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Performance Analysis of Brushless DC Motor Using Modified Queen Bee Evolution Based Genetic Algorithm Tuned PI Controller under Different Speed Conditions

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Authors' contributions

This work was carried out in collaboration between both authors. Author AR proposed, designed the study, managed the literature searches, performed the simulation, analysis and wrote the first draft of manuscript. Author MFZ supervised every stage of the work. Both authors read and approved the final manuscript.

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ABSTRACT

The modeling of BLDC motor and performance analysis under diverse operating speed settings has been presented in this paper. BLDC motors gaining more & more attention from different Industrial and domestic appliance manufacturers due to its compact size, high efficiency and robust structure. Voluminous research and developments in the domains of material science and power electronics led to substantial increase in applications of BLDC motor to electric drives. This paper deals with the modeling of BLDC motor drive system along with a comparative study of modified queens bee evolution based GA tuned & manually tuned control schemes using MATLAB /SIMULINK. In order to evaluate the performance of proposed drive, simulation is carried out at different Mechanical load & speed conditions. Test outcomes thus achieved show that the model performance is satisfactory.

Keywords: Brushless DC motor; genetic algorithm; back electromotive force; permanent magnet synchronous motor; proportional integral.

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1. INTRODUCTION

BLDC motor is best suited as variable-speed control AC motor drives due to simple construction and its overall cheaper price than other AC motors [1,2]. BLDC motor has excellent speed vs. torque characteristics, greater efficiency and improved dynamic response compared to brushed DC motors [3]. BLDC motor also delivers higher torque with features like compact size and robust design. For right torque production BLDC motor requires position information of rotor which is obtained by motion encoders or hall sensors. The machine is of three phase stator type with three phase distributed type winding and the motor torque depends on the respective position of the BEMF. Normally stator is energized by rectangular shape current while BEMF waveform of BLDC motor is of trapezoidal shape, therefore ideally it gives a constant torque but in practice the torque ripple appears due to imperfection in EMF waveform, current commutation and current ripple. The phase shift in EMF waveform occurs due to variation in slot shapes, skewness of slot, magnet of BLDCM etc. and hence all these causes need to be taken care of while designing motor. This paper presents a brushless DC motor Model with non sinusoidal BEMF waveform. Fig. 1 shows general block diagram of Brushless DC motor control drive.

For starting and generation of appropriate commutation sequence through Inverter Bridge, the BLDC motor necessitates a rotor position sensor. The inverter produces a new commutation signal after every successive 60 degrees rotation of rotor. In place of commutating the armature current using conventional brushes, electronic commutation is utilized in BLDCM, hence this motor is called electronic commutated motor. This removes the troubles associated [4] with conventional commutation, such as sparking during over speed and wear & tear of the commutator-brush assembly, thus making BLDC motor more compact & rugged as compared to a brushed dc motor.

The basic block diagram of BLDC motor drive contains power inverter, permanent BLDC motor, position sensors and controller. 3 phase inverter assembly transfers power from the constant voltage DC source to the brushless DC motor, which changes electrical energy into mechanical energy. BLDC motor has rotor position sensors made up of hall crystals. Command signals are used to generate necessary control. The command signal may be classified as torque, current, position, speed etc. [5]. The category of the BLDC motor is determined by the structure of the control algorithms utilized, two main categories on the basis of control algorithm are voltage source and current source based drives. PMSM with either sinusoidal BEMF or trapezoidal BEMF waveforms is used by both voltage source and current source based drive.

The size of inverter and power losses for the same size of machine is reduced for the Machine with a trapezoidal back-EMF [6]. Whereas sinusoidal back-EMF type machines are preferred in order to achieve constant torque. On the basis of back-EMF signal The BLDCM can be categorized into two types, such as sinusoidal back-EMF type or Non sinusoidal back-EMF type.

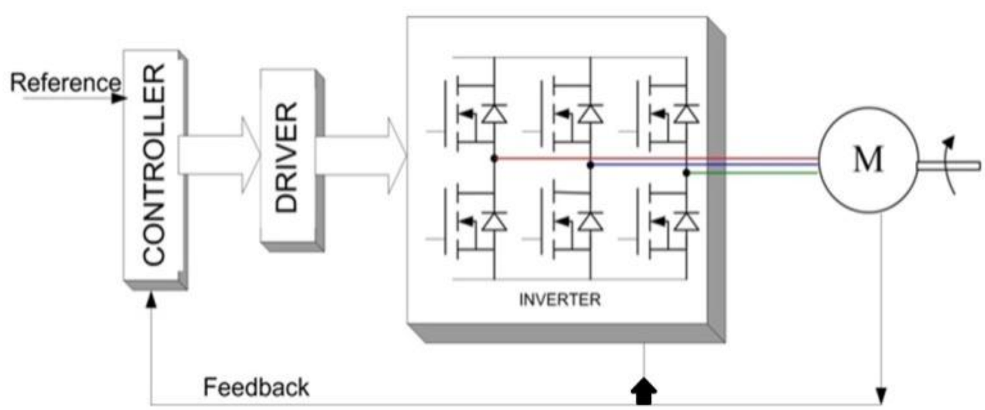

Fig. 1. BLDC motor control scheme

Trapezoidal BEMF excited BLDC motor is proposed in this work. To obtain better performance speed control, gain parameters of conventional PI controllers are optimized by queens bee GA optimization technique [7]. Genetic algorithm (GA) can be used for solving both constrained & unconstrained optimization problems. It's a natural selection process inspired from biological evolution. The algorithm frequently modifies a population of individual solutions. During each step, the genetic algorithm randomly picks individuals from the current population and utilizes them as parents to produce the new solutions for the subsequent generation. Over successive generations, the population progresses toward an optimum solution.

The conventional PI controller mainly reject or minimize the steady state type error and cancels the trouble arises due to relatively small change in load torque, while GA optimized controllers acts well with large and sudden change in reference quantity [8,9].

2. MATHEMATICAL MODELING OF BLDC MOTOR

$$V_a = Ri_a + L\, di_a/dt \quad \text{(i)}$$

$$V_b = Ri_b + L\, di_b/dt \quad \text{(ii)}$$

$$V_c = Ri_c + L\, di_c/dt \quad \text{(iii)}$$

Where,

R= Armature resistance per phase in ohm
L= Armature self-induction per phase in henry
i_a, i_b, i_c = Motor current in Ampere
e_a, e_b, e_c = Motor back-EMF in Volt
V_a, V_b, V_c = Terminal phase voltage in Volt

BEMF has a successive phase difference of 120° electrical & BEMF is a function of rotor position. Equations for phase BEMF are as follows:-

$$e_a = K_w(\theta_e) \quad \text{(iv)}$$

$$e_b = K_w(\theta_e - 2\pi/3) \quad \text{(v)}$$

$$e_c = K_w(\theta_e + 2\pi/3) \quad \text{(vi)}$$

Where,

K_w = BEMF constant per phase in V-sec./rad.
ω = rotor speed in rad./sec.
θ_e = rotor angle in degree electrical.

Electrical angel θ_e related to Mechanical angle θ_m as:-

$$\theta_e = (P/2)\, \theta_m \quad \text{(vii)}$$

Where,

P is the no. of rotor poles.

Total electromagnetic torque, T_e in N-M can be stated as follows:-

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\, \omega \quad \text{(viii)}$$

Mechanical torque generated by the motor shaft:-

$$T_l = T_e - J dw/dt - B\omega \quad \text{(ix)}$$

Where,

T_l = load torque in newton- meter
B = rotor friction constant in Nms.rads-1
J= rotor inertia constant in Kg-m^2

3. SPEED CONTROL OF BLDC MOTOR

The performance characteristics of Brushless DC motor drive with conventional controller as well as Modified queen bee based genetic algorithm tuned controllers have been investigated.

3.1 PI Controller

Conventional PI controller is used as a speed controller for attaining the reference speed with the help of actual speed. Error between reference speed and measured speed act as input signals to the PI controller. Due to its simple design and ease of applicability it is one of the most popular controllers in industries, its algorithm is expressed as follow:-

$$Y(t) = K_p\, e(t) + K_I \int e(t)dt$$

Values of the controller gain parameter K_P and K_I are obtained by trial and error method [10] for various reference speeds. During the manual tuning process system is kept operational. Initially gain K_d and K_I values are taken as zero. Than response of the system is observed for unit value of k_d. Value of gain K_p Increased slowly until the output of the Brushless DC motor started oscillations, then value of K_p gain is set to nearly half of that value for a quarter amplitude decaying type response. Finally the K_i gain increased until offset is removed considerably from the BLDCM output. Too much K_i gain change may leads to instability. Controller output must be limited to give the desired torque. Manual controller tuning, results in the following gain constant values.

Table 1. Manually tuned parameter values

K_p	K_i
0.15	75

3.2 Modified Queen Bee Based GA Tuned PI Controller

The modified version is truly inspired by nature and helps to enhance the exploration and exploitation capability of conventional algorithm. Every pool contains the fittest individual termed as queen bee. This fittest individual is allowed to mate through rest of the members (individual solutions) of the pool. Resulted solutions are checked against a predefined fitness function. The second fittest solution so obtained is allowed to build a new pool with half of pool members. In this way pools keeps on increasing by a factor of square generation by generation as shown in Fig. 2.

3.3 Implementation of Modified Queen Bee Based Algorithm

In case of PI controller, best possible combination of K_p and K_I is searched for, GA is a space search method and requires pre assumed spaces to search for best possible combination of scaling factors. Here in our case previously derived PI coefficients helps in assuming such spaces. Code utilizes the MATLAB platform and work together with machine simulation. A predefined fitness function chosen carefully, helped in improving the result generation by generation. Values of different GA parameters are as defined below in Table 2.

Table 2. Parameter values for algorithm

Parameter	Values
Crossover Probability	0.8
Normal Mutation Probability (pm)	0.01
Population Size	15*9=135
Individual Bit Length	10
Normal Mutation Rate (ξ)	0.6
Strong Mutation Probability (pm’)	0.4
Maximum No Of Pools	9

3.4 Tuning of PI Controller Parameters

In the previous work tuning of controller is done manually. Manual tuning is a tedious task in itself and requires expertise to obtain optimum solution. In fact to obtain an optimum solution is rare in case of manual tuning. Tuning of K_p and K_i utilizing GA enables one to search for optimum values from within the pre assumed spaces. Construction of PI controller is as shown below in Fig. 3.

Constant K1, K3 and K3 are directly picked by the codes, written utilizing MATLAB environment. Reciprocal of speed is taken as a fitness function.

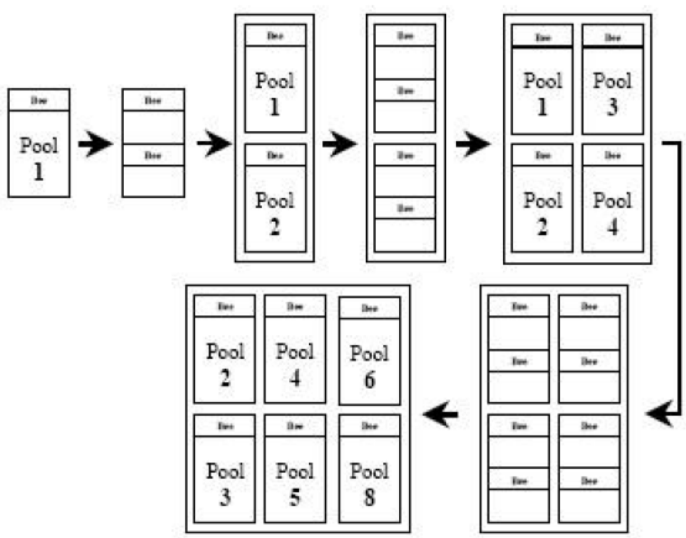

Fig. 2. Splitting of pool generation by generation

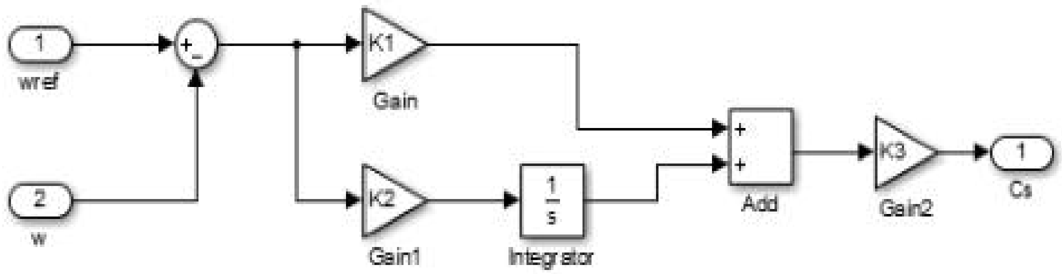

Fig. 3. PI controller with tunable parameter K1, K2 & K3

```
Algorithm 1:
//t: generation//, //n: population size in a pool//,
//pl: number of pools//, //P: populations//,
//pl_max: maximum number of pools//
//ξ: normal mutation rate//,
//p_m: normal mutation probability//,
//p'_m: strong mutation probability//,
//I_q: a queen bee//, //I_m: selected bee//
t ← 0: pl(t) ← 1; initialize P{pl(t)}; evaluate P{pl(t)}
while 1 (not terminate condition)
do
    t ← t+1
    while 2 [pl(t)]
    do 2
        select P{pl(t)} from P{pl(t-1)(*)}
        P{pl(t)}=[ I_q{pl(t-1)} , I_m{pl(t-1)} ]
        recombine P{pl(t)}; do crossover; do mutation (*)
        for i=1 to n
            if i ≤ (ξ×n)
                do mutation with p_m
            else
                do mutation with p'_m
            end if
        end for
        evaluate P{pl(t)}; search for new_I_q{pl(t)}
        if ( new_I_q{pl(t)} found )
            split the pool and new_pl(t) ← pl(t)+1
        else
            new_pl(t) ← pl(t)
        end if
        if (new_pl(t) > pl_max)
            pl(t) ← pl_max (oldest pool deleted)
        end if
    end while2
end while1
```

Fig. 4. Modified genetic algorithm

Fitness function verifies fittest solutions generation by generation. Maximum generation is 30 & Maximum numbers of pools are restricted to 9. Fig. 5 clearly shows the improved fitness trend.

Final values of the PI gain constant are K1 = 0.1689, K2 = 659.2742 and K3 = 0.09868.

4. SIMULATION AND RESULTS

Considering the BLDC with the design parameter as shown in Table 3. the simulation has been executed & the outcome are shown with help of graphs. Initially reference speed is fixed at 3000 rpm and load is applied to the motor at 0.01 sec. the variation in speed is observed using simulation. Now the reference speed is changed to 1000 rpm after 0.5 sec. under loaded condition to further analyze the controller effectiveness. The BEMF and current waveform are displayed by the simulation results and it shows in Figs. 9 & 12 that BEMF are displaced by 120 degrees from each other, similarly Figs. 8. & 11 shows that stator currents also displaced by 120 degrees from each other and current shape is quasi sinusoidal in nature.

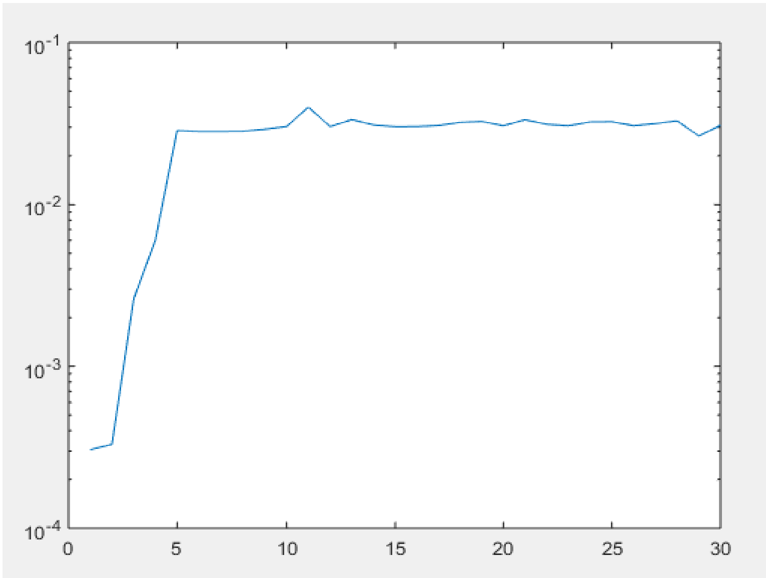

Fig. 5. Generation (x-axis) vs. Fitness (y-axis)

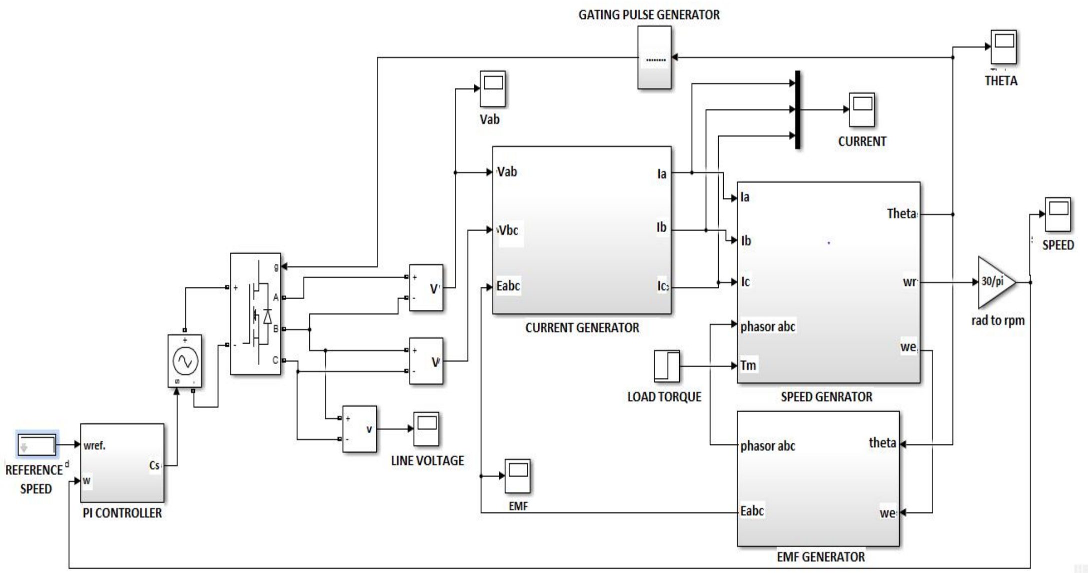

Fig. 6. Model of BLDC motor drive

4.1 Manually Tuned PI Controller Response

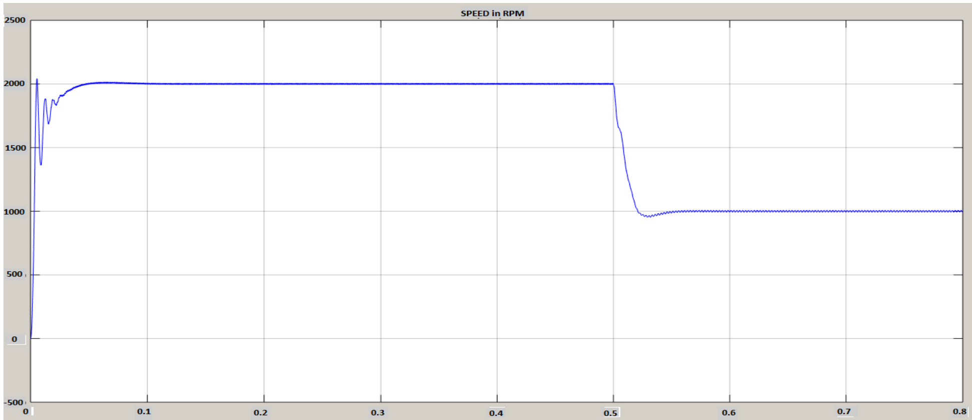

Fig. 7. Speed (y-axis) vs. time (x-axis)

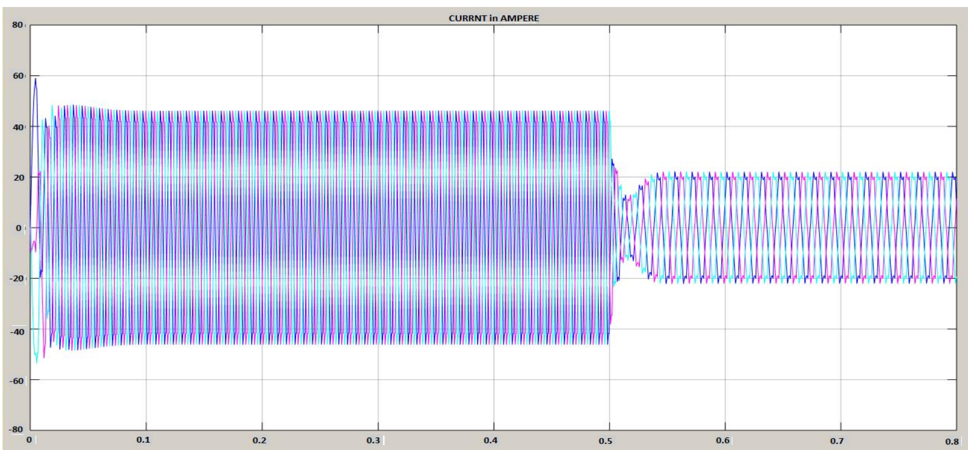

Fig. 8. Current (y-axis) vs. time (x-axis)

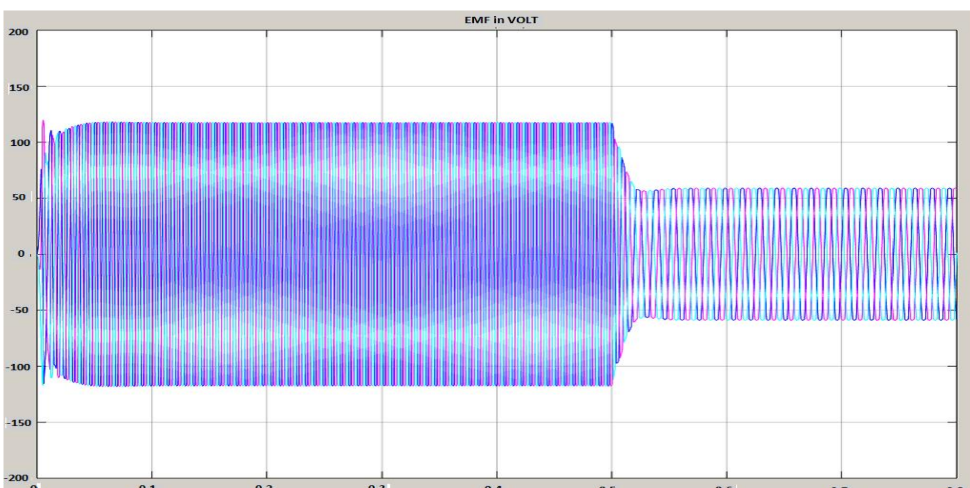

Fig. 9. Back EMF (y-axis) vs. time (x-axis)

4.2 Genetically Tuned PI Controller Response

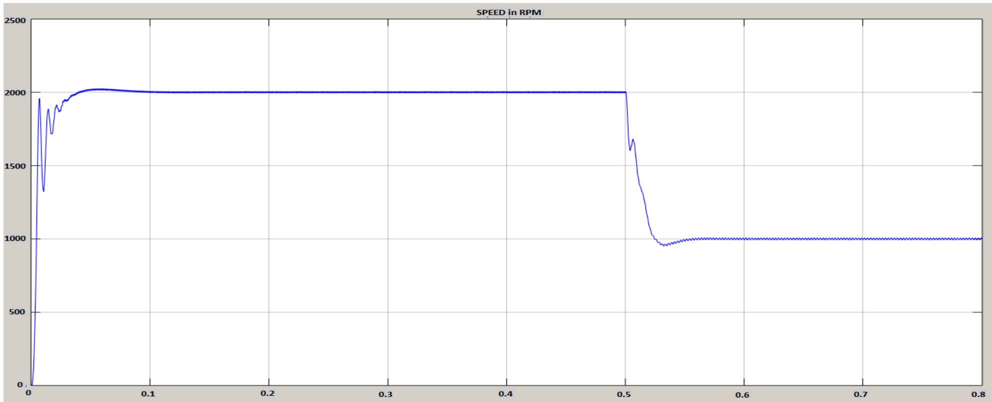

Fig. 10. Speed (y-axis) vs. time (x-axis)

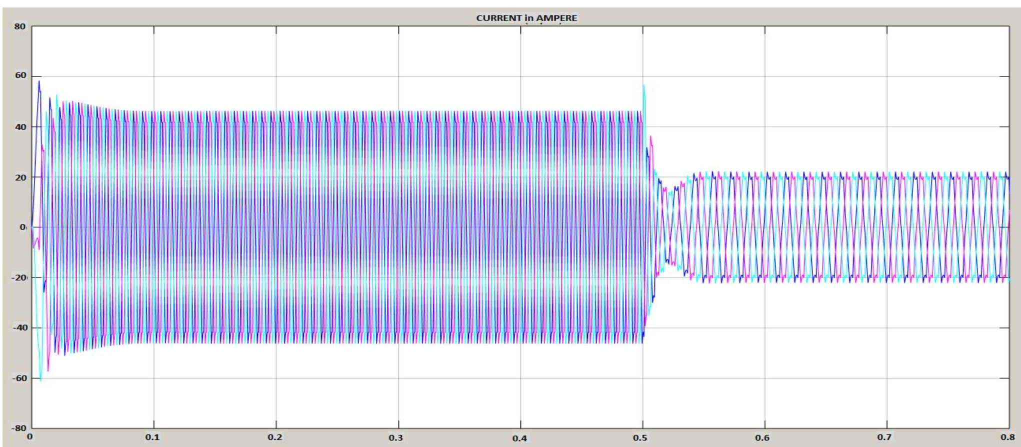

Fig. 11. Current (y-axis) vs. time (x-axis)

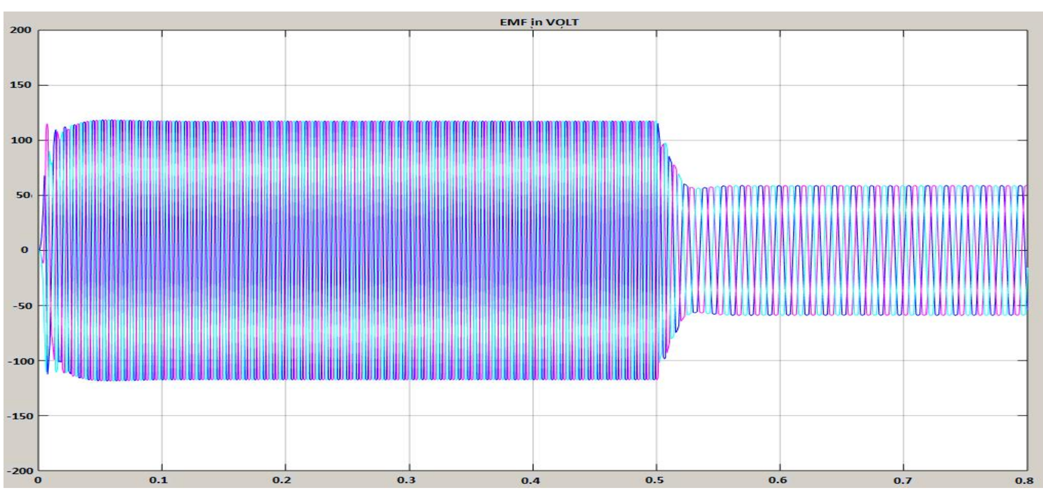

Fig. 12. BEMF (y-axis) vs. time (x-axis)

Table 3. BLDC motor parameter

No. of poles	8
No. of phases	3
Types of connection	Star
V_{dc}	500V
Resistance/phase	2.875Ω
Stator inductance	0.0085H
Moment of inertia, J	00008kg-m/s^2
Damping constant, B	0.001N-m/rad/s
Mechanical Load	5Nm

5. RESULTS AND DISCUSSION

Speed response of Brushless DC motor using PI controller & modified queens bee based GA tuned PI controller shown in figure above. Machine is loaded with a mechanical load of 5N at 0.01 sec, initially the speed reference is 2000 rpm and both the PI controller responds quickly, manually tuned PI controller overshoots 4.2%, which is larger than 3.125% overshoot of modified queens bee evolution based GA tuned PI controller. Settling time in case of manually tuned controller is 0.09 sec while its 0.1 second in case of modified queens bee evolution based GA tuned PI controller. After 0.5 sec of starting machine reference speed value is changed from 2000 rpm to 1000 rpm. Both PI controllers took almost the same amount of time to settle, which around 0.05 sec is after the change in reference. Simulation period for BLDC motor in case of both the controller is 0.8 second.

6. CONCLUSION

In the proposed work speed control of the machine is performed with the help of manually tuned PI controller and modified queens bee evolution based GA tuned PI controller at loaded conditions. MATLAB/Simulink environment is used to verify the results of two simulations. The results obtained are promising, settling time and offset error in case of modified queens bee evolution based GA tuned PI controller is lesser as compared to manually tuned PI controller. Manually tuned PI controller is little sluggish in settling the response, though overshoot in case of manually tuned PI controller is also well below the prescribed limit. Overshoot for modified queens bee evolution based GA tuned PI controller is lesser as compared to manually tuned PI controller. While setting time for both the PI controller is nearly same. Hence modified queens bee evolution based GA tuned PI controller meets the required performance, additionally the work clearly shows relative ease of tuning in case of modified queens bee evolution based GA tuned PI controller.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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