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Performance Analysis of Three-Phase PMSM using Advanced Controlled Techniques

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Abstract —*Thispaper represents advanced control techniques for the controlling of PMSM usingaGenetic Algorithm forposition and speed control of (PMSM). The use of a Hall Effect sensor for position control makes the motor heavier and the cost of the motor increases for three-phase PMSM. The conventional controlling techniques of PMSM include the PI control method, Sliding mode observer,Kalman filter, and the FOC algorithm technique. One of the major drawbacks of these conventional methods shows that constant motor torque is not achieved along with the non-uniform motor phase currents which increase the losses in PMSM. The traditional techniques show better performance for a discrete system but fail for continuous systems. To overcome these problems in PMSM, a Genetic algorithm is implemented in this research work. In position control, the approach is used to optimize the PI controller gains. Various controller strategies are used for the cascaded-loop position controller, speed controller, and current controller. The GA control technique, field-oriented control (FOC), and the sliding mode control technique are compared together in this research work. The objective target, which has been used for comparison, is the motor speed, motor torque, and the motor phase currents.The results have been verified and validated through MATLAB/Simulink. The results obtained with the Genetic algorithm, SMO-based PI controller shows better results compared to conventional controlling methods.*

Keywords *— Evolutionary Algorithm (EA), Genetic Algorithm (GA), Permanent Magnet Synchronous Motor (PMSM), Sliding Mode Observer (SMO)*

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I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) have acquired an expanding prominence where they are often utilized in high-performance drive applications, including servo systems, computer peripherals, machine tool drives electric vehicles, industrial robotics, and other industry applications [3].When compared to induction motors, PMSMs have several advantages, including the absence of rotor copper losses, which heat the rotor and reduce efficiency, a high torque to inertia ratio, great efficiency, and a high power factor are all desirable characteristics. These advantages make PMSMs competitive over induction motors. In applications requiring variable speed drives, PMSMs are preferable over dc motors due to their high torque-to-inertia ratio, outstanding power factor close to unity, rapid acceleration, and high efficiency.Position control system belongs to cascade control systems which require several control loops [4-6]. In this paper, different combinations of controllers are applied to the system using conventional PI controllers, fuzzy logic controllers with conventional PI controllers, and PI controllers optimized by Genetic algorithms. Simulation is used to forecast the performance of the drive system in all possible configurations. As comparison goals, the rise time, settling time, and steady-state error have all been used. In addition, the developed torque's response is studied [7]. It will be shown that applying genetic algorithm optimization to the PI controller in position control gives the best performance.PMSM drives have become more essential in motion control applications as magnetic materials, semiconductor power devices, and control theories have improved. The load is coupled to the rotor of the PMSM, resulting in minimal pulsation torque quality[1, 6]. During the phase transition, overlapping control may help to reduce torque pulsation.For this PMSM, the power inverter is required to operate at a higher switching frequency. As a result, it achieves noise reduction and overlap control. Direct control of stator currents is required to obtain the desired performance of PMSM as DC motor behavior. It is otherwise hard to do due to the tight coupling and nonlinear nature of AC motors.

As a result, to achieve the decoupling of critical variables, a specialized method must be devised. This problem has been overcome by vector control technology, also known as Field Oriented Control (FOC). A conventional synchronous motor is generally implemented with slip rings and a field winding [12].Synchronous motors are generally used whereas constant speed is desired under varying loads. Inverters or a variable voltage or frequency source can be used to control their speed. Speed control is the key factor in the PMSM motor for industrial applications. It is achieved by the Evolutionary Fuzzy PID Speed controller. Fuzzy logic controllers (FLCs) have recently piqued interest in several applications. FLC' have several advantages over traditional controllers, including the fact that they do not require a correct mathematical model, they can work with imprecise inputs, they can manage line linearity, they are more robust than typical nonlinear controllers. Evolutionary Fuzzy systems are hybrid Fuzzy systems that use evolutionary optimization strategies to improve and adapt Fuzzy expert knowledge [8].The evolutionary optimization approaches operate by encoding the optimization parameters in a gene-like structure, then applying Darwinian natural selection to identify a population with better parameters. Evolutionary optimization algorithms can be approached in a variety of ways, including evolution methods, evolutionary programming, genetic programming, and genetic algorithms. These algorithms have similar underlying concepts of evolution, but they differ mostly in their approach to parameter representation. Genetic algorithms (GA) are an evolutionary method that has been found to outperform other evolutionary strategies in the noisy, nonlinear, and uncertain optimization landscapes that characterize Fuzzy systems [14]. In control systems, PID control is a sort of feedback mechanism.

Three-term control is another name for this type of control; by controlling the three elements - proportional, integral, and derivative - we can obtain various control actions for a certain job. In the control system, the PID controller is believed to be the best. In a PID controller, two parameters can be used while the third is set to zero.As a result, the PID Controller is also known as the PI (Proportional Integral), PD (Proportional Derivative), or P or I (Proportional Integral Derivative). The integral term is in the responsibility of obtaining the system's target value, while the derivative term D is in charge of noise measurement [11].

PID Controllers were first employed as mechanical devices. In today's world, PID controllers are employed in PLCs (Programmable Logic Controllers). Kp, Ki, and Kd are the proportional, integral, and derivative parameters. The closed-loop control system is influenced by all of these variables. It affects the rising time, settling time, overshoot, and steady-state error. The GA-PI controller overcomes the PI controller's tuning complexity and high reaction time. For a PMSM, this work presents an evolutionary GA-PI controller design method. First, we construct a PI control design approach based on the common control engineering knowledge that when the transient error is big, the P and I gains should be increased while the D gain should be decreased. For asymptotic stability, the PI parameter must meet an inequality requirement [16]. Second, we present an Evolutionary Algorithm (EA) for optimizing and auto-tuning the control parameters of the Genetic Algorithm. Unlike most prior techniques, the proposed evolutionary auto-tuning methodology assures closed-loop stability for any GA control parameter vector created.

The following is a breakdown of the paper's structure. The first section contains the introduction. In sections II problem statement has been formulated. Section III gives the general description of the PI controller followed by section IV which states the Genetic Algorithm and the steps involved in the Algorithm [3-13]. Section V depicts the Motor Model followed by the System description in section VI. In section VII results implemented have been shown with a Conclusion.

II. MODELING OF PMSM

Permanent magnet synchronous motor has been widely studied for the last two decades. In the majority of methods used for PMSM, there is a set of equations dependent on rotor position. Representing the motor equations in the rotor reference frame, we will have a set of the equation that does not depend on rotor position. The d and q axis currents will be obtained from two transformations. The first part transfers the three-phase to two phases ($abc$to$\alpha\beta$).The second part carries over the quantities at the stationary frame to the rotational frame.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_B \\ i_C \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (2)$$

Where,
i_d-direct axis current component
i_q-quadrature axis current component
θ -represents the rotor position.
The electromechanical behaviorof the PMSM in the dq-frame is as follows:

$$V_q = Ri_q + \omega_r\lambda_d + \frac{d\lambda_q}{dt} \qquad (3)$$

$$V_d = Ri_d - \omega_r\lambda_q + \frac{d\lambda_q}{dt} \qquad (4)$$

$$V_0 = Ri_0 + \frac{d\lambda_0}{dt} \qquad (5)$$

$\lambda_q = L_q i_q$ (6)
$\lambda_d = L_d i_d + \lambda_m$ (7)
$T_e = \frac{3}{2} P\left(\lambda_m i_q + \left(L_d - L_q\right) i_d i_q\right)$ (8)
$\frac{d\omega_r}{dt} = \frac{P}{J}\left(T_e - B\omega_r - T_m\right)$ (9)
Where,
V_q-quadrature axis voltage component
V_d-direct axis voltage component
V_0-orthogonal axis voltage component
λ_q-quadrature axis flux linkage component
λ_d-direct axis flux linkage component
If the angle between stator and rotor field flux be kept at 90^0we will have:
$i_d{}^* = 0$ (10)
So, by this assumption and set $i_0 = 0$, determining $i_q$leads to control the electrical torque directly.
$T_e = \frac{3}{2} p\lambda_m i_q$ (11)

III. METHODOLOGY

A. PI Controller:
A PI controller's main goal is to eliminate the steady-state inaccuracy that a P controller causes. However, it harms the system's overall quickness of response and general stability. This controller is typically utilized in applications where system speed is not a concern.Because the PI controller is unable to forecast future system failures, it is unable to reduce the rise time and eliminate oscillations [4]. The PI parameters used in the computation must be tuned according to the nature of the system for best performance.

TABLE I. EFFECTS OF COEFFICIENTS

Parameter	Speed Response	Stability	Accuracy
increasing K_p	increases	decreases	improves
increasing K_i	decreases	decreases	improves

B. Field Oriented Control (FOC):
To achieve better dynamic performance, a more complex control scheme needs to be applied to control the PM motor. With the mathematical processing power offered by the microcontrollers, advanced control strategies can be implemented which use mathematical transformations to control AC machines like DC machines, providing control of flux and torque producing currents. Such decoupled torque and magnetization control is commonly called FOC.

The i_d and$i_q$components are compared to the references. At this point, this control structure shows an interesting advantage: it can be used to control either synchronous machine by simply changing the flux reference and obtaining rotor flux position. The outputs of the current regulators are V_{dref} andV_{qref} , they are applied to the inverse Park transformation. The outputs of this projection are $V_{\alpha ref}$ and $V_{\beta ref}$, which are the components of stator vector voltage in the (α, β) stationary orthogonal reference frame. These are the inputs of the space vector PWM.Theoutputs of this block are the signals that drive the inverter.

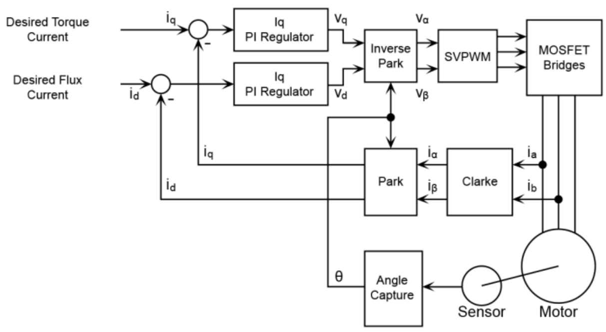

Fig 1. Block Diagram of Field Oriented PMSM Control System

In FOC, a control system aims to make the zero error
- Read currents zero
- Find the new error
- Correct the voltage signal so that error goes to zero

All this process occurs in closed-loop control with the help of a microcontroller. The microcontroller will do the process in the following algorithm:
1. Read current sensor value (feedback current)
   Read pedal output (reference current)
2. Find error between reference and feedback
3. Send error to the control block which generates voltage signal and send it to the inverter
4. Repeat – Interrupt process – a way of scheduling the tasks at specific intervals.

C. Genetic Algorithm (GA) Control:

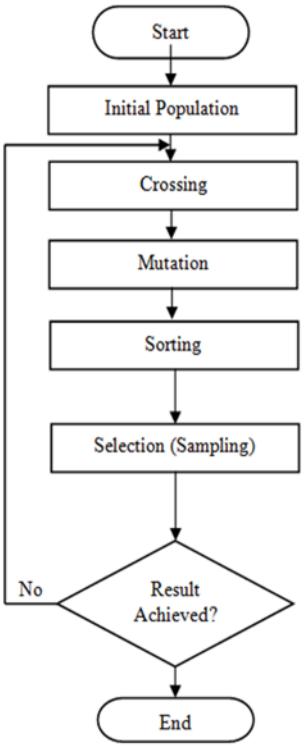

Fig 2. Identification algorithm flow chart

Genetic algorithms (GA) have been used to solve optimization problems [5, 11]. Therefore, the identification problem can be phrased as follows: the objective function minimum shall be found at which the mismatch error between the experimental data (e.g., currents and rpm of the motor being studied) and the obtained simulated data tends towards zero:

$$(\hat{a}_1, \hat{a}_2, \ldots., \hat{a}_n) = \arg\min \Delta X \qquad (12)$$

Where ($\hat{a}1$, a ̂2…, $\hat{a}n$) – objective function dependent on evaluations of identified parameters â; Δ – mismatch error between the experimental data and the obtained simulated data.

The most critical step is to select the objective (fitness) function.
In this study, the fitness function is calculated from the integral of the square error (ISE) to optimize the parameters of the PI controller [16]. The mathematical formula of ISE can be expressed by

$$J = \int_0^\infty \Delta\, e^2(t)dt \qquad (13)$$

where*e* is the parameter that is utilized to optimize the speed controller's performance. In the first step, $k_p$and $k_i$parameters are randomly produced during initialization. Following the minimum *J* is produced by PI parameters to acquire the minimum error for the best values.
The PMSM parameter identification method is depicted in Fig 3.

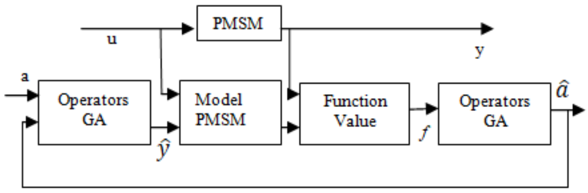

Fig 3. Flow chart of PMSM parameter identification process

(u – input effect vector; y – vector of measured state variableswhich transient responses are used for identification; ŷ– vector of evaluation of measured state variables; f – objective function value; a – vector of initial parameter combinations; â - vector of evaluation of PMSM parameters)

1. Initial Population
At this stage, the value search range is specified based on admissible values of various parameters of a specific motor.

2. Crossing
There are a lot of possible crossing operator variants [5, 9]. The “SBX crossover” has been selected in the article that has performed the best as regards the parameter identification speed among other analysed crossing operators, such as the simple crossover, arithmetical crossover, geometrical crossover, discrete crossover, etc.

3. Mutation
The real coding genetic algorithm assumes a specified percentage of mutation of all the genes of the current generation individuals in the population. This being the case, either one or more genes of the individual can be subjected to mutation. The new gene real value is calculated by the formula:

$$p = \tilde{p} \pm \Delta \qquad (14)$$

Where$p$ – new real gene; $\tilde{p}$ – previous gene value; Δ-parameter which value is close to the expected error. The symbol $\pm$ is taken at random.

4. Sorting (PMSM Modeling)
The sorting stage involves modelling the PMSM with selected parameter sets. After that, the algorithm compares the deviation of the behaviour of each individual within the population with the reference, calculating the objective function. The deviation function is as follows:

$$f\ (\hat{a}1, \hat{a}2, \dots \hat{a}\mathrm{n}) = \sum_k \frac{\int_0^t |yk\,(t) - \hat{y}k(t, \hat{a}1, \hat{a}2, \dots \hat{a}n)|dt}{\int_0^t |yk\ (t)|dt} \qquad (15)$$

where$f$ - objective function; $\hat{a}_n$ – evaluations of identified parameters; y_k – measured state variables; $\hat{y}_k$ – Evaluations of state variables; t– transient process time.

5. Selection (Sampling)
Selection is performed from the best individuals of the current

and previous generations based on the elitism and “new blood” strategy [9] ensuring avoidance of stagnation in the population.
GA stops as soon as it achieves the specified value of the objective function or reaches the maximum specified number of generations (iterations).

$$u(t) = k_p(e(t) + \frac{1}{T_i}\int_0^t e\,(t)dt) \quad (16)$$

$$e(t) = y_r(t) - y(t) \quad (17)$$

D. Sliding Mode Observer:
The control objective is to track a reference speed $\omega_{ref}$with the rotor's actual speed ω (i.e. the position and acceleration are not considered). The error signal between the reference and actual speeds can be written as $e = \omega_{ref} - \omega$.

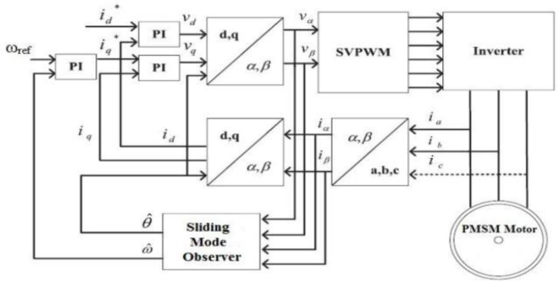

Fig 4. Block DiagramofSMO in PMSM

Figure 4.shows a sensorless control block diagram of a surface-permanent magnet synchronous motor based on an improved sliding mode observer. The whole system includes PMSM, a three-phase inverter module, an SVPWM module, a vector control module, and an improved SMO module.
The equation of states of the stationary coordinate system (αβ coordinate system) SPMSM is given be

$$\frac{di_\alpha}{dt} = -\frac{R_s}{L_s}i_\alpha - \frac{e_\alpha}{L_s} + \frac{u_\alpha}{L_s} \quad (18)$$

$$\frac{di_\beta}{dt} = -\frac{R_s}{L_s}i_\beta - \frac{e_\beta}{L_s} + \frac{u_\beta}{L_s} \quad (19)$$

Where e_α and e_β are given by

$$e_\alpha = -\psi_\omega \sin\theta \quad (20)$$

$$e_\alpha = \psi_\omega \cos\theta \quad (21)$$

Where u_α and u_β are two-phase stator voltages respectively;$i_a$andi_b are two-phase stator currents respectively; e_α and $e_\beta$are two opposite electromotive forces respectively; R_S is the stator resistance; q is the rotor position angle; L_S is the stator inductance; w is the rotor angular velocity; Y is the rotor flux.

IV. MATLAB/SIMULINK MODEL

The MATLAB/SIMULINK model of the GA-PI control system for PMSM is shown in Fig.5

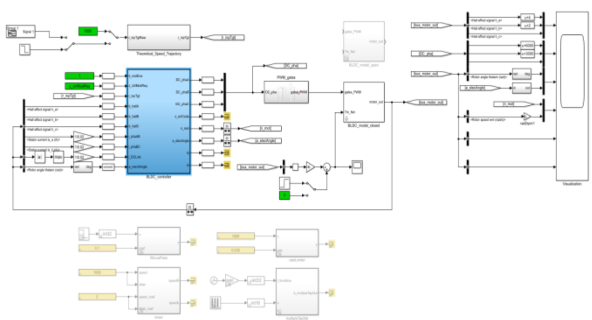

Fig 5. MATLAB/SIMULINK MODEL of GA-PI PMSM

It consists of three major blocks i.e.
1. Estimation Block
2. Diagnostics Block
3. Control Mode Manager

In GA-PI control the "Estimator" is specified with the motor ratings that have to be controlled within specified limits.Inputtargets of Hall sensors are given to the estimator. Thedesiredmotor position, motor angle, and motor speed are predefined in the Estimator region and feed to the Diagnostic and FOC

algorithm of PMSM.
In the “Diagnostics” region, an errorflag is generated when the motor parameters (torque, stator current, speed, and position) do not meet the specified ratings given in the Estimator region.It will diagnose the error generated and send it to the “Control mode Manager”.
The Control Mode Manager will decide the amount of precision to be controlled for the specific application. Comparing the generated error from the diagnostic region with the ratings specified in the estimator it will manipulate the motor control to be needed for torque and speed control of PMSM.

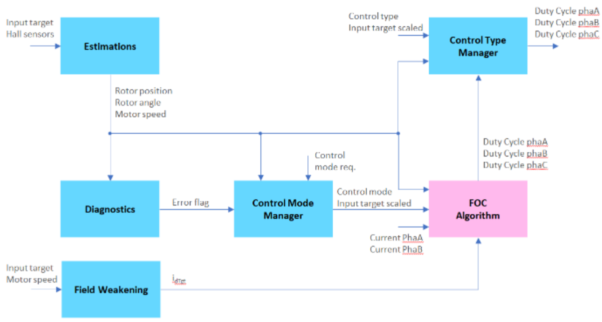

Fig6. Control block diagram of PMSM

V. RESULTS AND DISCUSSION

The parameter identification algorithm of PMSM has been checked using MATLAB/SIMULINK. The motor has been started in the vector control system and oscilloscope current and speed patterns have been recorded.The combinations of controllers are applied to the PMSM drive system.

The reference position is a step function having a final value of 6 rad and the load torque is 10N.m.Simulation has been carried out using MATLAB Simulink.
A. Hall Signals:
The Hall signals given to the FOC are used for the rotor positioning and identification. The rotor position is implemented based on the following table

TABLE II. SEQUENCE OF HALL SIGNALS

Hall A	Hall B	Hall C	Vector Hall
0	0	0	0
0	0	1	2
0	1	0	0
0	1	1	1
1	0	0	4
1	0	1	3

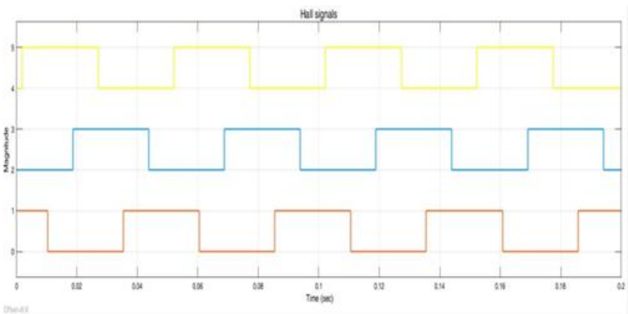

Fig7. Hall Signals Time Vs Magnitude

Pulse width for each phase is shown in Fig.7. It shows the changes in the width of the pulses concerning the amplitude and time of the pulses

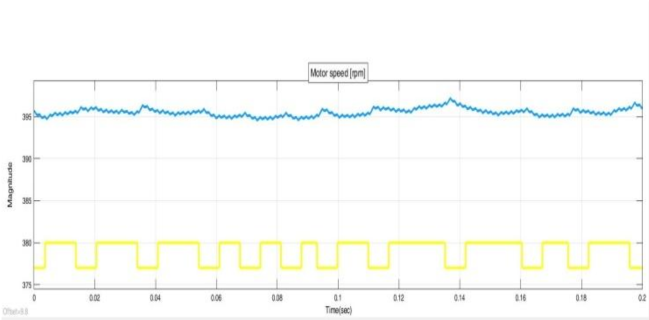

Fig 8. PI Controlled Motor Speed

Motor speed along with the reference speed is shown in Fig.8 in PI control of PMSM. The motor speed reaches 395 rad.

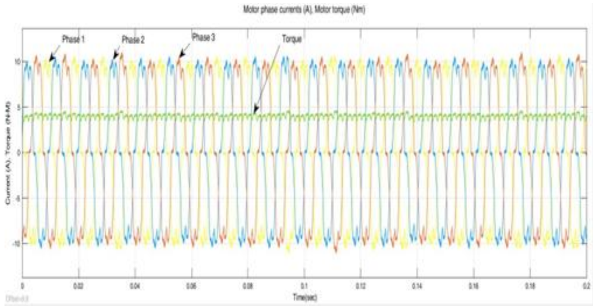

Fig 9. PI Controlled Motor phase currents

The current waveforms for three-phase PMSM and motor torque are shown in Fig 9.

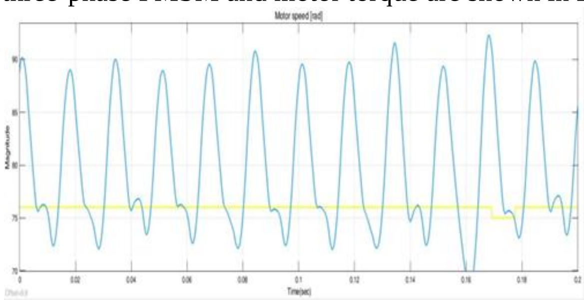

Fig 10. GA Controlled Motor Speed

A Genetic Algorithm based PI controller is used for controlling the speed of PMSM. The set speed is 395 rad

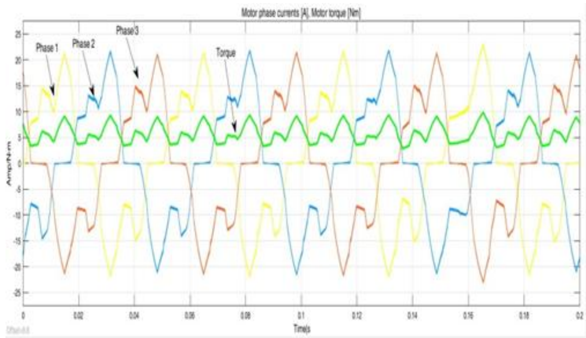

Fig 11. Waveform for Motor Torque and Three Phase Current in GA based model

The current waveform for three-phase current and motor torque is shown in Fig.11 Motor torque varies from 4 N-m to 8 N-m as shown in the figure. The fluctuations in torque are also achieved by using a Genetic Algorithm.

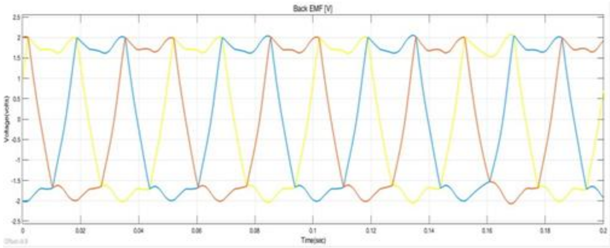

Fig 12. GA Controlled Motor back emf

The back EMF waveform for PMSM is varied from +200V to -200V which is obtained by using the GA based PI method is shown in Fig.12

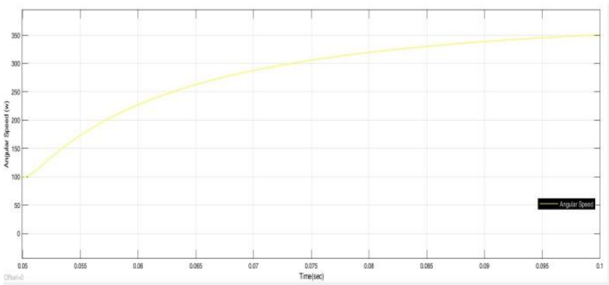

Fig13. SMO Controlled Motor Speed

Motor speedof PMSM with SMO is shown in Fig 13.It shows that constant motor speed is achieved in continuous mode with the help of SMO.

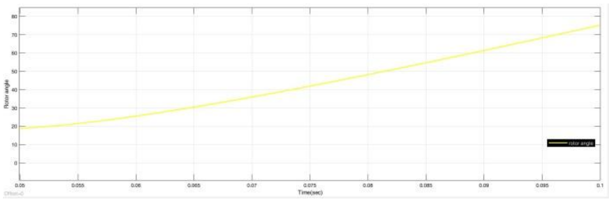

Fig14. Rotor angle position with SMO

Rotor angle position with SMO is shown in Fig 14.

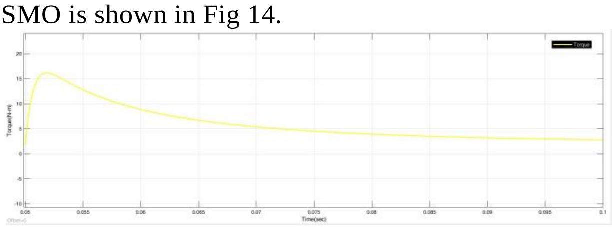

Fig 16. Motor Torque with SMO

Motor torque obtained with the help of SMO is shown in Fig 16. It is observed that a good starting torque (10 N-m) is achieved with the help of SMO and we a get a constant motor torque.

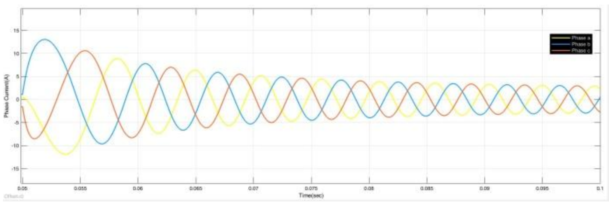

Fig 16. SMO Controlled Motor Phase current

The motor phase current for PMSM with help of SMO technique is shown in Fig 16.

IV. CONCLUSION

In this work, the performance analysis ofsensorless PMSM drives is investigated by using various advanced control techniques such as Field oriented control and sliding mode observer are employed. When the transient error is substantial, raising P and I gains can result in good transient performance. It is also observed that methods such as PI Control and SMO control are successful for discrete mode but fails for the continuous mode while GA method is suitable for continuous mode. Then GA is used to autotune the PI control parameters. The speed control of PMSM is achieved by using this method. This approach also offers improved dynamic performance and stability. The results reveal that the proposed control technique performs better than the conventional type in terms of motor torque and speed. This method is enabled to real-time motor applications to forecast and prevent the motor from the stability-related issues for closed-loop performance.

VII.APPENDIX

Type of motor: PMSM	Rated Power 2HP
Number of Phases: 3	Number of Poles: 4
Rated Current: 10A	Rated Voltage: 300V
Rated speed 1500 rpm	Stator Resistance (R_s):0.9585Ω
q-axis inductance(L_q):0.00525H	d-axis inductance(L_d):0.00525H

Motor moment of inertia (J): 0.0006328 Kg/m^2

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