PID Decoupling Controller Design for Electroslag Remelting Process Using Cuckoo Search Algorithm with Self-tuning Dynamic Searching Mechanism

Jie-Sheng Wang, and Shu-Xia Li

Abstract—**Mathematical model of electroslag remelting (ESR) process is established based on its technique features and dynamic characteristics. A new multivariable self-tuning PID controller tuned optimally by an improved cuckoo search algorithm is proposed to control the two-input-two output (TITO) ESR process. In order to improve the convergence velocity and optimization accuracy of cuckoo search (CS) algorithm, a new searching mechanism with a learning-evolving searching guider is proposed by combining the learning-evolving thought with Gaussian distribution. Then the new searching mechanism is combined with the Levy Flight searching mechanism according to a selection probability so as to form a new searching mechanism cuckoo search (MCS) algorithm. For solving the problem that the search space size and the scope cannot be decided exactly, a self-tuning dynamic searching space strategy is put forward. The search space is adjusted dynamically by following the best bird's nest location. Finally, the new searching mechanism cuckoo search algorithm with self-tuning dynamic search space (DMCS) is applied to the multivariable self-tuning PID decoupling controller. The simulation results show that the proposed control strategy can overcome dynamic conditions and the coupling problem of the system within a wide range, and it has an excellent control quality, stronger robustness and good working adaptability.**

Index Terms—**electroslag remelting process, multivariable system, PID controller, cuckoo search algorithm**

I. INTRODUCTION

ELECTROSLAG remelting Electroslag remelting (ESR) process is an advanced smelting method to make purified steels based on rudiment steel in order to reduce impurity and get the high-quality steel which is uniformity, density and crystal in vertical [1]. It is a typical strong coupling nonlinear complex industrial controlled object, a complex controlled object with strong coupling characteristics. And the traditional voltage swing control [2], remelting rate control, etc. control strategy is difficult to achieve satisfactory control effect. Therefore, the set value optimization method based on case-based reasoning [3], coordinated controller based on genetic algorithm optimization, the fuzzy adaptive control strategy and other intelligent control method are adopted to optimize and control the electroslag remelting (ESR) process. But all of them are not considered melting strong coupling characteristic between voltage and current loop of smelting, and in the primary loop short net resistance, slag resistance and mechanical properties of electroslag remelting process control affect the performance.

ESR process is a typical complex controlled object, which has multi-variable, distributed parameters, nonlinear and strong coupling features. During the early stage of research, the normal control methods include voltage swings, constant current, constant voltage and descending power. The voltage swing control method is adopted to adjust the voltage swing amplitude in order to control the electrode movements and maintain the stability of slag resistance [2]. The key technology of melting speed control mainly discussed [3]. The mathematical model of the time-variant system doesn't analysis the fundamental reasons causing voltage fluctuation at the expense of the current control accuracy in exchange for the smoothly control of the voltage swing. With the development of the control theory and modern optimization algorithm, the intelligent control strategies, which doesn't strictly depend on mathematical model, are used in the ESR process. The ESR model was analyzed and the cooperative control method was adopted for the melting rate and position of remelting electrodes, whose parameters are optimized by the improved genetic algorithm [4]. An intelligent control method was proposed for ESR process, which combines a variable frequency drive control strategy with the artificial neural network theory. The experiment results show the proposed control strategy improves the accuracy and intelligence level of the ESR furnace, stables the remelting current [5]. Aiming at the ESR process's requirements for electrode control system, a fuzzy adaptive PID control method was proposed, which just controls the smelting current and voltage separately without considering the

Manuscript received September 9, 2016; revised January 9, 2017. This work was supported by the Project by National Natural Science Foundation of China (Grant No. 51674140), the Program for Liaoning Excellent Talents in University (Grant No. LR2014008), the Project by Liaoning Provincial Natural Science Foundation of China (Grant No. 2014020177), the Program for Research Special Foundation of University of Science and Technology of Liaoning (Grant No. 2015TD04) and the Opening Project of National Financial Security and System Equipment Engineering Research Center (Grant No. USTLKFGJ201502 and USTLKEC201401).

Jie-Sheng Wang is with the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China; National Financial Security and System Equipment Engineering Research Center, University of Science and Technology Liaoning. (phone: 86-0412-2538246; fax: 86-0412-2538244; e-mail: wang_jiesheng@126.com).

Shu-Xia Li is a postgraduate student in the School of Electronic and Information Engineering, University of Science and Technology Liaoning, Anshan, 114051, PR China (e-mail: lishuxia9685@163.com).

coupling between the two controlled variables and the influences of the short net resistance in the main circuit, the slag resistance and the mechanical properties on the ESR process [6].

PID control is one of the earliest developed control strategy. It has been widely used in industrial process control field because it is simple in structure, good robustness and high reliability. The self-turning and optimization of the PID controller parameters is an important research field. With the rapid development of swarm intelligence theory, many PID controller parameters self-turning method based on swarm intelligence theory appear, such as genetic algorithm, cuckoo search algorithm and particle swarm optimization. But the genetic algorithm need reproduction, crossover and mutation operation, whose performance has a bigger dependence on parameters; while the cuckoo search algorithm has a slow convergence speed and its search precision is not high.

Cuckoo Search (Cuckoo Search Algorithm, CS) Algorithm is a new biological heuristic algorithm that put forward by Yang and Deb in 2009. The algorithm simulates the cuckoo behavior of seeking nests and spawning, and introduces a levy flight mechanism, which make it able to quickly and efficiently find the optimal solution [7]. In this paper, on the basis of technique features and dynamic characteristics of electroslag remelting (RSR) process a multivariable PID decoupling control method of electroslag remelting process based on improved cuckoo algorithm is proposed. The simulation and industrial test results verify that the proposed control method is effective.

II. Technique Flowchart and Mathematics Model of ESR Process

Electroslag furnace is a complex controlled object, whose production technique is more complex than other steelmaking methods. Now there are still having no a good mathematic model to describe the ESR process. In order to ensure the stability of ESR process and quality of the remelting metal, the reasonable technique parameters must be chosen. The technique flowchart of electroslag furnace is described in the Figure 1 [8]. The operation flow of the ESR process is illustrated as follows: Add slag → Start arc → Melting slag → Casting → Feeding → Remelting end → Thermal insulation → finished product. The technique of electroslag furnace may be divided into four stages: melting slag stage, exchange electrodes stage, casting stage and feeding stage. At the scene of the electroslag remelting industry, acquiring step responses of field voltage ΔU and remelting speed v by adding step disturbance to U_2 and I_2. Then adopting the curve fitting method gain the mathematical model of electroslag furnace under such condition [9].

$$\begin{bmatrix}\Delta U(s)\\ v(s)\end{bmatrix}=\begin{bmatrix}G_{11}(s) & G_{12}(s)\\ G_{21}(s) & G_{22}(s)\end{bmatrix}\begin{bmatrix}U_2(s)\\ I_2(s)\end{bmatrix}$$
$$=\begin{bmatrix}\dfrac{2.7s+5.4}{3s^2+15s+18} & \dfrac{0.33s^3+1.65s^2+2.31}{s^3+5s^2+18s}\\ \dfrac{8.1s+16.2}{s^2+4s+7} & \dfrac{s^2+8s+7}{s^3+4s^2+7s}\end{bmatrix}\begin{bmatrix}U_2(s)\\ I_2(s)\end{bmatrix} \quad (1)$$

III. Cuckoo Search Algorithm

A. Basic Cuckoo Search Algorithm

Cuckoo algorithm is mainly based on two aspects: the cuckoo's nest parasitic reproductive mechanism and Levy flights search principle. In nature, cuckoos use a random manner or a quasi-random manner to seek bird's nest location [7]. Most of cuckoos lay their eggs in other birds nest, let the host instead them to their raise pups. If the host found that the eggs are not its owns, it will either throw these alien eggs away from the nest or abandon its nest and build a new nest in other places [10-12]. However, some cuckoos choose nest that the color and shape of the host's eggs are similar with their owns to win the host's love, which can reduce the possibility of their eggs being abandoned and increase the reproduction rate of cuckoos.

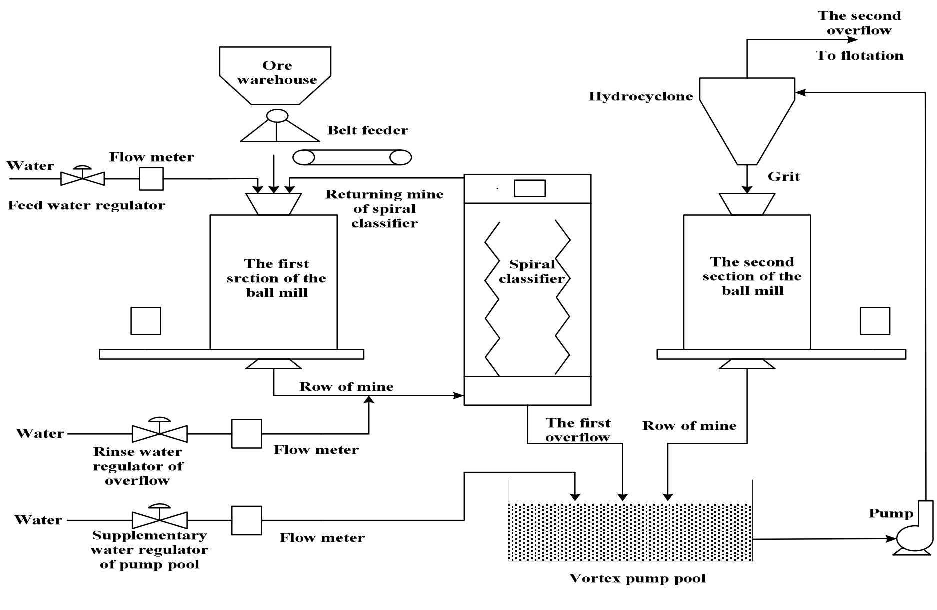

Fig. 1 Working principle of electroslag furnace.

In general, each cuckoo can only lays one egg, and each egg on behalf of one solution (cuckoo). The purpose is to make the new and potentially better solutions replace the not-so-good solutions (cuckoos). In order to study the cuckoo search algorithm better, the simplest method is adopted, that is to say only one egg is in each nest. In this case, an egg, a bird's nest or a cuckoo is no differences. For simplicity in describing the cuckoo search algorithm, Yang and Deb use the following three idealized rules to construct the cuckoo algorithm [10]:

(1) Each cuckoo only lays one egg at a time, and randomly choose bird's nest to hatch the egg.

(2) The best nest will carry over to the next generation.

(3) The number of available host nests is fixed, and the probability of a host discovers an alien egg is $P_a = [0,1]$. In this case, the host bird may will either throw the alien egg away or abandon its nest so as to build a new nest in a new location.

Cuckoo algorithm is based on random walk of Levy flight making search. Levy flight is a random walk, whose step size obeys Levy distribution, and the direction of travel is subject to uniform distribution. On the basis of these rules, updating formula of the cuckoo nest location is described as follows:

$$x_i^{(t+1)} = x_i^t + \alpha s_L \tag{2}$$

$$S_L = levy(\lambda) \tag{3}$$

where, x_i^t represents the position of the i-th nest at the t-th generation, x_i^{t+1} represents the position of the i-th nest at the $(t+1)$-th generation ; α is step control volume; $levy(\lambda)$ is a vector obeying Levy distribution:

$$L(s,\lambda) = \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}, (s \gg s_0) \tag{4}$$

where, $s_0 > 0$ represents the minimum step, Γ is a gamma function; the step of $levy(\lambda)$ obeys levy distribution. In general, levy distribution is usually expressed as follows:

$$L(\beta,\lambda) = \frac{1}{\pi}\int_0^\infty \cos(ks)\exp[-\beta|k|^\lambda]dk \tag{5}$$

In the Eq. (5), there is no any form of explicit analysis; therefore, it is difficult to obtain a random sample by the formula. But, when $s \gg s_0 > 0$, the Eq. (5) can be approximated as the following equation:

$$L(\beta,\lambda) = \frac{\beta\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi|s|^{1+\lambda}} \tag{6}$$

When $\beta = 1$, the Eq. (6) is equivalent to Eq. (5). Although the Eq. (6) can describe random walk behavior of the cuckoo algorithm, but it is not conducive to the description of the mathematical language, and is more disadvantageous to the writing of the program. So, Yang Xin She and Deb found that in the realization of the CS algorithm adopting Mantegna algorithm can well simulate random walk behavior of levy flight [13]. In this algorithm, the step length s can be represented as:

$$s = \frac{u}{|v|^{1/\lambda}}, 1 \le \lambda \le 2 \tag{7}$$

where s is leap path of levy flying ; Parameters u and v are subject to normal distribution shown as Eq. (8):

$$\mu \sim N(0,\sigma_\mu^2), v \sim N(0,\sigma_v^2) \tag{8}$$

$$\sigma_\mu = \left(\frac{\Gamma(1+\beta)\sin(\pi\beta/2)}{\Gamma[(1+\beta)/2]\beta 2^{(\beta-1)/2}}\right)^{1/\beta}, \sigma_v = 1 \tag{9}$$

This algorithm can generate samples approximate to levy distributed. In theory $s_0 \gg 0$, but in practice, s_0 can take a very small value, such as $s_0 = 0.1$.

B. New search mechanism cuckoo search algorithm (MCS)

In the basic CS algorithm, step size and the direction generating by using the levy flight search mechanism are highly random. It is known from Eq. (7) that the step size of levy flight completely depends on of the random number u and v, which makes the search, has characteristics of great randomness and blindness. And in the search process there is lack of information communication between cuckoos. The search is easy to jump from one region to another region, which leads to a low search accuracy and slow convergence speed. In order to make the search with a directivity and teleology and let the algorithm do search under a guider, inspired by the shuffled frog leaping(SFLA) algorithm and variation thought coming from differential evolution(DE) algorithm, in this article, the worst frog's update strategy of SFLA algorithm and variation idea are introduced into search of bird's nest locations.

In SFLA algorithm, in order to get more food faster, poor frog is influenced by good frog jump to the better frog [14]. Reference that of SFLA algorithm, in order to make a cuckoo hunt for better bird's nest faster, let it learn from the best cuckoo and improve the capability of communicating information with the best cuckoo. The introduction of variation thought make bird's nest has an ability of self-evolving, which can increase the diversity of bird's nest position, that is to say it can increase the diversity of solutions. For improving the search ability of the algorithm, with learning and evolving as the search wizard, the Gaussian distribution is added to the algorithm. Based on the thoughts above, the new search mechanism is as shown follows.

$$lem(i) = c_1(x_i - x_{best})G_1 + c_2(x_{r_1} - x_{r_2})G_2 \tag{10}$$

where, x_i is the i-th bird's nest location, x_{best} is the current best location, r_1 and r_2 are random number from (1, n), n is the number of bird's nest population, x_{r_1} and x_{r_2} are the bird's nest locations corresponded to a random number r_1 and r_2 , G_1 and G_2 obey the Gaussian distribution, c_1 is the learning scale and c_2 is evolution scale.

The values c_1 and c_2 control the learning and evolving ability of cuckoos. If c_1 and c_2 are set fixed values, it can make learning and evolution lack flexibility. In order to make the learning and evolution has a flexibility c_1 and c_2 changing as the following formula:

$$c_1 = (0.5 + \beta) / 2 \tag{11}$$

$$c_2 = (0.5 + \gamma) / 2 \tag{12}$$

where, β and γ are random number from [0, 1] and obey uniform distribution

Randomness and strong leap characteristics of Levy flight make the algorithm has stronger global searching ability. If fully use the search mechanism that proposed in this paper and abandon Levy flight search mechanism, it will lost the advantages of high searching ability owned by original algorithm, which will result in the algorithm difficult to jump out of local optimal solution. If fully use the Levy flight search mechanism, it will lead to the algorithm has a low search accuracy and slow convergence speed. Therefore, in order to exert advantages of both search mechanism, combining the new searching mechanism proposed in this paper with the Levy Flight according to a selection probability. It can be express as Eq. (13).

$$s_L = \begin{cases} levy(\lambda) & p < cr \\ lem(i) & p \geq cr \end{cases} \tag{13}$$

where, cr is selectiveprobability that balance the two search mechanism and it is constant, $0 < cr < 1$. And p obeys the uniform distribution $p \in [0,1]$.

When $p < cr$, adopting search mechanism of Levy flight to search bird's nest location of the next generation; When $p > cr$, using the search mechanism that proposed by this article to search bird's nest location.

C. Self-tuning dynamic search space

Selection of search space is very important, it not only influence convergence speed and searching accuracy of the algorithm. In many cases the area of optimal parameters is unknown. If search scope is set too small, within the limited search space the best parameter values won't be searched; if directly set a very large search scope, because the search scope is too large to search carefully, it may not be able to get good parameter values. The search scope is uncertain especially in the situations that the scope of optimal parameter value area cannot be estimated or there also exist better parameter values beyond the search scope that expected.

To solve this problem a self-tuning dynamic search space is put forward in this paper. Adjust the search space dynamically by following the best bird's nest location. After m iterations obtain a current best bird's nest location $X_{m-best} = (x_1, x_2, \cdots, x_d)$ (d is dimension of location), and then take the bird's nest location as a center, expand its space to the left and right sides and form a new search space. It can be expressed as Eq. (14). After each time running m iterations the algorithm adjusts its search space by itself according to the method described above. So every time generating new search space on the basis of expanding of the current best bird's nest location, By using this method it is not only ensure the size of search space is appropriate but also can obtain good parameters.

$$\varphi_1 X_{m-best} \leq X \leq \varphi_2 X_{m-best} \tag{14}$$

where, X is new bird's nest locations, X_{m-best} is the best bird's nest location obtained after each m iterations, ϕ_1, ϕ_2 is controlled variable of expand scope.

D. Algorithm Procedure of DMCS

The algorithm procedure of the improved cuckoo search algorithm (DMCS) is shown in Figure 2. The specific steps of DMCS algorithm are described as follows.

Step 1: Initialization. Randomly generate N bird's nest locations $X^0 = (x_1^0, x_2^0, \ldots, x_N^0)$, select the optimal bird's nest location and carry it over to the next generation;

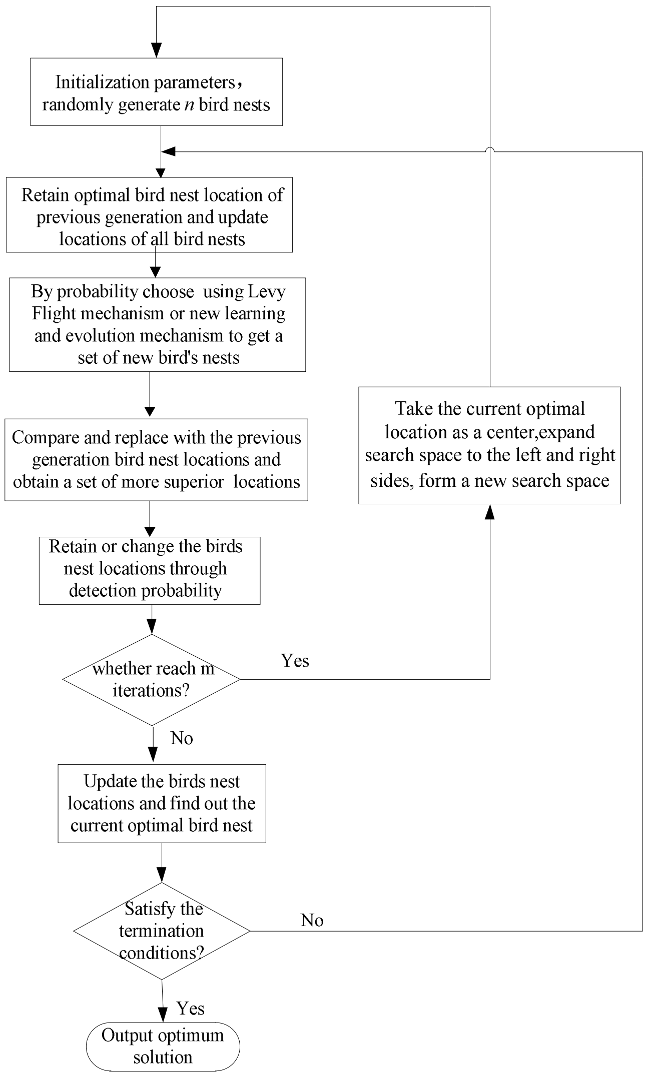

Fig. 2 Flow chart of DMCS algorithm.

Step 2: Search operation. Generate a random number that obeys uniform distribution $p \in [0,1]$, and then contrast it with the selection probability cr. If $p < cr$, using the Levy flight search mechanism to search for next generation bird's nest locations; If $p > cr$, using the search mechanism based on learning and evolution proposed in this paper as Eq.(10) to search for next generation bird's nest locations. Get a new set of bird's nest, and test them, then compare the testing results with the bird's nest position of previous generation and obtain a set of better nests.

Step 3: selecting operation. Generate a random number $r \in [0,1]$ that submits to uniform distribution, and contrast it with the detection probability $Pa = 0.25$. If $r > Pa$, bird's nest location $x_i^{(t+1)}$ is changed randomly, otherwise, unchanged. Test bird's nest locations that have changed compare them with locations of last step and choose bird's nest locations.

Step 4: Updating search space operation. After meet the updating condition, take the current optimal bird's nest location as a center, then form a new search space by expanding search space to the left and right sides on the basis of the center. Retain the best position and fitness value to the new search space. Return to the step 1 and start a new search.

Step 5: Judging operation. Calculate fitness value $f(\text{pb})$ and judge whether achieve termination conditions. if achieved, pb is the optimal solution, otherwise, return to Step 2 and start the next iteration.

IV. Self-Tuning of Multivariable PID Controller Parameters Based on DMCS

A. Multivariable PID Control Strategy

The PID controller is a regulator in accordance with the linear combination of the proportion, differential and integral of the error, which can be described as [15]:

$$u(t) = K_p\left[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + \frac{T_d de(t)}{dt}\right] \tag{15}$$

where, $K_i = K_P/T_i$, $K_d = K_p T_d$, and *e(t)* is feedback error.

B. Diagonal Matrix Decoupling

In this paper adopt the diagonal matrix decoupling control to eliminate coupling that between each channel of coupling system. DMCS algorithm is used to optimize PID control parameters and its structure is shown in Figure 3. Mathematical model of the system is described as above:

$$\begin{bmatrix}\Delta U(s)\\ v(s)\end{bmatrix} = \begin{bmatrix}G_{11}(s) & G_{12}(s)\\ G_{21}(s) & G_{22}(s)\end{bmatrix}\begin{bmatrix}U_2(s)\\ I_2(s)\end{bmatrix} \tag{16}$$

In order to realize decouple control object of ESR process, it can get the structure of decoupling control system according to the principle of diagonal matrix decoupling:

$$G_{11}(s)D_{12}(s) + G_{12}(s)D_{22}(s) = 0 \tag{17}$$

$$G_{21}(s)D_{11}(s) + G_{22}(s)D_{21}(s) = 0 \tag{18}$$

$$\begin{aligned}\frac{D_{12}(s)}{D_{22}(s)} &= -\frac{G_{12}(s)}{G_{11}(s)}\\ &= -\frac{0.33s^3 + 1.65s^2 + 2.31}{s^3 + 5s^2 + 18s} \Big/ \frac{2.7s + 5.4}{3s^2 + 15s + 18}\end{aligned} \tag{19}$$

$$\begin{aligned}\frac{D_{11}(s)}{D_{21}(s)} &= -\frac{G_{22}(s)}{G_{21}(s)}\\ &= -\frac{s^2 + 8s + 7}{s^3 + 4s^2 + 7s} \Big/ \frac{8.1s + 16.2}{s^2 + 4s + 7}\end{aligned} \tag{20}$$

Finally, after decoupling the transfer functions of controlled coupling object of ESR process is as follows:

$$G_{11}^*(s) = \frac{2.7s + 5.4}{3s^2 + 15s + 18} \tag{21}$$

$$G_{22}^*(s) = \frac{s^2 + 8s + 7}{s^3 + 15s + 18} \tag{22}$$

Therefore, after decoupling the transfer function matrix the system is that:

$$\begin{bmatrix}\Delta V(s)\\ v(s)\end{bmatrix} = \begin{bmatrix}G_{11}^*(s) & 0\\ 0 & G_{22}^*(s)\end{bmatrix}\begin{bmatrix}V_2(s)\\ I_2(s)\end{bmatrix} \tag{23}$$

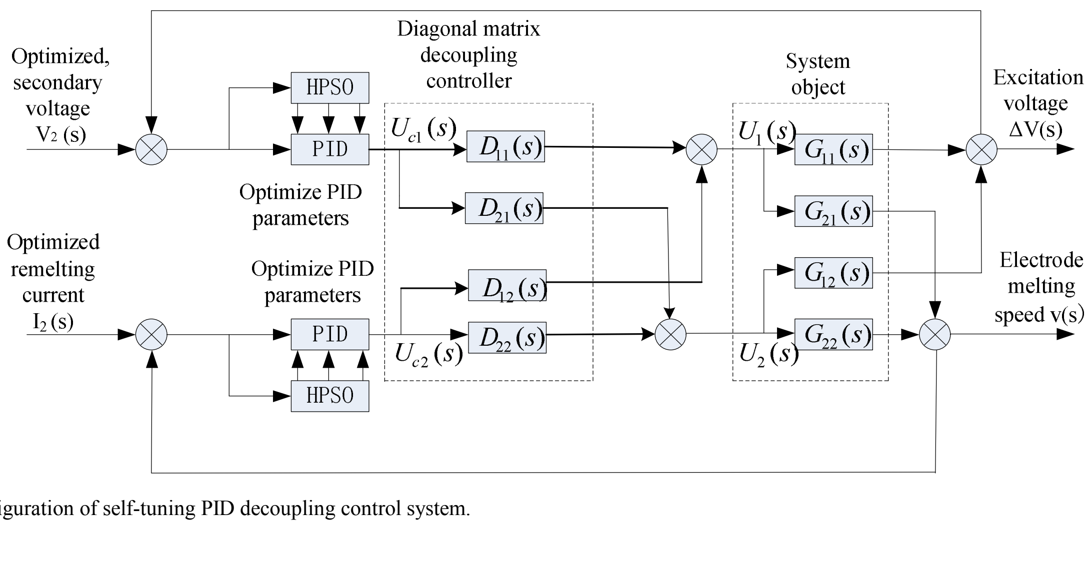

Fig. 3 Configuration of self-tuning PID decoupling control system.

After decoupling, the original coupled system is decomposed into two independent single input single output (SISO) control systems, which is shown as follows:

$$\Delta V(s) = G_{11}^{*}(s)V_2(s) \quad (24)$$

$$v(s) = G_{22}^{*}(s)I_2(s) \quad (25)$$

C. Coding and Fitness Function

In order to pursue a better control effect， use PID controller whose parameters are optimized based on the new searching mechanism cuckoo search algorithm with self-tuning dynamic search space (DMCS) to adjust the two above control channels. Because the design of the PID controller actually is an optimization problem of a multi-dimension function, the DMCS adopts real encode schema. The parameters of the multivariable PID controller can be directly encoded as follows:

$$X_1 = \{k_{p1}, k_{i1}, k_{d1}\},\ X_2 = \{k_{p2}, k_{i2}, k_{d2}\} \quad (26)$$

Optimization of control parameters aims to make the overall control error of system tends to zero, has faster response speed and small overshoot. In this paper, adopt the following four types of error integral criterion to make contrast experiment.

(1) Absolute error integral criterion (IAE)

$$IAE = \int_0^{\infty} |e(t)dt| \quad (27)$$

(2) Square error integral criterion (ISE)

$$ISE = \int_0^{\infty} e(t)^2\, dt \quad (28)$$

(3) Time multiply absolute error integral criterion (ITAE)

$$ITAE = \int_0^{\infty} t|e(t)|dt \quad (29)$$

(4) Time multiply square error integral criterion (ITSE)

$$ITSE = \int_0^{\infty} t^2 e(t)^2\, dt \quad (30)$$

D. Parameters Search Space

Due to the space scope that good parameters value of PID controller within is unknown, how to choose parameters search space is very important for obtaining better PID controller parameters. If the search space is too small, in the limited search space cannot get the best PID parameters; If set a large search space directly, the search space is too big to search carefully, in this method good PID control parameters may also not be obtained.

For solving this problem we adopt the self-tuning dynamic search space method that proposed above. Adjust the search space of PID parameters dynamically by following the best bird's nest location. After m iterations obtain a set of new and better PID parameters, and then take these group PID parameters as the center, by expanding its space to the left and right sides form a new search space. So every time after m iterations the algorithm adjusts PID search space by itself according to the method described above. So every time generating new search space of PID parameters on the basis of current best PID parameters, By using this method it is not only ensure the size of search space is appropriate but also can obtain good PID parameters. It can be expressed as the follow equations.

$$(1-\eta_1)*Kp_m \le Kp \le (1+\eta_2)*Kp_m \quad (31)$$

$$(1-\eta_1)*Ki_m \le Ki \le (1+\eta_2)*Ki_m \quad (32)$$

$$(1-\eta_1)*Kd_m \le Kd \le (1+\eta_2)*Kd_m \quad (33)$$

where, Kp , Ki and Kd are parameters of PID controller; Kp_m , Ki_m and Kd_m are values of PID controller parameters that obtained after each time running m iterations. Their initial values is PID parameters values that obtained by the critical proportion method. η_1 and η_2 are belong to [0, 1].

V. PID CONTROLLER OPTIMIZATION OF ESR PROCESS BASED ON DMCS OPTIMIZATION

In this article, PID diagonal matrix decoupling controller is adopted to decouple coupling object of electroslag remelting process decoupling. The original coupling control system is divided into two independent control system: system 1 and system 2. PID controller parameters of the two control systems are optimized by four algorithms: ZN algorithm, CS algorithm, the MCS algorithm and DMCS. Compare the simulation results of the four algorithms and simulation results of DMCS algorithm under four different fitness functions. Figure 4 is output responses of system 1 corresponding to 4 different algorithms under ITAE performance index. Figure 5 is output responses of system 1 using DMCS algorithm under four different performance indexes (ISE, IAE, ITAE and ITSE). Figure 6 is evolution of the ITAE performance index by CS and the MCS algorithm in system 1. Figure 7 is evolution of the ITAE performance index by DMCS algorithm in system 1. Figure 8 is output responses of system 2 corresponding to 4 different algorithms under ITAE performance index. Figure 9 is output responses of system 2 using DMCS algorithm under four different performance indexes. Figure 10 is evolution of the ITSE performance index by CS and the MCS algorithm in system 2. Figure 11 is evolution of the ITSE performance index by DMCS algorithm in system 2.

PID parameters of system 1 are shown as Table 1. Statistical results of its performance indexes (overshoot, rising time and adjustment time) are shown as Table 2. PID parameters of system 2 are shown as Table 3. The PID controller system performance statistics as shown in table 6. Its statistical results of performance indexes are shown as Table 4. Seen from simulation effect of decoupling control object using different algorithms and different performance, MCS and DMCS algorithm can get the satisfied PID controller parameters for ESR process. For System 1, its PID simulation effect by using DMCS algorithm is better than using other algorithms, and the simulation result is best when adopt ITAE as fitness function. For System 2, the overshoot amount is minimum when using MCS algorithm. Rising time and adjustment time are minimum when using DMCS algorithm. Taking into account the performance indexes of overshoot (Os), rising time (Tr) and adjustment time (Ts), DMCS has a higher control performance than ZN, CS and MCS method.

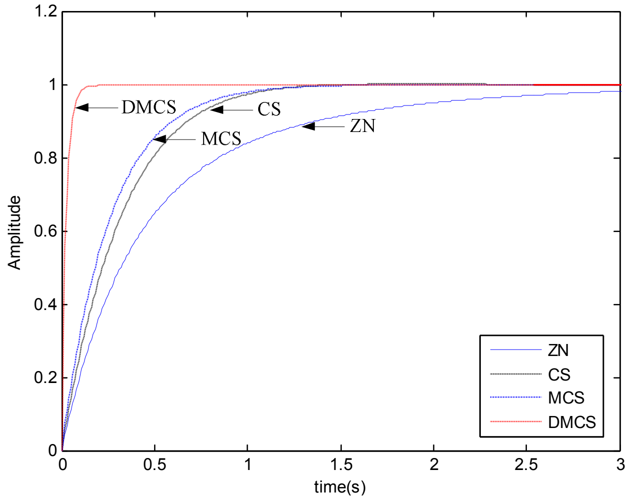

Fig. 4 Output responses of system 1 corresponding to four different PID tuning methods.

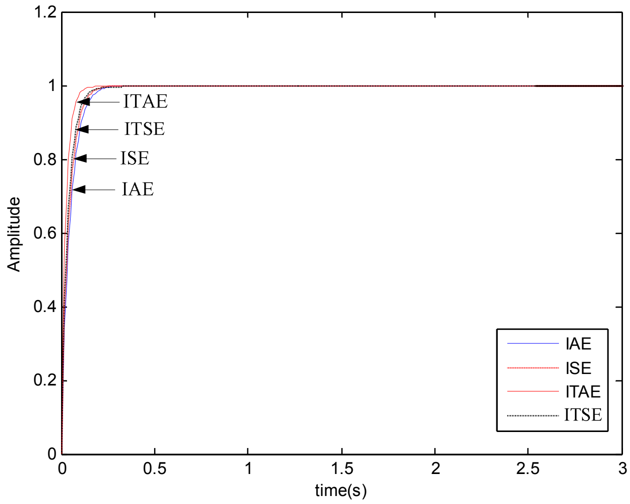

Fig. 5 Output responses of system 1 by using DMCS algorithm.

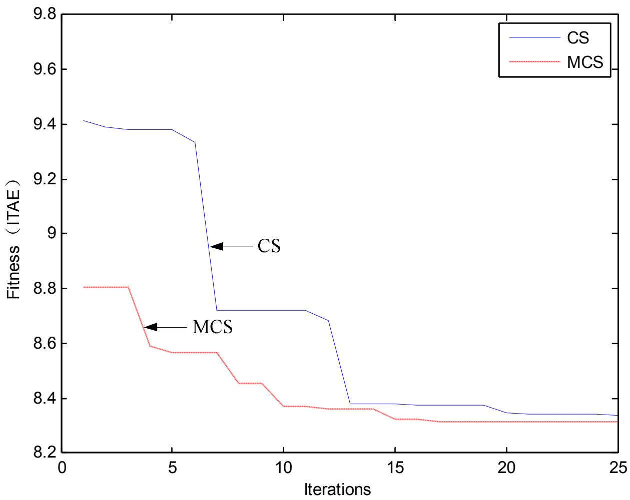

Fig. 6 Evolution of the ITAE performance index by CS and the MCS algorithm in system 1.

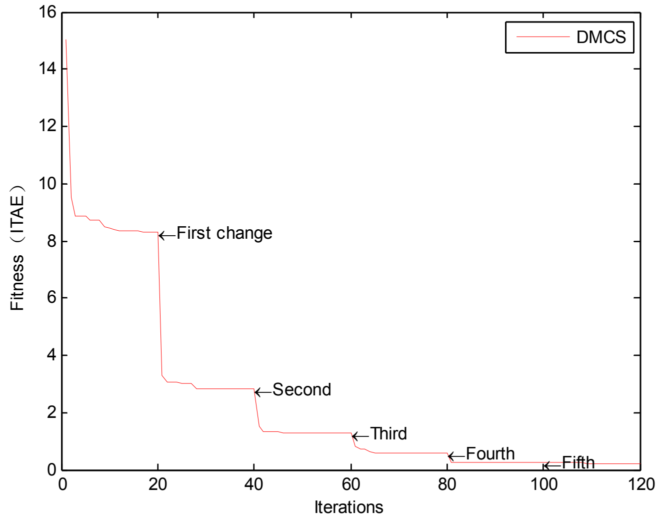

Fig. 7 Evolution of the ITAE performance index by DMCS algorithm in system 1.

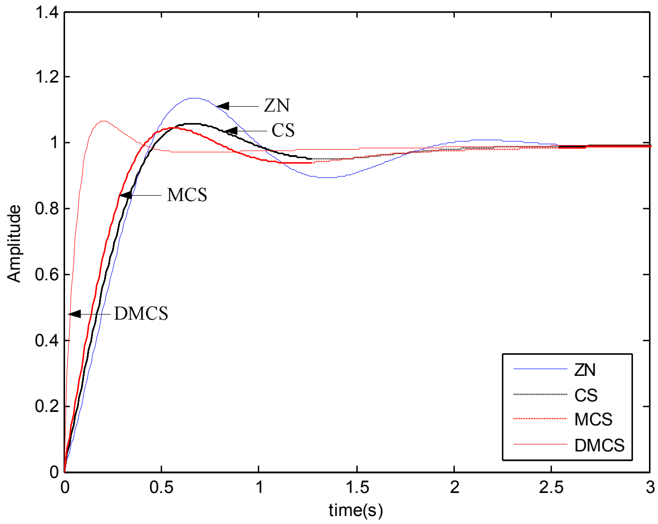

Fig. 8 Output responses of system 2 corresponding to four different PID tuning methods.

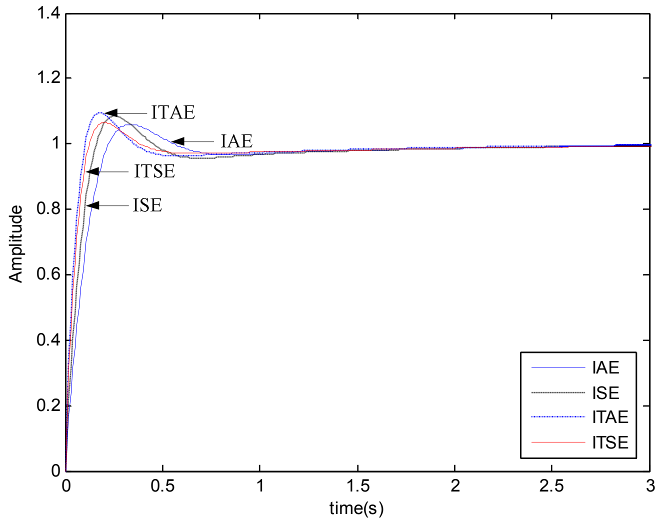

Fig. 9 Output responses of system 2 by using DMCS algorithm.

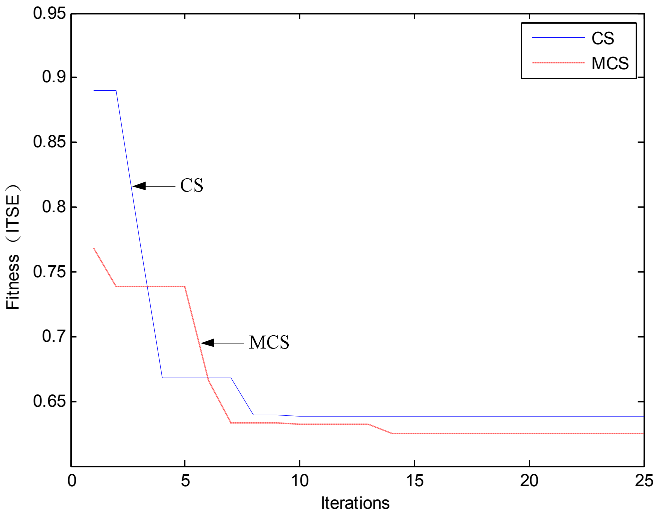

Fig. 10 Evolution of the ITSE performance index by CS and the MCS algorithm in system 2

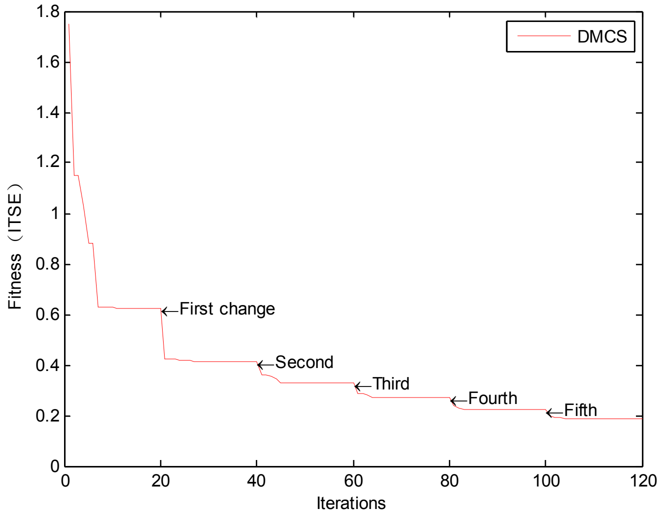

Fig. 11 Evolution of the ITSE performance index by DMCS algorithm in system 2.

TAB. 1 TUNED PARAMETERS OF SYSTEM 1 PID CONTROLLER

PID parameters	ZN	CS	MCS	DMCS			
		ITAE	ITAE	IAE	ISE	ITAE	ITSE
Kp	4.61	3.647	4.6397	23.491	49.357	53.056	42.431
Ki	5.90	11.218	12.9002	70.188	80.00	127.78	85.184
Kd	0.85	0.0847	0.0945	0.0043	0.874	0.1802	0.4088

TAB. 2 PERFORMANCE INDEXES OF SYSTEM 1 PID CONTROLLER

Performance indexes	ZN	CS	MCS	DMCS			
		ITAE	ITAE	IAE	ISE	ITAE	ITSE
Os (%)	0.32	0.132	0.015	0.008	0	0	0
Tr (s)	1.970	0.84	0.76	0.12	0.11	0.06	0.10
Ts (s)	1.980	0.85	0.78	0.14	0.12	0.07	0.12

TAB. 3 TUNED PARAMETERS OF SYSTEM 2 PID CONTROLLER

PID parameters	ZN	CS	MCS	DMCS			
		ITSE	ITSE	IAE	ISE	ITAE	ITSE
Kp	3.985	7.126	8.750	23.711	24.361	33.337	39.563
Ki	11.154	11.218	11.218	21.582	25.387	35.848	29.495
Kd	1.085	1.609	1.515	1.738	1.069	0.692	1.212

TAB. 4 PERFORMANCE INDEXES OF SYSTEM 2 PID CONTROLLER

Performance indexes	ZN	CS	MCS	DMCS			
		ITSE	ITSE	IAE	ISE	ITAE	ITSE
Os (%)	13.65	5.93	4.56	5.89	8.54	8.81	6.36
Tr (s)	0.39	0.40	0.35	0.19	0.13	0.08	0.10
Ts (s)	1.67	0.74	1.41	0.38	0.34	0.25	0.24

VI. Conclusion

Based on the technological characteristics, operation experience and the accumulated large number of historical datum of ESR process, the coupling model (secondary voltage, melting current, excitation voltage and original speed of consumable electrode) of ESR process are set up and a diagonal matrix decoupling controller is designed to decouple this model. The simulation results indicated that the proposed control strategy has many characteristics, such as good dynamic and steady performance, strong robustness, the adaptability of the various working conditions and anti-interference capacity. The unit power consumption of casting is effectively reduced and the product quality of the cast steel is improved greatly.

References

[1] F. Cao, W. Wang, and J. S. Wang, "Intelligent optimal setting control of electroslag remelting process based on knowledge mining and case-based Reasoning," *Information and Control*, vol. 39, no.1, pp. 114-119, 2010.

[2] L. Zhang, J. C. Wang, and J. B. Wang, "Analysis and application of two principles for ESR furnace swing control," *Metallurgical Industry Automation*, no.2, pp. 53-55, 2006.

[3] W. Z. Li, X. H. Jia, Xing-hua, J. C. Wang, and Y. S. Lin, "Improvement of consarc ESR furnace control system," *Journal of Iron and Steel Research*, vol. 19, no.4, pp. 99-101, 2007.

[4] L. L. Zhao, J. C. Song, X. H. Liu, and H. Y. Liu, "Intelligent control study based on genetic algorithm for electroslag remelting process," *Machinery & Electronics*, no.5, pp. 16-19, 2008.

[5] D. Y. Wang, G. Q. He, W. M. Song, Y. J. Kang, and J. Z. Liu, "Study and application on intelligent control of the ESR process," *Industrial heating*, vol. 34, no.6, pp. 42-45, 2005.

[6] W. Ren, X. F. Zheng, L. X. Jiang, H. U. Jie, and Y. Z. Yin, "Fuzzy adaptive PID control for electrode regulating system of electroslag furnace," *Metallurgical Industry Automation*, no.1, pp. 15-18, 2006.

[7] X. S. Yang, and S. Deb, "Cuckoo search: recent advances and applications," *Neural Computing and Applications*, vol. 24, no.1, pp. 169-174, 2014.

[8] J. S. Wang, C. X. Ning, and Y. Yang, "Multivariable PID decoupling control method of electroslag remelting process based on improved particle swarm optimization (PSO) algorithm," *Information*, vol. 5, no.1, pp. 120-133, 2014.

[9] J. S. Wang，and X. W. Gao, "Design of multivariable PID controller of electroslag remelting process based on improved shuffled frog leaping algorithm," *Control and Decision*, vol. 26, no.11, pp. 1731-1734, 2011.

[10] X. S. Yang, and S. Deb, "Engineering optimisation by cuckoo search," *International Journal of Mathematical Modelling and Numerical Optimisation*, vol. 1, no.4, pp. 330-343, 2010.

[11] A. H. Gandomi, X. S. Yang, and A. H. Alavi, "Cuckoo search algorithm: a metaheuristic approach to solve structural optimization problems," *Engineering with Computers*, vol. 29, no.1, pp. 17-35, 2013.

[12] K. Chandrasekaran, and S. P. Simon, "Multi-objective scheduling problem: hybrid approach using fuzzy assisted cuckoo search algorithm," *Swarm and Evolutionary Computation*, no.5, pp. 1-16, 2012.

[13] A. R. Yildiz, "Cuckoo search algorithm for the selection of optimal machining parameters in milling operations," *The International Journal of Advanced Manufacturing Technology*, vol. 64, no.1-4, pp. 55-61, 2013.

[14] P. Civicioglu, and E. Besdok, "A conceptual comparison of the cuckoo-search, particle swarm optimization, differential evolution and artificial bee colony algorithms," *Artificial Intelligence Review*, vol. 39, no.4, pp. 315-346, 2013.

[15] Y. W. Zhang, M. Gao, S. C. Yang, B. C. Li, and X. Gao, "A practical adaptive proportional-derivative guidance law," *Engineering Letters*, vol. 24, no.3, pp. 347-352, 2016.

Jie-sheng Wang received his B. Sc. And M. Sc. degrees in control science from University of Science and Technology Liaoning, China in 1999 and 2002, respectively, and his Ph. D. degree in control science from Dalian University of Technology, China in 2006. He is currently a professor and Master's Supervisor in School of Electronic and Information Engineering, University of Science and Technology Liaoning. His main research interest is modeling of complex industry process, intelligent control and Computer integrated manufacturing.

Shu-Xia Li is received her B. Sc. degree from University of Science and Technology Liaoning in 2012. She is currently a master student in School of Electronic and Information Engineering, University of Science and Technology Liaoning, China. Her main research interest is modeling methods of complex process and intelligent optimization algorithms.