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Field Voltage Speed Control of DC Motors Based Foraging Strategy

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Abstract

The speed of separately excited DC motor (SEDM) can be controlled above rated speed using field control method. The chopper circuit is used to control field voltage for achieving the desired speed. This work presents design and simulation of field control system for controlling the SEDM speed. The chopper firing circuit receives signal from controllers and then chopper gives variable voltage to the field circuit of the motor for achieving desired speed. There are two control loops, one for controlling current consists of relay and another for speed which consists of rate feed back controller tuned using bacterial foraging optimization technique (BFO). Modeling of SEDM is done. The complete model of DC drive is simulated using MATLAB (SIMULINK). BFO technique plays a vital role in controller tuning which improves the controller performance by improving the transient and steady state specifications. Also this technique makes the controller robust for any load changing as shown from simulation results. The proposed method is very efficient and could easily be extended for other global optimization problems.

Keywords: *Chopper, MATLAB SIMULINK, Bacteria Foraging Optimization Algorithm (BFOA), Separately Excited DC Motor (SEDM), Rate Feedback Controller.*

1. Introduction

Direct current (DC) motors have been widely used in many industrial applications such as electric vehicles, steel rolling mills, electric cranes, and robotic manipulators due to precise, wide, simple, and continuous control characteristics [1]. The DC motors have been popular in the industry control area for a long time, because they have enormous characteristics like, high start torque , high response performance, easier to be linear control etc. [2]. Since developments in the design of controlled rectifiers and DC–DC converters, the control of DC motors is realized more easily. For power electronic DC drive applications, the most commonly used DC machines are separately excited DC machines and permanent magnet DC machines. The main advantage of separately excited DC machines is that the armature and field windings are fed from different sources. This property allows obtaining the desired speed-torque characteristics. It is very common application to control the speed of DC motor by changing its terminal voltage. The desired variable voltage is obtained by a controlled rectifier or DC–DC converter [3]. Swarm Intelligence _SI_ is an innovative artificial intelligence technique for solving complex optimization problems. This discipline is inspired by the collective behaviors of social animals such as fish schools, bird flocks, and ant colonies. In SI systems, there are many simple individuals who can interact locally with one another and with their environments. Although such systems are decentralized, local interactions between individuals lead to the emergence of global behavior and properties [4]. In last few years, many researchers have posed different optimization techniques for enhancing speed tracking system [5]. A BFA is one such direct search optimization techniques which are based on the mechanics of natural bacteria and A PSO is one such direct search optimization techniques which are based on the behavior of a colony or

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a swarm of insects, such as ants, termites, bees and wasps. Advantages of the BFA and PSO for auto tuning are that they do not need gradient information and therefore can operate to minimize naturally defined cost functions without complex mathematical operations [6]. However, PSO suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. In addition, the algorithm cannot work out the problems of scattering and optimization. Also, the algorithm pains from slow convergence in refined search stage, weak local search ability and algorithm may lead to possible entrapment in local minimum solutions. Moreover, BFOA due to its unique dispersal and elimination technique can find favorable regions when the population involved is small. These unique features of the algorithms overcome the premature convergence problem and enhance the search capability. Hence, it is suitable optimization tool for power system controllers [5].

2. Mathematical Model of Separately Excited D.C. Motor

Figure (1) shows the equivalent circuit with armature voltage control and the model of a general mechanical system that incorporates the mechanical parameters of the motor and the mechanism coupled to it [7]. When a separately excited motor is excited by a field current of i_f and an armature current of i_a flows in the armature circuit, the motor develops a back emf and a torque to balance the load torque at a particular speed. The field current, i_f, of a separately excited motor is independent of the armature current, i_a, and any change in the armature current has no effect in the field current. The field current is normally much less than the armature current [8].
The instantaneous field current, i_f, is described as

$$V_f = R_f i_f + L_f \frac{\mathrm{di_f}}{\mathrm{dt}} \tag{1}$$

The instantaneous armature current can be found from

$$V_a = R_a i_a + L_a \frac{\mathrm{dia}}{\mathrm{dt}} + e_g \tag{2}$$

The motor back emf, which is also known as speed voltage, is expressed as

$$e_g = K_v \omega i_f \tag{3}$$

The torque developed by the motor is

$$T_d = K_t i_f i_a \tag{4}$$

The developed torque must be equal to the load torque

$$T_d = J \frac{\mathrm{d\omega}}{\mathrm{dt}} + B\omega + T_L \tag{5}$$

where ω = motor speed, rad/s, B = viscous friction constant, N-m/rad/s, K_v = voltage constant, V/A-rad/s, $K_t = K_v$ = torque constant, L_a = armature circuit inductance, H, L_f = field circuit inductance, H, R_a = armature circuit resistance, Ω, R_f = field circuit resistance, Ω, T_L = load torque, N-m

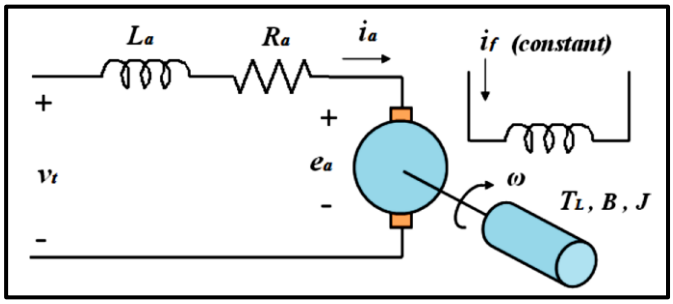


Figure 1: Equivalent circuit of separately excited dc motor

3. Bacterial Foraging Technique

In BFO the coordinates of a bacterium represent an individual solution to the optimization problem. Such a set of trial solution converges towards global optima following a foraging group dynamics of the bacteria population. [9]. The original Bacterial Foraging Optimization system consists of three principal mechanisms, namely, chemotaxis, reproduction, and elimination-dispersal. We briefly describe each of these processes as follows [10].

3.1. Chemotaxis

This process simulates the movement of an E. coli cell through swimming and tumbling via flagella. Bio- logically an Escherichia coli bacterium can move in two different ways. It can swim for a period of time in the same direction or it may tumble, and alternate between these two modes of operation for the entire lifetime [9]. Suppose $\vartheta^{i}(j, k, \ell)$ represents the bacterium at jth chemotactic, kth reproductive, and lth elimination-dispersal step. $C(i)$ namely, the run-length unit parameter, is the chemotactic step size during each run or tumble. Then, in each computational chemotactic step, the movement of the ith bacterium can be represented as:

$$\theta^{i}(j+1,k,\ell) = \theta^{i}(j,k,\ell) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^{T}(i)\Delta(i)}} \tag{6}$$

where Δ(i) is the direction vector of the jth chemotactic step. When the bacterial movement is run, Δ(i) is the same with the last chemotactic step; otherwise, Δ(i) is a random vector whose elements lie in [−1, 1]. With the activity of run or tumble taken at each step of the chemotaxis process, a step fitness, denoted as J(j,k,ℓ), will be evaluated [11, 10, 12].

3.2. Swarming

During the process of reaching towards the best food location it is always desired that the bacteium which has searched the optimum path should try to provide an attraction signal to other bacteria so that they swarm together to reach the desired location. In this process, the bacteria congregate into groups and hence move as concentric patterns of groups with high bacterial density [13]. It is always desired that when any one of the bacteria reaches the better location, try to attract other bacteria so that they reach the desired place more rapidly. The effect of swarming is to make the bacteria congre- gate into groups and move as concentric patterns with high bacterial density Mathematically, swarming can be represented by [12].

$$J_{cc}(\theta(i,\ j,\ k,\ \ell)) = \sum_{i=1}^{S} J_{cc}^{i}(\theta,\theta^{i}(j,k,\ell)) = \sum_{i=1}^{S}\left[-d_{attract}\, exp\left(-w_{attract}\sum_{m=1}^{p}\left(\theta_{m}-\theta_{m}^{i}\right)^{2}\right)\right] + \sum_{i=1}^{S}\left[-h_{repellant}\, exp\left(-w_{repellant}\sum_{m=1}^{p}\left(\theta_{m}-\theta_{m}^{i}\right)^{2}\right)\right] \tag{7}$$

3.3. Reproduction

The least healthy bacteria eventually die while each of the healthier bacteria (those yielding lower value of the objective function) asexually split into two bacteria, which are then placed in the same location. This keeps the swarm size constant [9]. Reproduction is the simulation of the natural reproduction phenomenon. By this operator, individuals with higher nutrient are survived and duplicated, which guarantees that the potential optimal areas are searched more carefully [11, 14]. The fitness value for *i*th bacterium after travelling N_c chemotactic steps can be evaluated by the following equation:

$$J_{health}^{i} = \sum_{j=1}^{N_c+1} J^{i}(j,k,\ell) \tag{8}$$

Here J_{health}^{i} represents the health of ith bacterium. The least healthy bacteria constituting half of the bacterial population are eventually eliminated while each of the healthier bacteria asexually split into two, which are then placed in the same location. Hence, ultimately the population remains constant [15].

3.4. Eliminate and Dispersal

The dispersion event happens after a certain number of reproduction processes. A lowest healthier bacterium chosen, according to a preset probability, to be dispersed and moved to another position within the environment. These events may prevent the local optima trapping effectively. According to a preset probability, some bacteria are chosen to be killed and moved to another position within the environment [16]. After every N_{re} times of reproduction steps, an eliminate-dispersal event happens. For each bacterium, a random number is generated between 0 and 1. If the random number is less than a predetermined parameter, known as P_e, the bacterium will be eliminated and a new bacterium is generated in the environment. The operator can be also regarded as moving the bacterium to a randomly produced position. The eliminate-dispersal events may destroy the chemotactic progress. But they may also promote the solutions since dispersal might place the bacteria in better positions. Overall, contrary to the reproduction, this operator enhances the diversity of the algorithm [11].

4. Control Arrangements for D.C. Drives

The most common arrangement, which is used with only minor variations from small drives of say 0.5 kW up to the largest industrial drives of several MW, is the so-called two-loop control. This has an inner feedback loop to control the current (and hence torque) and an outer loop to control speed. When position control is called for, a further outer position loop is added. A standard d.c. drive system with speed and current control is shown in **Figure (2)**. The primary purpose of the control system is to provide speed control, so the ‘ input ’ to the system is the speed reference signal on the left, and the output is the speed of the motor (as measured by a tachogenerator) on the right. As with any closed-loop system, the overall performance is heavily dependent on the quality of the feedback signal, in this case the speed-proportional voltage provided by the tachogenerator. It is therefore important to ensure that the tacho is of high quality (so that, for example, its output voltage does not vary with ambient temperature, and is ripple-free) and as a result the cost of the tacho often represents a signi fi cant fraction of the total cost [17].

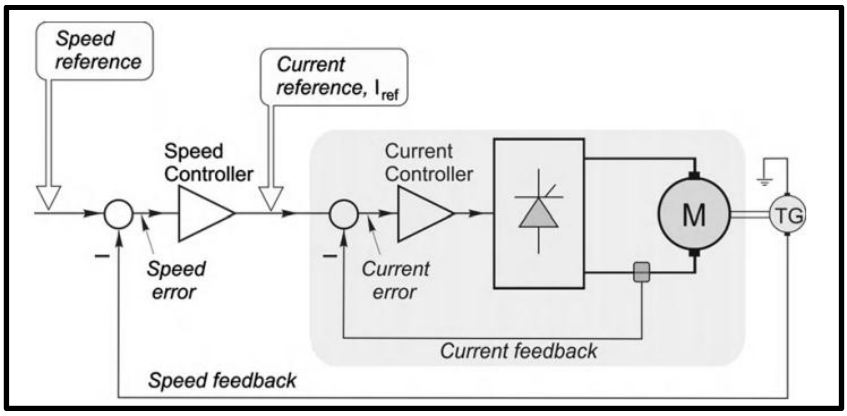


Figure (2): Schematic diagram of SEDM control system with current and speed feedback control loops

5. Simulation and Results

Field control system of SEDM is done using MATLAB SIMULINK which consists of two control loops; inner current control loop and outer speed control loop. The current control loop consists of hysteresis current controller (HCC) which is responsible for generating switching patterns required for the chopper circuit by comparing the actual current being drawn by the motor with the reference current. A positive pulse is generated if the actual current is less than reference armature current, whereas a negative pulse is produced if the actual current exceeds reference current. The speed control loop consists of rate feedback controller tuned using BFO algorithm. A Gate turn off (GTO) thyristor with its control circuit and a free-wheeling diode form the one quadrant chopper circuit. The mathematical model of SEDM is simulated using MATLAB toolbox based on it's dynamic electrical and mechanical equations. The field voltage source is changed based on control signal for adjusting

the motor speed and keeping the armature voltage source constant. The SEDM are loaded at different loads ranging from no-load to full-load for checking the controller's performance and robustness for load variations. The parameters values of SEDM used are shown in Table (1).

Table (1): SEDM parameters

Motor ratings and parameters	values
Power	3.73KW
Armature voltage	240 V
Speed	183.2596 radian/second
Field voltage (V_f)	150 V
Armature resistance (R_a)	0.78 Ω
Armature inductance (L_a)	0.016 H
Field resistance (R_f)	150 Ω
Field inductance (L_f)	112.5 H
$K_v = K_t$	1.234 H
Inertia of the rotor (J)	0.05 $Kg.m^2$
damping coefficient (B)	0.01 N.m.s

Figure (3) shows the closed loop simulink models of SEDM with chopper circuit.

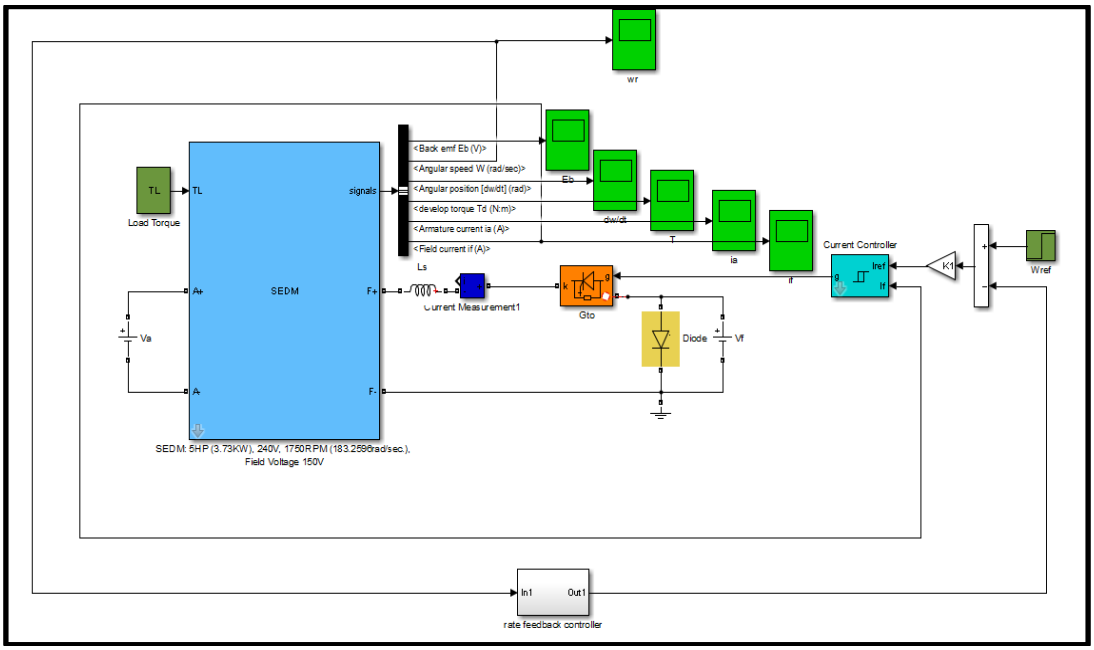


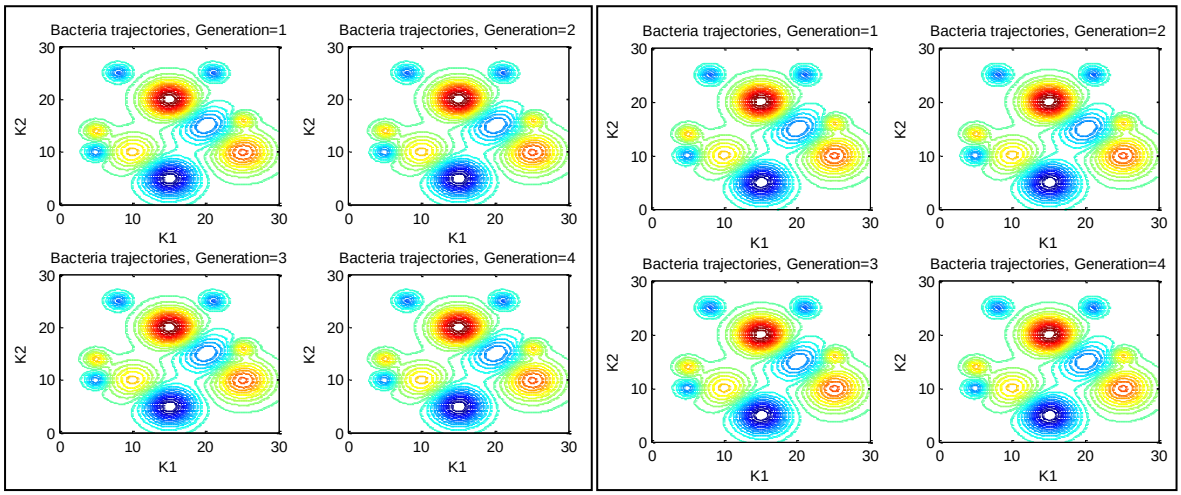
Figure 3: Complete field control system of SEDM with chopper circuit

The parameters of BFO algorithm are listed in Table (2).

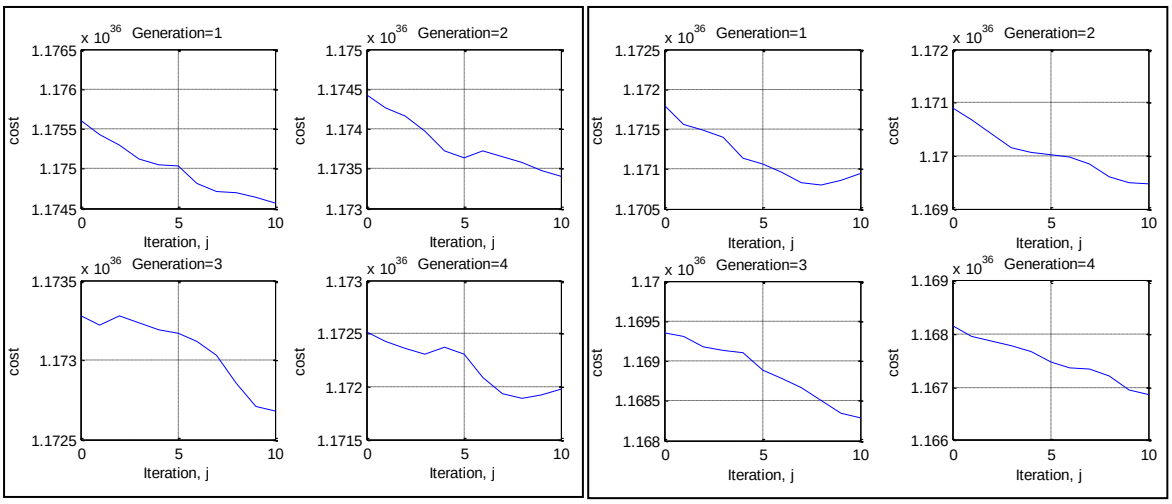
Table 2: BFO parameters used in tuning state feedback controller

BFO parameters	Parameters values
Number of bacteria in the population (s)	10
The length of swim (N_s)	2
Number of reproduction steps (N_{re})	4
Number of chemotactic step (N_c)	10
Number of elimination/dispersal events (N_{ed})	2
Number of bacteria splits per generation (S_r)	s/2
Probability of dispersal occurrence (P_{ed})	0.15

The rate feedback controller gains is (K1 = 0.9932 and K2=0.0135) which is obtained using BFO tuning algorithm. Figures (4) shows the contour plot for first & second elimination/dispersal event and the average cost plots for each generation for two elimination/dispersal events (Ned =2) for tuning the controller parameters. While Figures (5) show Motor time responses with field control at full- load.



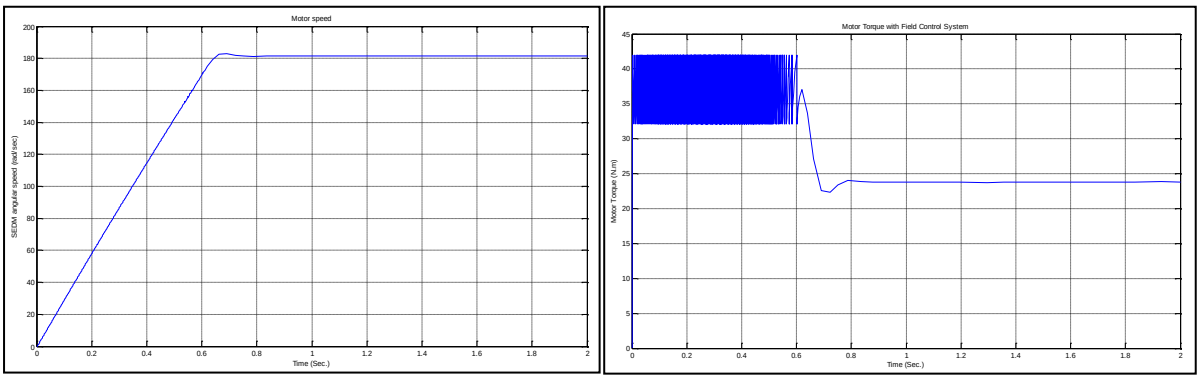
(a) (b)



(c) (d)

Figures 4: Bacteria trajectories and average cost plot

(a), (b) contour plot for first & second elimination/dispersal event for (K_1 & K_2)
(c),(d) average cost plot for first & second elimination/dispersal event respectively



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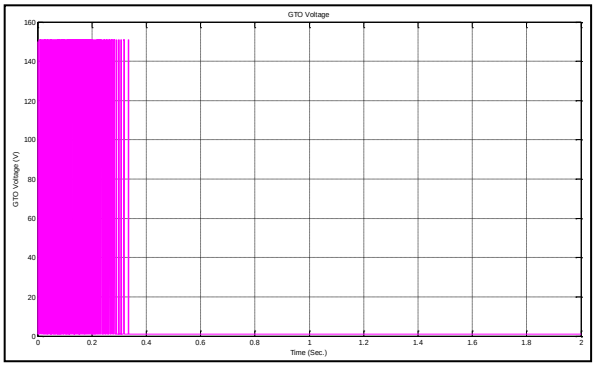
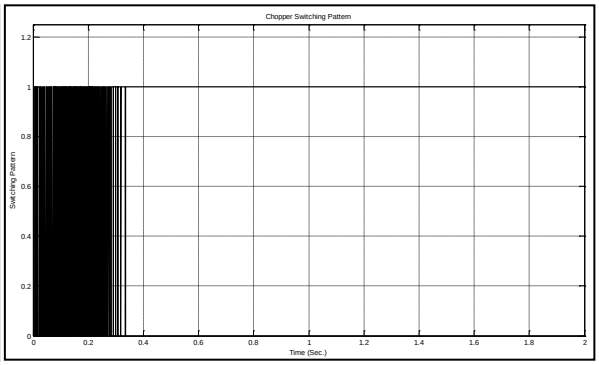
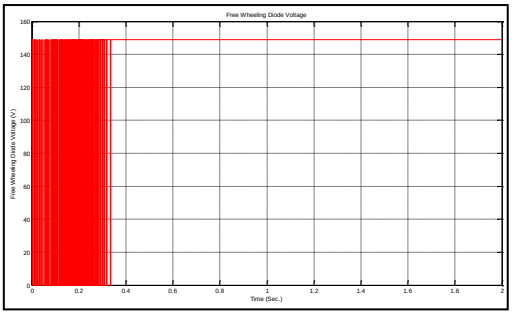


(b)



(d)



(e)

Figures 5: Motor time responses with field control at full- load

(a)Motor angular speed (rad/sec.) (b) Motor torque(N.m) (c) GTO voltage (V) (d)Chopper switching pattern (e) Freewheeling diode voltage (V)

The time response specifications of SEDM speed are (rise time = 0.501s, overshoot = 0, settling time = 0.637s) with field control. In field control method, to control the speed of SEDM when loading, the armature voltage kept constant while field voltage varied. The field voltage must be reduced to decrease the field current and hence the field flux this will cause to decrease motor torque and increase motor speed because the speed inversely proportional to field current. The reduction in field current will reduce the back emf instantaneously and this will cause armature current to increase resulting the motor speed increasing.

Conclusions

In this work the designing and simulation of field control system of SEDM are presented. The field control system consists of chopper (using GTO thyristor) as a converter for varying the field voltage in order to control the motor speed. There are two control loops, Inner control loop for controlling field current and outer control loop for motor speed control. The chopper circuit is used to provide variable (chopped) field voltages for controlling the motor speed above its rated speed. A freewheeling diode is connected for provide a current path when chopper is turned off. The chopper circuit can be controlled using a signal provided from the control loops which consist of rate feedback controller. The rate feedback controller is tuned using BFO technique for selection optimal controller parameters. This technique required less execution time due to the small numbers of bacterias as well as it has fast convergence ability due to motility behaviour and search ability. These features make this technique to be useful for other practical optimization problems.

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