# Whale Optimization Algorithm for Active Damping of LCL-Filter-Based Grid-Connected Converters

Mohammed Mazen Hato*, Soufiene Bouallègue*‡

* Research Laboratory in Automatic Control (LA.R.A), National Engineering School of Tunis (ENIT),
University of Tunis El Manar, BP 37, Le Belvédère, 1002 Tunis, Tunisia, Tel: +216 71 87 47 00; Fax: +216 71 87 27 29
(mohammedhato.89@gmail.com, soufiene.bouallegue@issig.rnu.tn)

‡ Corresponding Author, Soufiene Bouallègue, High Institute of Industrial Systems of Gabès, 6011 Gabès,
Tel: +216 75 291 788, Fax: +216 75 297 974, soufiene.bouallegue@issig.rnu.tn.

**Abstract-** Grid-connected converters which are equipped with LCL-filters have drawn more and more attention due to their capability to accomplish a better harmonic reduction in comparison with the L-filters based ones. However, due to the resonance problem of the LCL-filters, stability issues may emerge in the current loop in case of the resonance peak is not fairly damped. Active damping strategy is preferred to the passive one due to the power losses on passive resistor and its additional cost. The capacitor current feedback active damping control approach, which is based on voltage oriented of Proportional Integral (PI), can be adopted as a good candidate to outperform the resonance hazard. Since the selection of PI controllers' parameters and capacitor current gains by iterative trials-errors based procedure becomes a time consuming and difficult task, an optimization problem under operating time-domain restrictions is modeled for tuning these decision variables. Such an optimization based-current feedback active damping control problem is managed by means of the advanced Whale Optimization Algorithm (WOA). To evaluate the effectiveness of the introduced WOA metaheuristic, an empirical comparison study with the homologous Water Cycle Algorithm (WCA), Grey Wolf Optimizer (GWO), Artificial Bee Colony (ABC) and Particle Swarm Optimization methods is achieved. Statistical analysis is performed by using nonparametric Friedman's rank and Bonferroni-Dunn's test to check the significance of each algorithm. Demonstrative simulations highlight that the WOA method provides competitive solutions in terms of robustness and performance for the active damping controllers' tuning problem.

**Keywords** Active damping, grid-connected converter, LCL-filter, PI tuning, whale optimization algorithm, Bonferroni-Dunn's and Friedman's tests.

## Nomenclature

| | | | |
|---|---|---|---|
| $C_{bus}$ | DC-link capacitance | $L_T$ | filter total inductance |
| $C_f$ | filter capacitance | $R_d$ | filter damping resistance |
| $e_{g(a,b,c)}$ | grid voltages in phases a, b, c | $R_g$ | filter grid side resistance |
| $e_{g(d,q)}$ | d-q axis grid voltage | $R_i$ | filter converter side resistance |
| $i_{C(a,b,c)}$ | filter capacitor current in phases a, b, c | $R_{load}$ | resistive load |
| $i_{C(d,q)}$ | d-q axis capacitor current | $S_{(a,b,c)}$ | switching signals for upper IGBTs |
| $i_{g(a,b,c)}$ | grid current in phases a, b, c | $S'_{(a,b,c)}$ | switching signals for lower IGBTs |
| $i_{g(d,q)}$ | d-q axis grid current | $S_{(d,q)}$ | d-q switching components |
| $i_{i(a,b,c)}$ | converter current in phases a, b, c | $V_{bus}$ | DC-link voltage |
| $i_{i(d,q)}$ | d-q axis converter current | $V_{C(a,b,c)}$ | capacitor voltage in phases a, b, c |
| $i_{load}$ | resistive load current | $V_{C(d,q)}$ | d-q axis capacitor voltage |
| $L_g$ | filter grid side inductance | $V_{i(a,b,c)}$ | converter voltage in phases a, b, c |
| $L_i$ | filter converter side inductance | $V_{i(d,q)}$ | d-q axis converter voltage |

## 1. Introduction

Grid-connected converters are vastly adopted to transmit the power with the growing penetration of renewable energy sources and distributed power generation systems [1, 2]. This type of converters provides sinusoidal injected input currents, unity power factor and a controllable DC-link voltage. However, these converters need filters to minimize the high frequency content generated by Pulse Width Modulation (PWM) switching. To meet the grid code requirements, the LCL-filter is predominant in reducing the utility current harmonics. Indeed, it can lead to a better attenuation of harmonics using small values of inductances, which makes it a preferred option for higher power applications. However, the resonance phenomena of the LCL-filter must be mitigated fairly in order to prevent the possible instability of these systems [3].

One way for managing this problem is employing a passive damping circuit. The passive damping is gained by adding a pure resistor branch in series or in parallel with the inductors or capacitors of the LCL-filter [4]. Nonetheless, this passive method causes high power losses which are not acceptable for higher power systems. As an alternative and effective solution are the well-known active damping techniques. They basically consist in changing the control structure to guarantee the system stability without dissipative elements [5, 6]. A wide amount of literature on the active damping of LCL-filter is available. The existing active damping techniques can be parted into two classes. One type is implemented by connecting a filter, directly in cascade with the current controller which attempts to remove the resonance peak. Notch filter [5], high pass filter [7], and lead-lag compensator [8] are the most common methods used in this group. Another type of active damping techniques is based on feeding an extra feedback loop as a new state variable to the current PI controller to provide the damping effect for the resonance problem. Several active damping methods have been proposed previously in this category including various controlled state variables [9-12].

In this paper, the capacitor current feedback active damping method is presented due to its straightforward design method and simple implementation. The most challenging task in this method is the suitable choice of control system parameters, in which the value of the proportional capacitor current should be selected with great caution. Moreover, the choice of control parameters via trials-errors based techniques could be time consuming and subject to errors. In addition, the classical PI tuning methods such as the symmetrical optimum [13], Ziegler-Nichols [14], Tyreus-Luyben [15] and Cohen-Coon [16] techniques require the designer to be very customary with the characteristics and dynamics of the controlled system. Hence, introducing a systematic method to adjust these design gains is a promising action and meeting metaheuristics based hard optimization notion may award an efficient solution [17].

In this manner, little works have been addressed in the literature. In [18], the Particle Swarm Optimization (PSO) was presented to determine the parameters of an adaptive controller including PI and proportional resonance components for a LCL-filter based grid-connected inverter. In addition, in [19], PSO and differential evolution algorithms are used to determine the gains of PI controllers for a photovoltaic power plant based on a LCL-filter. In [20], a differential evolution algorithm is adopted to optimize the design parameters of a LCL-filter and set the basic parameters of the proportional resonant controller. In [21], a grey wolf optimizer is used to find the parameters of PID controllers in the direct power control design for three phase inverters. In [22], a cooperative foraging optimization algorithm has been proposed to generate the parameters for LCL filter and PI current controllers. Therefore, since the optimal choice of PI gains and the capacitor current one contribute to an important role in the controller performance. Hence, looking forward for an active tuning method considers important action rather than exhausting and expensive trials-errors based approaches [17].

Lately, many advanced metaheuristics algorithms have been proposed and successfully introduced in various engineering issues [23-25]. With numerous search principles, like as evolutionary computation, swarm intelligence and memetic hybridization, these methods significantly conducted notable performance in comparison with other relatively outdated ones. In this side, the Water Cycle Algorithm (WCA) [23], Grey Wolf Optimizer (GWO) [24] and Artificial Bee Colony (ABC) [26] are particularly cited. The rationale behind of the chosen of these algorithms is their superiority and effectiveness as well as their multiple new variables. In this work, an advanced nature-inspired metaheuristics optimization algorithm, called Whale Optimization Algorithm (WOA), is introduced to optimize the effective gains of the PI controllers for the capacitor current feedback active damping method. This algorithm imitates the social behaviour of humpback whales which is distinguished by their unrivalled approach of hunting familiar as the bubble-net feeding manner [25, 27].

In accordance with the above-mentioned studies, this work investigates the WOA method to adjust the parameters of PI controllers and the coefficients of the capacitor current feedback. These effective control parameters represent the decision variables of the formulated problem to minimize various performance criteria such as the Integral Absolute Error (IAE), Integral Square Error (ISE) and Integral Time Square Error (ITSE) and under operational constraints. The optimization problem is completely solved by the introduced WOA-based metaheuristic. All demonstrative results are compared with those of PSO, ABC, GWO and WCA algorithms as well as the classical tuning methods like Ziegler-Nichols and pole placement techniques.

The remainder of this paper is arranged as follows. Section 2 discusses the formulation of the PI controllers tuning problem for the capacitor current active damping strategy. The proposed WOA metaheuristic is detailed in Section 3. In Section 4, the demonstrative results of the WOA-tuned PI controllers tuning are carried out. Several comparison and statistical studies are given in order to show the superiority and effectiveness of the proposed metaheuristics-based active damping approach. Concluding remarks are summarized in Section 5.
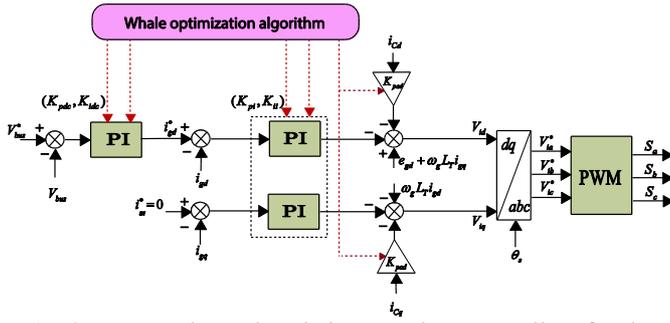
## 2. Active damping parameters' tuning

### 2.1. Problem statement

The system topology of the three-phase two-level grid-connected converter with a LCL-filter is shown in Fig. 1.



**Fig**. 1. Topology of the LCL-filter based grid-connected converter.

For control design aims, the mathematical representation for the LCL-filter in the d-q reference frame is given by the following model [8]:

$$
\begin{cases}
L_T \dfrac{di_{gd}(t)}{dt} = -R_T i_{gd}(t) + \omega_s L_T i_{gq}(t) + e_{gd}(t) - V_{id}(t) \\[2mm]
L_T \dfrac{di_{gq}(t)}{dt} = -R_T i_{gq}(t) - \omega_s L_T i_{gd}(t) + e_{gq}(t) - V_{iq}(t) \\[2mm]
C_{bus} \dfrac{dV_{bus}(t)}{dt} = S_d i_{gd}(t) + S_q i_{gq}(t) - i_{load}(t)
\end{cases}
\tag{1}
$$

where $L_T = L_i + L_g$ and $R_T = R_i + R_g$.

In this work, a voltage-oriented PI control strategy is employed for regulating the grid-side currents $i_{g(a,b,c)}$. Such a control system is designed based on the average model of the converter in the d-q synchronous reference frame [12, 29]. This control structure is consisting of three PI control loops; one is employed for the DC-link voltage and two others for the d-q current variables as depicted in Fig. 2. In the literature, the gains of PI current controllers are usually tuned using a technical optimum, i.e. damping factor $\xi = 0.707$ for 4% overshoot whereas the gains of PI DC-link voltage is selected using the symmetrical optimum [13, 30, 31]. In this design, the PWM strategy is used for the signals modulation.



**Fig. 2**. Damping strategy for the voltage-oriented PI control.

The current closed-loop control of the LCL-filter is generally unstable, which the phase plot of the loop gain passes $-180°$ at the resonance frequency. To stabilize the current loop, the resonance peak should be under 0 dB line. The active damping based capacitor current method is a solution that seems more attractive especially with several kilowatts power systems [12, 28]. Therefore, the feedback of the current via the LCL-filter capacitor results resonance damping and a simple proportional controller is used.

Hence, the transfer function between the grid current $i_g$ and the converter voltage reference $V_i$ is given as:

$$
G_{ad}(s) = \frac{1}{L_i s} \frac{z_{LC}^2 K_{pac}}{s^2 + 2\left(K_{pac}/2L_i \omega_{res}\right)\omega_{res} s + \omega_{res}^2}
\tag{2}
$$

where $z_{LC} = 1/\sqrt{L_g C_f}$, $\omega_{res} = \sqrt{L_i + L_g/C_f L_i L_g}$ is the resonance frequency and $K_{pac}$ is the capacitor current coefficient.

It can be noted from Eq. (2), that the damping term is changed thanks to the feedback capacitor current coefficient $K_{pac}$. However, since the value of this coefficient redounds to the total loop gain of the closed loop transfer function of the current controller, it should be chosen with great caution. Large values of such an effective control parameter may lead the system instability and small values cannot sufficiently damp the resonance phenomenon [12]. Moreover, the PI gains which are tuned by the classical well-known technical optimum (TO) and symmetrical optimum (SO) methods will produce a poor dynamic response and considerable steady-state error. Hence, this paper proposes a systematic technique to tune the controllers' parameters for DC-voltage, current control loops and capacitor current coefficient based on an advanced metaheuristics algorithms. On the other hand, to ensure the stability of the current control loops, the gains of current controllers and capacitor's current coefficients should be limited in certain regions. These regions will be determined based on the bode plot of the system. These limitations are considered as operational constraints for the formulated optimization-based tuning problem.

### 2.2. Tuning problem formulation

The suitable values of $K_p$ and $K_i$ gains of PI controllers are usually set by trials-errors based proceedings [32]. This non-systematic and hard action becomes more difficult and time consuming, particularly in the complex applications. So, the formulation of the tuning of $K_{pdc}$, $K_{idc}$, $K_{pi}$, $K_{ii}$ and $K_{pac}$ parameters as an optimization problem is a promising resolution. Such a difficult optimization problem can be efficiently managed by means of recent global metaheuristics algorithms [17, 33]. So, the following scheme of Fig. 3 is proposed for the metaheuristics-tuned PI controllers for the LCL-filter based grid converter.

The decision variables of such an optimization problem are the gains of PI controllers and capacitor current components which are given as:

$$
\boldsymbol{x} = \left[K_{pdc}, K_{idc}, K_{pi}, K_{ii}, K_{pad}\right]^T \in \mathrm{S} \subseteq \widetilde{\phantom{x}}^{5}_{+}
\tag{3}
$$

where $\mathrm{S} = \left\{\boldsymbol{x} \in \widetilde{\phantom{x}}^{5}_{+}, \boldsymbol{x}_{low} \leq \boldsymbol{x} \leq \boldsymbol{x}_{up}\right\}$ denotes the bounded search space.

**Fig. 3.** Proposed metaheuristics-tuned PI controllers for the LCL-filter based converter.

The defined objective functions are minimized taking into account a scope of time-domain restrictions. These are concerning to the maximum overshoot $\delta^{max}$, steady-state error $E_{ss}$, rise time $t_r$ and/or settling time $t_s$ of the closed-loop system step-response [17, 33]. So, the adjusting issue associating the PI controllers of the LCL-filter based converter can be expressed as follows:

$$
\begin{cases}
\text{minimize } f_m(\boldsymbol{x}), m \in \{IAE, ISE, ITSE\} \\
\boldsymbol{x} = \begin{bmatrix} K_{pdc}, K_{idc}, K_{pi}, K_{ii}, K_{pad} \end{bmatrix}^T \in \mathrm{S} \subseteq \widetilde{\phantom{x}}^5_+ \\
\text{subject to :} \\
g_1(\boldsymbol{x}) = \delta_{cd} - \delta_{cd}^{max} \le 0 \\
g_2(\boldsymbol{x}) = \delta_{cq} - \delta_{cq}^{max} \le 0 \\
g_3(\boldsymbol{x}) = \delta_{dc} - \delta_{dc}^{max} \le 0
\end{cases}
\tag{4}
$$

where $f_m : \widetilde{\phantom{x}}^5_+ \to \widetilde{\phantom{x}}, m \in \{IAE, ISE, ITSE\}$ are the cost functions defined as the well-known IAE, ISE and ITSE performance criteria [17], $g_q : \widetilde{\phantom{x}}^5_+ \to \widetilde{\phantom{x}}, q \in \{1, 2, 3\}$ are the problem inequality constraints. The terms $\delta_c$ and $\delta_{dc}$ are the overshoots of the controlled current and DC-voltage states, respectively, $\delta_c^{max}$ and $\delta_{dc}^{max}$ denote their maximum given values.

Since the optimization problem (4) is a multi-objective type, i.e. regarding the tracking errors on the DC-voltage, direct and quadrature currents dynamics, aggregation mechanisms are adopted to assemble all objective functions into one single cost according for each of the considered performance criteria. The related objective functions are defined and aggregated separately for IAE, ISE and ITSE performance index, respectively, as follows:

$$
f_{IAE}(\boldsymbol{x}) = \overbrace{w_{cd} \int_0^T |e_{cd}(\boldsymbol{x}, t)| dt}^{f_{IAE,cd}} + \overbrace{w_{cq} \int_0^T |e_{cq}(\boldsymbol{x}, t)| dt}^{f_{IAE,cq}} + \overbrace{w_{dc} \int_0^T |e_{dc}(\boldsymbol{x}, t)| dt}^{f_{IAE,dc}}
\tag{5}
$$

$$
f_{ISE}(\boldsymbol{x}) = \overbrace{w_{cd} \int_0^T e_{cd}^2(\boldsymbol{x}, t) dt}^{f_{ISE,cd}} + \overbrace{w_{cq} \int_0^T e_{cq}^2(\boldsymbol{x}, t) dt}^{f_{ISE,cq}} + \overbrace{w_{dc} \int_0^T e_{dc}^2(\boldsymbol{x}, t) dt}^{f_{ISE,dc}}
\tag{6}
$$

$$
f_{ITSE}(\boldsymbol{x}) = \overbrace{w_{cd} \int_0^T t e_{cd}^2(\boldsymbol{x}, t) dt}^{f_{ITSE,cd}} + \overbrace{w_{cq} \int_0^T t e_{cq}^2(\boldsymbol{x}, t) dt}^{f_{ITSE,cq}} + \overbrace{w_{dc} \int_0^T t e_{dc}^2(\boldsymbol{x}, t) dt}^{f_{ITSE,dc}}
\tag{7}
$$

where $T$ denotes the total simulation time, $w_{cd} > 0$, $w_{cq} > 0$ and $w_{dc} > 0$ are the weighting coefficients of the aggregation functions satisfying $w_{cd} + w_{cq} + w_{dc} = 1$, and $e_j(.), j \in \{dc, cd, cq\}$ denote the tracking errors between the plant output and the relative set-point values i.e. $e_{dc}(\boldsymbol{x}, t) = V_{dc}^* - V_{dc}(\boldsymbol{x}, t)$, $e_{cd}(\boldsymbol{x}, t) = i_{dg}^* - i_{dg}(\boldsymbol{x}, t)$ and $e_{cq}(\boldsymbol{x}, t) = i_{qg}^* - i_{qg}(\boldsymbol{x}, t)$.

Various techniques have been proposed to handle constrained optimization problems. One of these approaches is to set penalties on the cost functions of problem (4). In this work, the external static penalty method is adopted by means of the following equation [17, 33]:

$$
\varphi_m(\boldsymbol{x}) = f_m(\boldsymbol{x}) + \sum_{q=1}^{n_{con}} \Lambda_q \max\left[ 0, g_q(\boldsymbol{x}) \right]^2
\tag{8}
$$

where $\Lambda_q$ are prescribed penalty parameters and $n_{con}$ denotes the number of inequality problem constraints.

## 3. Proposed whale optimization algorithm

The Whale Optimization Algorithm (WOA) is a recent metaheuristic proposed by S. Mirjalili and A. Lewis [25]. It is a nature-inspired global method which imitates the hunting behavior of humpback whales in finding and hunting the prey. The humpback whales tend to hunt and attack herds of small fishes or krill that are near to the surface. This is achieved by producing specific bubbles in a spiral or nine shaped paths around the prey. The WOA mimicked the bubble-net hunting technique to carry out the optimization. Hence, the mathematical representation of each phase in the WOA concept is explained in the following sections.

### 3.1. Encircling prey

The WOA initially anticipates that the current best candidate solution is the objective prey or is near to the optimum. This assumption is still correct until the best solution appears as there is no prior knowledge of the optimal solution in the search domain. The remaining candidates change their positions according to the best search one according to the following motion equations [25, 27]:

$$
\boldsymbol{x}_{k+1} = \boldsymbol{x}_k^* - A_k . \Delta_k
\tag{9}
$$

$$
\Delta_k = \left| C_k . \boldsymbol{x}_k^* - \boldsymbol{x}_k \right|
\tag{10}
$$

$$
A_k = 2\boldsymbol{a}_k . \boldsymbol{r}_k - \boldsymbol{a}_k
\tag{11}
$$

$$
C_k = 2 . \boldsymbol{r}_k
\tag{12}
$$

where $k$ denotes the current iteration, $x_k^*$ is the position vector of the best solution and $x_k$ is the position vector, $a_k$ is linearly decreased vector from 2 to 0 over the course of iterations, $r_k$ as a random vector in [0,1] and "." denotes the element-by-element multiplication operator.

### 3.2. Bubble-net hunting method

This phase presents the exploitation mechanism of such an algorithm. It is hybrid of combined methods that can be mathematically presented as follows.

### 3.3. Shrinking encircling

The value of $a_k$ in Eq. (11) is reduced and consequently conducts the change of $A_k$. This implies that $A_k$ is a random value ranging between the period $[-a, a]$ where $a$ is reduced from 2 to 0 over the course of iterations. The novel position of humpback whale can update its value anywhere between the past candidate position and the current best one.

### 3.4. Spiral position update

The distance between the positions of the humpback whale and the prey is computed as shown in Eq. (10). Then, a mathematical equation of the spiral motion is created to mimic the motion of helix format by humpback whales. This can be described by the following equation [25, 27]:

$$x_{k+1} = \Phi_k . e^{bl} . \cos(2\pi l) + x_k^* \tag{13}$$

where $\Phi_k = |x_k^* - x_k|$ denotes the distance from the humpback whale to the prey and $b$ is a constant in order to determining the form of the logarithmic spiral. In addition, $l$ is a random value in the interval $[-1,1]$.

It observed that during the attacking mechanism, the humpback whales swim around the prey based on above two paths simultaneously. Due to this manner, there is a possibility of 50% to switch between the shrinking encircling technique and spiral-shaped method to update the next positions of the whales as follows:

$$x_{k+1} = \begin{cases} x_k^* - A_k . \Delta_k & \text{if } \rho < 0.5 \\ \Phi_k . e^{bl} . \cos(2\pi l) + x_k^* & \text{if } \rho \geq 0.5 \end{cases} \tag{14}$$

where $\rho$ is a random number in $[0,1]$.

The humpback whales explore randomly for its prey in accordance with the location of each other. Therefore, $A_k$ is set with random values greater than 1 or less than -1 in order to allow the search candidate to transfer away from the reference whale or leader. Unlike the exploitation technique, the updated location of a search candidate has done based on a randomly selected search candidate rather than the best search candidate obtained yet as follows:

$$\Delta_k = |C_k . x_k^{rand} - x_k| \tag{15}$$

$$x_{k+1} = x_k^{rand} - A_k . \Delta_k \tag{16}$$

where $x_k^{rand}$ is a random position vector selected from the present iteration.

Finally, a flowchart of the proposed WOA-tuned PI control approach is shown in Fig. 4.
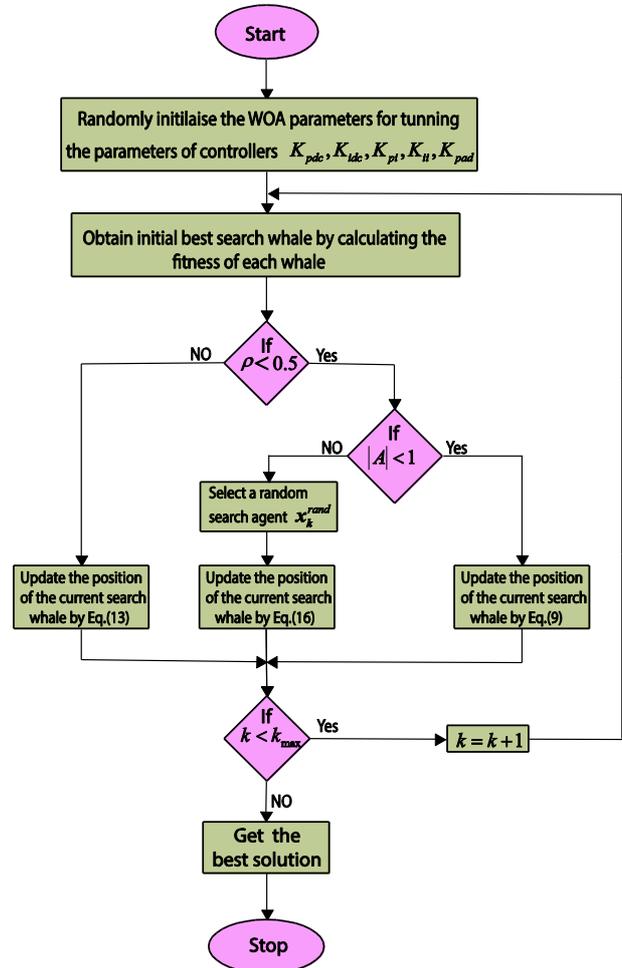


**Fig. 4.** Flowchart of the WOA-tuned PI and capacitor current parameters.

## 4. Simulation results and discussion

### 4.1. Numerical experiments

The individual parameters of the studied LCL-filter based grid-connected converter were taken from [28] and are given in Table 1.

**Table 1**. Parameters of the LCL-filter based converter model.

| Parameters | Values (unit) |
|---|---|
| Rated converter power | 2.2 kVA |
| Grid line voltage (RMS) | 380 V |
| LCL-filter grid side inductance | 1.6 mH |
| LCL-filter capacitance | 4.7 μF |
| LCL-filter converter side inductance | 1.6mH |
| Switching frequency | 8 kHz |

In order to assess the performances of the WOA-tuned PI controllers and proportional capacitor current gains, the proposed metaheuristic is proceeded on an Intel R CoreTMi5 CPU computer at 2.5 GHz and 8 GB of RAM. To reinforce the effectiveness of the proposed WOA method, the homologous PSO, PSO-gbest, ABC, WCA and GWO algorithms are considered for comparison purposes.

For all proposed algorithms, the values of the used common parameters, i.e. population size $N_{pop} = 50$ and maximum number of iterations $k_{max} = 200$, were selected to be equal. In fact, this selection has been achieved after many independent runs of these methods. We manage to boost the number of iterations for various values of the population size as shown in Table 2. The specific control parameters for each algorithm are selected as:

- PSO: cognitive and social coefficients $c_1 = c_2 = 2$, inertia weight decreasing linearly from $w_{max} = 0.9$ to $w_{min} = 0.4$;
- PSO-gbest: degree of uncertainty $\sigma_{max} = 0.15$, $\sigma_{min} = 0.001$ and $\alpha = 0.5$;
- ABC: limit of abandonments $L = 125$;
- WCA: summation number of rivers $N_{sr} = 10$, max. distance $d_{max} = 1e - 10$.

To adjust the PI controllers' parameters for the current, DC-link voltage and proportional capacitor current loops, the proposed WOA and the other reported algorithms are executed 10 independent times. The optimization problem (4) is minimized under various performance criteria, i.e. the IAE, ISE and ITSE indices. These performance indexes are calculated taking into account that a load step is performed. This is achieved by changing the value of the load $R_{load}$ at the simulation time $t = 0.4 \sec$.

Table 3 gives the statistical results attained by the introduced algorithms under minimizing the cost functions described in Eq. (5) to Eq. (7). It can be clearly observed that the proposed WOA produces very competitive solutions with the reported algorithms. Table 4 summarizes the obtained gains for the PI controllers for each of the proposed optimization methods and under the best case of optimization of the problem (4) for the IAE performance criterion. Indeed, these tuned PI controllers' gains lead to the best transient and steady-state responses of the entire reported algorithms.

**Table 3**. Statistical results of optimization problem (4) through 10 independent runs: IAE index case.

| Algorithms | Best | Mean | Worst | STD |
|---|---|---|---|---|
| PSO | 0.1775 | 0.1941 | 0.2178 | 1.5 E -02 |
| PSO-gbest | 0.1883 | 0.1944 | 0.2023 | 3.9 E-03 |
| ABC | 0.1765 | 0.1832 | 0.1878 | 3.6 E-03 |
| WCA | 0.1543 | 0.1544 | 0.1545 | 8.6 E-05 |
| GWO | 0.1532 | 0.1537 | 0.1539 | 1.8 E-04 |
| WOA | 0.1529 | 0.1532 | 0.1534 | 1.6 E-04 |

**Table 4**. Optimized PI controllers' gains.

| PI gains | Algorithms | | | | | |
|---|---|---|---|---|---|---|
| | PSO | PSO-gbest | ABC | WCA | GWO | WOA |
| $K_{pdc}$ | 3.3 | 86.7 | 35 | 41.6 | 56.3 | 3.4 |
| $K_{idc}$ | 145 | 227.3 | 250 | 400 | 57.3 | 287 |
| $K_{pi}$ | 1.02 | 0.77 | 1.4 | 1.9 | 2 | 1.8 |
| $K_{ii}$ | 258 | 164.8 | 135 | 340 | 340 | 340 |
| $K_{pad}$ | 20 | 26.8 | 8 | 0.1 | 0.19 | 0.32 |

**Table 2**. Comparison results with different numbers of iterations and population size.

| Population size $N_{pop}$ | Max. Iteration $k_{max}$ | IAE criterion | | | | | |
|---|---|---|---|---|---|---|---|
| | | Algorithms | | | | | |
| | | PSO | PSO-gbest | ABC | WCA | GWO | WOA |
| 20 | 50 | 0.3263 | 0.2557 | 0.2075 | 0.1557 | 0.1557 | 0.1558 |
| | 100 | 0.2648 | 0.2344 | 0.2013 | 0.1558 | 0.1557 | 0.1556 |
| | 200 | 0.2125 | 0.2089 | 0.1996 | 0.1556 | 0.1558 | 0.1554 |
| 30 | 50 | 0.3078 | 0.2503 | 0.2047 | 0.1555 | 0.1555 | 0.1556 |
| | 100 | 0.2473 | 0.2280 | 0.1976 | 0.1557 | 0.1555 | 0.1548 |
| | 200 | 0.2078 | 0.2029 | 0.1953 | 0.1556 | 0.1546 | 0.1540 |
| 50 | 50 | 0.2821 | 0.2301 | 0.1867 | 0.1554 | 0.1544 | 0.1542 |
| | 100 | 0.2488 | 0.2129 | 0.1851 | 0.1549 | 0.1543 | 0.1536 |
| | 200 | 0.1885 | 0.1921 | 0.1796 | 0.1543 | 0.1538 | 0.1532 |

In addition, Fig. 5 shows the convergence histories of the proposed algorithms under the case of IAE index. It is shown that the proposed WOA metaheuristic outperforms the other reported methods in terms of the fastness and non-premature convergence as well as the solutions quality. Fig. 6 approves that the WOA-based method for the ISE criterion gives the best solution as a second order or class after the WCA one. Finally, the converge curve of the reported algorithms under the ITSE performance index is depicted in Fig. 7.
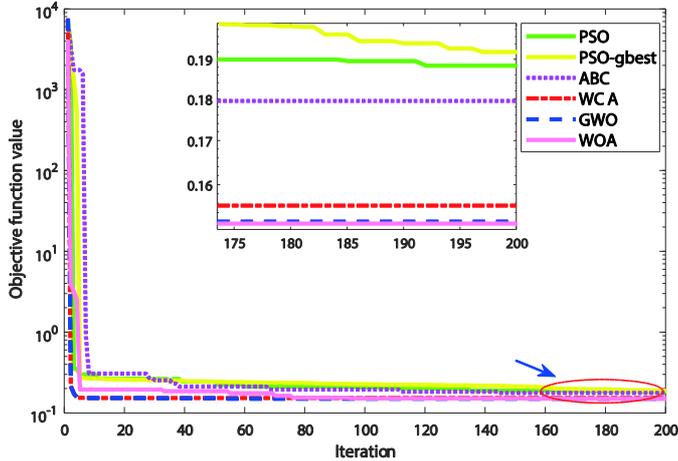


**Fig. 5.** Convergence rates comparison: IAE criterion.
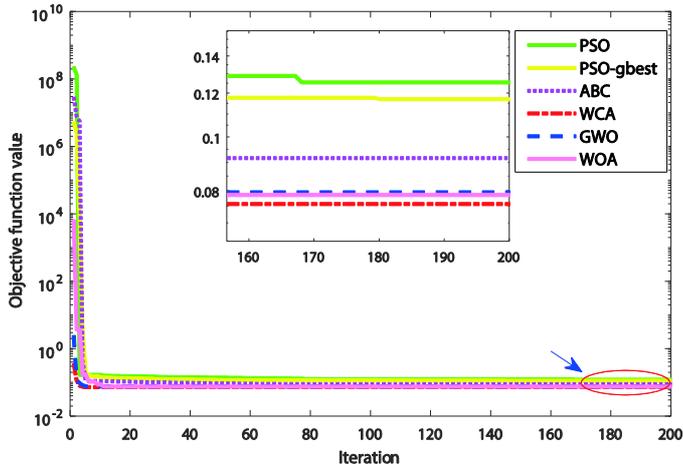


**Fig. 6.** Convergence rates comparison: ISE criterion.
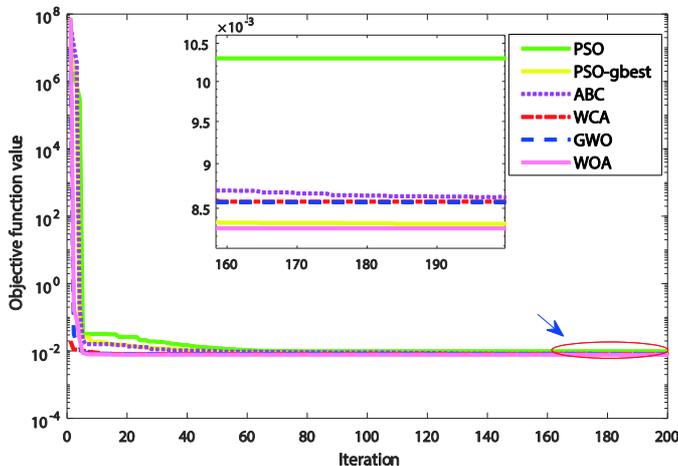


**Fig. 7.** Convergence rates comparison: ITSE criterion.

From these results, the superiority of the WOA metaheuristic is still shown in terms of exploitation and exploration capabilities for local and global searches. This further justifies the use of such a recent global metaheuristic for the design and tuning of the proposed voltage-oriented PI control strategy of the grid-connected converter.

In order to assess the control executions of the metaheuristics-tuned controllers', the closed-loop response of the DC-link voltage under a change in the resistor load is presented in Fig. 8. Indeed, at the beginning, the first value of the load resistor is set to 400 Ω. The system is test without any changing in the load but at the time 0.4 sec.This is performed by adding another equal value load resistor in parallel. From this result, it can be noticed that the WOA can control the DC-link voltage dynamics with higher performance compared to the other algorithms for the IAE index. All time-domain performances related to the controlled DC-link voltage dynamics under a change resistor load are given and compared in Table 5 where $\delta$, $t_r$, $t_s$ and $E_{ss}$ denote, the overshoot, rise time, settling time and steady-state error, respectively.
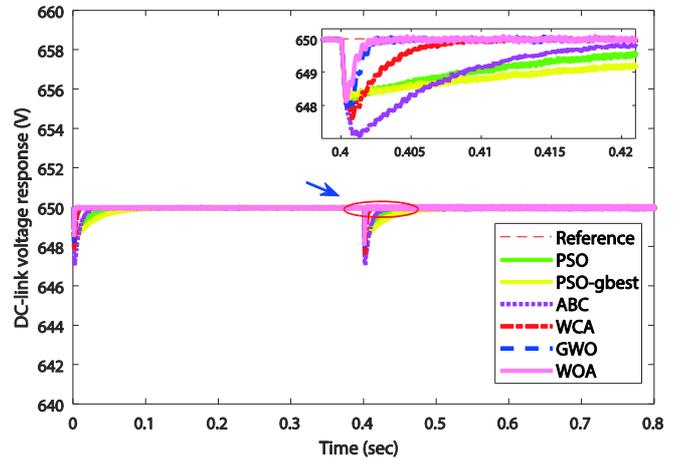


**Fig. 8.** DC-link voltage responses against load variation for different metaheuristics-tuned PI controllers.

**Table 5**. Time-domain performances for controlled DC-link voltage under load changes.

| Algorithms | δ (%) | $t_r$ (sec) | $t_s$ (sec) | $E_{ss}$ |
|---|---|---|---|---|
| PSO | 0.6 | 0.06 | 0.397 | 0.013 |
| PSO-gbest | 0.61 | 0.10 | 0.399 | 0.003 |
| ABC | 1.4 | 0.12 | 0.11 | 0.004 |
| WCA | 1.03 | 0.02 | 0.397 | 0.010 |
| GWO | 0.87 | 0.01 | 0.398 | 0.002 |
| WOA | 0.80 | 0.003 | 0.399 | 0.001 |

In the remaining results, we selected the optimal parameters of the controllers for the WOA method. The bode plot of the open-loop system is depicted in Fig 9. From this result, it can be observed that the gain margin is $\Delta G = 13.8$ dB and the phase one is $\Delta \phi = 48.1°$. The gain and the phase margins demonstrate the stability of the system.
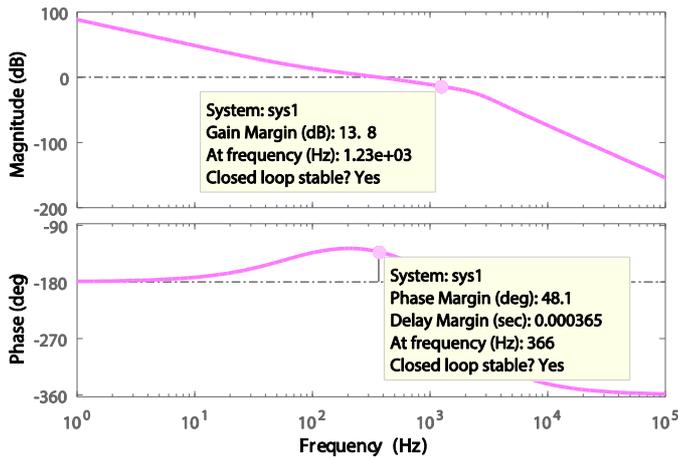
**Fig. 9.** Bode plot of the open-loop system: WOA-based tuning case.

To compare the Total Harmonic Distortion (THD) of the AC currents for the reported algorithms, Table 6 collects the THD values calculated up to the 50th order for these algorithms. It is shown that the WOA-based PI design approach achieved a better attenuation with a THD value about 1.43 %.

**Table 6.** Total Harmonic Distortion of grid current

| Algorithms | THD of the AC grid currents (%) |
|---|---|
| PSO | 1.80 |
| PSO-gbest | 1.88 |
| ABC | 1.63 |
| WCA | 1.56 |
| GWO | 1.56 |
| WOA | 1.43 |

Fig. 10 presents the harmonics spectrum of the AC grid currents and Fig. 11 shows the dynamic responses of the AC currents associated to the load change of the LCL filter-based grid-converter at the time 0.4 sec.
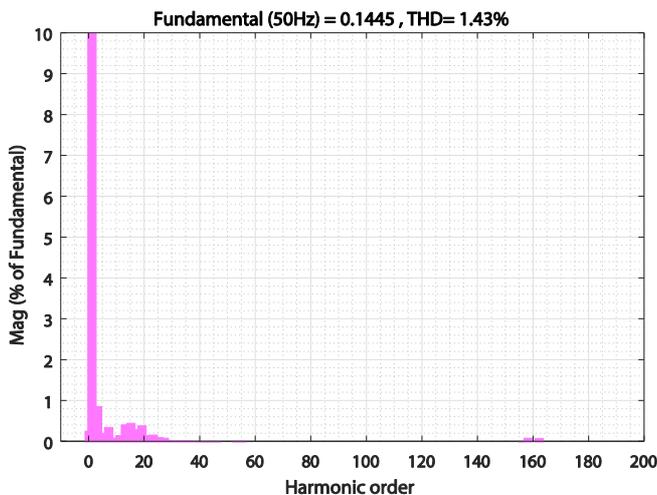


**Fig. 10.** Harmonics spectrum of the AC grid current: WOA-based tuning case.
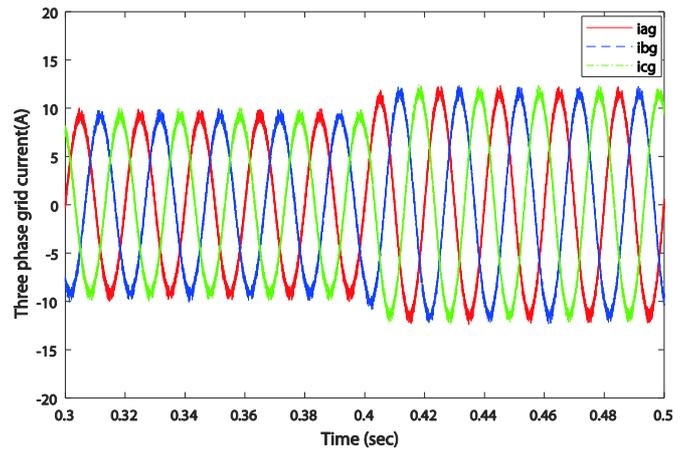


**Fig. 11.** Dynamic response of the AC grid currents under load change.

### 4.2. Comparison of classical PI and WOA-tuned PI controllers

A comparison of the proposed WOA-based tuning approach with the classical Ziegler-Nichols, Tyreus-Luyben, Cohen-Coon and SO-based pole assignment methods is performed for the PI controllers' design as summarized in Table 7. The obtained results for the proposed WOA-tuned PI controllers are comparable with those obtained by these classical methods but with less computational complexity and a remarkable reduction of the design time and resources. Such a comparison highlights the superiority of the WOA algorithm to systematically tune the DC-link voltage and currents PI controllers.

**Table 7.** Time-domain performances of the DC-link voltage control loop.

| Methods | $\delta$ (%) | $t_r$ (sec) | $t_s$ (sec) | $E_{ss}$ |
|---|---|---|---|---|
| Cohen-Coon | 0.910 | 0.051 | 0.197 | 0.001 |
| Ziegler-Nichols | 0.950 | 0.015 | 0.013 | 0.003 |
| Tyreus-Luyben | 2.010 | 0.049 | 1.040 | 0.006 |
| SO method | 10.800 | 0.010 | 0.017 | 0.007 |
| WOA method | 0.820 | 0.003 | 0.199 | 0.004 |

Fig. 12 describes the transient responses of the DC-link voltage loop around a final set-point value of 650V for different tuned PI controllers. The aim is to show the difference between the classical tuning methods and the advanced optimization-based ones. Referring to this result, the WOA-tuned PI controller indicates better performances in comparison with the other reported methods. Roughly, the time-domain responses of the controlled LCL grid-connected converter are damped and the rise time is further reduced. The tracking dynamic is little oscillating and the steady-state is rapidly reached in the case of WOA-tuned PI controllers.

### 4.3. Statistical analysis and comparison

In this part, the algorithms mean executions related to the different optimization indices will be sorted to assess the best operating one according to its average objective function performance.
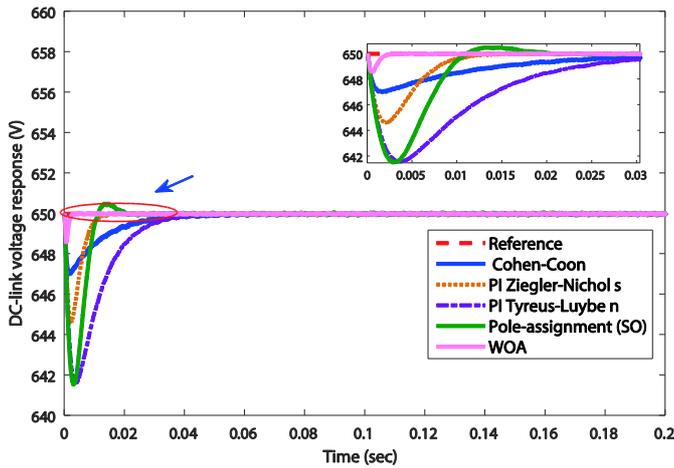
**Fig. 12.** Transient responses of the DC-link voltage for different designed PI controllers.

Moreover, a statistical comparison based on the nonparametric Friedman and pair wise post hoc Bonferroni-Dunn tests is carried out by using these mean performances [34]. Friedman test is only performed to check whether there is a significant difference in the performances of the reported algorithms. However, for further analysis, the Bonferroni-Dunn test can determine the significant difference between the proposed WOA method and each other algorithm based on the results of Friedman test. The principle of the ranking in Friedman test is that the algorithm attains the best mean value ranks the lowest, while the one has the worst mean value is given the highest rank [36]. The results of the

Friedman test for all the proposed methods are provided in Table 8. One can note that the proposed WOA metaheuristic has worthily attained lowest average ranks compared to the remaining methods.

Here, a statistical analysis has been performed to highlight the importance of the WOA-based tuning method over other algorithms. The Friedman's test for six algorithms and three indices provides the F-score of 4.5625 [35]. The F-statistics value is 3.33 with a confidence level of 95%. Since the computed F-score is greater than the F-statistics value, the null hypothesis is declined. Hence, it can be deduced that the performances of the algorithms are statistically different. Hence, the Bonferroni-Dunn's test is applied to express the extent of the supremacy of the proposed WOA algorithm over each of the reported algorithms. To this end, the critical difference in the summation ranks at 95% confidence level is 6.903.

Moreover, the absolute differences of the summation individual ranks for all reported algorithms between each other are presented in Table 9. It can be clearly deduced that the execution of the WOA is clearly superior to the PSO, PSO-gbest and ABC algorithms. Indeed, the Bonferroni-Dunn's critical difference is smaller than the absolute difference of the summation individual ranks for the WOA method related to other algorithms. At 70 % confidence level, the Bonferroni-Dunn's critical difference in the summation ranks is 3.3866 which signifies that the performances of WOA over the WCA and GWO algorithms.

**Table 8**. Rank based statistical analysis of mean performances.

| Algorithms | IAE | | ISE | | ITSE | | Average rank based all indices |
|---|---|---|---|---|---|---|---|
| | Score | Rank | Score | Rank | Score | Rank | |
| PSO | 0.1941 | 5 | 0.1255 | 6 | 0.01030 | 6 | 5.66 |
| PSO-gbest | 0.1944 | 6 | 0.1171 | 5 | 0.00834 | 2 | 4.3 |
| ABC | 0.1832 | 4 | 0.9184 | 4 | 0.00862 | 5 | 4.3 |
| WCA | 0.1544 | 3 | 0.0751 | 1 | 0.00858 | 4 | 2.6 |
| GWO | 0.1537 | 2 | 0.0799 | 3 | 0.00857 | 3 | 2.6 |
| WOA | 0.1532 | 1 | 0.0784 | 2 | 0.00829 | 1 | 1.3 |

**Table 9**. Paired comparisons between proposed metaheuristics.

| | PSO | PSO-gbest | ABC | WCA | GWO |
|---|---|---|---|---|---|
| WOA | 13 | 9 | 9 | 4 | 4 |
| PSO | - | 4 | 4 | 9 | 9 |
| PSO-gbest | - | - | 0 | 5 | 5 |
| ABC | - | - | - | 5 | 5 |
| WCA | - | - | - | - | 0 |

On what concerns the average computational time, it is clear that the WOA achieved the second best computation time after the WCA but their values are much closer to each other as proved in Fig. 13. Moreover, the WOA metaheuristic has the preference in term of the internal parameters that should be tuned to that of the WCA one. This

latter has the internal parameters $N_{sr}$ and $d_{max}$ whereas the WOA does not have any internal parameters.

From these demonstrative results, it is shown that the uniformity of solutions is clearly observed with the WOA metaheuristic case for most numerical experiments independently performed on problem (4). For such a reformulated PI design problem, the WOA algorithm outperforms all other methods in terms of solutions quality and non-premature convergence. The computation time is always the least in the case of WOA-tuned PI control which further proves the contribution of the proposed metaheuristics-based tuning approach versus the given Cohen-Coon, Ziegler-Nichols, Tyreus-Luyben and Symmetrical Optimum based methods.
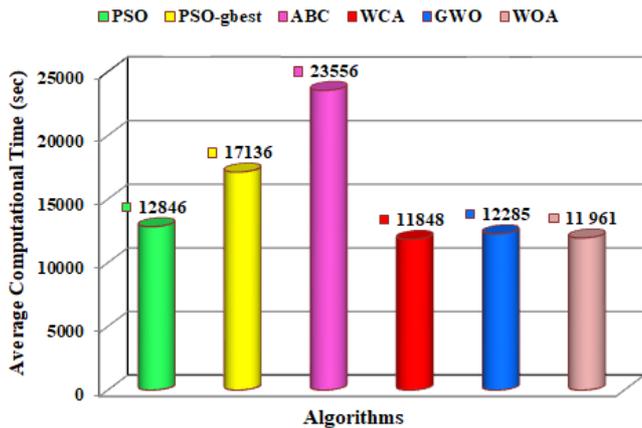
**Fig. 13.** Computational time requirements of the introduced algorithms.

## 5. Conclusion

This paper proposes an intelligent metaheuristics-based design procedure to tune the PI controllers' gains for the voltage-oriented control of a LCL grid-connected converter. The active damping strategy based on a capacitor current loop is applied to outperform the resonance phenomena. The controllers tuning is formulated as a constrained optimization problem under several operational constraints and stability margins of the current controllers. An advanced WOA metaheuristic is implemented to solve such a formulated tuning problem. To assess the performance superiority of the proposed WOA-tuned PI controllers, a comparison study with other similar metaheuristics is performed. The demonstrative results conduct that the proposed WOA introduces very completive results compared to other proposed approaches in terms of global search capabilities, robustness and non-premature convergence. Moreover, the dynamic responses of the DC-link voltage and the AC grid currents for the WOA-tuned PI controllers are compared with other reported algorithms under the same configuration and conditions. The WOA gives a better transient response in terms of time domain performances. In addition, the THD of AC grid currents is reduced to the lowest value achieving a better attenuation by the WOA method. Further comparisons are performed with the classical Ziegler-Nichols, Cohen Coons and Tyreus-Luyben tuning approaches to indicate that the proposed WOA-tune PI controllers method is a competitive with good execution in terms of effectiveness and robustness criteria.

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