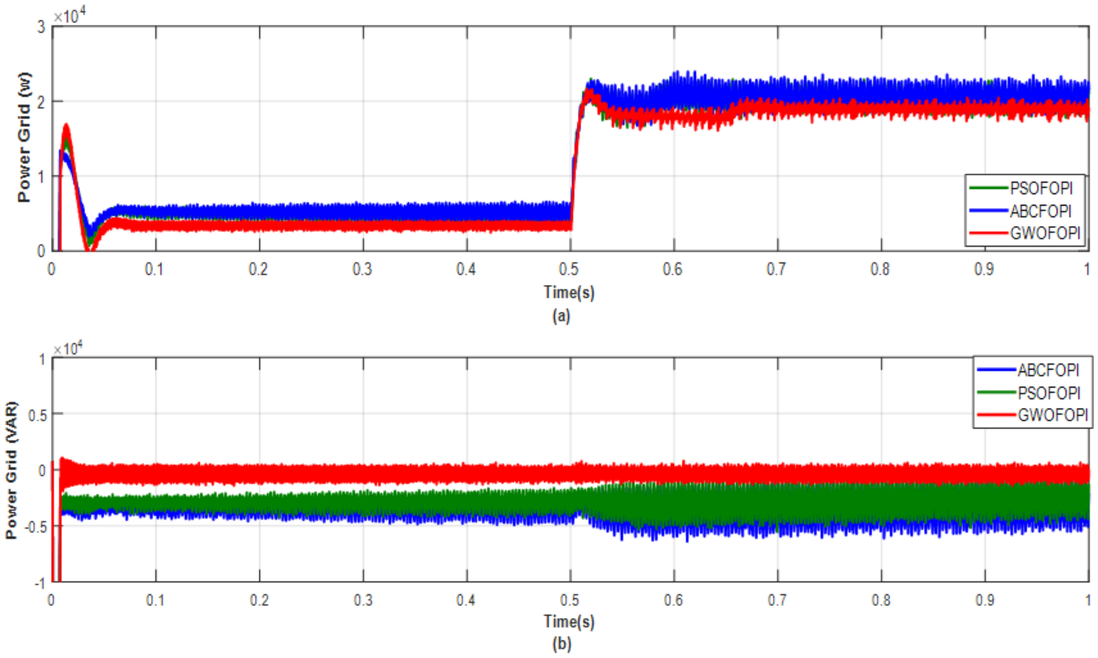

Fig 14. Active and reactive powers dynamic behaviour of grid of the PSO-FOPI, ABC-FOPI, GWO-FOPI controllers

The objective of this work is to use meta-heuristic algorithms to obtain the optimal values of the parameters of the three fractional order PI controllers, one for the V_{dc}voltage regulation loop and two for the quadratic current I_q and the current direct I_d. Table 5 presents the meta-heuristic control parameters the parameters variation interval of the three FOPIs. Table 6 presents the optimal parameters resulting at the end of the excuses of the meta-heuristic algorithms.

A comparative study of three meta-heuristic algorithms (PSO, ABC and GWO) was presented. Table.3 gives the mean absolute error (MAE), the root mean square error (RMSE) and the distortion rate of the alternating current injected into the grid (THD) for the three algorithms used.

Table.7 shows that GWO-FOPI gives a lower error in terms of MAE=0.04529, RMSE=0.3103 which is lower compared to those obtained from PSO-FOPI and ABC-FOPI. We also note that the THD is 1.72%, which is the lowest and complies with IEEE standards.

Note that the PSO-FOPI controller improves the performance of the FOPIs because THD is reduced to 6.64% and MAE= 0.37578, RMSE=0.48852. ABC-FOPI offer mean absolute error MAE=0.45220, RMSE=0.56862, THD=7.81% these parameters are slightly improved by applying GWO-FOPI.

Figure 12 shows the FFT of the three controllers FOPI-PSO, FOPI-ABC, FOPI-GWO of the current injected into the Grid. Fig 12 reveals that the three algorithms give good THD values which remain below 8% the GWO is the best compared to the other algorithms with a THD = 1.71%.

Figure 13 presents the direct current (I_d), quadratic (I_q) and DC voltage (V_{DC}) of the three controllers PSO-FOPI, ABC-FOPI, GWO-FOPI. Thus, the GWO-FOPI is better than PSO-FOPI, ABC-FOPI in terms of dynamic performance and efficiency.

The dynamic reactions of the active and reactive powers introduced into the grid are shown in Fig. 14. The simulation results show that the GWO-optimized FOPI settings enable having the best grid.

6. CONCLUSION

This work focuses on improving the dynamic behaviour of the grid-connected PV system. The aim is to improve the quality of the current injected into the grid and to have a more robust PV system by improving the performance of the DC/AC control system, which comprises three loops - a voltage control loop and two DC and quadratic current control loops (Id, Iq) supplied by PLL voltage control loop (V_{dc}) and two DC and quadratic current (Id, Iq) control loops supplied by PLL. Each of these three loops is controlled by a fractional PI controller (FOPI) whose parameters KP, KI and λ are optimized by using metaheuristic approaches to improve the dynamic response of the grid-connected PV system. Thus, the values of the parameters KP, KI and λ of FOPI controllers are optimized by three metaheuristic approaches: PSO, ABS and GWO. Consequently, a comparative study was carried out between the meta-heuristic approaches used to define the best that provides the best parameters for the FOPI controllers.

The results reveal that GWO-FOPI provides the best power factor and THD values. As a result, GWO-FOPI is better than ABC-FOPI, PSO- FOPI in terms of efficiency, dynamic response, stability and robustness.

This work focuses on improving the dynamic behaviour of the grid-connected PV system. The essential goal is the improvement of the current injected into the network by making it closer to sinusoidal and having a more robust PV system by improving the performance of the DC/AC control system which includes a voltage control loop and two quadratic and direct current control loops. Each of these two loops is driven by a fractional order PI (FOPI) controller. The parameters of the three controllers are adjusted by the use of meta-heuristic approaches in order to improve the dynamic response of the network connected PV system. Subsequently, the values of the parameters of the FOPI controllers are adjusted using the three proposed meta-heuristic approaches: PSO, ABC, GWO. Thus, a comparative study is presented between the three approaches (PSO, ABC, GWO) in order to obtain the optimal values of the parameters (K_p, K_I, λ) The simulation results show that the GWO provides the best MHT power factor value. Therefore, the GWO is better than the PSO, ABC in terms of efficiency, dynamic response, stability and robustness.

The prospect is to combine the fractional order regulator with a fuzzy system FFOPI to have a self-adjustment of the parameters.

Future research will include a comparative study between the 7-level NBC inverter and the 9-level NBC inverter. Also, we will suggest replacing FOPI controllers by ANFIS-based fractional Order PI (ANFIS-FOPI) controllers. The same tests will be performed to compare the performance of the FOPI and ANFIS-based fractional.

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