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Compensators design of DC motors using bacterial foraging optimization technique

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Abstract This paper presents the design of compensators for speed control of separately excited dc motor (SEDM) based on bacterial foraging optimization (BFO) technique. The social foraging behavior of Escherichia (*E. Coli*) bacteria has been used to optimize compensator performance by adjusting it's parameters (pole and zero locations as well as compensator gain).The SEDM mathematical model is used because it's more reality to the actual plant rather than linear transfer function model in the control design and studies and give more accurate results. The mathematical model is simulated using MATLAB R2014a simulink toolbox. The SEDM is loading for different loads ranging from no-load to full-load to test the compensator behavior and it's robustness for wide range of loadings variations. The results are compared with compensators designed using root locus method. The results show the superiority of BFO versus root locus method for both lead and lag-compensators design, which leads to improve the transient and steady state of speed responses of SEDM for different loads. The proposed method is very efficient and could easily be extended for other global optimization problems.

Keywords Bacterial Foraging Optimization (BFO), Escherichia (*E.Coli*) Bacteria, Separately Excited DC Motor (SEDM), Compensators, Performance Indices.

Introduction

Direct - current (DC) motors are one of the most widely used prime movers in the industry today. Years ago, the majority of the small servomotors used for control purposes were ac. In reality, ac motors are more difficult to control, especially for position control, and their characteristics are quite nonlinear, which makes the analytical task more difficult. DC motors, on the other hand, are more expensive, because of their brushes and commutators, and variable-flux dc motors are suitable only for certain types of control applications [1]. 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 [2]. DC machines are characterized by their versatility. By means of various combinations of shunt-, series-, and separately-excited field windings they can be designed to display a wide variety of volt-ampere or speed-torque characteristics for both dynamic and steady-state operation. Because of the ease with which they can be controlled systems of DC machines have been frequently used in many applications requiring a wide range of motor speeds and a precise output motor control [3-4].

Optimization is associated with almost every problem of engineering. The underlying principle in optimization is to enforce constraints that must be satisfied while exploring as many options as possible within tradeoff space. There exists numerous optimization techniques. Bio-inspired or nature inspired optimization techniques are class of random search techniques suitable for linear and nonlinear process. Hence, nature based computing or nature computing is an attractive area of research. Like nature inspired computing, their applications areas are also numerous. To list a few, the nature computing applications include optimization, data analysis, data mining, computer graphics and vision, prediction and diagnosis, design, intelligent control, and traffic and transportation systems. Most of the real life problem occurring in the field of science and engineering may be modeled as nonlinear optimization problems, which may be unimodal or multimodal [5].

In recent years, chemotaxis (i.e. the bacterial foraging behavior) as a rich source of potential engineering applications and computational model has attracted more and more attention. A few models have been developed to mimic bacterial foraging behavior and have been applied for solving some practical problems. Among them, bacterial foraging optimization is a population-based numerical optimization algorithm presented by Passino. BFO is a simple but powerful optimization tool that mimics the foraging behavior of *E. coli* bacteria. Until now, BFO has been applied successfully to some engineering problems, such as optimal control, harmonic estimation, transmission loss reduction, and machine learning [6].

Mathematical Model of Separately Excited D.C. Motor

The system contains a separately excited D.C. motor (SEDM), a model based on the motor specifications needs to be obtained, as shown in Figure 1. The electrical armature and field circuit can model the motor. In this simple model R_a and L_a indicate the equivalent armature coil resistance and inductance respectively and R_f and L_f indicate the equivalent field resistance and inductance respectively, v_a is the voltage supplied by the power source. The basic motor equations are:

$$T_d = K_f\, i_f\, i_a = K_m\, i_a \tag{1}$$

$$e_g = K_f\, i_f\, \omega_m = K_m\, \omega_m \tag{2}$$

$$V_a = e_g + R_a\, i_a + L_a \frac{d i_a}{dt} \tag{3}$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}\left(K_m\, i_a - T_L - B\, \omega_m\right) \tag{4}$$

Where $K_m = K_f\ i_f$, is a constant, e_g is the back electromotor force, T_d is the torque of the motor, T_L is the torque of the mechanical load; J is the inertia of the rotor and B is the damping coefficient associated with the mechanical rotational system of the motor [4].

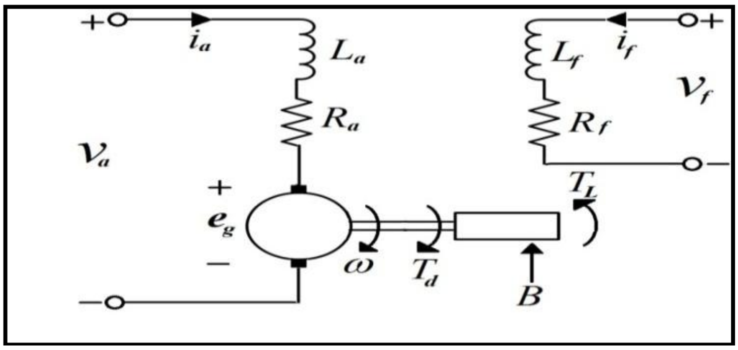


Figure 1: Equivalent circuit of separately excited dc motor

Compensators

Every control system is designed to meet certain performance specifications. But if the performances of a control system is not up to expectations as per desired specifications, then it is required that some change in the system is needed to obtain the desired performance. The change can be in the form of adjustment of forward-path gain or inserting a compensating device in control systems. Gain adjustment seems to be most direct and simple way to design. However in most practical cases, the gain adjustment does not provide the desired result. As is usually the case, increasing the gain reduces the steady state error but results in oscillatory transient response or even in instability. Under such circumstances, it is necessary to introduce some kind of corrective subsystems to force the chosen plant to meet the given specifications. These subsystems are known as compensators and their job is to compensate for the deficiency in the performance of the plant.

Compensation Networks

A compensator is a physical device which may be an electrical network, mechanical unit, pneumatic, hydraulic or a combination of various types of devices. The following electrical compensating networks are generally used [7]: (1) Lead network or lead compensator (2) Lag network or lag compensator (3) Lag-lead network or lag-lead compensator.

Description of *E Coli* Bacterium Motility Behavior

E. coli bacterium can move in two different ways: it can "run" (swim for a period of time) or it can "tumble," and it alternates between these two modes of operation its entire lifetime (i.e., it is rare that the flagella will stop rotating). If the flagella rotate clockwise, each flagellum pulls on the cell and the net effect is that each flagellum operates relatively independent of the others and so the bacterium "tumbles" about (i.e., the bacterium does not have a set direction of movement and there is little displacement) as shown in Figure 2a. To tumble after a run, the cell slows down or stops first. Since bacteria are so small they experience almost no inertia, only viscosity, so that when a bacterium stops swimming, it stops within the diameter of a proton. Call the time interval during which a tumble occurs a "tumble interval." If the flagella move counterclockwise, their effects accumulate by forming a "bundle" (it is thought that the bundle is formed due to the viscous drag of the medium) and hence, they essentially make a "composite propeller" and push the bacterium so that it runs (swims) in one direction (Figure 2a).

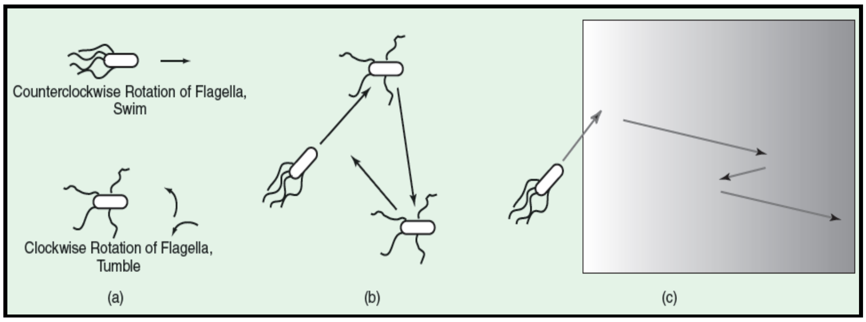


Figure 2: Bundling phenomenon of flagella

Chemotaxis and Climbing Nutrient Gradients

The motion patterns (called "taxes") that the bacteria will generate in the presence of chemical attractants and repellents are called "chemotaxes." if an *E. coli* is in some substance that is neutral, in the sense that it does not have food or noxious substances, and if it is in this medium for a long period of time (e.g., more than one minute), then the flagella will simultaneously alternate between moving clockwise and counterclockwise so that the bacterium will alternately tumble and run. This alternation between the two modes will move the bacterium, but in random directions, and this enables it to "search" for nutrients (Figure 2b).

Next, suppose that the bacterium happens to encounter a nutrient gradient (e.g., serine) as shown in Figure 2c. The *change* in the concentration of the nutrient triggers a reaction such that the bacterium will spend more time swimming and less time tumbling. As long as it travels on a positive concentration gradient (i.e., so that it moves towards increasing nutrient concentrations) it will tend to lengthen the time it spends swimming (i.e., it runs farther). Finally, suppose that the concentration of the nutrient is constant for the region it is in, after it has been on a positive gradient for some time. In this case, after a period of time (not immediately), the bacterium will return to the same proportion of swimming and tumbling as when it was in the neutral substance so that it returns to its standard searching behavior [8].

Bacterial Foraging Optimization

The Bacterial Foraging Optimization (Passino 2002) is based on foraging strategy of *E. coli* bacteria. The foraging theory is based on the assumption that animals obtain maximum energy nutrients 'E' in a suppose to be a small time 'T'. The basic Bacterial Foraging Optimization consists of three principal mechanisms; namely chemotaxis, reproduction and elimination-dispersal. The brief descriptions of these steps involved in Bacterial Foraging are presented below [5]. To define our optimization model of *E. coli* bacterial foraging, we need to define a population (set) of bacteria, and then model how they execute chemotaxis, swarming, reproduction, and elimination/dispersal [8].

Chemotaxis

In the classical BFO, a unit walk with random direction represents a "tumble" and a unit walk with the same direction in the last step indicates a "run". Suppose $\theta^i(j, k, \ell)$ represents the bacterium at j^{th} chemotactic, k^{th} reproductive, and ℓ^{th} 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 i^{th} bacterium can be represented as:

$$\theta^i(j+1,k,\ell) = \theta^i(j,k,\ell) + C(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}} \tag{5}$$

where Δ(i) is the direction vector of the j^{th} 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 $J(i,j,k,\ell)$, will be evaluated [6].

Swarming

During the movements, cells release attractants and repellents to signal other cells so that they should swarm together, provided that they get nutrient-rich environment or avoided the noxious environment. The cell-to cell attraction and repelling effects are denoted as:

$$J_{cc}(\theta,P(j,k,\ell)) = \sum_{i=1}^{S} J_{cc}^{i}(\theta,\theta^{i}(j,k,\ell)) = \sum_{i=1}^{S}\left[-d_{attract}\ exp\left(-w_{attract}\ \sum_{m=1}^{p}\left(\theta_m-\theta_m^i\right)^2\right)\right] + \sum_{i=1}^{S}\left[-h_{repellant}\ exp\left(-w_{repellant}\ \sum_{m=1}^{p}\left(\theta_m-\theta_m^i\right)^2\right)\right] \qquad (6)$$

where $J_{cc}(\theta,P(j,k,\ell))$ is the objective function value to be added to the actual objective function to present time varying objective function, S is the total number of bacteria, P is the number of variables involved in the search space, $\theta = [\theta_1, \theta_2, \ldots, \theta_P]^T$ is a point on the optimization domain, and θ_m^i is the m^th components of the i^th bacterium position θ^i.$d_{attract}$, $w_{attract}$, $h_{repellant}$, and $w_{repellant}$ are different coefficients used for signaling [9].

Reproduction and Elimination/Dispersal

After N_c chemotactic steps, a reproduction step is taken. Let N_{re} be the number of reproduction steps to be taken. For convenience, we assume that S is a positive even integer. Let

$$Sr = S / 2 \qquad (7)$$

be the number of population members who have had sufficient nutrients so that they will reproduce (split in two) with no mutations. For reproduction, the population is sorted in order of ascending accumulated cost (higher accumulated cost represents that it did not get as many nutrients during its lifetime of foraging and hence, is not as "healthy" and thus unlikely to reproduce); then the S_r least healthy bacteria die and the other S_r healthiest bacteria each split into two bacteria, which are placed at the same location [8]. Figure (4) shows the Flowcharts of foraging process.

Simulation and Results

The simulation is doing using MATLAB tool box**.** This work is based on designing lead and lag compensators for speed control of SEDM using BFO technique. SEDM is loading with different loads to see the performance of the designing compensators, and then comparing the results with compensators designed using root-locus method to show the superiority of compensators based on BFO.

Design Requirements

Since the most basic requirements of a motor are that it should rotate at the desired speed, the steady-state error e_{ss} of the motor speed should be less than 2%, the settling time T_s for 2% criterion should be less than 1sec, percent overshoot less than 50%. The performance index used in this work is ITAE.

Simulation of SEDM using Matlab/Simulink

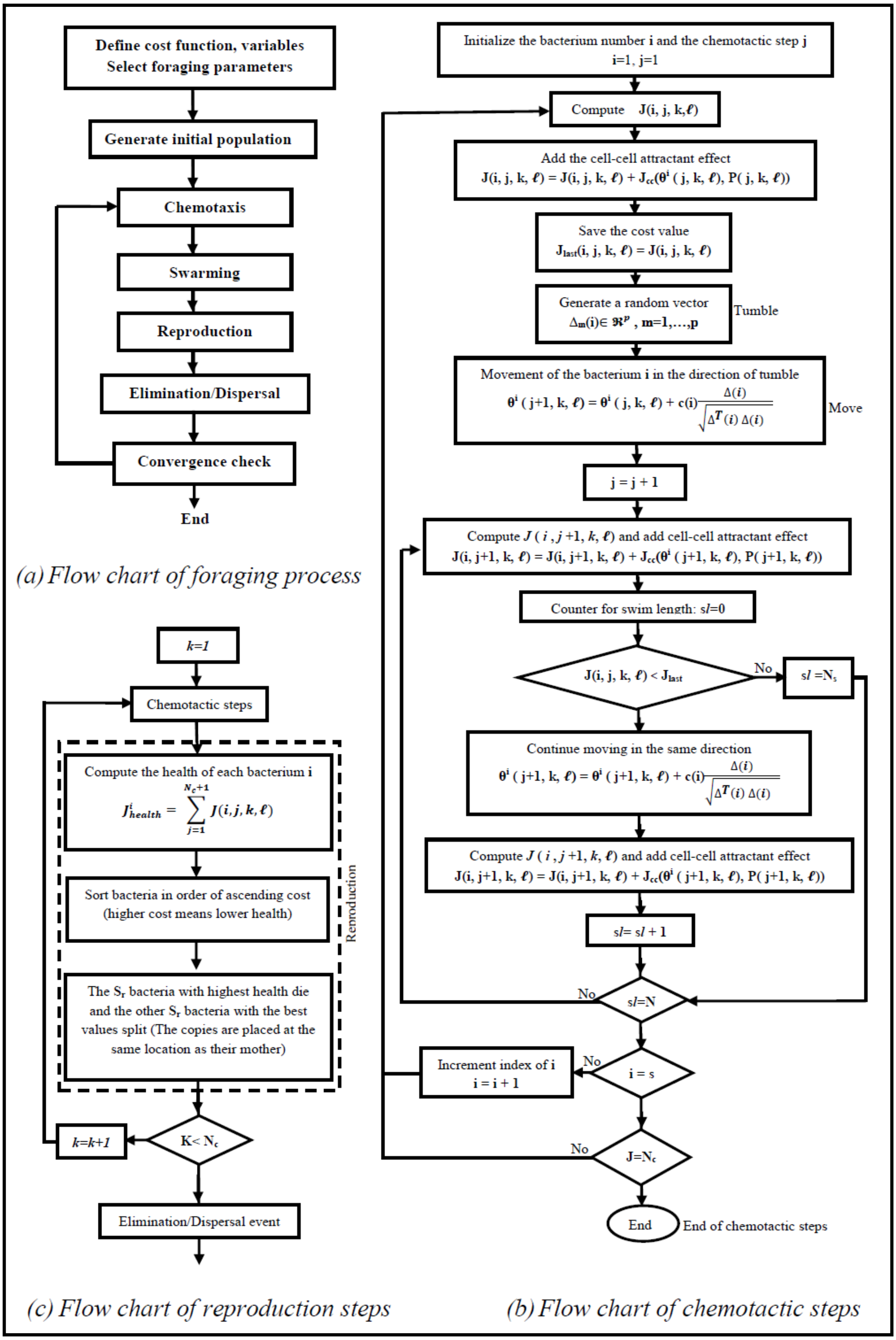
The proposed mathematical model is developed from the mechanical and electrical dynamic equations of the SEDM, equations (1), (2), (3) & (4). The simulink of the SEDM mathematical model is shown in Figure (4).

SEDM Rating & Parameters

The parameters values of SEDM used in the simulation is taken from MATLAB/Toolbox and shown in Table 1.

Table 1: 10 hp, 500V supply, 1750 R.P.M. SEDM parameters

Motor parameters	Values
Field Voltage (V_f)	300 V
Armature resistance (R_a)	4.712Ω
Armature inductance (L_a)	0.05277 H
K_m	2.242
Inertia of the rotor (J)	0.04251 Kg.m^2
damping coefficient (B)	0.003406 N.m.s



(a) Flow chart of foraging process

(c) Flow chart of reproduction steps

(b) Flow chart of chemotactic steps

Figure 3: Flowchart of foraging process [10]

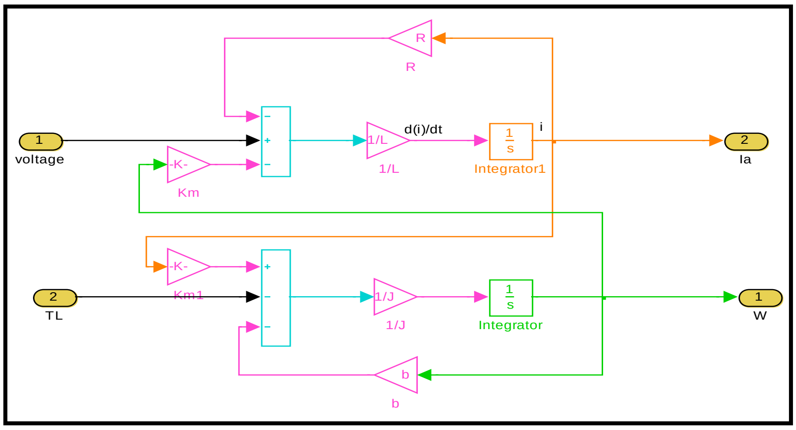


Figure 4: SEDM simulation using MATLAB/SIMULINK

SEDM Loads

The SEDM are loaded for four different loads (assumed). These loads are:(no-load, (0.3 of full-load) as a light load, (0.5 of full-load) as a half full load, and finally (full-load). Figure 5 shows the complete simulink model of closed loop control system for SEDM.

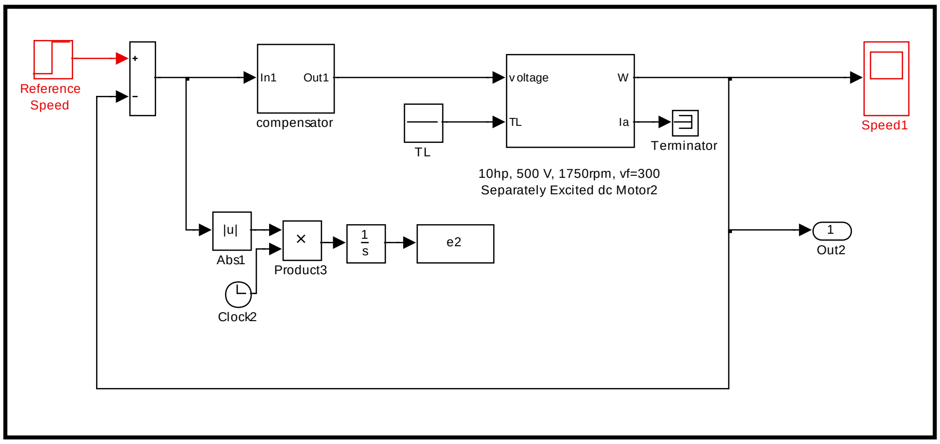


Figure 5: Closed loop speed control system of SEDM

Lead Compensator Design using BFO

The parameters of BFO algorithm are listed in Table 2, while the obtained compensator parameters are listed in Table 3.

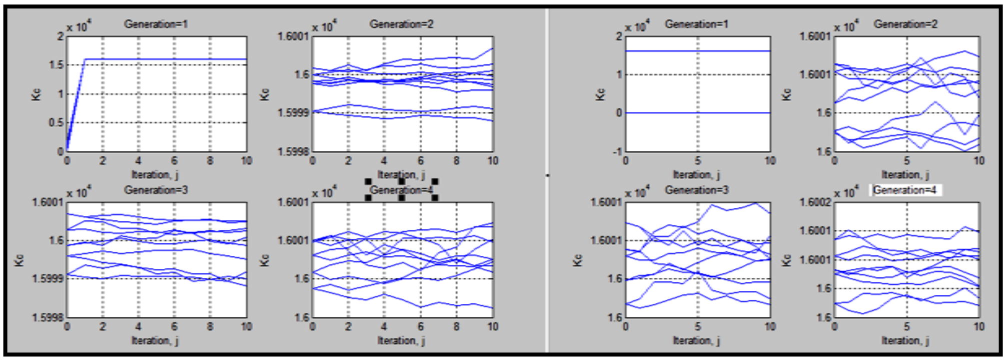
Table 2: BFO parameters used in tuning lead-compensator

BFO 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})	0.25
Height of repellent effect (h_{rep}.)	0.1
Width of repellent effect (w_{rep}.)	10
Width of attractant effect (w_{attr}.)	0.2
Width of attractant effect (d_{attr}.)	0.1

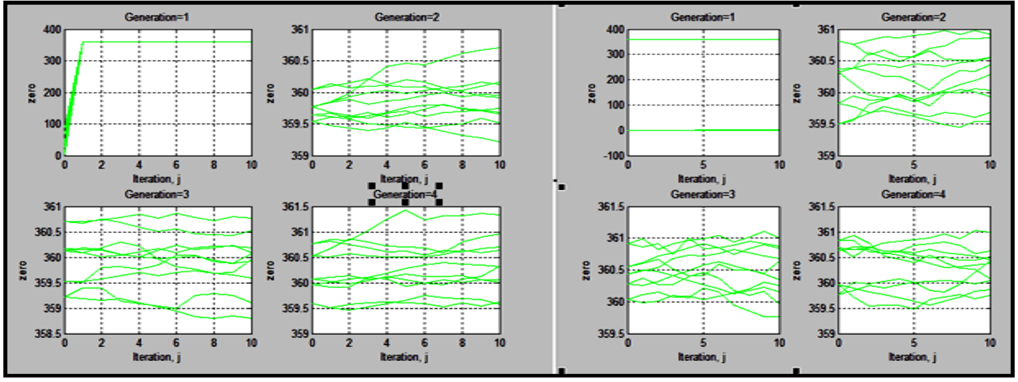
Table 3: Lead Compensator Parameters

Controller parameters	Root-locus method	BFO technique
Compensator gain (K_c)	2391.8	16000
Pole location (P)	-896.79	- 6303.5
Zero location (Z)	- 89.898	- 360.5684

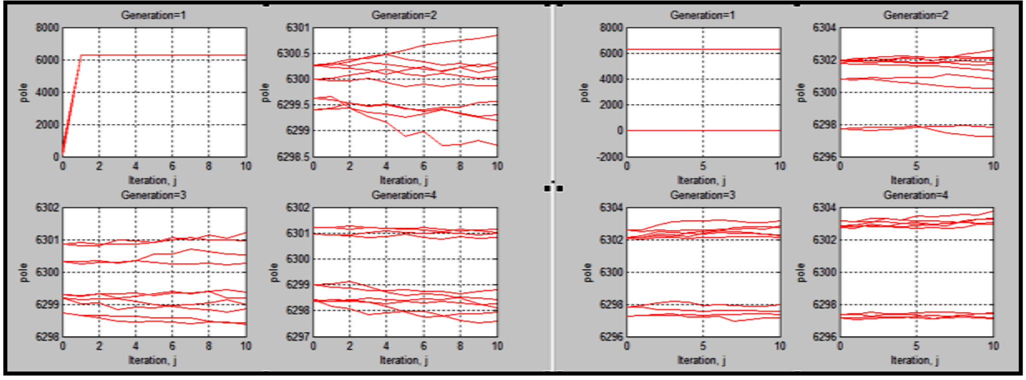
Figures 6 shows the bacteria (S=10) motility behavior or bacteria trajectories for tuning lead compensator parameters. This motility behavior depends on bacteria average cost achieved during each iteration (chemotactic step N_c). The generation number represent reproduction step (N_{re}) while iteration j represent chemotactic steps (N_c). These bacteria motility behavior achieved for two elimination/dispersal events (Ned =2). For every generation at the end of all chemotactic steps, the compensator parameters are obtained with best cost (or fitness) value which represents the best value of compensator parameters.



(a)first elimination/dispersal event　　(b)second elimination/dispersal event



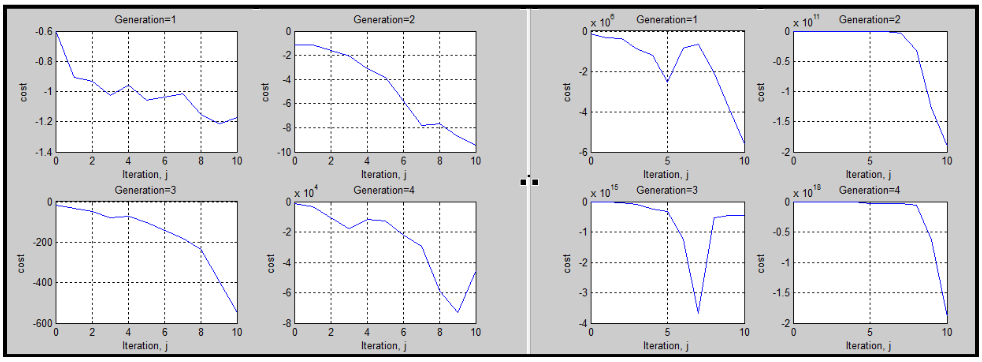
(c)first elimination/dispersal event　　(d)second elimination/dispersal event



(e)first elimination/dispersal event　　(f)second elimination/dispersal event

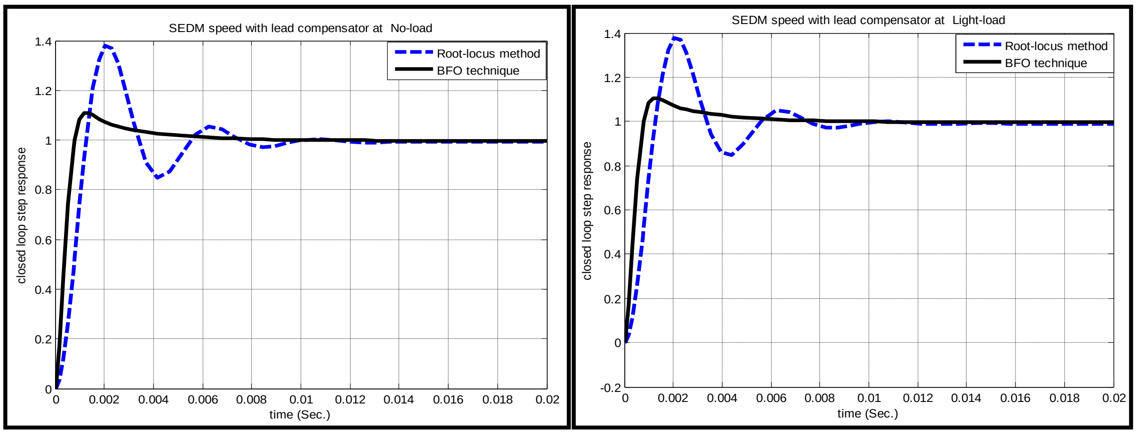
Figures 6 (a, b, c, d, e, f): Bacteria trajectories

Figures 7 shows the average cost plots for each generation for two elimination/dispersal events (Ned =2).

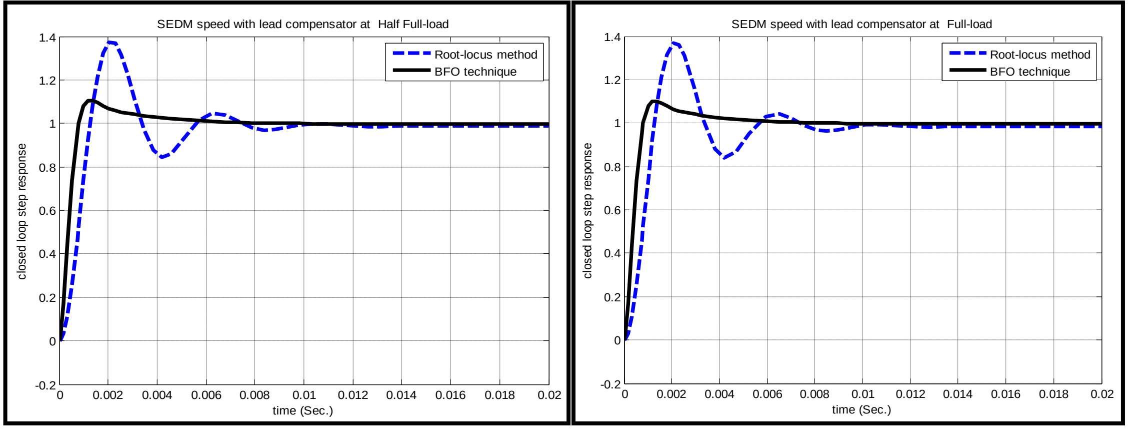


Figures 7: Average cost plot for bacteria trajectories

The speed step responses of SEDM with different loads for lead compensators based on both designing methods are shown in Figures 8 (a, b, c, and d).



(a) SEDM at no-load (b) SEDM at light load



(c) SEDM at half full-load (d) SEDM at full-load

Figures (8) (a, b, c, d): SEDM speed responses with lead compensator at different loads

The transient response specifications of SEDM speed response are listed in Table 4 for lead compensator with different loading conditions.

Table 4: Transient Response Specifications

	Rise time (S)	Peak time (S)	% overshoot	Settling time (S)
SEDM at no-load				
Root-locus	0.00126	0.0020	38.19	0.0091
BFO	0.0008	0.0012	10.88	0.0048
SEDM at light-load				
Root-locus	0.00127	0.00204	37.77	0.00923
BFO	0.0008	0.00119	10.64	0.0047
SEDM at half full-load				
Root-locus	0.00128	0.002037	37.49	0.0093
BFO	0.0008	0.001188	10.49	0.00465
SEDM at full-load				
Root-locus	0.00129	0.0020712	37.09	0.009518
BFO	0.0008	0.001196	10.12	0.004453

LAG COMPENSATOR DESIGN USING BFO

The parameters of BFO algorithm are listed in Table 5, while the obtained compensator parameters are listed in Table 6.

Table 5: BFO parameters used in tuning lag-compensator

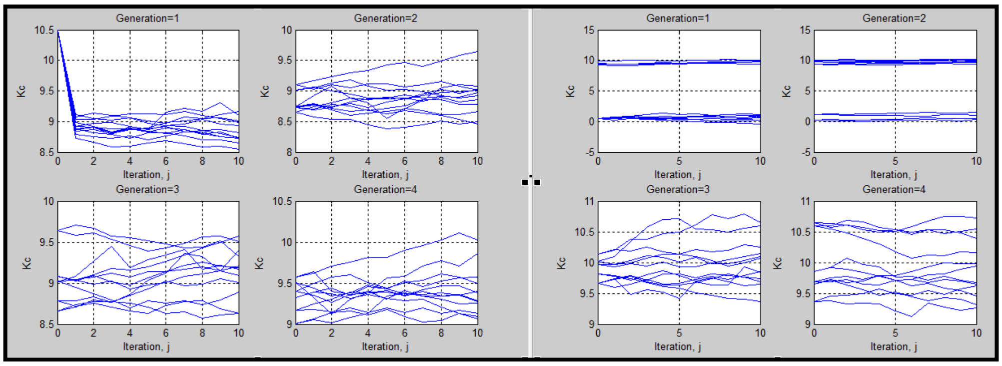
BFO Parameters	Values
Number of bacteria in the population (S)	12
The length of swim (N_s)	2
Number of reproduction steps (N_{re})	4
Number of chemotactic step (N_c)	10
Number of elimination/dispersal events (N_{ed})	2
Number of bacteria splits per generation (S_r)	S / 2
Probability of dispersal occurrence (P_{ed})	0.5
Height of repellent effect (h_{rep}.)	0.1
Width of repellent effect (w_{rep}.)	10
Width of attractant effect (w_{attr}.)	0.2
Width of attractant effect (d_{attr}.)	0.1

Table 6: Lag Compensator Parameters

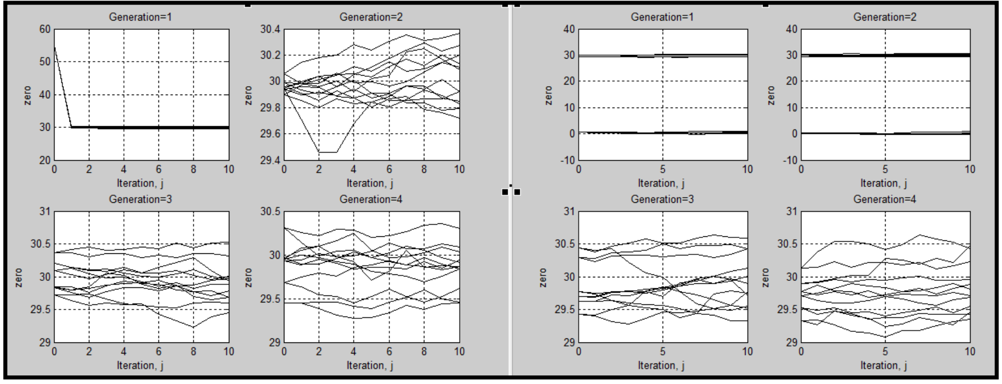
Controller parameters	Root-locus method	BFO technique
Compensator gain (K_c)	6.8075	9.7163
Pole location (P)	-0.9265	-0.3663
Zero location (Z)	-53.834	-30.6410

Figures 9 shows the bacteria (S=10) motility behavior or bacteria trajectories for tuning lag compensator parameters. This motility behavior depends on bacteria average cost achieved during each iteration (chemotactic step N_c). The generation number represent reproduction step (N_{re}) while iteration j represent chemotactic steps (N_c). These bacteria motility behavior achieved for two elimination/dispersal events (Ned =2).

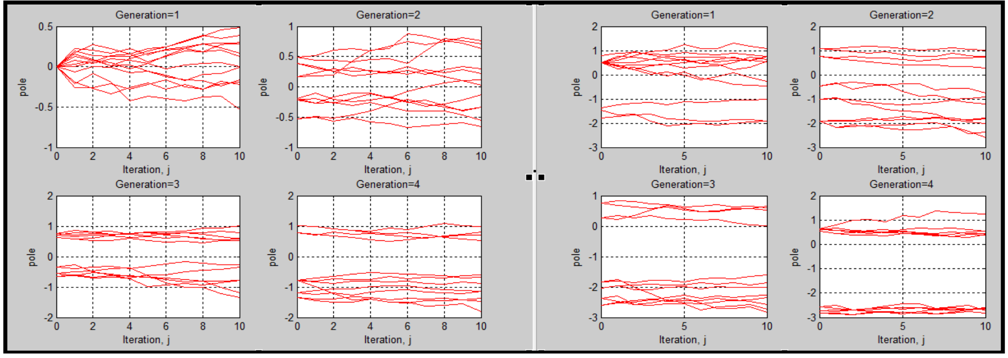
For every generation at the end of all chemotactic steps, the compensator parameters are obtained with best cost (or fitness) value which represents the best value of compensator parameters.



(a)first elimination/dispersal event (b)second elimination/dispersal event



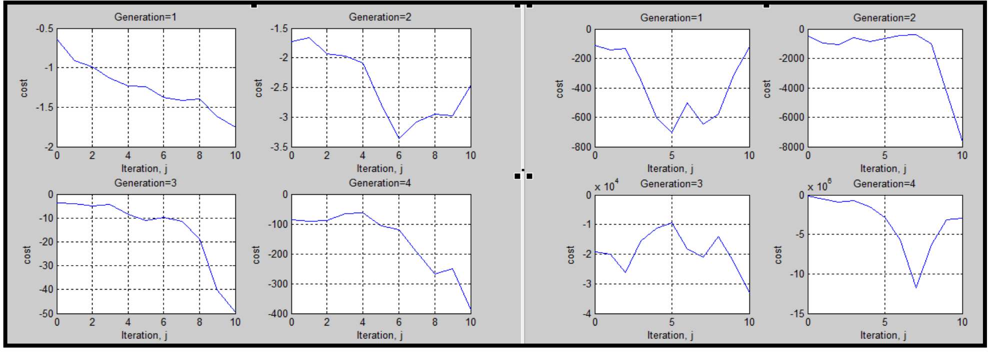
(c)first elimination/dispersal event (d)second elimination/dispersal event



(e)first elimination/dispersal event (f)second elimination/dispersal event

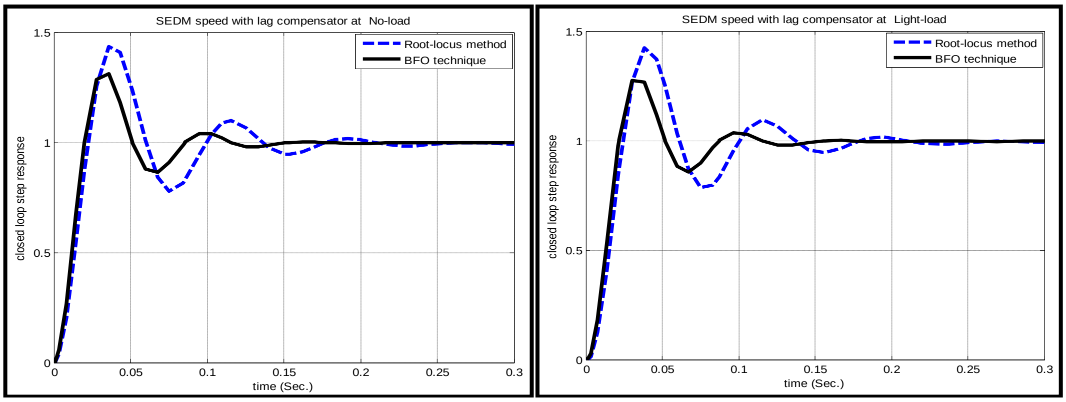
Figures (9) (a, b, c, d, e, f): Bacteria trajectories

Figures 10 shows the average cost plots for each generation for two elimination/dispersal events (Ned =2).

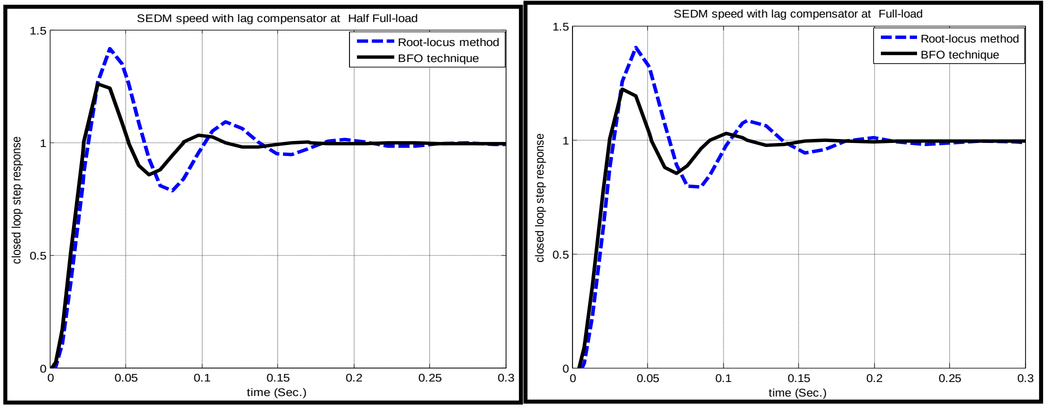


Figures 10: Average cost plot for bacteria trajectories

The speed step responses of SEDM with different loads for lag compensators based on both designing methods are shown in Figures 11 (a, b, c, and d).



(a) SEDM at no-load (b) SEDM at light load



(c) SEDM at half full-load (d) SEDM at full-load

Figures (11) (a, b, c, d): SEDM speed responses with lag compensator at different loads

The transient response specifications of SEDM speed response are listed in Table 7 for lead compensator with different loading conditions.

Table 7: Transient Response Specifications

	Rise time (S)	Peak time (S)	% overshoot	Settling time (S)
SEDM at no-load				
Root-locus	0.0202	0.0361	43.6	0.1701
BFO	0.0228	0.0361	31.25	0.1347
SEDM at light-load				
Root-locus	0.0244	0.0384	42.41	0.1718
BFO	0.0216	0.0302	27.29	0.1367
SEDM at half full-load				
Root-locus	0.0254	0.0397	41.66	0.1732
BFO	0.0226	0.0313	25.92	0.1383
SEDM at full-load				
Root-locus	0.0278	0.0422	40.58	0.2369
BFO	0.025	0.0335	22.28	0.1417

Conclusions

In this work, BFO technique has been used to design lead and lag compensators for speed control of SEDM. BFO is used to find optimal compensators parameters (gain, pole and zero locations). The results are compared with compensators designed using root-locus method. The SEDM is simulated using mathematical model which is more reality and accurate for representation the actual plant. The SEDM is loading for different loads ranging from no-load to full-load for testing the controller robustness and reliability for load changing conditions. From simulation results the following tips can be concluded:

1. The BFO technique is robust and efficient for controllers tuning such as compensator design.

2. BFO best than root-locus method for designing compensators.
3. BFO required less execution time (fast computations process).
4. Small execution time of BFO algorithm is due to the small numbers of bacteria parameters.
5. BFO has fast convergence due to the bacteria social behavior for finding nutrient concentration and it is efficient tool for optimization problems.
6. The proposed compensators are robust for wide range of loading conditions.
7. The proposed compensators improved the time response specifications for speed control purpose of SEDM for different loads.
8. Speed response with lead compensator is faster than speed response with lag compensator (as seen from Table 4 and Table 7).It is generally preferred that a system respond to a command quickly, but prefer to use the lag compensator even though it is slower than the lead compensator due to following reasons: by responding more slowly it requires less control effort than the lead compensator. Less control effort means that less power is consumed and that the various components can be sized smaller since they do not have to supply as much energy or withstand the higher voltages and current required of the lead compensator.

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