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Tuning of PI Speed Controller in DTC-SVM of Five Phase IPMSM Based on Biogeography Based Optimization (BBO) Algorithm

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Abstract

Proportional-Integral (PI) controllers are used in many industrial applications, as they have a simple structure and a robust performance. For tuning the control parameters of a PI controller, different methods have been proposed such as evolutionary algorithms. In this paper, Biogeography Based Optimization (BBO) algorithm is used for tuning the control parameters of a PI speed controller of a five-phase interior permanent magnet synchronous motor drive system fed by a three to five –phase matrix converter. Combination of BBO algorithm with the new drive scheme resulted good speed and torque responses with small overshooting both in steady-state and transient behaviours.

Keywords*:* biogeography based optimization, direct torque control, HSI

1. Introduction

One of the most popular methods in controlling variable speed drives is Direct Torque Control (DTC) [1]. The aim of this method is to compensate the error between reference and actual quantities of flux and torque by selecting appropriate voltage vector from converter. Matrix Converter (MC), as an ac-ac converter, can be a good alternative to the conventional Voltage Source Inverters (VSIs). Owing to the absence of bulky DC-link capacitors, such converter has a long lifetime and has the capability of operating in high temperatures. Thus, the MC can be used in many applications where weight, reliability and volume are important factors. Application of multiphase drives in high reliability areas such as aerospace applications, ships electric propulsion, electric vehicles are growing annually. Some of the important advantages of multiphase motors over traditional three phase ones are: improvement of torque per RMS ampere, increasing of torque frequency pulsations, reducing stator current per phase without the need of increasing voltage per phase, lowering the DC link current harmonics and good fault tolerances [2-3]. DTC of a five phase Interior Permanent Magnet Synchronous Motor (IPMSM) fed by a three to five-phase MC has been presented in [4-6] where sinusoidal currents, good torque and speed responses, operation in close to unity input power factor and regenerative braking capability were the features of the mentioned drive system.

Proportional-Integral (PI) controller is the most common controller used in industry applications, due to its simple structure and robust performance in a wide range of operation. Many strategies proposed for tuning the PI controller gains such as Ziegler-Nichols, root-locus and pole assignment [7-9]. These model-based strategies need an accurate model of the system and highly dependent on the actual operating conditions.

In recent years, many Evolutionary Algorithms (EAs), such as the Genetic Algorithm (GA), Particle Swarm Optimization (PSO) and Bacteria Foraging Optimization (BFO) have been proposed, which are more or less successful in handling various non-linear optimization problems. These techniques perform search in complex, large and multimodal landscapes and provide near-optimal solutions for objective or fitness function of an optimization problem. The use of EAs in tuning of different controller parameters in three-phase drives is practical due to their fast convergence and reasonable accuracy. Biogeography Based Optimization (BBO) is one of the algorithms that is proposed for searching optimal solutions of a given problem. Biogeography is a science that describes the movement of species among different places during many years.

In this paper, BBO algorithm is used to tune the parameters of the PI speed controller of a five-phase IPMSM drive system fed by a three to five –phase MC. Good speed and torque responses during steady state and dynamic conditions with small overshooting after each disturbances and stable convergence characteristic shows that BBO is a powerful optimization method for solving the PI controller parameters problem.

2. THREE TO FIVE-PHASE MC

A three to five-phase MC is a single stage converter that connects 3 input phases to 5 output phases as illustrated in Fig.1. Each power switch is bidirectional and has a switching function which is defined as follows:

$$S_{jk}(t)=\begin{cases}0 & \text{switch, } S_{jk} \text{ is open}\\ 1 & \text{switch, } S_{jk} \text{ is closed}\end{cases} \qquad (1)$$

$$j=\{A,B,C\},\quad k=\{a,b,c,d,e\}$$

As the MC is fed by a voltage source, the input terminal should not be directly shorted. On the other hand, load has typically an inductive nature. For this reason the output terminal must not be opened at any instant. So only one switch can be in on-state in each leg at any instant:

$$S_{Aj}+S_{Bj}+S_{Cj}=1 \qquad (2)$$

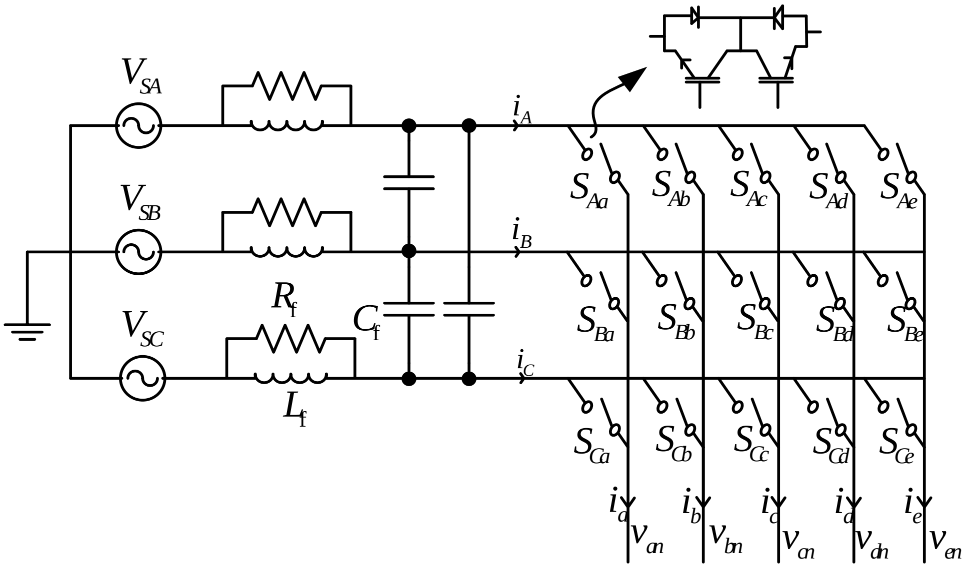

Figure 1: Schematic diagram of three-phase to five-phase MC

The state of the MC switches can be represented using the following transformation matrix:

$$T = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{Ac}(t) & S_{Bc}(t) & S_{Cc}(t) \\ S_{Ad}(t) & S_{Bd}(t) & S_{Cd}(t) \\ S_{Ae}(t) & S_{Be}(t) & S_{Ce}(t) \end{bmatrix} \tag{3}$$

The input line to neutral-voltages and input currents are obtained by the following equations:

$$\begin{aligned} [V_o(t)] &= [T][V_i(t)] \\ [I_i(t)] &= [T^t][I_O(t)] \end{aligned} \tag{4}$$

3. Five phase IPMSM

In this section, the mathematical model of a five-phase IPMSM will be derived. In principle, in a five-phase system, all the five-phase variables can be transferred into two vector planes, $d-q$ and z_1-z_2. The harmonics of the order $10n \pm 1$(n is an integer) with the 'abcde' phase sequence are related to $d-q$ plane and the harmonics of the order $10n \pm 3$with the 'acebd' phase sequence are related to z_1-z_2plane. Therefore, two space vectors can be defined to describe a five-phase IPMSM as follows:

$$f_{d-q}^{s} = \frac{2}{5}(f_{as} + af_{bs} + a^2 f_{cs} + a^3 f_{ds} + a^4 f_{es}) \tag{5}$$

$$f_{z_1-z_2}^{s} = \frac{2}{5}(f_{as} + a^3 f_{bs} + af_{cs} + a^4 f_{ds} + a^2 f_{es}) \tag{6}$$

where $a = \exp(j2\pi/5)$ and f can be stator current, stator voltage and stator flux space vectors. Fig.2 shows the two orthogonal two-dimensional vector planes. By applying a transformation matrix which is shown in Eq. (7), the variables of five-phase motors will be obtained in synchronous rotating reference frame, where θ is rotor angular velocity.

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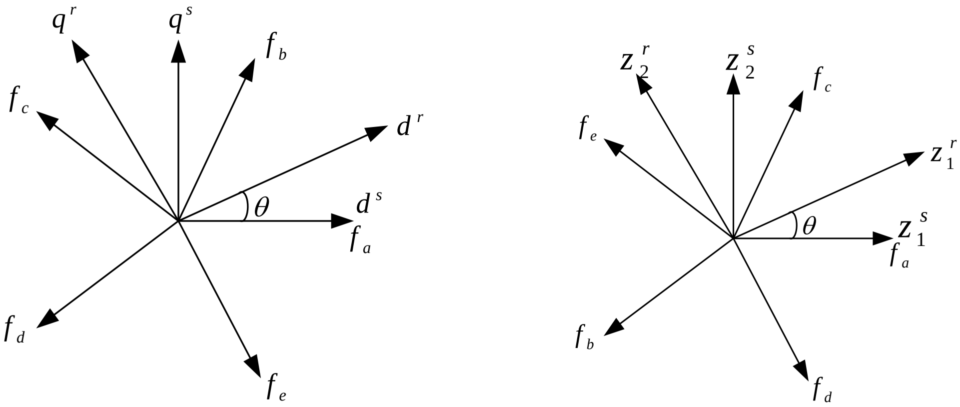

(a) **(b)**

Fig.2: Two orthogonal two-dimensional vector planes: a) $d-q$ plane, b) $z_1 - z_2$ plane

$$T(\theta)=\frac{2}{5}\begin{bmatrix} \cos(\theta) & \cos(\theta-\frac{2\pi}{5}) & \cos(\theta-\frac{4\pi}{5}) & \cos(\theta+\frac{4\pi}{5}) & \cos(\theta+\frac{2\pi}{5}) \\ \sin(\theta) & \sin(\theta-\frac{2\pi}{5}) & \sin(\theta-\frac{4\pi}{5}) & \sin(\theta+\frac{4\pi}{5}) & \sin(\theta+\frac{2\pi}{5}) \\ \cos(\theta) & \cos(\theta+\frac{4\pi}{5}) & \sin(\theta-\frac{2\pi}{5}) & \cos(\theta+\frac{2\pi}{5}) & \cos(\theta-\frac{4\pi}{5}) \\ \sin(\theta) & \sin(\theta+\frac{4\pi}{5}) & \sin(\theta-\frac{2\pi}{5}) & \sin(\theta+\frac{2\pi}{5}) & \sin(\theta-\frac{4\pi}{5}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \qquad (7)$$

3.1. Motor model in $d-q$ plane

$$\begin{aligned} V_{qs} &= r_s i_{qs} + \omega\lambda_{ds} + \frac{d\,\lambda_{qs}}{dt} \\ V_{ds} &= r_s i_{ds} - \omega\lambda_{qs} + \frac{d\,\lambda_{ds}}{dt} \end{aligned} \qquad (8)$$

where

$$\begin{aligned}\lambda_{ds} &= L_d i_{ds} + \lambda_m \\ \lambda_{qs} &= L_q i_{qs}\end{aligned} \tag{9}$$

3.2. Motor model in $z_1 - z_2$ plane

$$\begin{aligned}V_{z1s} &= r_s i_{z1s} + \frac{d\lambda_{z1s}}{dt} \\ V_{z2s} &= r_s i_{z2s} + \frac{d\lambda_{z2s}}{dt}\end{aligned} \tag{10}$$

where

$$\begin{aligned}\lambda_{z1s} &= L_{ls} i_{z1s} \\ \lambda_{z2s} &= L_{ls} i_{z2s}\end{aligned} \tag{11}$$

where r_s is the stator winding resistance, i_{ds} , i_{qs} , λ_{ds} and λ_{qs} are the stator currents and stator fluxes in $d-q$ reference frame and λ_m is the permanent magnet flux and i_{Z1s} , i_{Z2s} , λ_{Z1s} and λ_{Z2s} are the stator currents and stator fluxes in $Z_1 - Z_2$ reference frame respectively. The electromagnetic torque in terms of stator flux linkage and $d-q$ current space vectors will be derived as follows:

$$T_e = \frac{5p}{2}[\lambda_m i_{qs} + (L_d - L_q) i_{qs} i_{ds}] \tag{12}$$

Where p is the number of pole pairs.

4. DTC strategy

The aim of this method is to compensate the error between reference and actual quantities of flux and torque by selecting appropriate voltage vector from the converter. Neglecting the stator resistance, there is a direct relation between the converter output voltage vector and the variation of stator flux linkage. DTC model with MC consists of three hysteresis controllers for controlling torque, flux and input power factor in an appropriate quantity which is called the bandwidth of the hysteresis controller. An optimum switching table is then used to select the appropriate voltage vector of the MC based on the location of the stator flux and the input power factor. Fig.3 shows the schematic diagram of DTC of five-phase IPMSM using three to five-phase MC [4].

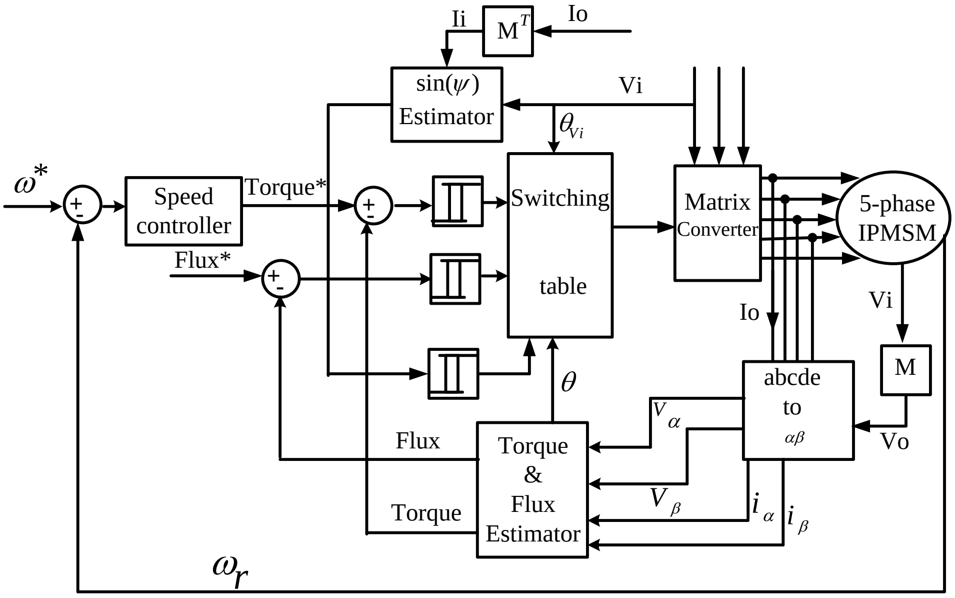

Figure 3: Schematic diagram of DTC of five-phase IPMSM using matrix converter

5. Biogeography Based Optimization

Biogeography is the study of the geographical distribution of biological organisms. In BBO, a habitat is a possible solution of a problem and defined as an island (area) that is geographically isolated from other islands. Habitat suitability index (HSI) [10-11] is a feature that indicates habitat is a proper place for living or not. Obviously, habitat with a high HSI is a better place and more crowded than habitat with low HSI. Habitat with low HSI tries to copy good features from high HSI habitats to improve their living parameters. So, migration is used to share features between habitats.

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High HSI habitats have many species that emigrate to other habitats but they will not tend to host more species, due to their large population. On the other hand, low HSI habitats like to have more species and their species rarely emigrate to other places. So, emigration rate of high HSI habitats is greater than low HSI ones, and therefore, immigration rate of high HSI habitats is lower than low HSI habitats. Variables that define the habitability of a place are called suitability index variables (SIV). HSI is a function of SIVs. Consider H as a matrix of N habitat where each habitat contains m SIV:

$$H = \begin{pmatrix} SIV_{11} & \cdots & SIV_{1m} \\ \vdots & \ddots & \vdots \\ SIV_{N1} & \cdots & SIV_{Nm} \end{pmatrix} \quad (13)$$

In this paper, λ is the immigration rate and μ is the emigration rate. Fig.4 shows the relation between number of species and immigration and emigration rates. The largest possible number of species that the habitat can support is $S_{\max}$, at which point immigration rate becomes zero, while emigration rate reaches its maximum value (E).

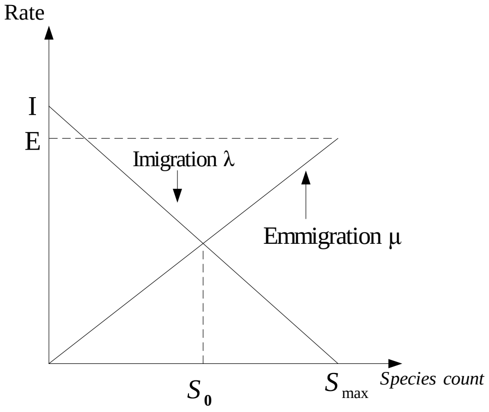

Figure 4: Species model of a habitat

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According to Fig.4, E is the maximum value of emigration rate and I is the maximum value of immigration rate. λ and μ are calculated by equations as Eq. (14) and Eq. (15) [10-11].

$$\mu_k = \frac{E_K}{n} \tag{14}$$

$$\lambda_k = I\,(1 - \frac{K}{n}) \tag{15}$$

which (k) indicates the number of species in the habitat (i) at that time (step) and n is the maximum number of species that a habitat can host. It can be seen from Fig.4 that $n = S_{\max}$

5.1. Migration

For a specified optimization problem, habitats are possible solutions and each habitat is an array of SIVs. SIVs are integers that selected inside their feasible values. HSI is analogous to “fitness” in other population-based optimization algorithms (GAs, for example). According to HIS value, λ and μ are calculated for each habitat separately. The emigration and immigration rates of each solution are used to probabilistically share information between habitats with probability P_{mod}, known as habitat modification probability. Mathematically, a probabilistic model based on emigration and immigration rates denotes the probability that a habitat contains (s) species at time $(t + \Delta t)$ [11]:

$$P_S(t + \Delta t) = P_S(t)(1 - \lambda_S \Delta t - \mu_S \Delta t) + P_{S-1}\lambda_{S-1}\Delta t + P_{S+1}\mu_{S+1}\Delta t \tag{16}$$

where λ_S and μ_S are the immigration and emigration rates of a habitat, when there are s species in the habitat. Assuming $\Delta t \to 0$, the following equation can be derived:

$$\dot{P} = \begin{cases} -(\lambda_S + \mu_S)P_S + \mu_{S+1}P_{S+1} & S = 0 \\ -(\lambda_S + \mu_S)P_S + \lambda_{S-1}P_{S-1} + \mu_{S+1}P_{S+1} & 1 \le S \le S_{MAX} - 1 \\ -(\lambda_S + \mu_S)P_S + \lambda_{S-1}P_{S-1} & S = S_{MAX} \end{cases} \quad (17)$$

Each habitat member has an associated probability which indicates its importance as a solution for a given problem. If the probability of a given solution is very low, then that solution is likely to mutate to some other solution. Similarly if the probability of some other solution is high, then that solution has very little chance to mutate. So it should be noted that very high HSI solution and very low HSI solutions have less chance to create more improved SIV in the later stage. But medium HSI solutions have better chance to create much better solutions after mutation operation .Mutation rate of each habitat can be calculated in terms of species count probability using the following equation [11].

$$m(s) = m_{\max}\left(\frac{1-P_S}{P_{\max}}\right) \quad (18)$$

In order to tune the mentioned controller PI parameters with BBO algorithm, the error between reference and actual speed should be considered as HSI function:

$$HSI = \int_0^t (\omega^* - \omega)^2 t.dt \quad (19)$$

Fig. 5 shows the flowchart of the proposed method to solve the problem.

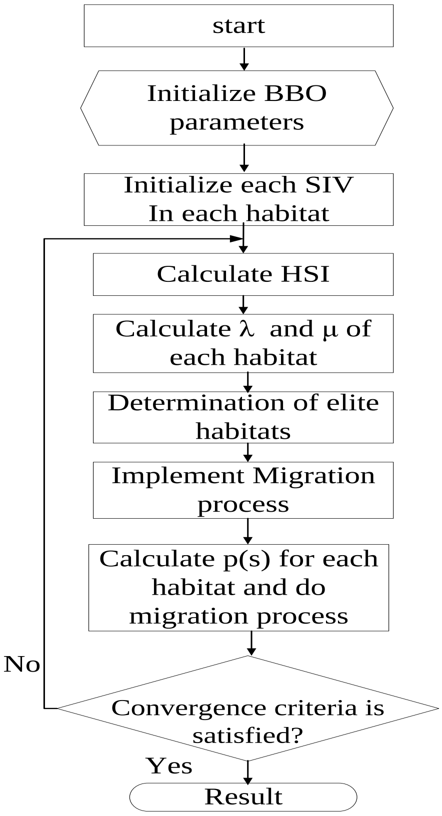


Figure 5: Flowchart diagram for BBO algorithm

6. Simulation result and discussion:

In this stage BBO algorithm is applied to tune the control parameters of a PI speed controller of the drive system using matlab/simulink. The control parameters of the BBO are listed in table1and the parameters of the IPMSM are given in table 2. The optimized values obtained from BBO are substituted in the drive system to test the operation of the motor with the proposed gains. At first the motor was tested under rated load and 1000 RPM. As can be seen in Fig.6, the drive tracks the torque reference very well. The speed response in rated load is shown in Fig.7. Clearly, the speed response has a small overshoot and takes a short time to reach the steady state.

Table1: Initial parameters of BBO algorithm

Number of habitats (H)	60
Number of iteration (T)	60
number of SIVs	2
maximum emigration rate (E)	1
maximum immigration rate (I)	0.6
maximum mutation rate ($m_{\max}$)	0.005
probability modification (P_{mod})	1
elitism parameter (P)	5

Table 2: Five phase IPMSM parameters

P	L_d	L_q	B	J	R_s	ψ_f
2	18mh	42mh	0.005	0.025	0.7	0.5(wb)

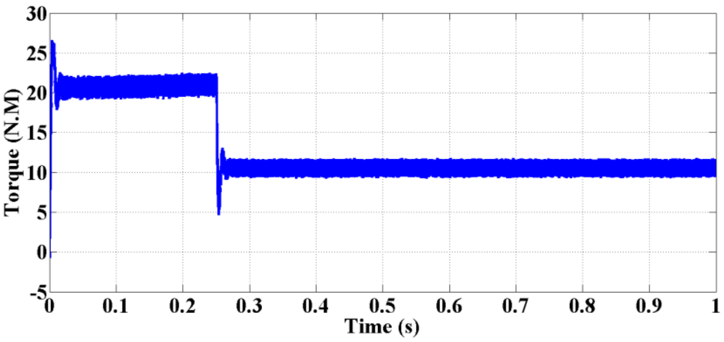


Figure 6: Estimated torque at rated load and 1000 rpm

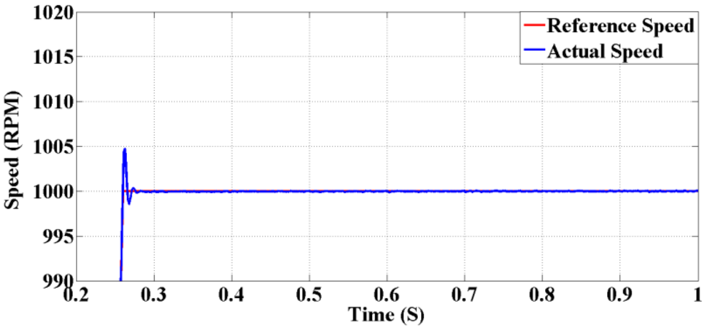


Figure 7: Speed response at rated load and 1000 rpm

The dynamic behavior of the torque has been tested with the reference step torque command from10 Nm to -10 Nm at 1000 RPM. In Fig.8, from 0 s to 0.6s, drive is in motoring operation and the filtered input current is in phase with input voltage (Fig.9). When the torque is reversed from 10 Nm to -10 Nm at 0.6 s, the filtered input current becomes out of phase with the voltage by 180^0. This is true as MC passes electric power from motor to the grid during regenerative braking operation. As it shown in Fig.10, after step command, speed recovers with small overshooting and follows the reference with a small error (less than 0.2%).In Fig.11, the D-Q flux experienced small disturbance during step change and then follows the flux reference very well. Fig (12) illustrates the HSI obtained by the tuning technique during rated load. The HIS quantity rose to a peak of 0.25 and remained steady during the following time. Table 3 summarizes the numerical results.

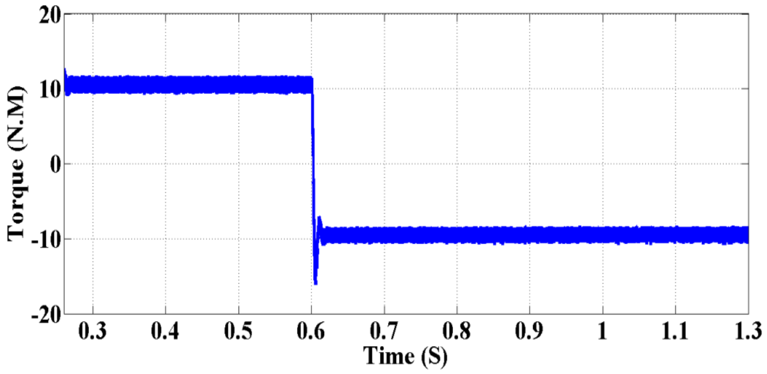


Figure 8: Estimated torque during step torque command

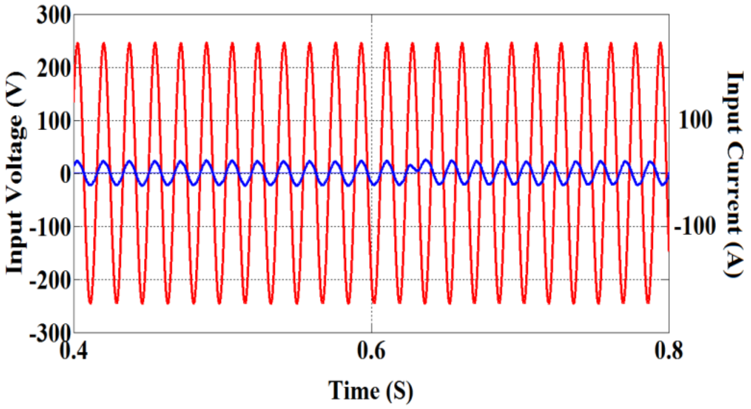


Figure 9: Filtered input current during step torque command

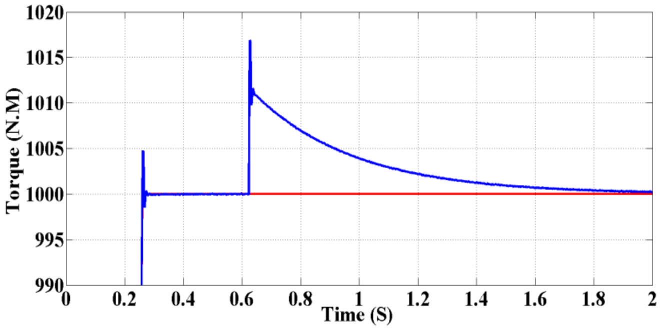
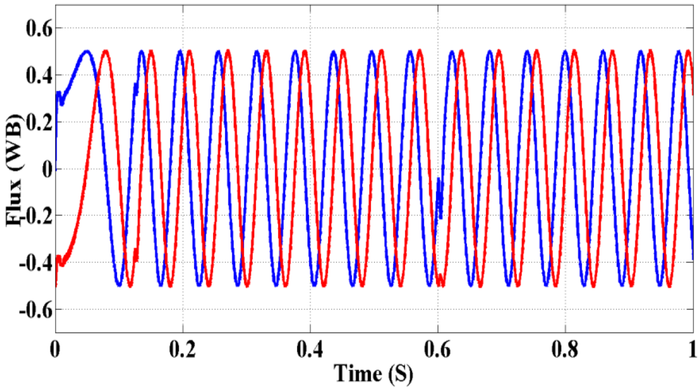


Figure 10: speed response for the proposed scheme during step torque command



(b)

Figure 11: D-Q fluxfor the proposed scheme during step torque command

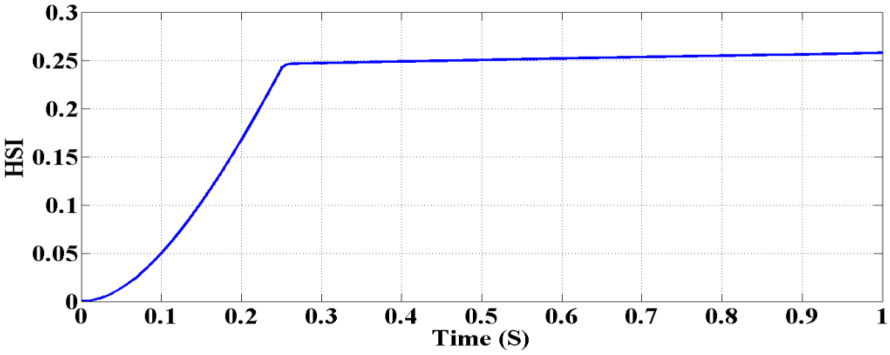


Figure 12: HSI value during simulation process for the rated load

Table 3: Proportional gains and speed response analysis

Kp	1.73
Ki	4.98
Max overshoot during steady state	0.5%
Max overshoot during torque transient	1.8%
Speed error during steady state	Almost zero
Speed error during torque transient	0.2%

Conclusion

Gain tuning of a PI speed controller based on Biogeography Based Optimization (BBO) algorithm for a Direct Torque Control (DTC) model of a five-phase motor is presented in this paper. After tuning the control parameters of the PI controller, operation of the drive system was analysed with the proposed gains. Numerical results show that BBO algorithm is a powerful optimization method for solving the PI controller parameters problem.

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