Optimization of the Lyapunov Based Nonlinear Controller Parameters in a Single-Phase Grid-Connected Inverter

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ABSTRACT

In this paper, optimization of the backstepping controller parameters in a grid-connected single-phase inverter is studied using Imperialist competitive algorithm (ICA), Genetic Algorithm (GA) and Particle swarm optimization (PSO) algorithm. The controller is developed for the system based on state-space averaged model. By selection of a suitable Lyapunov function, stability of the proposed controller is proved in a wide range of operation. Considering different optimization algorithms, steady-state and dynamic responses of the developed system are studied. In addition, THD values for different test are compared. Finally, to verify accuracy of the proposed method, designed controller is simulated using MATLAB/Simulink software.

KEYWORDS: Grid-connected inverter, nonlinear controller, Imperialist competitive algorithm (ICA), Genetic Algorithm (GA) and Particle swarm optimization (PSO) algorithm.

1. INTRODUCTION

Considering recent advantages of science and technology in the last century, application of the fossil fuels are increased which has been creating many environmental problems such as ozone layer hole. So, in order to protect the environment and use clean energy resources the Kyoto Protocol was adopted. Nowadays clean and renewable energy resources including fuel cells, photovoltaic (PV) and wind energy have been used widely in different applications such as grid-connected systems which injects the obtained power from DC sources intro grid. These inverters mostly include the voltage source inverters (VSI) with a filter in the output.

Recent advances in the manufacturing of power electronic devices have led to excessive use of pulse width modulation (PWM) inverters in the industry. The overall performance of inverter is studied by the total harmonic distortion (THD), transient and steady-state responses and efficiency. Recently many closed loop control methods are presented to improve performance of the inverters. For example, the linear control [1], passivity-based control [2], Lyapanov-based control [3], repetitive control [4, 5], the resonant integrators [6] and sliding mode control [7] have been reported. The proposed methods in [1, 2, 7] are applicable only for stand-alone systems. In [8] a general overview of a single-phase inverter for distributed generators (DG) systems have been introduced.

In [9] have suggested a new single-phase inverter that can be operated as a stand-alone or grid-connected systems. Although, in [8, 9], both performances have been investigated by different circuit topologies and modern control methods, however the stability of the proposed method is not analyzed in a wide range and hence it cannot be generally used in commercial products. In [10], a sliding mode controller (SMC) for single-phase grid-connected inverter with LCL filter is proposed to eliminate tracking error of the network current and reduce THD. For example, the possibility of chattering and steady state error limits its industrial application. Also in [10], the equivalent series resistance of the inductor is ignored while these values can affect response of the controller. In [11] have introduced a backstepping controller (BSC) for a high performance grid-connected inverter in stand-alone applications so that, DG units can operate individually or in a grid-connected mode. In [11], in spite of using a BSC, the L filter is used as a passive filter.

In order to achieve the best THD, transient response, and efficiency in the range of reference current variations and model parameters, the control parameters must be selected carefully. Small-signal model of the inverter can provide a good insight to find control parameters. However, it still requires trial and error to find the optimal parameters according to the nonlinear characteristics. Optimization algorithms are the kinds of methods that can obtain optimal values of these parameters if the appropriate objective function can be defined. Optimization algorithms inspired by nature have demonstrated considerable success as intelligent optimization methods besides classical methods. Among these methods, the imperialist competitive algorithm (ICA) [12], genetic algorithm (GA) [13] and particle swarm optimization algorithm (PSO) [14] can be mentioned. These methods have been used in solving many optimization problems for various fields such as determining the optimal path for automatic factors and optimal design of controllers for industrial processes.

According to the research conducted by authors, no paper is proposed so far in the case of designing control parameters in a nonlinear method using optimization algorithms in the grid-connected inverters.

In this paper, a BSC method in the single-phase DC to AC grid-connected converter with L filter is optimized by considering the designed equivalent series resistance of the inductor and controller parameters using ICA, GA and PSO and their results are compared with each other.

The purpose of this paper is Lyapunov based nonlinear control of a single-phase grid-connected inverter that its power topology is shown in Fig. 1. In this figure L are filter inductor, r_L are equivalent series resistance of L, V_{dc} is DC line voltage, i is the current of L and u is inverter switching signal which its value is 0 or 1.

2. THE GRID-CONNECTED SNIGLE PHASE INVERTER

To design a grid-connected inverter, its dynamic model must be obtained first. In

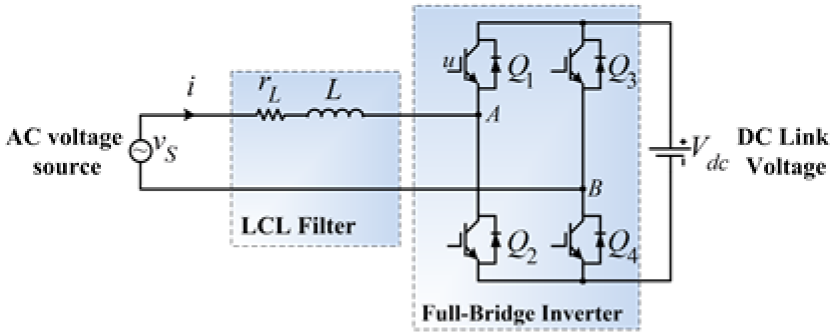

Fig.1. Power topology of the grid-connected inverter

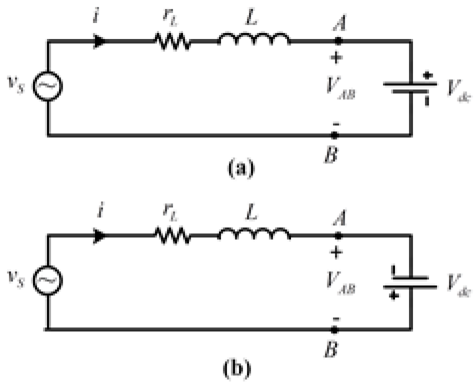

Fig.2. Equivalent circuit of grid-connected inverter in switching mode a) $u = 1$ and b) $u = 0$

this section, dynamic model of the grid-connected inverter with L filter is extracted. By applying Kirchhoff's laws to the circuit in Fig. 1 and taking the values $u = 0$ and $u = 1$, the Equations (1) can be written. Also Fig. 2 shows the equivalent circuit of grid-connected inverter with L filter in switching mode ($u = 1$ and $u = 0$).

$$\begin{cases} \frac{di}{dt} = \frac{1}{L}v_s - \frac{r_L}{L}i + \frac{1}{L}V_{dc} & for\ u = 0 \\ \frac{di}{dt} = \frac{1}{L}v_s - \frac{r_L}{L}i - \frac{1}{L}V_{dc} & for\ u = 1 \end{cases} \quad (1)$$

Averaged model of the circuit is obtained as follows:

$$\frac{di}{dt} = \frac{1}{L}v_s - \frac{r_L}{L}i - \left(\frac{1-2\mu}{L}\right)V_{dc} \quad (2)$$

where i represent mean values of the state variables and μ is the mean value of u.

3. CONTROLLER DESIGN

In this section, a BSC with L filter for grid-connected inverter with the purpose of controlling i is designed.

Tracking error signal is defined as follows:

$$z = x - x_d = i - i_{ref} \quad (3)$$

where $x = i$, $x_d = i_{ref}$ and x_d is the reference value of x. By deriving from Equation (3):

$$\dot{z} = \dot{x} - \dot{x}_d = \frac{1}{L}v_s - \frac{r_L}{L}i - \left(\frac{1-2\mu}{L}\right)V_{dc} - \dot{x}_d \quad (4)$$

If the Lyapunov function is selected as:

$$V_1 = 0.5z^2 \quad (5)$$

then its time derivation is:

$$\dot{V}_1 = z\dot{z} = z\left(\frac{1}{L}v_s - \frac{r_L}{L}i - \left(\frac{1-2\mu}{L}\right)V_{dc} - \dot{x}_d\right) \quad (6)$$

Finally the control law for grid-connected inverter is designed as follow:

$$u = \frac{L}{2V_{dc}}\left[c_1 z + \frac{1}{L}v_s - \frac{r_L}{L}i + \frac{1}{L}V_{dc} - \dot{x}_d\right] \quad (7)$$

in which $c_1 > 0$ is design parameter; then

$$\dot{V} = -c_1 z_1^2 \quad (8)$$

4. OPTIMIZATION OF THE DESIGNED CONTROLLER

In this paper, three optimization algorithms (ICA, GA and PSO) is used to optimize the parameters of the BSC in single-phase grid-connected DC to AC converter with LCL filter. It should be noted that to optimize the parameters, the PWM carrier signal amplitude is selected as the second parameter (c_2) as well as the designed controller parameters c_1.

4.1 Imperialist competitive algorithm (ICA)

Imperialist competitive algorithm (ICA), which is used to adjust the designed controller parameters, is a method in the field of evolutionary computation to find the optimal solution of different optimization problems. This algorithm, with mathematical modelling of social-political development process, presents an algorithm for solving optimization problems. Like all of the evolutionary algorithms, the ICA approach constitutes the basic set of possible solution in GA. These initial responses are known as country. In this algorithm, the countries are divided into two categories; *"colony"* and *"imperialist"*. Each imperialist, depending on its strength, controls a number of colonies whose colonizes. Assimilation policy and imperialist competitive constitute the main part (core) of this algorithm. According to the assimilation policy in which historically imposed on the colonies by imperialist countries such as France and Britain, these countries have tried to destroy the language, culture and customs of the colonized country by using methods such as construction of schools in their own language. In presenting this algorithm, this policy is done by moving colonies of an empire according to a special equation. Fig. 3 shows this movement. According to Fig. 3, x and θ are uniformly distributed random numbers which formulated as follows [12, 15]:

$$x \sim U(0, \beta \times d) \quad (9)$$

$$\theta = U(-\gamma, \gamma) \quad (10)$$

where $1 < \beta < 2$, d is the distance between colony and imperialist and γ is the parameter that adjust the deviation from the main path. The values of ICA parameters are set according to Table 1.

ICA optimization algorithm can be summarized as [12]:

(1) Initialize the empires by choosing some random points on the function.

(2) Change the position of the colonies toward their imperialist countries.

(3) If there is a colony in an empire that would cost less than that of imperialist, replace the position of colony with the imperialist.

(4) Calculate the total cost of all empires (Considering the costs of both imperialist and its colonies).

(5) Select the weakest colony or colonies from the weakest empire and give it or them to the one which is most likely to possess it.

(6) Remove the weak empires.

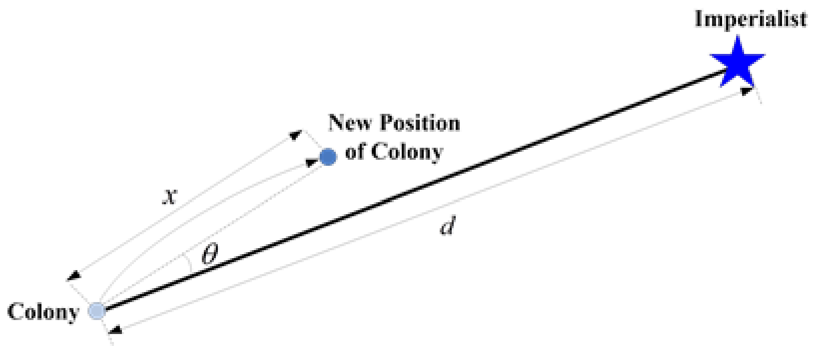

Fig. 3. Colonies movement towards imperialist (assimilation policy)

(7) Stop the process if there is only one empire, otherwise go to 2.

Table 1. The Parameters of the ICA approach

Parameter	*Value*
Number of Countries	40
Number of Imperials	10
Max Decades	30
β	1.7
γ	0.35
P Revolution	0.35

4.2 Genetic Algorithm (GA)

GA is a repetitive search approach that operates on a set of strings called "*chromosomes*". These strings encode possible solutions of the problem that GA is being used to solve and the set is ran and improved repeatedly in the following way: each string is assessed by considering its *"fitness"*'. Then the strings are *"mated"*, with new strings being made from elements of the strings that mate, and with the strings having more fitness and also a greater likelihood of taking part in the reproductive process. Therefore it is more likely to pass on its feature via partial inclusion in new strings to the next 'generation' of strings. With new generation, the process is repeated. If all process goes well, natural choice of the fittest should make sure that overall, the fitness of the *"population"* of strings will rise as will the fitness of the fittest individual solution found. In this way, GA can be used in solving optimization problems [13, 16, 17]:

GA optimization algorithm can be considered are as follows [18]:

(1) Initialize the binary chromosome strings of *"Population size"*.
(2) Decode the strings and assess the figure of demerit of each string.
(3) Choose the best strings to increase the figure of demerit from minimum value.
(4) Copy the best strings and paste them on the non-selected strings.
(5) Combine and develop it to generate off strings.
(6) Update the genetic cycle and stop the process.

The values of GA parameters are set according to Table 2.

Table 2. The Parameters of the GA approach

Parameter	*Value*
Population size	40
Number of Iteration	30
Parents (off springs) Ratio	0.9

$Mutants\ Population\ size\ Ratio$	0.02
$Tournament\ Selection\ size$	3
$Selection\ pressure$	10

4.3 Particle swarm optimization (PSO) algorithm

In this algorithm, there are a number of birds which called particles and they are distributed in the search space function that attempts to minimize (or optimize) their amount. Each particle calculates the value of objective function in a position that placed. Then, by using the combination of current location information and the best previous location and also the information of one or more particles from the best particles in the complex, a direction would be chosen to move. The PSO is appropriate to solve the complicated problems which have several local optimal solutions. No way exists to solve such problems or if they exist, the appropriate answer would not be obtained. PSO algorithm parameters are set according to Table 3 [14, 19].

Table 3. The Parameters of the PSO approach

$Parameter$	$Value$
$Population\ size$	40
$number\ of\ iteration$	30
$PSO\ parameter\ C1$	2
$PSO\ parameter\ C2$	2
$PSO\ momentum\ or\ inertia$	0.9

In this paper, the above algorithms are used to optimize the BSC parameters of a single-phase grid- connected DC to AC inverter with LCL filter which the purpose of optimization is reducing the current error. The objective function (OF) is expressed according to Equation (11) [19]:

$$OF = \int_0^{\infty} t|e(t)|dt \qquad (11)$$

In which t is time and $e(t)$ is the difference between the reference and real current. Table 4 shows the values of designed controller parameters which have obtained by ICA, GA and PSO. Also Fig. 4 shows the convergence of objective function in each algorithm.

5. SIMULATION

Table 5 shows the parameters values of single-phase grid- connected DC to AC inverter.

First test: Fig. 5 shows the simulation results of network current, capacitor voltage and current error in steady state using ICA, GA and PSO by considering the reference current amplitude to 35 A. Also Table 6 shows the values of NMSE and THD for output current. It should be noted that the value of normalized mean square error (NMSE) can be calculated as follows [11]:

$$NMSE(z_1) = \frac{1}{x_{max}T}\sum_{n=1}^{T} z_1^2(n) \qquad (12)$$

In which z_1 is the controlled current error, x_{max} the maximum amount of reference current and T is the total sample time. **Second test:** Fig. 6 shows the simulation results of THD for various network currents which have obtained using ICA, GA and PSO. It should be noted that the acceptable value of THD for this range of current is equal to 5% [20].

Table 4. Optimized controller parameters by ICA, GA and PSO

	ICA	GA	PSO
C_1	5.907641×10^5	1.072890×10^6	1.19×10^6
C_2	4.726	8.545	8.666

Table 5. The parameters of single-phase grid-connected DC to AC inverter

$Circuit\ Parameters$	$Value$
$filter\ inductor\ (L_1)$	$1.2\ mH$
$L_1\ Equivalent\ series\ resistance\ (r$	$0.25\ \Omega$
$filter\ inductor\ (L_2)$	$0.4\ mH$
$L_2\ Equivalent\ series\ resistance\ (r$	$0.08\ \Omega$

$\boldsymbol{filter\ capacitor(C)}$	$\boldsymbol{50\ \mu F}$
$\boldsymbol{Grid\ Voltage\ (V_s)}$	$\boldsymbol{220\ V_{rms}}$ $\boldsymbol{/50\ Hz}$
$\boldsymbol{Rated\ DC\ Voltage\ (V_{dc})}$	$\boldsymbol{500\ V}$
$\boldsymbol{Switching\ Frequency\ (F_s)}$	$\boldsymbol{20\ kHz}$

Table 6. THD and NMSE values of output current in the first test

	$\boldsymbol{THD}$ (%)	$\boldsymbol{NMSE}$
$\boldsymbol{ICA}$	$\boldsymbol{0.04}$	$\boldsymbol{0.0015904}$
$\boldsymbol{GA}$	$\boldsymbol{0.06}$	$\boldsymbol{0.0022118}$
$\boldsymbol{PSO}$	$\boldsymbol{0.04}$	$\boldsymbol{0.0013759}$

Third test: Fig. 7 shows the results of output current harmonics for the coefficients obtained by ICA, GA and PSO in the power of 5kVA. Table 7 also shows the NMSE and THD values of output current.

Table 7. The NMSE and THD values of output current in third test.

	$\boldsymbol{THD}$ (%)	$\boldsymbol{NMSE}$
$\boldsymbol{ICA}$	$\boldsymbol{0.043}$	$\boldsymbol{0.0014161}$
$\boldsymbol{GA}$	$\boldsymbol{0.064}$	$\boldsymbol{0.0019441}$
$\boldsymbol{PSO}$	$\boldsymbol{0.043}$	$\boldsymbol{0.0012096}$

Fourth test: Fig. 8 shows the step response of designed controller for the coefficients obtained by ICA, GA and PSO. Reference current amplitude at t = 0.041 sec has increased from 10 A to 20 A.

6. CONCLUSIONS

In this paper, controller parameters in a single-phase grid connected inverter are selected using different optimization algorithms. Considering THD and NMSE values in different tests, it is clear that PSO algorithm shows better response compared with ICA and GA approaches. Also, the designed nonlinear controller can stably control inverter in a wide range of operation.

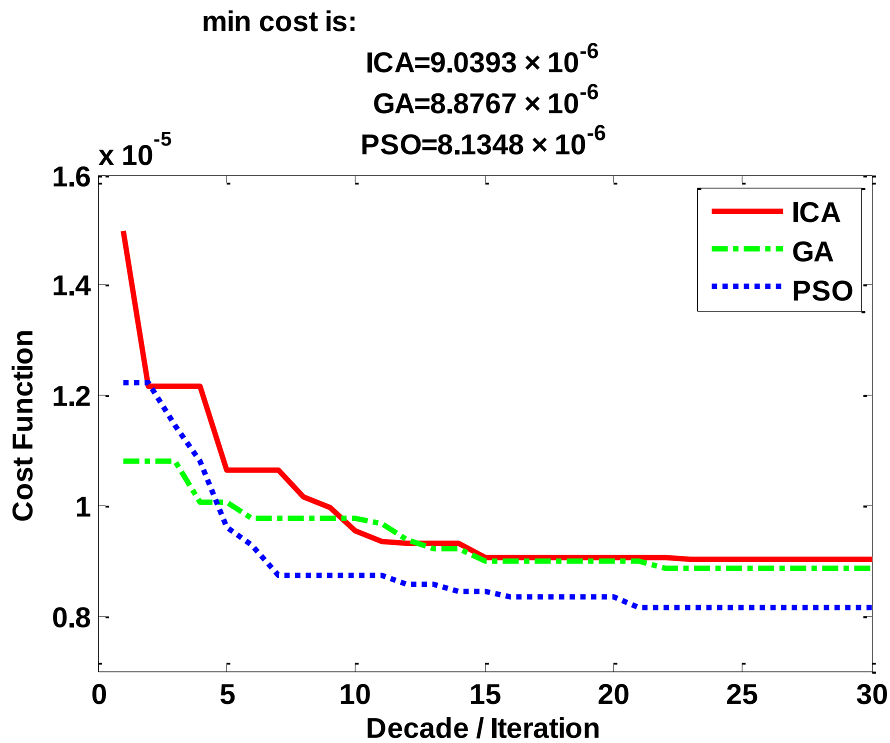

Fig.4. Objective function convergence in ICA, GA and PSO algorithms

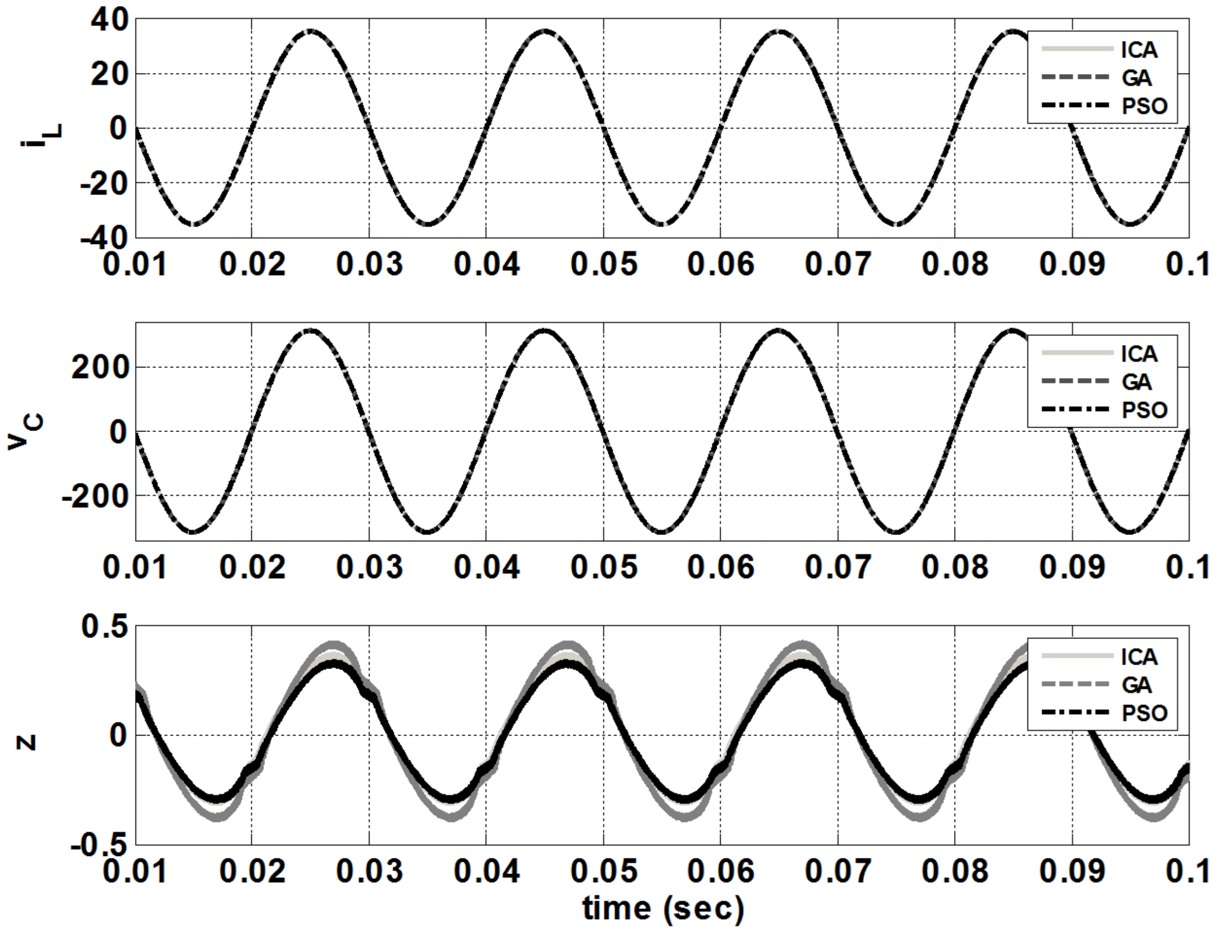

Fig.5. Simulation results of the grid-connected inverter during steady-state operation

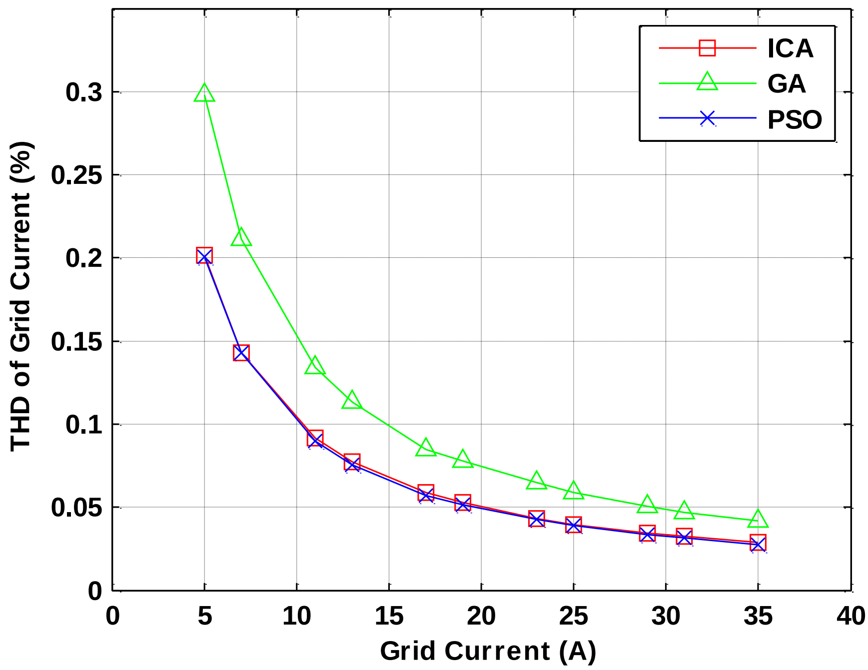

Fig.6. The simulation results of THD for various network currents which have obtained by ICA, GA and PSO

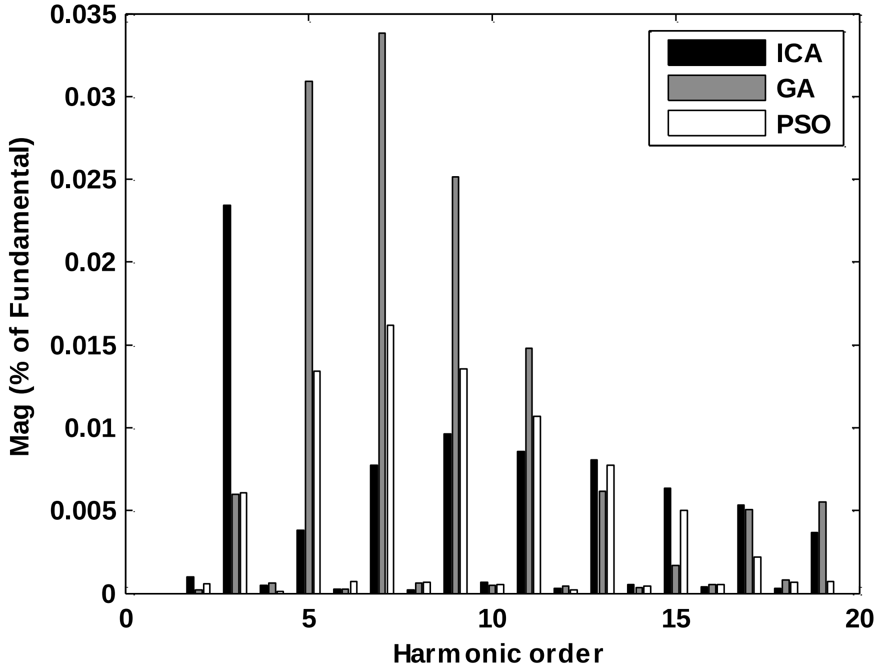

Fig.7. The output current harmonics for different coefficients obtained with ICA, GA and PSO algorithms in the third test

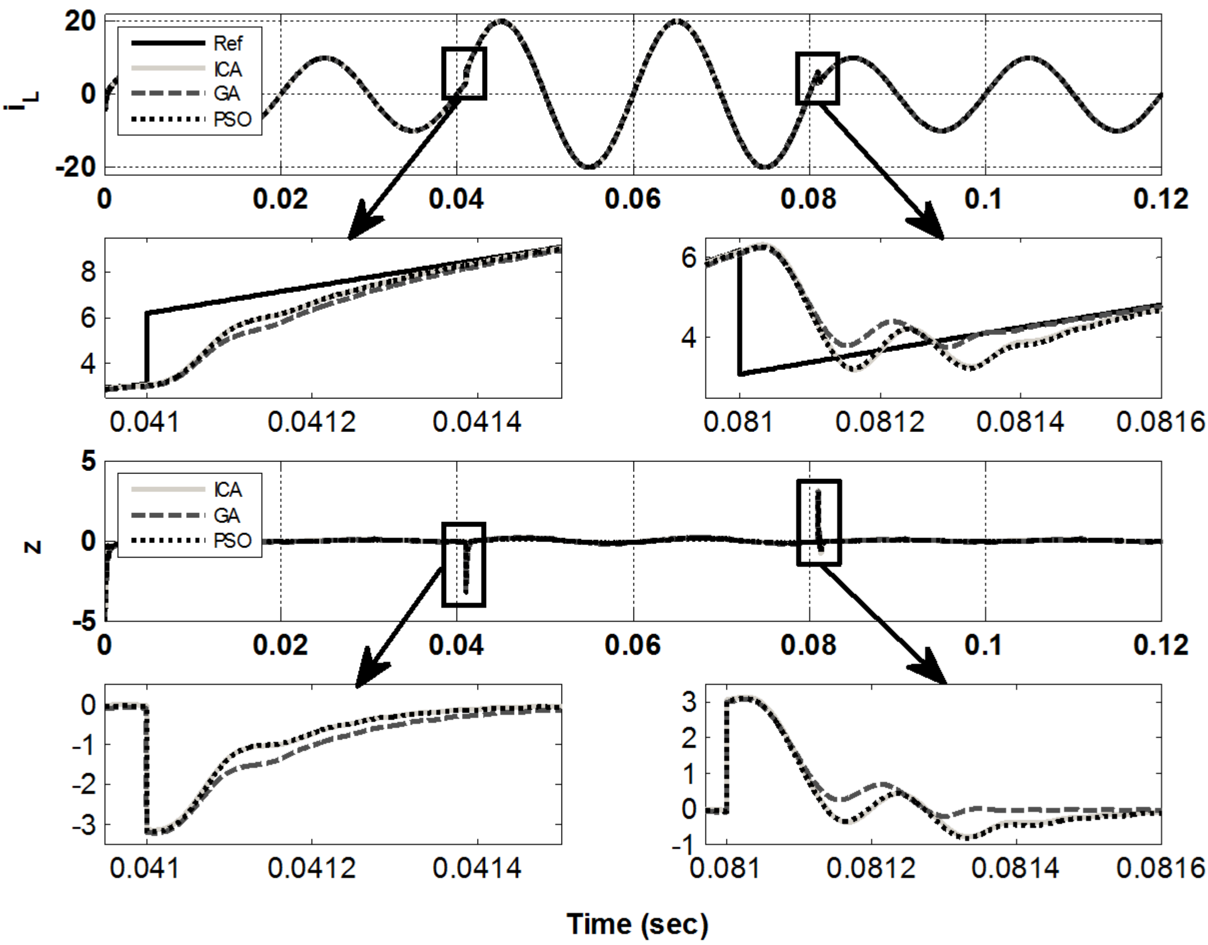

Fig.8. The step response of designed controller for the coefficients obtained by ICA, GA and PSO

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