MPSO-Based Performance Optimization and Analysis of Permanent Magnet Synchronous Motor

Mohammed Rizwan
B.Tech Student Department of Electrical and Electronics Engineering , Mahatma Gandhi Institute of Technology , mohammedrizwan_eee225a0212@mgit.ac.in

Gudise Rahul
B.Tech Student Department of Electrical and Electronics Engineering , Mahatma Gandhi Institute of Technology , gudiserahul_eee225a0209@mgit.ac.in

Dr.Ch.Vinay Kumar
Assistant Professor , Department of Electrical and Electronics Engineering , Mahatma Gandhi Institute of Technology , chvinaykumar_eee@mgit.ac.in

Abstract

Permanent Magnet Synchronous Motors (PMSMs) are widely used in electric and hybrid vehicles due to their high efficiency, high power density, and constant speed operation synchronized with the supply frequency. However, PMSM drive systems exhibit strong nonlinear behavior arising from motor dynamics, load variations, and system uncertainties, making effective speed control a challenging task. Conventional PID controllers tuned using the Ziegler–Nichols (ZN) method perform satisfactorily under linear operating conditions but suffer from degraded performance under nonlinear and dynamic conditions. To overcome these limitations, this work proposes a Modified Particle Swarm Optimization (MPSO)–based PID tuning approach to enhance the dynamic performance of PMSM drives. The MPSO algorithm optimally adjusts PID parameters to achieve improved speed regulation, faster transient response, and better robustness under varying operating conditions. The PMSM drive model is simulated during starting, load application, and load removal scenarios. Simulation results demonstrate that the MPSO-tuned PID controller provides significantly superior performance compared to the conventional ZN-tuned PID controller, making it well suited for electric and hybrid vehicle applications.

Introduction

Permanent Magnet Synchronous Motors (PMSMs) are a class of AC electric motors that convert electrical energy into mechanical energy through magnetic interaction. These motors employ permanent magnets in the rotor to generate the excitation field, eliminating the need for external field windings. Due to this configuration, PMSMs exhibit high efficiency, compact size, and improved power density compared to conventional electric motors.

The operating speed of a PMSM is directly synchronized with the electrical frequency of the applied alternating current. As a result, the motor maintains a constant rotational speed irrespective of load variations. This constant speed characteristic is achieved through the interaction between a rotating magnetic field produced by the stator and a constant magnetic field generated by the permanent magnets in the rotor. Such synchronized operation ensures precise speed control and stable performance.

Owing to their superior efficiency and excellent dynamic characteristics, PMSMs have gained widespread adoption in modern industrial and automotive applications. In particular, automotive manufacturers increasingly prefer PMSMs for electric and hybrid vehicles, where energy efficiency, reliability, and high torque density are critical requirements. The growing demand for sustainable transportation solutions has further accelerated the integration of PMSMs in electric vehicle propulsion systems, making them a key component in next-generation mobility technologies.

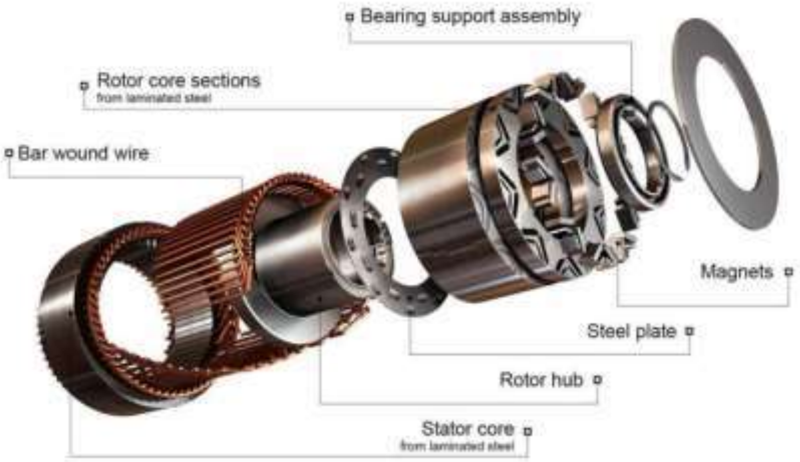

Figure :1 PMSM *parts*

Figure :2 *Permanent magnet synchronous motor*

When a three-phase AC supply is applied to the stator windings, a rotating magnetic field is produced that rotates at a speed proportional to the supply frequency. The permanent magnets mounted on the PMSM rotor generate a constant magnetic field. The interaction between the rotating magnetic field of the stator and the constant magnetic field of the rotor produces electromagnetic torque in accordance with Ampere's law, thereby causing the rotor to rotate.

If an initial rotation is imparted to the rotor in the same direction as the rotating magnetic field, the opposite magnetic poles of the stator field and the rotor attract each other. This attraction results in the interlocking of the rotor poles with the rotating magnetic field of the stator, enabling synchronous operation. However, when a PMSM is directly connected to a three-phase AC supply, it lacks inherent starting torque. Consequently, a PMSM is not self-starting and requires an external starting mechanism or appropriate control strategy for successful operation.

In a Permanent Magnet Synchronous Motor (PMSM), the rotor is equipped with permanent magnets made of high-coercive-force materials to ensure stable magnetic performance. Based on the rotor construction, PMSMs are broadly classified into two types:

- **PMSM with salient-pole rotor**, in which the quadrature-axis inductance is different from the direct-axis inductance, i.e., Lq≠LdL_q \neq L_dLq=Ld.
- **PMSM with non-salient (cylindrical) pole rotor**, in which the quadrature-axis inductance is equal to the direct-axis inductance, i.e., Lq=LdL_q = L_dLq=Ld.

The stator of a PMSM consists of an outer frame and a laminated magnetic core with embedded windings. Typically, two-phase or three-phase windings are employed to generate the rotating magnetic field. Based on the stator winding configuration, PMSMs can be classified into:

- **PMSM with distributed windings**, where the windings are spread over several slots to produce a near-sinusoidal magnetic field.
- **PMSM with concentrated windings**, where the windings are concentrated around individual stator teeth, offering advantages such as reduced copper loss and compact design.
- A **distributed winding** consists of several coils placed in multiple slots of the motor stator, commonly referred to as stator teeth. This winding arrangement distributes the conductors over a number of slots, resulting in a smoother magnetic field distribution. In contrast, a **concentrated winding** involves winding a single coil around an individual stator tooth. The selection of winding type depends on factors such as motor dimensions, performance requirements, and specific application constraints.
- The primary distinction between distributed and concentrated windings lies in the waveform of the **back electromotive force (back EMF)** generated by the permanent magnets. Back EMF is the voltage induced in the stator windings due to the relative motion between the stator conductors and the magnetic field produced by the rotor. Distributed windings typically produce a more sinusoidal back EMF waveform, whereas concentrated windings tend to generate a non-sinusoidal or trapezoidal back EMF, which influences torque ripple, efficiency, and control strategy.

Methodology

The Permanent Magnet Synchronous Motor (PMSM) is modelled using the d–q reference frame theory, which simplifies the analysis of three-phase machines by transforming stator quantities into rotating reference axes aligned with the rotor.

- Sinusoidal distribution of stator windings
- Negligible magnetic saturation and core losses
- Constant permanent magnet flux
- Balanced three-phase system

The stator voltage equations of PMSM in the synchronous rotating reference frame are given by:

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \lambda_f)$$

Where:

- V_d, V_q – d- and q-axis voltages
- i_d, i_q – d- and q-axis currents
- L_d, L_q – d- and q-axis inductances ($L_q > L_d$ for IPMSM)
- R_s – stator resistance
- ω_e – electrical angular speed
- λ_f – permanent magnet flux linkage

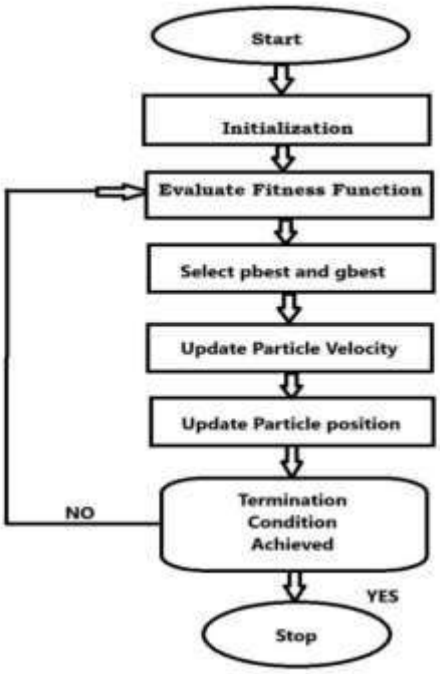

Figure: 3 Flow of work

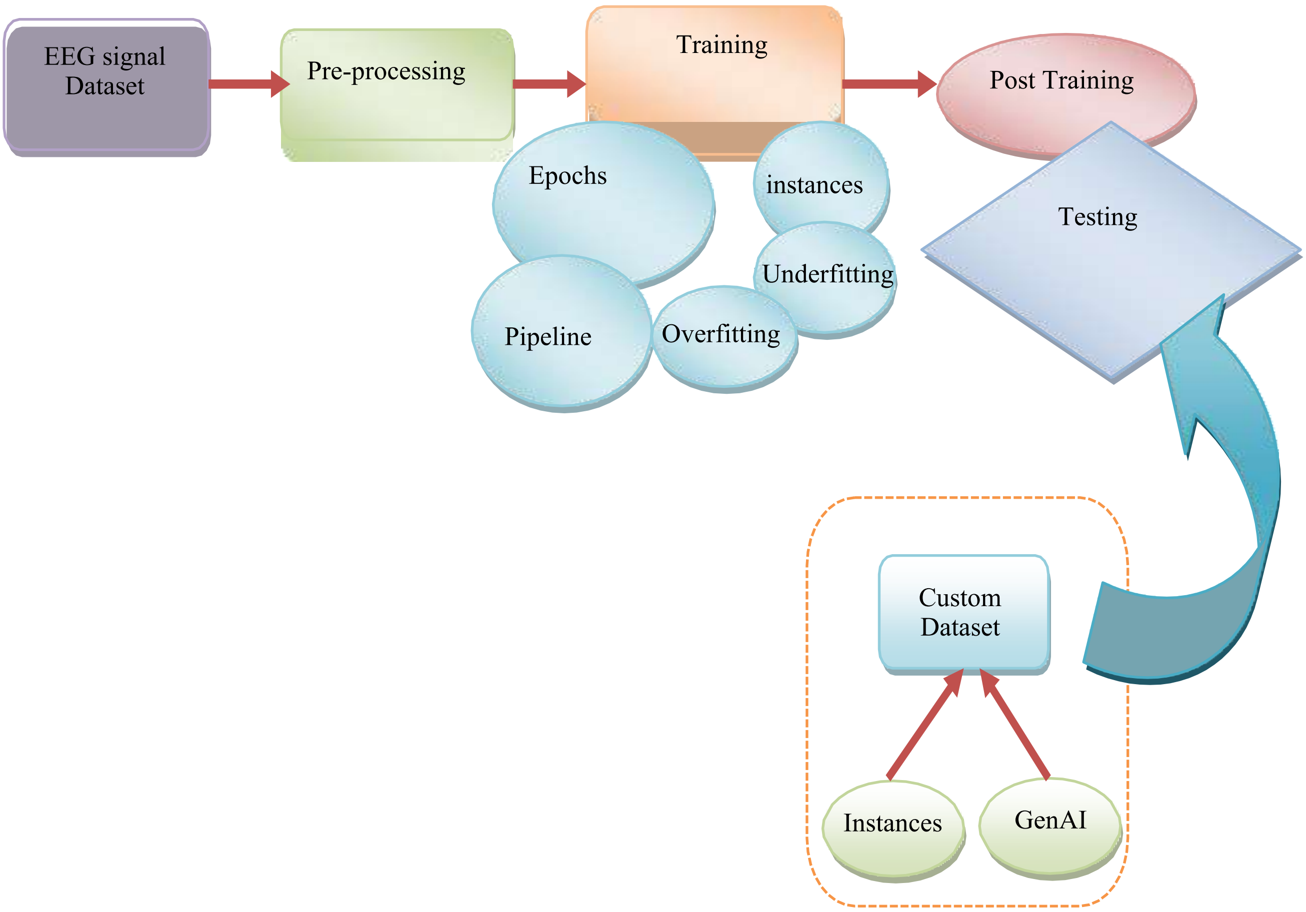

Figure: 4 Block diagram of proposed model

The starting performance of the PMSM was evaluated under no-load conditions with a reference speed of 1000 rpm. During startup, the electromagnetic torque initially increased to overcome inertia and friction and eventually settled to its reference value of zero Nm once the motor reached steady state. It was observed that the Ziegler–Nichols tuned PID controller resulted in a large percentage overshoot and a comparatively longer settling time in the motor speed response. In contrast, the Modified Particle Swarm Optimization (MPSO) based PID controller enabled the motor speed to reach and settle at the desired reference value more rapidly, exhibiting reduced overshoot and improved settling time, thereby demonstrating superior dynamic performance over the conventional Z–N method.

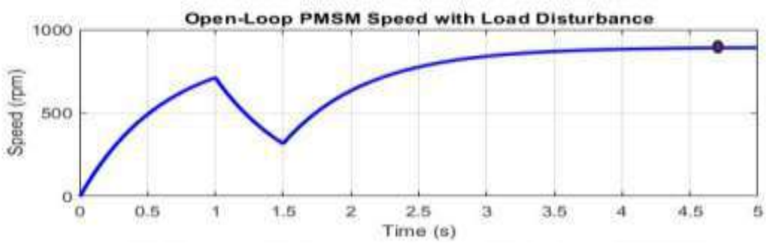

Figure:5 *Load disturbance characteristics of PMSM Model*

The responses of the PMSM under load application at t=1t = 1t=1 s and load removal at t=1.5t = 1.5t=1.5 s are illustrated in Fig. 5 and 6 for output torque and speed. When compared with the conventional Ziegler–Nichol's method, the Modified Particle Swarm Optimization (MPSO) based controller exhibits smaller peak time and reduced settling time during both load application and load removal conditions. These results clearly indicate that the dynamic performance and disturbance rejection capability of the PMSM drive are significantly improved when using the MPSO technique.

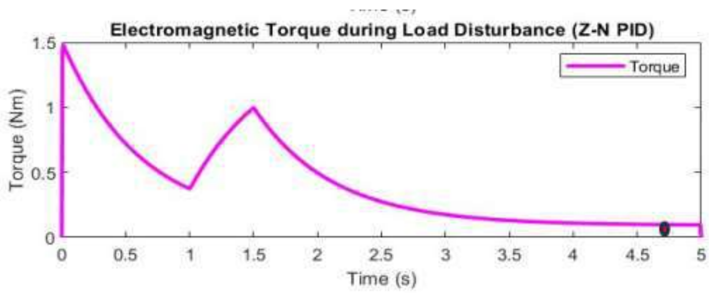

Figure: 6 *Load disturbance characteristics of PMSM Model*

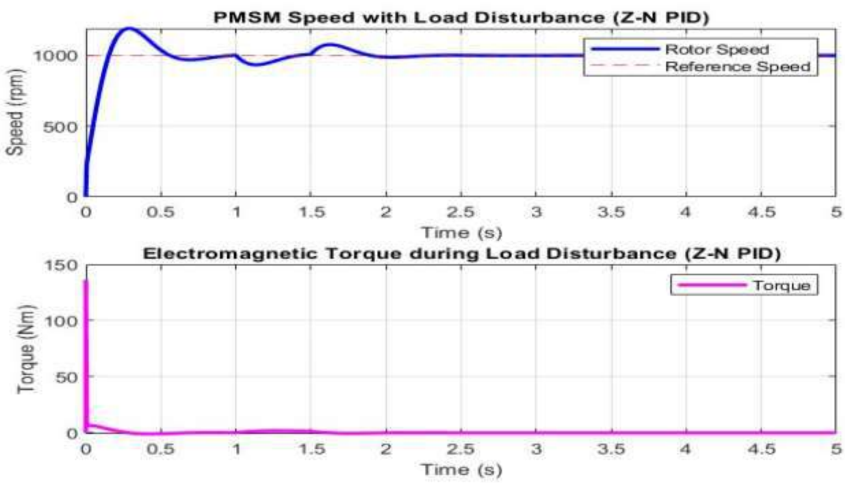

Figure: 7 *LDC of PMSM model with ZN tuned PID controller*

This plot illustrates the PMSM response to load variation when controlled using a Ziegler–Nichols tuned PID controller. Although the closed-loop control significantly improves performance compared to open-loop operation, the system still exhibits noticeable oscillations and a relatively higher settling time, indicating limited damping and slower dynamic response under load disturbances. This graph highlights the superior performance of the MPSO-tuned PID controller, which exhibits minimal speed deviation during load disturbances and rapid recovery to the reference speed, demonstrating excellent transient response and robustness. Compared to the conventional Ziegler–Nichols method, the AI-based tuning techniques significantly improve dynamic behavior. The transient response specifications obtained using

MPSO, MOGA, and Z–N tuned PID speed controllers further confirm that AI-optimized controllers achieve reduced overshoot, shorter settling time, and improved disturbance rejection, with MPSO providing the best overall performance among the methods considered.

Conclusion

In this work, the performance and stability of the PMSM drive have been significantly enhanced by effective tuning of the PID controller parameters using an AI-based technique, namely Modified Particle Swarm Optimization (MPSO). The results obtained with the proposed MPSO-tuned PID controller were systematically compared with those of the conventional Ziegler–Nichols tuned PID controller. It is observed that the proposed controller provides superior transient performance by optimally selecting PID gains, resulting in reduced rise time, minimal peak overshoot, and faster settling time when compared to the Z–N method. Simulation studies under various operating conditions such as starting, speed reversal, load application, and load removal demonstrate that the MPSO-based approach ensures improved speed response, smoother torque characteristics, and reduced stator current oscillations. Furthermore, the proposed control strategy is robust, efficient, and easy to implement, making it suitable for practical industrial applications. The comparative analysis clearly highlights the effectiveness of AI-tuned PID control over conventional tuning methods for achieving enhanced static and dynamic performance of PMSM drives.

References

[1] R. Krishnan, “Permanent Magnet Synchronous and Brushless DC Motor Drives”, U.S.A., CRC Press Taylor & Francis Group, 2010.

[2] B. K. Bose, “Modern Power Electronic and Drives” The University of Tennessee, Knoxville, Upper Saddle River, NJ07458, 2001

[3] PAN Tian-hong, LI Shao-yuan, “Adaptive PID control for nonlinear systems based on lazy learning control Theory and Applications”, 2009.

[4] I J Nagrath and M Gopal, “Control System Engineering,” New Age International Publishers, Edition 2005.

[5] Katsuhiko Ogata, “Modern Control Engineering,” Prentice Hall ofIndia, New Delhi, 4th Ed., June 2002.

[6] J Astrom and T Hagglund, "PID Controllers- Theory, Design and Tuning," Instrument Society of America, 2nd edition, 1995.

[7] J. Kennedy, R. Eberhart, "Particle swarm optimization," Proc. IEEE Int.Conf. Neural Networks, vol. 4, pp. 1942-1948 in 1995

[8] S. Rajasekaran and G. A. Vijayalakshmi Pai, *Neural Networks, Fuzzy Logic and Genetic Algorithm: Synthesis and Applications*, 5th ed., New Delhi, India: Prentice Hall of India, July 2005.

[9] P. Pillay and R. Krishnan, "Modelling of permanent magnet motor drives," *IEEE Transactions on Industrial Electronics*, vol. 35, no. 4, pp. 537–541, Nov. 1988.

[10] B. Singh, B. P. Singh, and S. Dwivedi, "DSP-based implementation of hybrid speed controller for vector-controlled permanent magnet synchronous motor drive," in *Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE)*, July 9–12, 2006,