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Simulation and Analysis of PMSM Speed Control Employing a Hybrid ANN-PID Approach

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ABSTRACT

This paper presents a simulation study and performance evaluation of a speed control system for a Permanent Magnet Synchronous Motor (PMSM) using a hybrid Artificial Neural Network (ANN) and Proportional-Integral-Derivative (PID) controller. The proposed hybrid ANN-PID controller in this paper is intended to provide enhanced dynamic response, reduce steady-state error, and increase disturbance rejection under changing load conditions. The control system designed is simulated and tested in the MATLAB/Simulink environment, comparing and contrasting the motor speed tracking performance, torque response, and current dynamics. Simulation results confirm that the hybrid controller performs better than the conventional PID controller in terms of speed regulation precision, response speed, and mechanical load disturbances tolerance. The study suggests that the combination of ANN and PID control is a very good approach to PMSM speed regulation, which proves to be reliable and effective for engineering practice.

Introduction

Permanent Magnet Synchronous Motors (PMSMs) are becoming more widely used across a range of industrial applications Especially related to electric and hybrid cars that rely on renewable energy due to their low energy consumption, efficiency, compactness, low maintenance needs, and very good dynamic performance. Properties such as smooth torque generation, high torque-to-weight ratio, and the capability to attain high precision speed and position control make permanent magnet synchronous motors highly suitable for state-of-the-art automation and electromechanical systems. Applications involving PMSMs include robots, computer numerical control machine tools, electric and hybrid electric vehicles, aerospace actuators, renewable energy systems such as wind turbines, and high-performance industrial drives [1, 2]. The speed control of PMSM is usually required with high accuracy in order to ensure operation accuracy, especially in the case of variable load condition or external disturbance. Conventional control approaches, i.e., the Proportional-Integral-Derivative (PID) controller, are popular due to their simplicity and performance [3]. Nevertheless, PID controllers will encounter difficulties in addressing the nonlinearities and parameter uncertainties of PMSM systems, and thus result in poor performance in the presence of dynamic and uncertain conditions [4,5].

To alleviate these shortcomings, some advanced control methods have been suggested. Fuzzy logic controllers have proven efficient in managing nonlinearity and uncertainty in PMSM speed control. Artificial Neural Networks (ANNs) are a promising option owing to their learning capability, ability to approximate intricate nonlinear functions, and adaptability to variations in system parameters [6,7]..

1. Literature Review

Recent advances in PMSM speed control increasingly rely on intelligent control techniques to break the limitations of the aforementioned traditional methods. Garcia et al. suggested a modulated model predictive speed control (M-MPSC) system with constant switching frequency and improved tolerance to parameter variations, which has a fast dynamic response and improved stability compared to conventional finite-set MPC methods [8]. Premkumar and Priya added to this with a neural-network-based model predictive control (NN-MPC) for PMSM drives with high transient response and minimal steady-state error under parameter variation, but at the cost of increased computational complexity [9].

In order to further enhance flexibility, Abdelwanis et al. proposed a fuzzy-PID hybrid controller for PMSM-pumps that dynamically varies PID gains according to fuzzy logic in order to deliver minimum overshoot, faster settling, and improved robustness when loads change [10]. Askour et al. conducted an experimental comparison between a Takagi–Sugeno fuzzy logic controller (TS-FLC) and a conventional PI controller implemented via DSP; the TS-FLC outperformed in terms of smoother operation, especially during speed reversal and load disturbances [11].

This paper presents a simulation study and performance analysis of a hybrid ANN-PID controller applied to PMSM speed regulation. The hybrid controller is designed and implemented in MATLAB/Simulink, and its effectiveness is evaluated under various operating scenarios including load variations and reference speed changes. Comparative analysis with a conventional PID controller highlights the benefits of the hybrid approach in terms of accuracy, robustness, and dynamic response. Figure (1) represents the block diagram system.

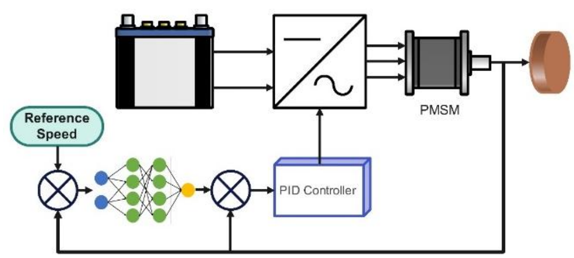

Figure (1): PMSM speed control system block diagram

2. Methodology

This section presents the complete modelling, control system design, and simulation setup for the proposed hybrid Artificial Neural Network–Proportional Integral Derivative (ANN-PID) speed control of a Permanent Magnet Synchronous Motor (PMSM). The methodology is organized into five main parts: mathematical modelling of the PMSM, conventional PID controller design, ANN-based controller development, hybrid ANN-PID control strategy, and simulation setup. The complete simulation model for the designed system is shown in Figure (2).

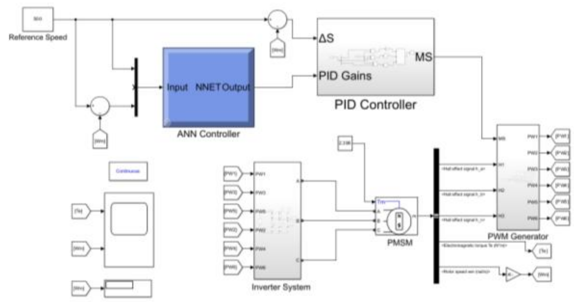

Figure (2): MATLAB/ Simulink of designed system

2.1 Experimental Setup

The PMSM dynamic behavior is expressed in the d-q rotating reference frame to simplify the analysis and control. The surface-mounted type is assumed $(L_d = L_q = L_s)$ which eliminates saliency effects.

The stator voltage equations are:

$$v_d = R_s i_d + L_s \frac{di_d}{dt} - \omega_e L_s i_q \quad (1)$$

$$v_q = R_s i_q + L_s \frac{di_q}{dt} + \omega_e L_s i_d + \omega_e \lambda_m \quad (2)$$

Where:

- v_d, v_q = d-axis and q-axis stator voltages (V)
- i_d, i_q = d-axis and q-axis stator currents (A)
- R_s = stator resistance (Ω)
- L_s= stator inductance (H)
- ω_e= electrical angular speed (rad/s)
- λ_m = permanent magnet flux linkage (Wb)

The electromagnetic torque equation is:

$$T_e = \frac{3P}{4} \lambda_m i_q \quad (3)$$

The mechanical dynamics follow Newton's second law for rotation:

$$J \frac{dw_m}{dt} + B\omega_m = T_e - T_L \quad (4)$$

Where:

- J = moment of inertia (kg·m²)
- B = viscous friction coefficient (N·m·s)
- ω_m = mechanical angular speed (rad/s)
- T_L = load torque (N·m)

These equations form the fundamental basis for PMSM modelling in MATLAB/Simulink, enabling integration with control algorithms for speed regulation [12, 13].

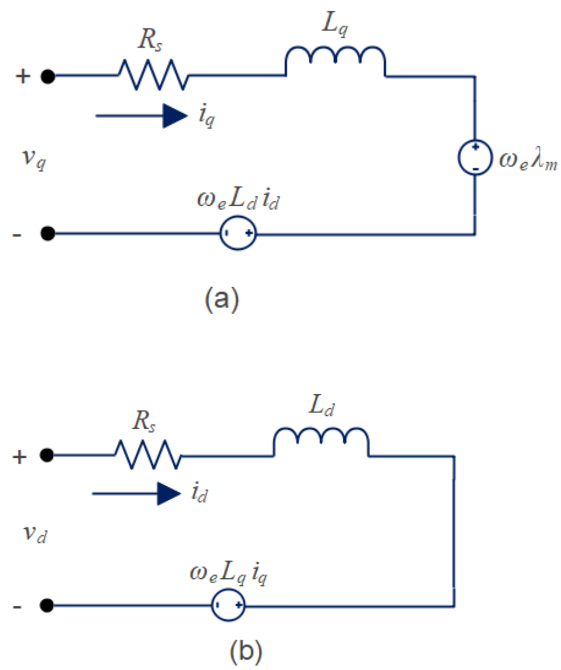

Figure (3): d-q axis equivalent circuit of PMSM. (a) q-axis equivalent circuit; (b) d-axis equivalent circuit.

The numerical values for the coefficients of the PMSM which is used in the proposed system are shown in the table 1.

Table 1: Coefficients value of the PMSM

Coefficient	Value
Rs	0.585 Ω
Ls	0.000785 H
J	0.27 Kg.m²
B	4.047e-05 N.m. s
λm	0.1194 Wb

2.2 Conventional PID Controller Design

A conventional PID controller is implemented as the baseline speed regulator for the PMSM. The controller output is:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \quad (5)$$

Where:

- *e(t)* = speed error signal = ω_{ref} - ω_m
- K_p, K_i, K_d = proportional, integral, and derivative gains

The Ziegler–Nichols tuning method was used for initial parameter estimation, followed by fine-tuning to minimize overshoot, improve settling time, and enhance robustness under variable load torque conditions. Although the PID controller provides satisfactory performance under nominal conditions, its fixed gains limit adaptability to sudden changes in operating parameters [14-16]. The PID Controller simulation is shown in Figure (4).

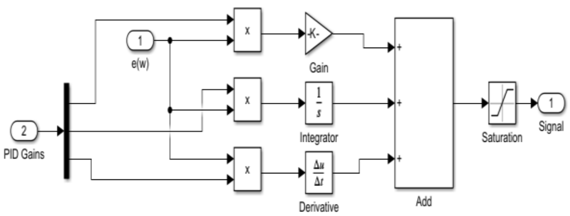

Figure (4): PID Controller MATLAB/ Simulation

2.3 ANN Controller Design

The Artificial Neural Network (ANN) in the proposed hybrid ANN-PID scheme serves as an adaptive supervisory mechanism to dynamically tune the proportional, integral, and derivative gains of the PID controller in real time. The reason behind this adaptation is that it enhances the capability of the controller in dealing with the nonlinear characteristics of the PMSM and maintaining high performance in the face of load disturbances and variations in the parameters. The ANN adopted in this work is a three-layer feed-forward network: an input layer with three neurons corresponding to the speed error, e(t), the change in the error, Δe(t), and the estimated load torque, TL(t); a hidden layer with ten neurons that uses a hyperbolic tangent sigmoid activation function to capture the non-linear relationships; and an output layer with three neurons producing ΔKp, ΔKi, and ΔKd values, using a pure linear activation function.

The network weights are initialized by offline supervised training. Training data are obtained from simulations of PMSM under different operating conditions: for each operating condition, optimal PID gains are determined using the Ziegler-Nichols method and then manually fine-tuned in order to minimize overshoot and settling time. Since nonlinear mappings are involved, the Levenberg-Marquardt backpropagation algorithm is used, owing to its fast convergence and suitability for nonlinear mappings. MSE is used as performance measure, while early stopping is used to avoid overfitting.

In real-time operation, the ANN receives instantaneous error signals and outputs gain corrections, which are added to the nominal PID gains according to

$$K_p(t) = K_{p0} + \Delta K_p, K_i(t) = K_{i0} + \Delta K_i, K_d(t) = K_{d0} + \Delta K_d \quad (6)$$

This mechanism allows the control system to continue adapting, improving its transient response, reducing overshoot, and maintaining robust performance despite uncertainties in the system.

The ANN controller was trained for 500 epochs, which was sufficient to minimize training error without overprocessing. The dataset was divided into three parts: 70% for training, 15% for verification, and 15% for testing. This system has made sure that the ANN-PID hybrid control system for PMSM is well established and works efficiently. Figure (5) represents MATLAB Simulink design for ANN controller and its layers.

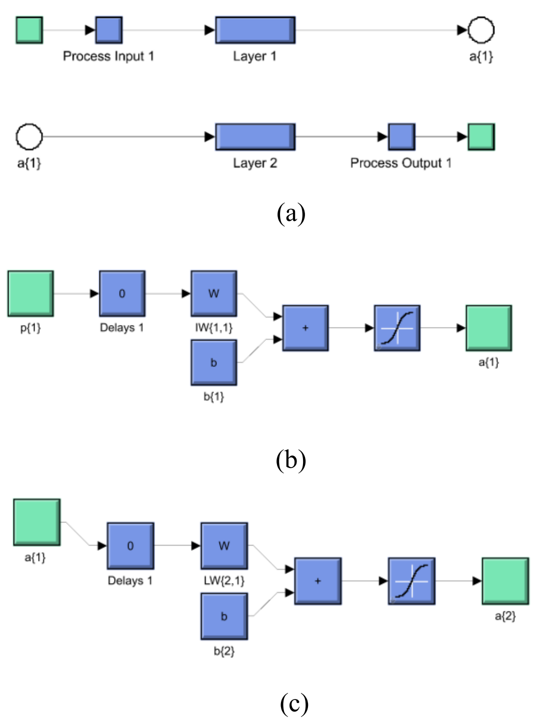

Figure (5): (a) ANN controller MATLAB Simulation design, (b) layer 1, and (c) layer 2

3. Hybrid PID-ANN Control System

The hybrid PID-ANN control approach integrates the stability and simplicity of a conventional PID controller with the adaptive learning capability of an ANN. Under this scheme, the PID controller is responsible for guaranteeing a fast transient response with stability, whereas the ANN continuously adapts the parameters of the PID controller in real time to cope with system nonlinearities, parameter variations, and external disturbances. Using the speed error and its derivative as inputs, the ANN optimizes the proportional, integral, and derivative gains to maintain high performance under a wide range of operating conditions.

The integration of ANN in the PID system allows the control system to achieve improved robustness, minimum overshoot, reduced settling time, and improved steady-state accuracy compared to when used individually with separate PID or ANN controllers. A block diagram of the hybrid system describes the way the ANN block collaborates with the PID loop to generate an adaptive control signal for the PMSM to facilitate efficient and reliable speed regulation under fluctuating loads and disturbances.

It can be clarifying the procedure of working the proposed system by presenting the steps in a simple flow chart diagram in figure (6).

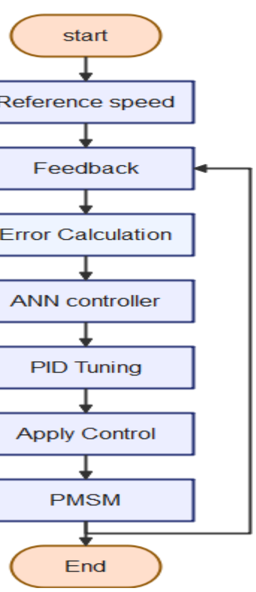

Figure (6): Flow chart diagram of the propose system

Results and Analysis

This study examines the dynamic performance of a hybrid PID–ANN controller in regulating a Permanent Magnet Synchronous Motor (PMSM) under constant mechanical load torque of 10 N·m. at sampling time 50*10-6 second. The aim of the controller is to regulate rotor speed for stepped reference commands with torque robustness and stability.

In Figure (7) there are three various transitions in the reference speed profile: an initial rise from 0 to 300 rad/s at 0.5 s, a sudden drop to 50 rad/s at 2.5 s, and a third one to 150 rad/s at 3.5 s. The test is focused on examining the response of the controller at high-speed, low-speed, and mid-speed operating points.

The speed of the rotor tracks closely the reference trajectory with negligible delay and high precision. During the initial period of acceleration, rotor speed climbs to 300 rad/s within about 0.3 seconds, or a rise time of 0.2–0.3 s. The system maintains this speed well, with negligible steady-state error, once more demonstrating that the controller is able to sustain operation at high speeds and with load. Upon a drop in the reference to 50 rad/s, the rotor speed falls off smoothly and comes to rest within 0.2 seconds, without overshoot or oscillation. The final transition to 150 rad/s is tracked very closely and rotor speed comes to rest in 0.3 seconds. During the transitions, the steady-state error is close to zero, while overshoot is small, reflecting very good speed regulation.

The electromagnetic torque Te gives an indication of the effort produced by the controller in countering the permanent mechanical load and dynamic effect: During the starting acceleration, the torque is maximum and around 25–30 N·m to oppose the inertia and friction in addition to the 10 N·m load. Once the rotor reaches the steady speed value of 300 rad/s, it stabilizes at around 20 N·m, considering the presence of both the load and residual dynamic compensation. In the case of speed reference reduction to 50 rad/s, the delivered torque falls to almost 0 N·m while catching the lower kinematic demand. After the first acceleration up to 150 rad/s, ripples of about 15–20 N·m are experienced before stabilization. The result confirms that the hybrid PID–ANN controller guarantees fast dynamic response, with settling times below 0.3 s, accurate speed tracking independently from set point level, and adaptive stable torque modulation according to the mechanical demand. The nonlinear compensation due to the ANN element provides improvement in nonlinear compensation and load adaptability, while the PID contribution ensures deterministic control and a baseline stability. This makes a powerful and sensitive control system working under extended load conditions and changing speeds.

Thus, the hybrid controller is a good candidate for the precise speed regulation of PMSMs with torque smoothness and robustness against mechanical disturbances. The study results create the possibility of its use in industrial, automotive, and robotics applications where there may be fixed loading situations with dynamic speed profiles.

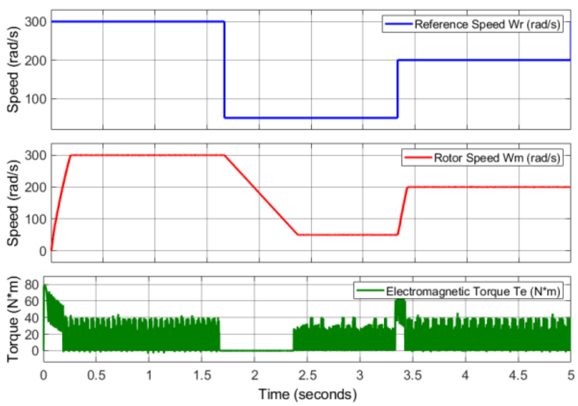

Figure (7): Dynamic response of the hybrid PID–ANN controller applied to a PMSM under constant mechanical torque. Top: Reference speed Wr (rad/s). Middle: Rotor speed Wm (rad/s). Bottom: Electromagnetic torque Te (N·m).

Figure (8) illustrates the dynamic performance of the hybrid PID–ANN controller applied to a PMSM under a constant reference speed of 200 rad/s, while the mechanical load torque varies over time. The mechanical load (blue curve) first starts at a high value of 40 N·m that represents heavy loading. At 1.5 seconds, the torque falls sharply down to 10 N·m, simulating the event of a sudden unloading. Later, at 3.5 seconds, the torque is increased again to 20 N·m, introducing a disturbance in the form of a moderate load. Despite such abrupt changes, the rotor speed (red curve) remains remarkably stable around the reference value. It starts at about 190 rad/s, reaching the 200 rad/s reference within the first 0.2 seconds and maintains this level within a very small fluctuation range throughout the whole simulation. This demonstrates the good performance of the controller against load disturbances by maintaining a good speed regulation. The electromagnetic torque (green curve) dynamically responds to the dynamic change of the mechanical load: it starts at about 80 N·m to compensate for the high initial load and the inertia of the system, and stabilizes at about 40 N·m at 0.5 seconds, following the mechanical torque. Once the load goes down to 10 N·m, the electromagnetic torque becomes very stable, reflecting the buffer to system stability ensured by the controller. By increasing the load to 20 N·m at 3.5 seconds, the torque rises again with seeming oscillations that signify active compensation. These results reflect the robustness of the hybrid PID–ANN controller against the changes in load. The PID block promises baseliner stability, while nonlinearities and sudden load changes are compensated by the ANN block. Overall, the system provides accurate speed tracking and dynamic torque correction, which witnesses its suitability for high-performance control under changing mechanical conditions.

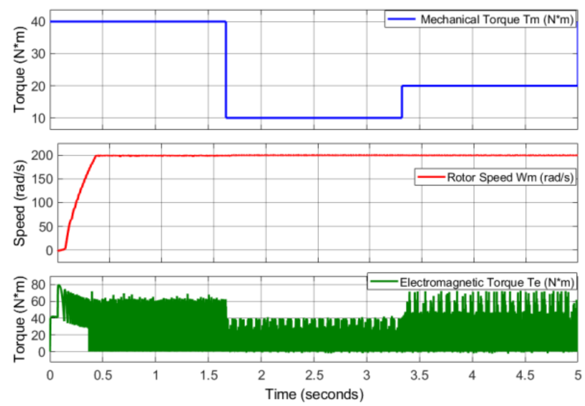

Figure (8): Rotor Speed and Electromagnetic Torque Response of PMSM Controlled by Hybrid PID–ANN Scheme under Constant Reference Speed of 200 rad/s and Time-Varying Mechanical Load

This work is based solely on simulation without practical testing, which may lead to discrepancies in actual application due to sensor noise and variations in the motor's physical parameters under operating conditions. Furthermore, the scope of the tests is limited and does not include a comprehensive mathematical analysis of stability or a broad evaluation of different load and speed conditions.

Conclusion

In this study, the effectiveness of a hybrid PID–ANN control strategy for PMSM with changing mechanical load conditions and references speed has been confirmed. The suggested strategy combines the simplicity and robustness of traditional PID control with the adaptability and learning capabilities of artificial neural networks to ensure rigid speed control and quick torque response, the controller enabled easy tracking of the reference speed, irrespective of whether the mechanical load was at rest or in motion, the PMSM reaches the reference speed (300 rad/s) at only 0.3s see figure (7).

Its ability to reject disturbance and acceptance of nonlinear system dynamics show it to be robust and versatile, its notice from figure (8) when the mechanical torque drops form (40-10) N*m the PMSM still constant, the ANN part was responsible for enhancing the response of the system to transient disturbances, while the PID took care of smooth and stable operation of all this, the hybrid PID-ANN controller is the most appropriate to utilize in motor control that is required to operate optimally, specifically if the load is changing or the environment needs to be very precise. Because of its robustness and adaptability, it is the most appropriate to be implemented in current industrial and automation systems.

The future study recommends implementing the proposed system on actual hardware or using HIL for practical performance verification, in addition to developing the neural network and improving real-time learning capabilities, expanding testing to include multiple operating conditions, and conducting deeper stability analysis to ensure higher reliability in industrial applications.

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