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Double Closed-Loop PI Control of Three-Phase Inverters by Binary-Coded Extremal Optimization

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ABSTRACT How to design an effective and efficient double closed-loop proportional–integral (PI) controller for a three-phase inverter to obtain satisfied quality of output voltage waveform is of great practical significance. This paper presents a novel double closed-loop PI controller design method for a three-phase inverter based on a binary-coded extremal optimization (BCEO) algorithm. The basic idea behind the proposed method is first formulating the optimal design problem of double closed-loop PI controller for a three-phase inverter as a typical constrained optimization problem, where the total harmonic distortion and the integral of time weighted absolute error of output voltage waveform are weighted as the optimization objective function, and then a BCEO algorithm is designed to solve this formulated problem. The superiority of the proposed method to Z-N empirical method, binary-coded genetic algorithm, binary-coded particle swarm optimization is demonstrated by both simulation and experimental results on a 20-kW three-phase inverter with nominal and variable loads.

INDEX TERMS Closed-loop PI controller, three-phase inverter, extremal optimization, design optimization.

I. INTRODUCTION

It has been widely recognized that Proportional-Integral-Derivative (PID) control is still one of the simplest but most effective control strategies for real engineering systems such as power converters and power systems [1], [2], although a variety of advancements have been gained in control theories and practices [3]–[5]. As one of well-known traditional empirical tuning techniques, Ziegler-Nichols (Z-N) method [6] has been widely applied to design PID controllers for various control systems in practice, but it relies seriously on the empirical rules of the designers and it is hard to adapt variable operations in complex systems. One of the critical issues of the control of power converters is how to optimally design an effective and efficient PI controller to obtain high-quality performances such as high stability, satisfied transient and steady-state indices, low total harmonic distortion (THD) and strong robustness.

This topic of design optimal PID controllers for engineering systems by using evolutionary algorithms has attracted considerable attentions recently [7], [8]. For example, genetic algorithm (GA) [9], [10], particle swarm optimization (PSO) [11]–[13], differential evolution (DE) [14], and extremal optimization (EO) [15]–[18] have been utilized to optimize the PID controllers for complex systems. However, there are only few applications of these optimization algorithms into the control of power converters and power systems [19]–[22]. Al-Saedi et al. [20] proposed an optimal PI based voltage-frequency power controller by using PSO for an inverter based distribution generation unit in an autonomous microgrid operation. Similarly, the authors presented a PSO- based power flow control method in grid-connected microgrid operation under variable loads conditions [21]. In [22], an optimal PI control strategy based on harmony search algorithm is presented for a grid-side voltage source cascaded converter with two additional loops in order to implement smooth transition of islanding and resynchronization operations in a distributed generation system. From these above reported research works, it is obvious that optimization algorithms play significant roles in optimal design of PI controllers for power converters in distributed generation systems or microgrids. Motivated by the basic idea behind these methods, we propose a novel double

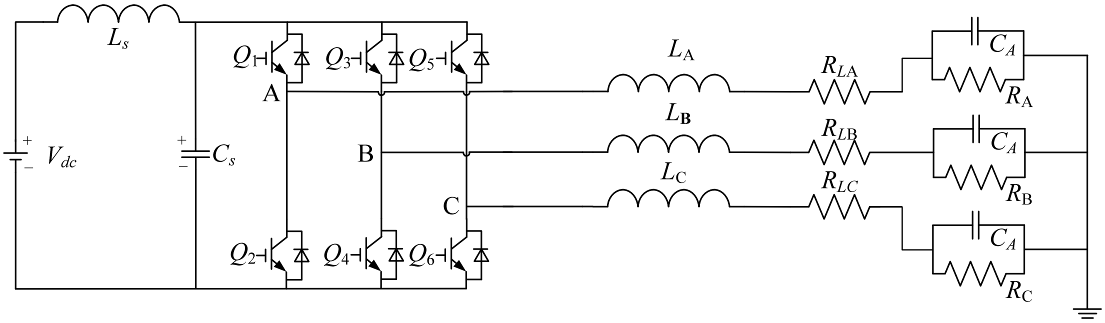


FIGURE 1. Circuit diagram of a three-phase inverter.

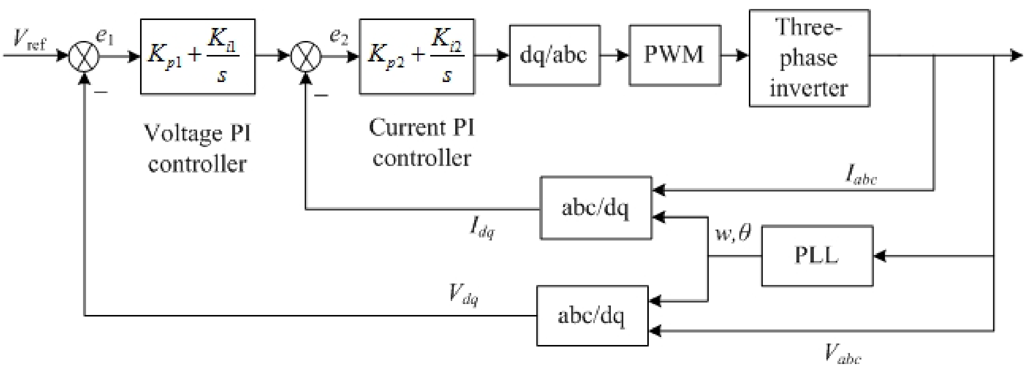


FIGURE 2. The block diagram of a three-phase inverter with double closed-loop PI controller.

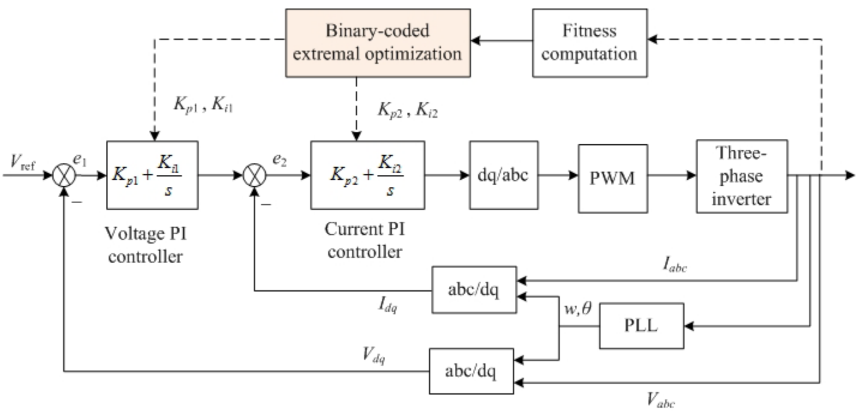


FIGURE 3. The schematic diagram of BCEO-based double closed-loop PI controller design method for a three-phase inverter.

closed-loop PI controller design method for a three-phase inverter by using binary-coded extremal optimization (BCEO). The key idea is firstly formulating the optimal design problem of double closed-loop PI controller for a three-phase inverter as a typical constrained optimization problem, where the total harmonic distortion (THD) and the integral of time weighted absolute error (ITAE) of output voltage waveform are weighted as the optimization objective function. Then, BCEO is designed to solve this optimization problem.

Extremal optimization [23], [24] is an effective and efficient optimization framework originally inspired by far-from-equilibrium dynamics of self-organized criticality (SOC) [25]. It has been increasingly considered to provide a novel insight into optimization domain because it merely selects against the bad instead of favoring the good randomly or according to a power-law probability distribution, so EO and its modified versions have been successfully applied to various benchmark and real-world engineering optimization problems [26], [27]. Nevertheless, there are only few

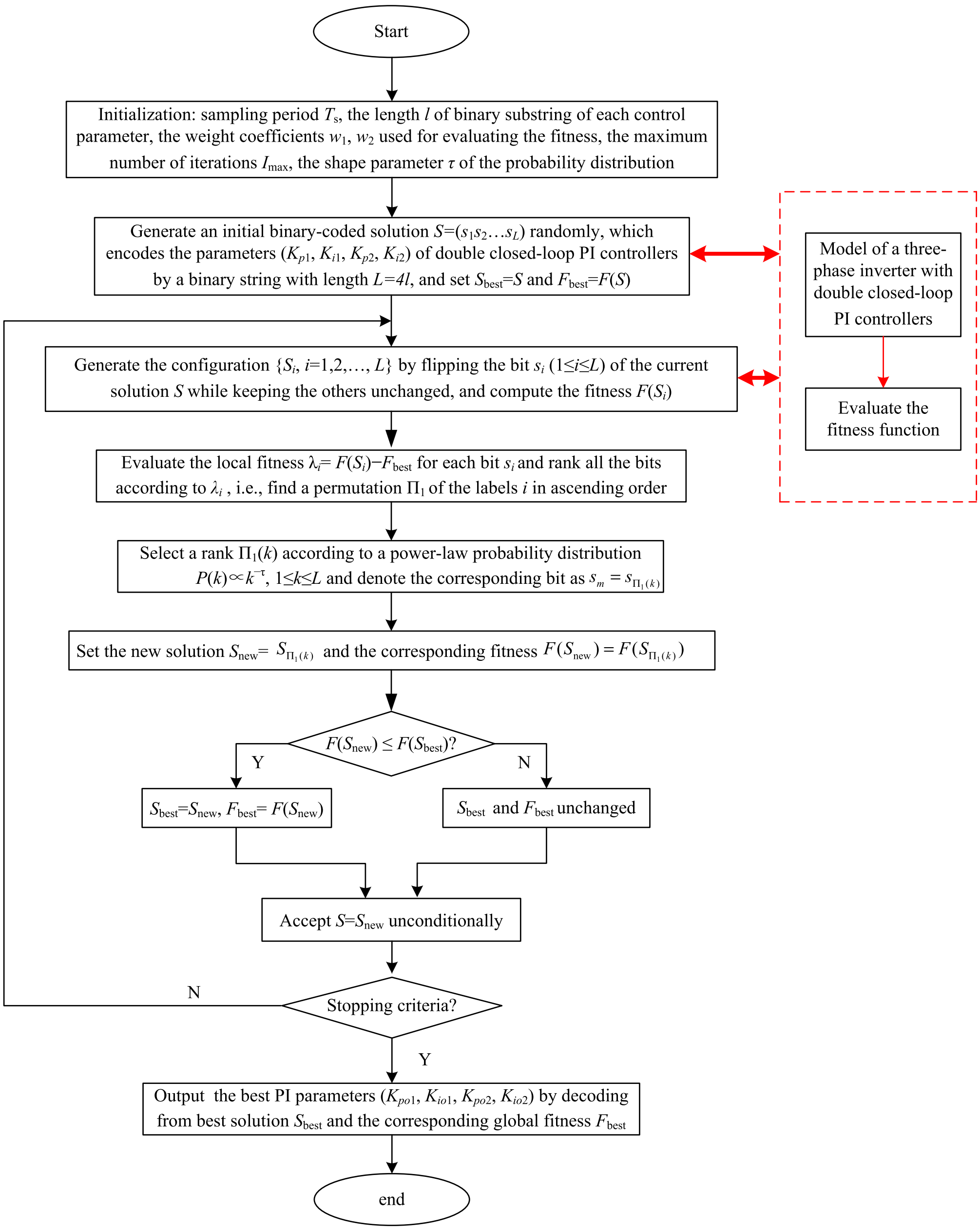


FIGURE 4. The flowchart of BCEO-based double closed-loop PI controller design method.

applications of EO into the design of PID controllers for complex control systems [15]–[18]. To the best of our knowledge, EO has not yet been applied to the control of power converters. Therefore, this work may be considered as the first contribution of EO for the optimal control of power converters.

The rest of this paper is organized as follows. Section II presents the problem formulation concerning the optimal control issue of a three-phase inverter. In section III, BCEO-based double closed-loop PI controllers design method is proposed. The simulation results on a three-phase inverter are compared and discussed in section IV. Furthermore, section V presents the experimental results on a real 20 kW three-phase inverter. Finally, we give the conclusion and open problems in section VI.

II. PROBLEM FORMULATION

Circuit diagram of a three-phase inverter [28] is shown in Fig.1. Here, V_{dc} is the voltage of DC bus, L_s and C_s are the inductance and capacitance of DC side, respectively, C_A is the capacitance of LC filter, L_A and R_A are the equivalent inductance and resistance of LC filter. The corresponding block diagram of double closed-loop PI controller for a three-phase inverter is presented in Fig.2. Here, K_{p1} and K_{i1} are

TABLE 1. The adjustable parameters setting of BCEO, BCGA and BCPSO used in simulation.

Algorithm	Parameters setting
BCGA	Population size=40, I_{max}=30, selection parameter β=0.7, the crossover probability p_c=0.6, the mutation probability p_m=0.001, binary-coded length of each variable l=10.
BCPSO	Population size=40, I_{max}=30, inertia weight w_{max}=0.5, w_{min}=0.5, the upper limit of velocity V_{max}=4, acceleration factors c_1=1.0, c_2=1.0, l=10.
BCEO	I_{max}=30, τ=1.20, l=10

TABLE 2. Statistical performance of BCGA, BCPSO and BCEO.

Algorithm	SR %	f_{min}	f_{median}	f_{max}	f_{mean}	f_{sd}
BCGA	70	0.0052	0.0087	0.0223	0.0095	0.0061
BCPSO	90	0.0024	0.0026	0.0189	0.0044	0.0046
BCEO	**100**	**0.0020**	**0.0024**	**0.0025**	**0.0023**	**0.0001**

the proportional and integral parameter of voltage outer-loop PI controller, respectively. K_{p2} and K_{i2} are the proportional and integral parameter of current inner-loop PI controller, respectively.

In order to obtain satisfied output voltage waveform of a three-phase inverter, the optimal design issue of double closed-loop PI controller with four parameters including K_{p1}, K_{i1}, K_{p2} and K_{i2} is formulated as a typical constrained optimization problem, where the total harmonic distortion (THD) and the integral of time weighted absolute error (ITAE) of output voltage waveform are weighted as an optimization objective function to be minimized. The detailed formulation is as follows:

$$\begin{aligned} \min\ F(\mathbf{x}) &= w_1 \int_0^{T_{\max}} t\,|e_1(t)|dt + w_2 THD_V \\ \mathbf{x} &= (K_{p1}, K_{i1}, K_{p2}, K_{i2}) \\ s.t.\ l_1 &\le K_{p1} \le u_1 \\ l_2 &\le K_{i1} \le u_2 \\ l_3 &\le K_{p1} \le u_3 \\ l_4 &\le K_{i2} \le u_4 \end{aligned} \tag{1}$$

Where w_1, w_2 are the weighted coefficients, $T_{\max}$ is the maximum time of time window, THD_V is the total harmonic distortion (THD) of output voltage, l_1, l_2, l_3 and l_4 are the lower limits of K_{p1}, K_{i1}, K_{p2} and K_{i2}, respectively, u_1, u_2, u_3 and u_4 are the upper limits of K_{p1}, K_{i1}, K_{p2} and K_{i2}, respectively.

III. THE PROPOSED BCEO-BASED DOUBLE CLOSED-LOOP PI CONTROL METHOD FOR THREE-PHASE INVERTER

In this section, we present a novel BCEO-based double closed-loop PI control method for a three-phase inverter. The basic idea behind the proposed method is encoding the double closed-loop PI controller parameters into a binary string, evaluating the control performance of a double closed-loop PI controller by an effective objective function described as equation (1) with weighted ITAE and THD of output voltage, selecting the bad elements based on power-law probability distribution and updating the solutions by binary mutation on the selected ones. The schematic diagram and flowchart of the proposed method is shown as Fig.3 and Fig.4, respectively.

The detailed steps of the proposed algorithm are described as follows:

***BCEO-based double closed-loop PI controller design algorithm*:**

Input: The model of a three-phase inverter with a double closed-loop PI controller, sampling period T_s, the length l of binary substring corresponding to each control parameter, the lower limits constraints (l_1, l_2, l_3 l_4) and upper limits constraints (u_1, u_2, u_3, u_4) of the control parameters (K_{p1}, K_{i1}, K_{p2}, K_{i2}), the weight coefficients w_1, w_2 used for evaluating the fitness, the maximum number of iterations $I_{\max}$, the shape parameter τ of the probability distribution.

Output: The best solution S_{best} (the best PI parameters K_{po1}, K_{io1}, K_{po2}, K_{io2}) and the corresponding global fitness F_{best}.

(1). Generate an initial binary-coded solution $S = (s_1 s_2 \ldots s_L)$ randomly subjecting to the lower limits constraints (l_1, l_2, l_3 l_4) and upper limits constraints (u_1, u_2, u_3, u_4), which encodes the parameters (K_{p1}, K_{i1}, K_{p2}, K_{i2}) of double closed-loop PI controller by a binary string with length $L = 4l$, and set $S_{\text{best}} = S$ and $F_{\text{best}} = F(S)$ by the formulation (1);

(2). Generate the candidate solutions $\{S_i, i = 1, 2, \ldots, L\}$ by flipping the bit s_i $(1 \le i \le L)$ of the current solution S while keeping the others unchanged, and compute the fitness $F(S_i)$ by the formulation (1);

(3). Evaluate the local fitness $\lambda_i = F(S_i) - F_{\text{best}}$ for each bit s_i and rank all the bits in ascending order of the values of λ_i , i.e., find a permutation $\prod_1$ of the labels i such that $\lambda_{\Pi_1(1)} \le \lambda_{\Pi_1(2)} \le \ldots \le \lambda_{\Pi_1(L)}$;

(4). Generate a random number r between 0 and 1 firstly, then select a rank $\prod_1(k)$ according to a power-law probability distribution $P(k) \propto k^{-\tau}$, $1 \le k \le L$ and denote the corresponding bit as s_m, i.e., $s_m = s_{\Pi_1(k)}$;

(5). Set the new solution $S_{\text{new}} = S_{\Pi_1(k)}$ and the corresponding fitness $F(S_{\text{new}}) = F(S_{\Pi_1(k)})$;

(6). If $F(S_{\text{new}}) \le F_{\text{best}}$, then set $S_{\text{best}} = S_{\text{new}}$ and $F_{\text{best}} = F(S_{\text{new}})$;

(7). Accept $S = S_{\text{new}}$ unconditionally;

(8). Repeat the step 2 to step 7 until the maximum number of iterations $I_{\max}$ is satisfied;

(9). Obtain the best PI parameters (K_{po1}, K_{io1}, K_{po2}, K_{io2}) by decoding from best solution S_{best} and the corresponding global fitness F_{best}.

From the above description, it is clear that the proposed BCEO-based double closed-loop PI controller design method has only selection and mutation operations on the basis of individual-based iterated mechanism from the perspective of

TABLE 3. The best controller parameters and the corresponding THD performance of output voltage obtained by different methods.

Algorithm	THD_{VA} (%)	THD_{VB} (%)	THD_{VC} (%)	K_{po1}	K_{io1}	K_{po2}	K_{io2}
Z-N method	2.80(0.95)	10.44(0.97)	8.93(0.98)	0.0245	36.9502	8.5924	140.3226
BCGA	1.73(0.49)	8.73(0.46)	8.23(0.47)	0.0782	78.0059	4.1545	147.0674
BCPSO	1.50(0.36)	8.73(0.37)	8.07(0.37)	0.0391	80.7918	8.1623	107.4780
BCEO	**1.14(0.33)**	**8.18(0.34)**	**7.82(0.31)**	0.0558	94.7214	9.1593	47.33608

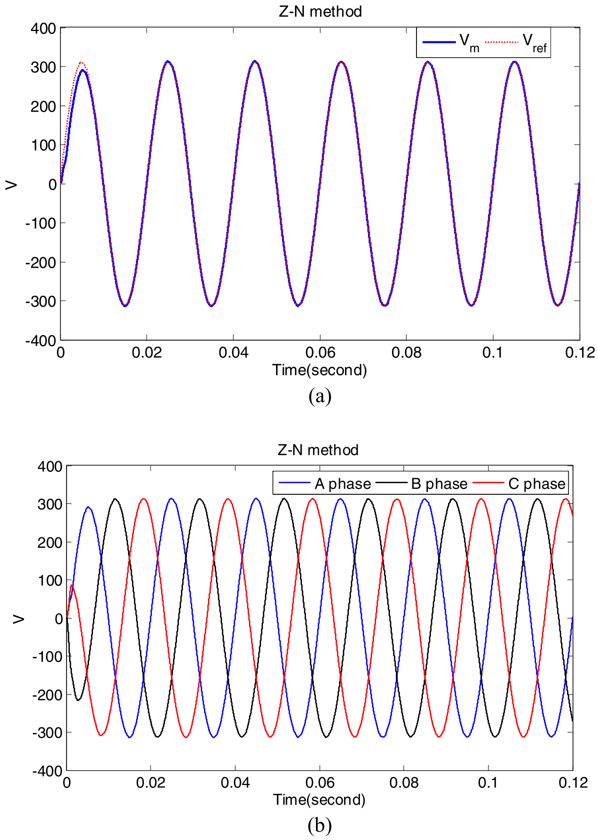


FIGURE 5. The voltage waveform of three-phase inverter with the best controller obtained by Z-N method. (a) A phase and reference voltage waveform. (b) Three phase voltage waveform.

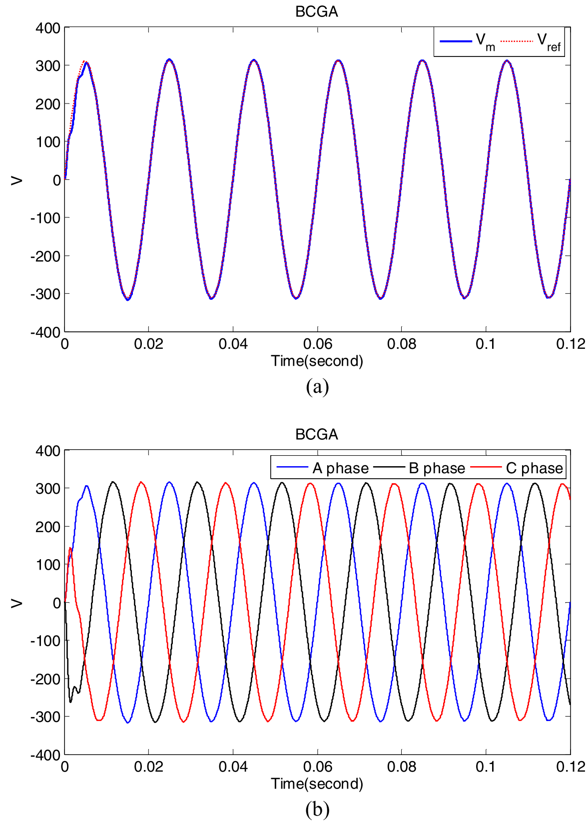


FIGURE 6. The voltage waveform of three-phase inverter with the best controller obtained by BCGA. (a) A phase and reference voltage waveform. (b) Three phase voltage waveform.

evolutionary algorithm. Nevertheless, other popular evolutionary algorithms such as binary-coded GA (BCGA) [30] and binary-coded PSO (BCPSO) [12] adopt more complex operations and population-based iterated mechanism. Moreover, the proposed BCEO-based double closed-loop PI controller design method has less adjustable parameters than BCGA [30] and BCPSO [12]. More specially, except the maximum number of iterations $I_{\max}$ and the length l of binary substring corresponding to each controller parameter, only one power-law distribution parameter τ [29] needs to tune in BCEO. However, three additional adjustable parameters such as the population size, the crossover probability and mutation probability should be determined in BCGA and more parameters including the population size, inertia weight and acceleration factors should be tuned in BCPSO. Therefore, the proposed BCEO-based double closed-loop PI controller design method for a three-phase inverter is considered to be simpler than BCGA and BCPSO based methods from the perspective of design simplicity. Additionally, the superiority of the proposed BCEO to BCGA and BCPSO in terms of control performance will be demonstrated by the compared simulation and experimental results on a three-phase inverter in the next two sections.

IV. SIMULATION RESULTS

To demonstrate the effectiveness of the proposed BCEO algorithm, this section presents the simulation results on a 20kW three-phase inverter. The four parameters of double closed-loop PI controller are optimized by traditional Z-N method [6], BCGA [30], BCPSO [12] and BCEO. The system parameters for a three-phase inverter are as follows: $V_{\mathrm{dc}} = 560$V, $L_{\mathrm{s}} = 1.08$mH, $C_{\mathrm{s}} = 4700\mu$F, $C_{\mathrm{A}} = 40\mu$F, $L_{\mathrm{A}} = L_{\mathrm{B}} = L_{\mathrm{C}} = 2.5$mH, $R_{\mathrm{LA}} = R_{\mathrm{LB}} = R_{\mathrm{LC}} = 0.1\Omega$, $R_{\mathrm{A}} = R_{\mathrm{B}} = R_{\mathrm{C}} = 24\Omega$. The lower and upper limits of the double closed-loop PI controller parameters are set as: $l_1 = l_2 = l_3 = l_4 = 0, u_1 = 1, u_2 = 150, u_3 = 10, u_4 = 150$. The sampling time T_s is set as 10^{-6} second and the weighted

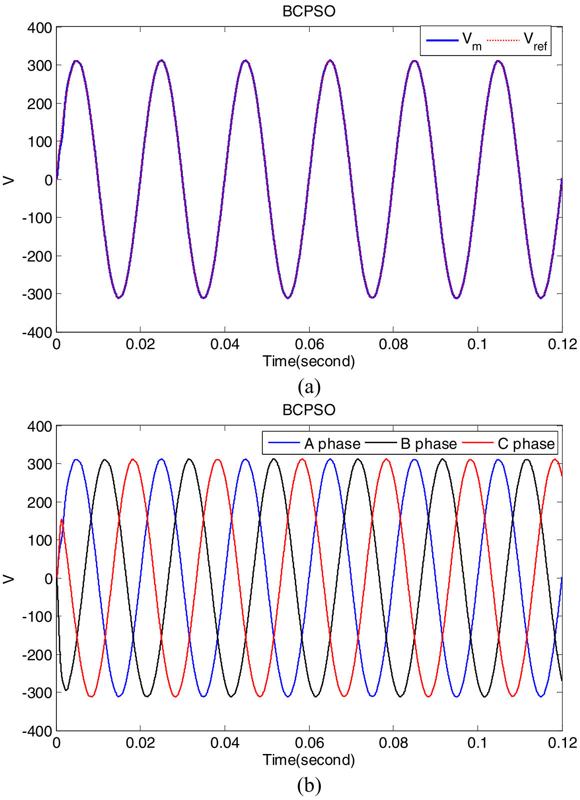


FIGURE 7. **The voltage waveform of three-phase inverter with the best controller obtained by BCPSO. (a) A phase and reference voltage waveform. (b) Three phase voltage waveform.**

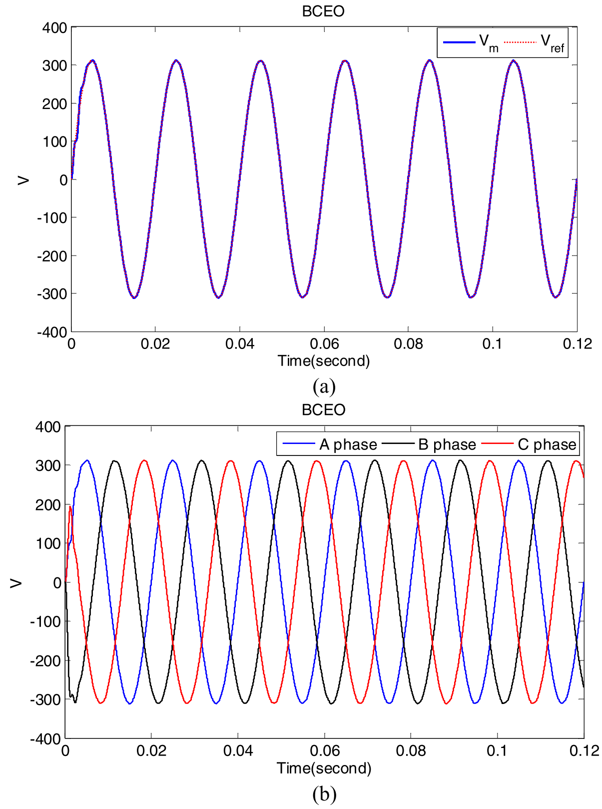


FIGURE 8. **The voltage waveform of three-phase inverter with the best controller obtained by BCEO. (a) A phase and reference voltage waveform. (b) Three phase voltage waveform.**

TABLE 4. **Comparison of the THD (%) Values of Three Phase Voltages Obtained by Different Methods When Loads Increase Suddenly From 0kW to 6kW.**

Algorithm	THD_{VA} (%)	THD_{VB} (%)	THD_{VC} (%)
Z-N method	3.04	5.67	4.02
BCGA	1.66	4.01	3.73
BCPSO	1.70	4.35	3.40
BCEO	**1.39**	**3.81**	**3.22**

coefficients w_1, w_2 are set as 0.1 and 1, respectively. It should be noted that the optimal values of the weighted coefficients w_1 and w_2 are determined by considering the importance and the orders of magnitude of the performance indices, and they are also determined by trial and error in practice.

Table 1 shows the adjustable parameters of BCEO, BCGA and BCPSO used in the following simulations and experiments. All the following simulations have been implemented on by MATLAB software on a 2.50 GHz PC with i7-3537U processor and 4 GB RAM.

In order to enable readers understand how to use the proposed algorithm more clearly, the above described three-phase inverter is taken to illustrate the use of BCEO algorithm step by step.

Step 1: Generate an initial binary-coded solution $S = (s_1 s_2 \ldots s_{40})$ =(1101100111, 0110100111, 1011111010, 10000111010) subjecting to the lower and upper limits constraints randomly, which encodes the four parameters $(K_{p1}, K_{i1}, K_{p2}, K_{i2})$ of double closed-loop PI controller by a binary string with length $L = 4l = 40$, and set $S_{\text{best}} = S$ and $F_{\text{best}} = F(S) = 1.1506$ by running the Simulink model of the three-phase inverter and evaluating the fitness according to the formulation (1).

Step 2: Generate the candidate solutions $\{S_i,\ i = 1, 2, \ldots, 40\}$ by flipping the bit s_i $(1 \le i \le 40)$ of the current solution S while keeping others unchanged, and compute the fitness $F(S_i)$ by the formulation (1). For example, flip the bit $s_1 = 1$ of S and keep others unchanged, then S_1 and $F(S_1)$ is obtained as follows: S_1 = (**0**101100111, 0110100111, 1011111010, 10000111010), and $F(S_1)$ =1.1459. By the similar method, the other candidate solutions $\{S_i,\ i = 2, \ldots, 40\}$ and corresponding fitness $F(S_i)$ are also obtained.

Step 3: Evaluate the local fitness $\lambda_i = F(S_i) - F_{\text{best}}$ for each bit s_i, e.g., $\lambda_1 = F(S_1) - F_{\text{best}} = 1.1459 - 1.1506 = -0.0047$, and rank all the bits in ascending order of the values of λ_i , i.e., find a permutation $\prod_1$=(29, 10, 9, 27, 20, 26, 8, 39, 19, 25, 24, 2, 16, 17, 22, 14, 3, 21, 35, 18, 37, 12, 6, 13, 38, 15, 5, 4, 7, 23, 1, 36, 34, 32, 11, 33, 31, 40, 28, 30) of the labels $i$such that $\lambda_{\Pi_1(1)} \le \lambda_{\Pi_1(2)} \le \ldots \le \lambda_{\Pi_1(40)}$.

Step 4: Generate a random number r between 0 and 1 firstly, e.g., $r = 0.4387$, then select a rank $\prod_1(k) = \prod_1(2) = 10$ according to a power-law probability distribution $P(k) \propto k^{-\tau} = k^{-1.20}$, $1 \le k \le 40$ and denote the corresponding bit as $s_m = s_{10}$. More specifically, the

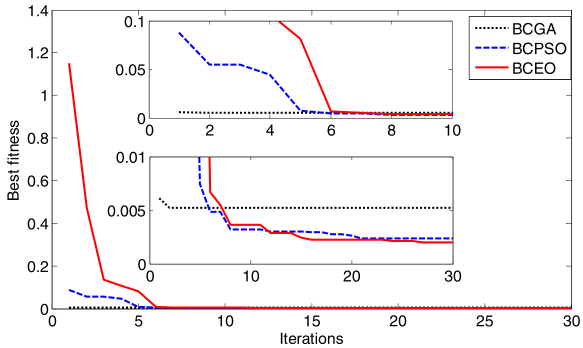


FIGURE 9. **Comparison of the convergence process of BCEO, BCGA and BCPSO.**

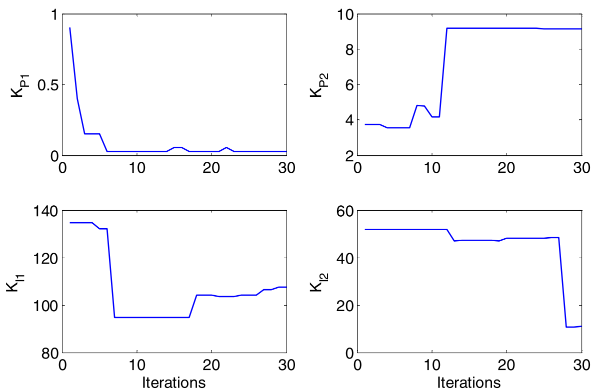


FIGURE 10. **The parameters evolutionary process of BCEO.**

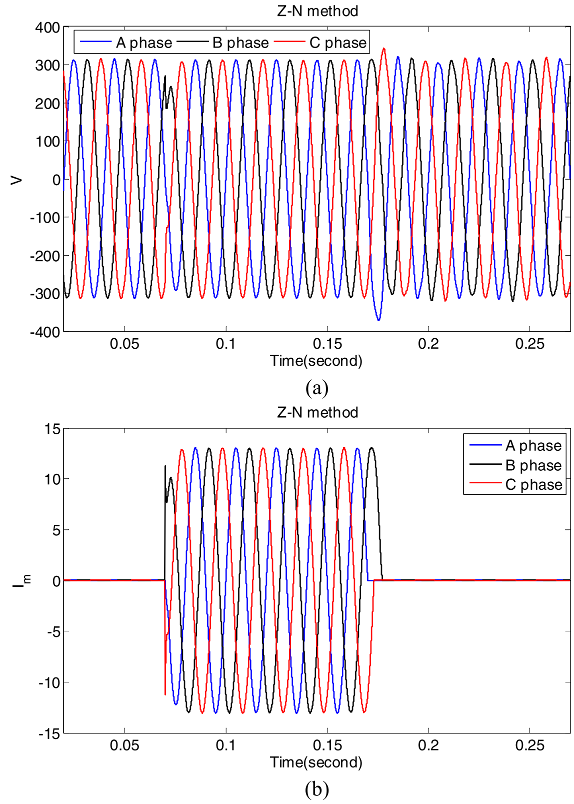


FIGURE 11. **The voltage and current waveform under the variable loads obtained by Z-N empirical method. (a) Three phase voltage waveform. (b) Three phase current waveform.**

cumulative power-law probability $P_c(k)$ of each bit k is computed as follows:

$$P_c(k) = \frac{\sum_{h=1}^{h=k} h^{-1.20}}{\sum_{m=1}^{m=40} m^{-1.20}}, \quad k = 1, 2, \ldots, 40$$

Because $P_c(2) = 0.4476 < r = 0.4387 < P_c(3) = 0.5310$, the selected rank $\prod_1(k)$ is set as $\prod_1(2)$ and the corresponding bit is obtained as 10 by searching $\prod_1$.

Step 5: Set the new solution $S_{\text{new}} = S_{\Pi_1(k)} = S_{10}$, and the corresponding fitness $F(S_{\text{new}}) = F(S_{\Pi_1(k)}) = F(S_{10}) = 0.4725$.

Step 6: Because $F(S_{\text{new}}) = 0.4725 \leq F_{\text{best}} = 1.1506$, set $S_{\text{best}} = S_{\text{new}}$ and $F_{\text{best}} = F(S_{\text{new}})$.

Step 7: Accept $S = S_{\text{new}}$ unconditionally;

Step 8: Repeat the step 2 to step 7 until the maximum number of iterations $I_{\max} = 30$ is satisfied;

Step 9: Obtain the best PI parameters (K_{po1}, K_{io1}, K_{po2}, K_{io2}) by decoding from best solution S_{best} and the corresponding global fitness F_{best}.

A. COMPARED RESULTS UNDER NOMINAL CONDITION

Each evolutionary algorithm has been implemented 20 independent runs in the following simulation. The statistical results of BCGA, BCPSO and BCEO including success rate (SR%), the minimum ($f_{\min}$), median (f_{median}), maximum ($f_{\max}$), mean (f_{mean}), and standard deviation (f_{sd}) values of the final output fitness are shown in Table 2. It is clear that BCEO outperforms BCGA and BCPSO in terms of all the indices.

Additionally, Table 3 presents the best controller parameters with the minimum fitness values and the corresponding THD values of three-phase voltage obtained by the traditional Z-N empirical method, BCGA, BCPSO and BCEO. It should be noted that the THD values are evaluated by considering the starting dynamic process occurring during the first cycle, so the values of THD_{VB} and THD_{VC} are very large. In fact, the THD values in brackets are much smaller by ignoring the starting dynamic process. The voltage waveform of the three-phase inverter with the best controllers obtained by Z-N method, BCGA, BCPSO and BCEO are shown in Fig.5 to Fig.8, respectively. It is evident that the voltage waveform of A phase denoted as V_{mA} obtained by BCEO is the closest to the reference voltage and its THD values of three phase voltage denoted as $THD_{VA}(\%)$, $THD_{VB}(\%)$, THD_{VC} (%) respectively are also the least. On the other hand, the THD values of the output voltages obtained by BCGA, BCPSO and BCEO are all better than that by Z-N empirical method.

Moreover, the convergence process of BCEO, BCGA and BCPSO are compared in Fig.9. Clearly, the best fitness of

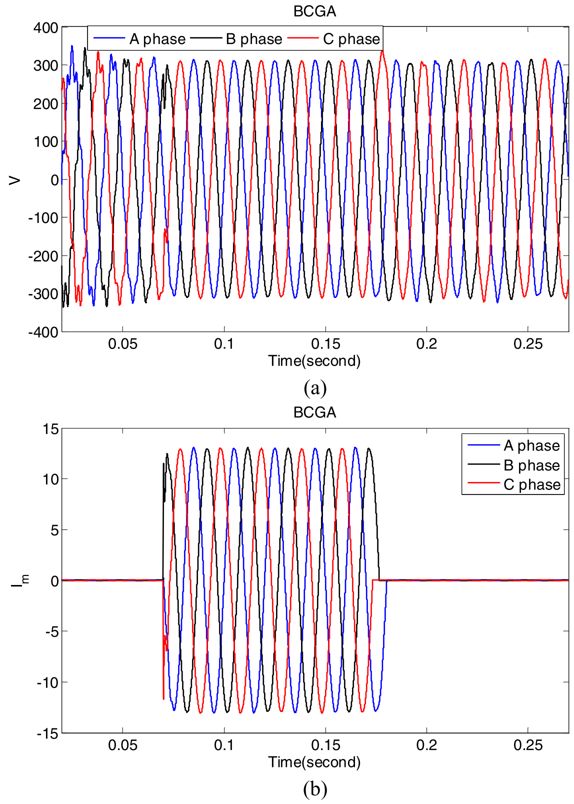


FIGURE 12. The voltage and current waveform under the variable loads obtained by BCGA. (a) Three phase voltage waveform. (b) Three phase current waveform.

TABLE 5. Comparison of the THD (%) values of three phase voltages obtained by different methods when loads decrease suddenly from 6kW to 0kW.

Algorithm	THD_{VA} (%)	THD_{VB} (%)	THD_{VC} (%)
Z-N method	4.22	3.12	3.97
BCGA	3.01	3.12	3.11
BCPSO	3.03	2.84	2.49
BCEO	**2.47**	**2.25**	**2.62**

TABLE 6. Comparison of the experimental THD (%) values of three phase voltage obtained by different methods under nominal condition with nominal 6kW loads.

Algorithm	THD_{VA} (%)	THD_{VB} (%)	THD_{VC} (%)
Z-N method	2.70	2.67	2.68
BCGA	2.39	2.27	2.48
BCPSO	2.26	2.26	2.24
BCEO	**1.89**	**1.95**	**1.98**

BCEO at the beginning is larger than that of BCGA and BCPSO because BCEO starts its optimization process from a completely random solution, but that of BCEO is better than those of other two algorithms after 12 iterations. It is noted that premature convergence of BCGA is very obvious for the control of a three-phase inverter because its best fitness has not been improved since the second iteration. In addition, in order to further analyze the convergence characteristics

TABLE 7. Comparison of the experimental THD (%) values of three phase voltage obtained by different methods when the loads increase suddenly from 0kW to 6kW.

Algorithm	THD_{VA} (%)	THD_{VB} (%)	THD_{VC} (%)
Z-N method	5.75	5.69	5.10
BCGA	3.52	4.14	3.83
BCPSO	3.05	4.38	3.84
BCEO	**2.41**	**3.85**	**3.28**

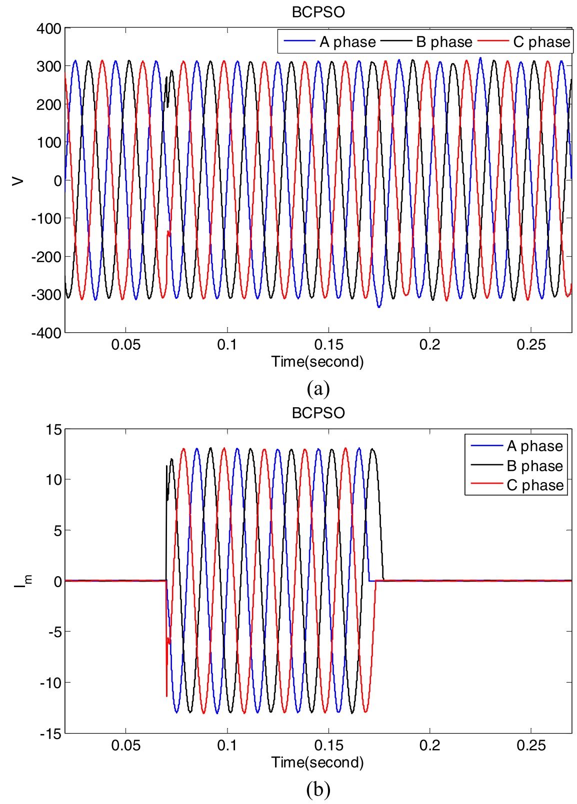


FIGURE 13. The voltage and current waveform under the variable loads obtained by BCPSO. (a) Three phase voltage waveform. (b) Three phase current waveform.

of BCEO, Fig10 presents the evolutionary process of these double closed-loop PI controller parameters. In this sense, BCEO has better ability than BCGA and BCPSO to explore the problem space of the double closed-loop PI controller for a three-phase inverter.

B. ROBUSTNESS AGAINST VARIABLE LOADS CONDITIONS

In order to compare the robustness against variable loads conditions of different methods, this subsection presents the comparison of the dynamic voltage and current waveforms under the variable loads conditions obtained by Z-N empirical method, BCGA, BCPSO and BCEO, which are shown as Fig.11 to Fig.14, respectively. Here, the variable loads conditions are set as the loads increase suddenly from 0kW to 6kW at 0.07 second while the loads decrease suddenly from 6kW to 0kW at 0.17 second. Table 4 and Table 5 also present the THD values of three-phase voltages under the variable loads

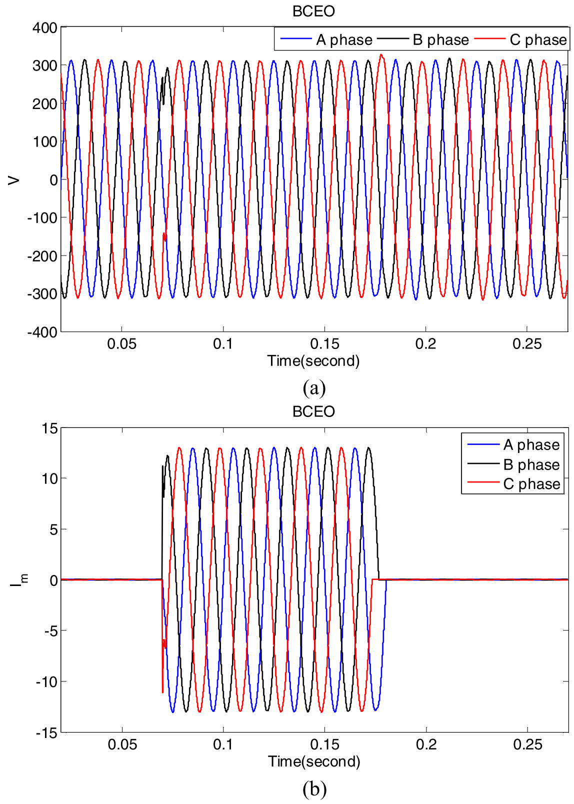


FIGURE 14. The voltage and current waveform under the variable loads obtained by BCEO. (a) Three phase voltage waveform. (b) Three phase current waveform.

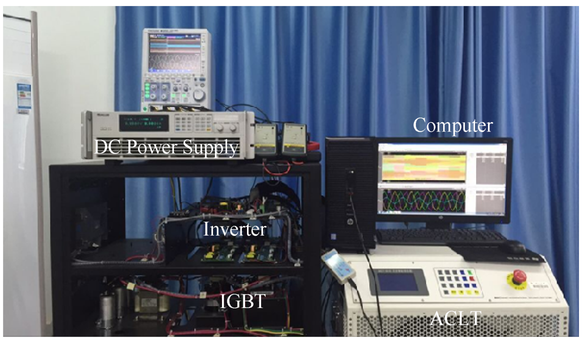


FIGURE 15. The experimental platform of a 20kW three phase inverter.

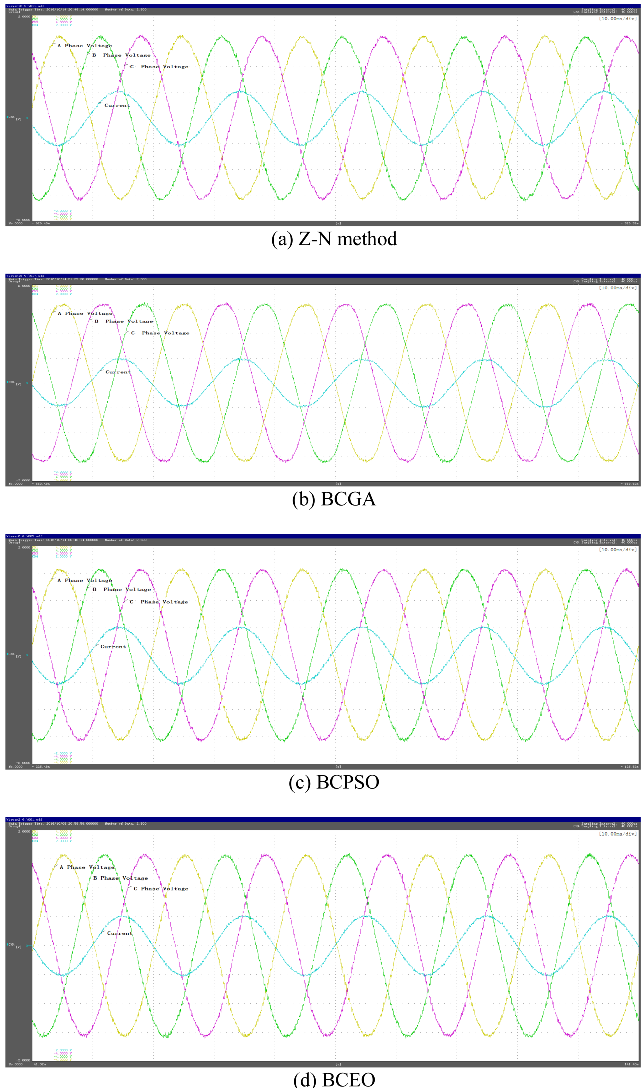


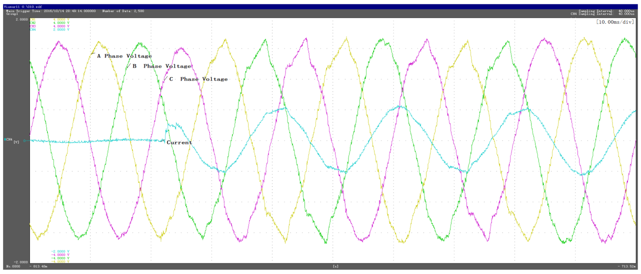
FIGURE 16. The experimental voltage and current waveform obtained by different methods under nominal condition with 6kW loads. (a) Z-N method. (b) BCGA. (c) BCPSO. (d) BCEO.

conditions obtained by these four different methods. Clearly, the THD values of three-phase values obtained by BCEO are still lower than those obtained by other three methods under the variable loads conditions. In other words, the BCEO-based double closed-loop PI controller has better robustness against variable loads than Z-N empirical method, BCGA and BCPSO.

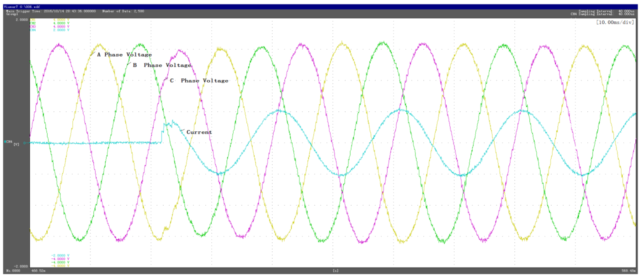
V. EXPERIMENTAL RESULTS

In order to further verify the effectiveness of the proposed method, this section presents the experimental results on a real 20kW three-phase inverter. The system parameters of the three-phase inverter are the same as those in simulation studies and the experimental platform for the control of a three-phase inverter is shown as Fig.15. Because of the limits (16A) of rated current in DC power supply, the following experiments only test the performance of the three-phase inverter with nominal 6kW loads and variable loads from 0kW to 6kW and from 6kW to 0kW. Fig.16 presents the voltage and current waveform obtained by Z-N method, BCGA, BCPSO and BCEO under nominal condition with 6kW loads and Table 6 shows the corresponding THD (%) values of three phase voltage by different methods. Clearly, BCEO outperforms BCPSO, BCGA and Z-N method in terms of THD values of three-phase voltage.

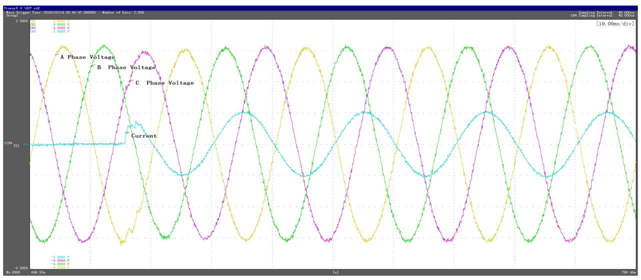
Similarly, two experiments are designed to compare the performance obtained by different methods when the loads increase suddenly from 0kW to 6kW and the loads decrease suddenly from 6kW to 0kW. The voltage and current wave-



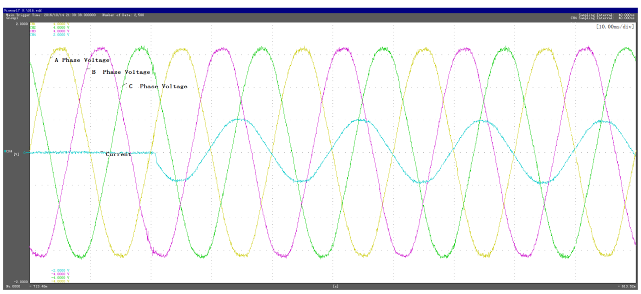
(a) Z-N method



(b) BCGA

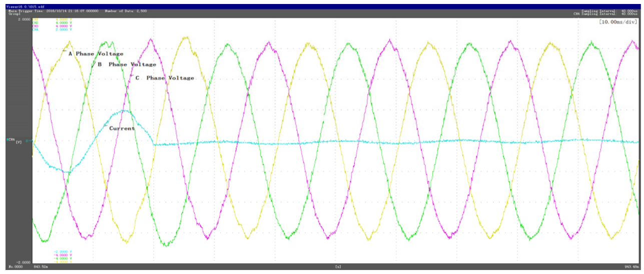


(c) BCPSO

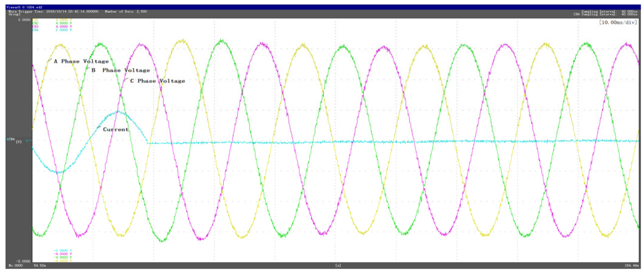


(d) BCEO

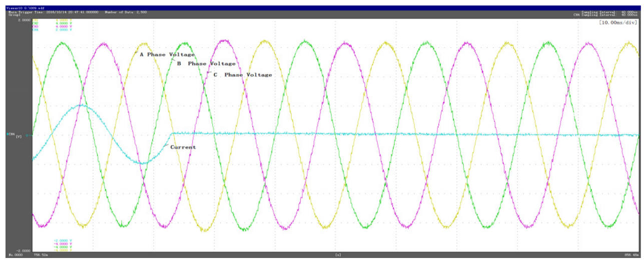
FIGURE 17. The experimental voltage and current waveform obtained by different methods when loads increase suddenly from 0kW to 6KW. (a) Z-N method. (b) BCGA. (c) BCPSO. (d) BCEO.



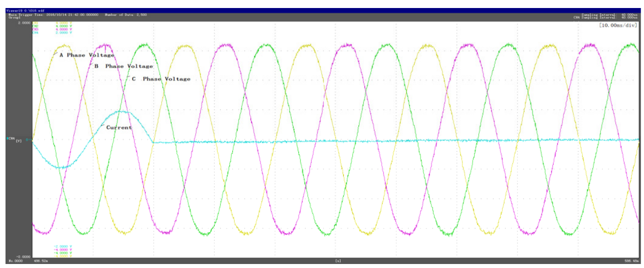
(a) Z-N method



(b) BCGA



(c) BCPSO



(d) BCEO

FIGURE 18. The experimental voltage and current waveform obtained by different methods when loads decrease suddenly from 6kW to 0kW. (a) Z-N method. (b) BCGA. (c) BCPSO. (d) BCEO.

TABLE 8. Comparison of the experimental THD (%) values of three phase voltage obtained by different methods when the loads decrease suddenly from 6kW to 0kW.

Algorithm	THD_{VA} (%)	THD_{VB} (%)	THD_{VC} (%)
Z-N method	4.54	3.99	4.26
BCGA	3.12	3.21	3.23
BCPSO	3.14	2.98	2.93
BCEO	**2.57**	**2.32**	**2.65**

form obtained by different methods in these two experiments are shown as Fig.17 and Fig.18, respectively, and the corresponding THD values of three phase voltage are shown in Table 7 and Table 8, respectively. It is evident that BCEO performs the best among these four methods.

VI. CONCLUSION AND OPEN PROBLEMS

In this paper, a novel BCEO-based double closed-loop PI controller design method is proposed for the optimal control of three-phase inverters. The key operations of this method include encoding the double closed-loop PI controller parameters into a binary string, evaluating the control performance by an effective weighted objective function by considering both ITAE and THD of output voltage, selecting the bad elements based on power-law probability distribution and updating the solutions by binary mutation on the selected ones. One of the most attractive advantages is the relative simplicity of BCEO comparing with the existing popular evolutionary algorithms, such as BCGA [30] and BCPSO [12]. More specially, only selection and mutation should be designed from the evolutionary algorithms points of view and fewer adjustable parameters need to be tuned in BCEO. Furthermore, the simulation and experimental results on a 20kW three-phase inverter have shown that the proposed BCEO-based PI design method is better than Z-N method [6], BCGA [30] and BCPSO [12] in terms of control performance under both the nominal and variable loads conditions. Therefore, the proposed BCEO- based closed-loop PI method is considered as promising for the optimal control of power converters in engineering. Nevertheless, the performance of BCEO can be further improved by a highly tailored method of the adaptive mechanism of power-law distribution parameter. On the other hand, the extension of BCEO to more complex power converters and power systems is another significant subject of future investigation. Because several technological and economical requirements should be often satisfied simultaneously for the design and operation of three-phase inverters in a specific engineering application [31], an accurate formulation and an effective solution method from the perspective of multi-objective optimization are worth to study in future.

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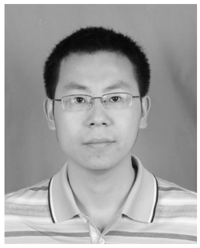

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