International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 38 العدد
Part 1 المجلد

المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ

http://www.doi.org/10.62341/inad3258

Received	2025/12/29	تم استلام الورقة العلمية في
Accepted	2026/01/19	تم قبول الورقة العلمية في
Published	2026/01/20	تم نشر الورقة العلمية في

Design, Analysis, and Performance Evaluation of Backstepping Control for Permanent Magnet Synchronous Motor Drives

Tareq N. Elgargani[1], Nuradeen k. Fethalla[2], Abdulkarim A. Hudoud[3], Salem O. Abid[4]

1,2- University of Elmergib, Faculty of Engineering Alkhums-Libya
3- University of Azzaytuna, Faculty of Engineering Tarhuna-Libya
4- University of Alasmarya Islamic, Faculty of Engineering Zliten-Libya

tngargany@elmergib.edu.ly

Abstract

Permanent-magnet synchronous motor drive (PMSMD) exhibit superior power density and efficiency, yet its highly coupled, parameter-sensitive, and non-linear dynamics challenge traditional linear controllers. This paper presents a complete Lyapunov-based Backstepping controller that are systematically exploits the nonlinear d-q model to obtain globally stable, disturbance-robust, and sensorless-capable current and speed regulators. Magnet Synchronous Motor Drive utilizing the Backstepping control technique, characterized by its recursive and systematic approach for synthesizing nonlinear control laws based on Lyapunov stability theory. The primary aim of this control scheme is to establish a virtual control at each synthesis step, thereby ensuring the convergence of the motor's speed to its desired setpoint and the direct-axis current to zero, which facilitates maximum torque operation. The methodology involves an initial definition of the PMSM's state model within the d-q reference frame, followed by the systematic synthesis of the Backstepping controller. A comparison between Backstepping and Neural Network controller is done in this study. The results obtained demonstrate the superiority of Backstepping approach in meeting the demanding requirements of PMSM drive systems. Simulation results, obtained using

http://www.doi.org/10.62341/inad3258

MATLAB/Simulink environment, effectively demonstrate the efficacy of the proposed speed control.

Keywords: PMSM drive Model, Backstepping controller, Neural Network controller (NN), Speed control.

تصميم وتحليل وتقييم أداء التحكم بطريقة الرجوع التدريجي لمحركات الدفع ذات المغناطيس الدائم المتزامن

طارق القرقني[1]، نورالدين فتح الله[2]، عبد الكريم حدود[3]، سالم اعبيد[4]
1، 2 جامعة المرقب، كلية الهندسة، الخمس، ليبيا
3 جامعة الزيتونة، كلية الهندسة، ترهونة، ليبيا
4 الجامعة الاسمرية الإسلامية، زليتن، ليبيا
tngargany@elmergib.edu.ly

الملخص

تتميز محركات الدفع المتزامنة ذات المغناطيس الدائم (PMSMD) بكثافة طاقة وكفاءة عاليتين، إلا أن ديناميكياتها المتداخلة والحساسة للمعاملات اللاخطية تشكل تحدياً للمتحكمات الخطية التقليدية. يقدم هذا البحث إطار عمل متكامل يعتمد على تقنية التحكم باستخدام طريقة (Backstepping) التي تعتمد على نظرية ليابونوف لتحقيق الاستقرارية، تم العمل بنموذج (d–q) اللاخطي بشكل منهجي للحصول على الاستقرار، مقاومة للاضطرابات، ومنظمات التيار والسرعة القادرة على العمل بدون حساسات. يعتمد نظام دفع المحرك المتزامن بالمغناطيس الدائم على تقنية التحكم (Backstepping) ، التي تتميز بنهجها التكراري والمنهجي في توليف قوانين التحكم اللاخطية استناداً إلى نظرية استقرار ليابونوف. الهدف الأساسي من هذا النظام هو إنشاء تحكم افتراضي في كل خطوة توليف، مما يضمن تقارب سرعة المحرك إلى نقطة الضبط المطلوبة، وتيار المحور المباشر إلى الصفر، الأمر الذي يسهل تحقيق عزم الدوران الأقصى. تتضمن المنهجية تعريفاً أولياً لنموذج حالة (PMSM) ضمن إطار الإحداثيات (d–q) ، يتبعه منهجية تصميم لمتحكم (Backstepping). كما تم إجراء مقارنة بين متحكم (Backstepping) ومتحكم الشبكة العصبية (NN) في هذه الدراسة. و قد أظهرت النتائج المُتحصّل عليها

http://www.doi.org/10.62341/inad3258

تفوق طريقة (Backstepping) في تلبية المتطلبات الصارمة لأنظمة (PMSM). تم عرض نتائج المحاكاة باستخدام بيئة (MATLAB/Simulink) للتحقق من فعالية التحكم المقترح في السرعة.

الكلمات المفتاحية: نموذج المحرك التزامني ثلاثي الطور PMSM، متحكم التراجع، متحكم الشبكة العصبية، التحكم في السرعة.

Introduction

The Permanent-Magnet Synchronous Motor (PMSM) has firmly established itself as a cornerstone of modern electric drive systems. Celebrated for its high-power density, exceptional efficiency, and superior dynamic performance, the PMSM is the engine of choice for a diverse range of high-performance applications, from the precision demands of industrial robotics and computer-numerically-controlled (CNC) machine tools to the transformative fields of electric vehicles (EVs) and marine electric propulsion [1,2,3]. However, harnessing the full potential of the PMSM is a complex control challenge. Its mathematical model is inherently nonlinear and multivariable, with strong coupling between its electrical and mechanical states . This complexity is compounded in real-world operations by inevitable uncertainties, including internal parameter variations due to temperature flux and magnetic saturation, and external disturbances such as abrupt load torque changes [4]. For decades, the industry standard has relied on linear control methods, particularly the Proportional-Integral (PI) controller, prized for its simplicity and ease of implementation within a Field-Oriented Control (FOC) scheme [5]. Yet, this very simplicity becomes a limitation, as linear controllers are inherently ill-suited to manage the nonlinear dynamics of the PMSM, often resulting in sluggish response, significant overshoot, and poor disturbance rejection [6]. This performance gap has catalyzed a significant shift in research towards sophisticated nonlinear control strategies. Among these, the backstepping control methodology has emerged as a particularly powerful and systematic framework. Unlike methods that seek to cancel out nonlinearities, backstepping works with them. It is a recursive design procedure that decomposes the complex, high-order motor system into a series of simpler, lower-order subsystems. By constructing a control law step-by-step and rigorously anchoring

http://www.doi.org/10.62341/inad3258

each step in Lyapunov stability theory, backstepping guarantees global asymptotic stability, robust performance, and precise setpoint tracking [7, 8, 9, 10,11]. While a standalone backstepping controller marks a substantial improvement, its performance can still be degraded by persistent and unknown disturbances. This recognition has spurred the development of advanced hybrid control schemes that merge the structured stability of backstepping with the strengths of other advanced techniques.
In light of this extensive body of work, this paper synthesizes the design and evolution of backstepping control for PMSMs. It explores the fundamental principles of the method and critically examines the performance enhancements achieved through its various Neural networks control. By comparing between backstepping and Neural network controller, we underscore the superiority of backstepping approach in meeting the demanding requirements of PMSM drive systems.

Literature Review

For instance, integrating sliding mode control introduces inherent robustness against model uncertainties and disturbances [12]. The integration of computational intelligence, through fuzzy logic systems and neural networks, offers a model-free approach to adaptively learn and compensate for system uncertainties, leading to highly resilient controllers like fuzzy approximation-based backstepping [13]. Simultaneously, advancements in sensorless control, utilizing observers like the Extended State Observer (ESO) and specialized backstepping observers, seek to eliminate physical sensors for reduced cost and increased reliability, without sacrificing estimation accuracy [14]. Direct Torque Control (DTC) is a popular strategy for Permanent Magnet Synchronous Motors (PMSMs) due to its fast dynamic response and low dependency on motor parameters. However, a significant limitation of traditional DTC is its reliance on a PI controller in the speed loop, which can lead to a sluggish speed response. While improvements have been made to reduce torque and flux ripple, such as multi-stage hysteresis controllers and sliding mode controllers combined with space vector modulation, these methods often fail to account for sudden changes in system parameters. This hybrid approach not only enhances the performance of traditional DTC but also actively suppresses the

http://www.doi.org/10.62341/inad3258

negative effects of parameter deviations, thereby significantly improving the system's robustness [15]. Achieving high-precision position tracking for PMSMs is a critical challenge, especially in complex application environments where nonlinear factors degrade control performance. While traditional PID control struggles in these scenarios, sliding mode control (SMC) offers a robust alternative due to its insensitivity to parameters and disturbances. Many researchers use sliding surfaces that can only drive PMSM system states to a bounded region and often suffer from chattering [16, 17]. Previous research has improved SMC by incorporating elements like fractional calculus to reduce chattering or by combining it with backstepping control to enhance robustness. To combat this, a controller that merges an improved sliding mode reaching law with a nonlinear disturbance observer (NDOB). The improved reaching law ensures accurate position tracking, while the NDOB estimates and compensates for nonlinear disturbances in real-time. Simulation results confirm that this method reduces tracking error and improves both response speed and anti-interference capability [18]. Predictive control, while powerful, can suffer from steady-state error, often requiring a load torque estimator. This composite design is tested to mitigate the adverse effects of model mismatches and unknown disturbances on the PMSM's dynamic response [19]. Mechanical sensors for position and speed in PMSM drives increase cost, complexity, and reduce reliability, making sensorless control an attractive and challenging research area. Among various state observers, the Extended Kalman Filter (EKF) stands out for its optimal performance in noisy, nonlinear systems. The EKF provides robust estimation of the rotor speed and position, overcoming the challenges posed by the system's strong nonlinearity and sensor limitations. [20]. A fractional-Order Adaptive Backstepping Fuzzy PID (FOAB-FPID) controller is designed, combining the advantages of fuzzy control and fractional-order theory. Simulation and experimental results demonstrate the superior control effect of this method [21, 22, 23]. A nonlinear control strategy based on input-output linearization is proposed for permanent magnet synchronous motor drives, achieved by transforming the inherent nonlinearities of the PMSM model into a linearized system [24]. Notwithstanding the differences among them, advanced controllers—including optimal

http://www.doi.org/10.62341/inad3258

and robust strategies—are routinely benchmarked against the industry-standard PI controller. For example, MPC has been compared with PI in PMSM applications in [25]. The rotor speed obtained from the PI controller in the speed control loop is compared to the reference speed to generate an error signal [26]. Conventional PMSM control systems face significant challenges, including the controller's sensitivity to motor parameter variations and its vulnerability to disturbances. Upon fluctuations in motor parameters or the onset of disturbances, the baseline controller exhibits limited adaptability and robustness to interference [27]. The IBSC, is designed via a systematic Lyapunov-based methodology, overcomes the deficiencies of conventional PI controllers in handling nonlinearities and disturbances while minimizing steady-state error through integral action. The effectiveness of this hybrid SLPS-IBSC-EKF strategy is demonstrated through comparative simulations and validated experimentally on a dSPACE DS1104 real-time control platform [28,29].

Mathematical Modeling of PMSM Drive

- Dynamic Model in the d-q Reference Frame

The mathematical modeling of a Permanent Magnet Synchronous Motor drive is a crucial step in the design and analysis of its control system. While the motor's behavior can be described in the stationary abc reference frame, the resulting equations are nonlinear and time-varying, which complicates the control design process. To overcome this, the model is typically transformed into the synchronously rotating d-q reference frame, which simplifies the equations and facilitates the implementation of the control system. In this frame, the d-axis is aligned with the rotor's magnetic flux, and the q-axis is orthogonal to it. This transformation, known as the Park transformation, converts the three-phase stator currents and voltages into two DC components, i_d and, i_q, and v_d and, v_q, respectively. The resulting dynamic model in the d-q frame consists of a set of coupled, nonlinear differential equations that describe the relationships between the stator voltages, currents, and the rotor's electrical angular velocity.

The dynamic model of the PMSM drive in the d-q reference frame is given by the following set of equations [30]:

http://www.doi.org/10.62341/inad3258

$$\frac{di_d}{dt} = -\frac{R}{L} i_d + p\omega i_q + \frac{v_d}{L} \quad (1)$$
$$\frac{di_q}{dt} = -\frac{R}{L} i_q - p\omega i_d - \frac{p\phi_f}{L}\omega + \frac{v_q}{L} \quad (2)$$
$$\frac{d\omega}{dt} = \frac{3p\phi_f}{2J} i_q - \frac{B}{J}\omega - \frac{T_L}{J} \quad (3)$$

Where R, L stator resistance/inductance, p pole-pairs, ϕ_f PM flux, J inertia, B friction, T_L load torque.

- **State-Space Form**

Define state vector $\mathbf{x} = [x_1\ x_2\ x_3]^T = [\omega\ i_q\ i_d]^T$ yields:

$$\dot{\mathrm{x}} = \mathrm{A(x)x + Bu + d} \quad (4)$$

To formulate the design problem, according to equations (1)-(3), the state space model of the PMSM can be rewritten as the following nonlinear system:

$$\mathrm{A(x)} = \begin{bmatrix} -\frac{B}{J} & \frac{3p\phi_f}{2J} & 0 \\ -\frac{p\phi_f}{L} & -\frac{R}{L} & -px_1 \\ 0 & px_1 & -\frac{R}{L} \end{bmatrix},\ \mathrm{B} = \begin{bmatrix} 0 & 0 \\ \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix},\ \mathrm{d} = \begin{bmatrix} -\frac{T_L}{J} \\ 0 \\ 0 \end{bmatrix} \quad (5)$$

- **Recursive Backstepping Design**
  - **Goal:** Track smooth speed reference $\omega^*(t)$ while regulating $i_d^* = 0$.
    - **Step 1**-Speed Error Subsystem

Let $z_1 = \omega^* - x_1$. Choose control Lyapunov function (CLF) $V_1 = \frac{1}{2} z_1^2$.

$$\dot{V}_1 = z_1(\dot{\omega}^* - a_1 x_2 - a_2 x_2 x_3 + a_3 x_1 + d) \quad (6)$$

View x_2 as virtual control. Desired x_2^*:

http://www.doi.org/10.62341/inad3258

$$x_2^* = \frac{1}{a_1}\left(\dot{\omega}^* + a_3 x_1 + \hat{d} + k_1 z_1\right), \quad k_1 > 0 \tag{7}$$

$\hat{d}$ is an estimate of $\frac{T_L}{J}$. Then $\dot{V}_1 = -k_1 z_1^2$.

- **Step 2**- q-Axis Current Error

Define $z_2 = x_2^* - x_2$. Augment CLF: $V_2 = V_1 + 1/2\, z_2^2$.

$$v_q^* = \frac{1}{b_4}\left(k_2 z_2 + z_1 a_1 + \dot{x}_2^* - b_1 x_1 - b_2 x_1 x_3 + b_3 x_2\right) \tag{8}$$

Yielding

$$\dot{V}_2 = -k_1 z_1^2 - k_2 z_2^2 \tag{9}$$

- **Step 3**- d-Axis Current Error

Let $z_3 = 0 - x_3$. Final CLF $V_3 = V_2 + 1/2\, z_3^2$.

$$v_d^* = \frac{1}{b_7}\left(k_3 z_3 - b_5 x_1 x_2 + b_6 x_3\right) \tag{10}$$

Overall $\dot{V}_3 = -\sum k_i z_i^2 < 0$. This guarantees the asymptotic convergence of the d-axis current tracking error to zero, therefore the d-axis current converges to its desired value i_{d-ref}.

Description of control objective and methodology

The core principle of the backstepping control methodology involves stabilizing cascaded subsystems, thereby conferring properties of robustness and global asymptotic stability in the Lyapunov sense. This constitutes an iterative design procedure that generates a virtual control input at each stage, ensuring the system's convergence to its equilibrium state. This can be achieved through the sequential application of Lyapunov functions, incrementally stabilizing each phase of the synthesis.

The objective is to formulate a control strategy that guarantees the existence of a positive definite Lyapunov function, whose derivative consistently remains negative definite. The iterative construction of this Lyapunov function is contingent upon the system’s preceding state. By progressively augmenting the prior Lyapunov control

http://www.doi.org/10.62341/inad3258

function, a new composite Lyapunov function can be constructed, thereby establishing the overall stability of the system.
Figure (1) illustrates the comprehensive (PMSM) control system, comprising a synchronous motor coupled to a load, a voltage source inverter, and two field-oriented controllers.

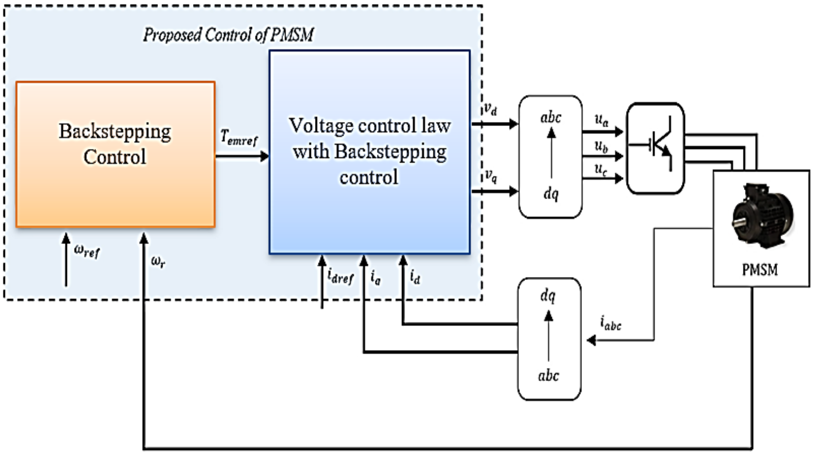


Figure 1. Block diagram of Backstepping control of PMSM

The external loop, serving as the primary controller, employs a univariate predictive control strategy for speed regulation. Within this external loop, robust predictive control is implemented to maintain the motor's speed at its designated reference level. Conversely, the internal loop, constituting the secondary controller, features a d-axis control law that adopts the command strategy of. Given the article's primary focus on (PMSM) speed control, the d-axis control is realized through a backstepping control algorithm, specifically designed to establish a constant d-axis current. Similarly, the q-axis control is formulated utilizing an integral backstepping control algorithm to ensure torque stabilization at the predetermined reference level.

The Role of Stator Current in a PMSM drive

In a (PMSM) drive, the stator current isn't just a source of power-it's the primary tool we use to precisely control the motor's behavior. Think of it like the gas pedal and steering wheel of a high-performance car combined, it doesn't just make the car go, it

http://www.doi.org/10.62341/inad3258

controls *how* it goes. Unlike a simple AC induction motor, the PMSM has its own strong, permanent magnetic field on the rotor. Our job with the stator current is to create a second rotating magnetic field that "locks on" to this rotor field, pulling it around to generate motion. The real magic lies in how we break down the stator current into two separate, independent components to control Torque and speed with exceptional precision.

Breaking Down the Current: The d-q Model

To make control easier, researchers use a mathematical transformation that shifts our perspective. Instead of looking at the three messy, alternating currents (I_a, I_b, I_c) in the physical motor windings, we imagine the current as two direct current (DC) components in a fictional, rotating frame that's stuck to the rotor itself. These two components are:

1. **The d-axis current (I_d): The "Field-Weakening" Current**

- The 'd' stands for "direct," as this component is aligned directly with the north-south poles of the rotating permanent magnet.
- Since the magnet's field is already fixed, pushing current in this direction doesn't primarily produce torque. Instead, it either reinforces or, more commonly, opposes the permanent magnet's own field.
- Why would we oppose it? At high speeds, the motor's back-electromotive force (Back-EMF) becomes so high that the inverter can't push enough voltage to increase speed further. By using a negative I_d, we intentionally "weaken" the total magnetic field, allowing the motor to run faster than its base speed-a crucial technique known as field-weakening.

2. **The q-axis current (I_q): The "Torque-Producing" Current**

- The 'q' stands for "quadrature," meaning this current is perpendicular (90 degrees ahead) to the magnet's axis.
- This is the real workhorse. The I_q component is directly responsible for generating electromagnetic torque. It's the force that tries to "drag" the rotor's field along, making it spin.

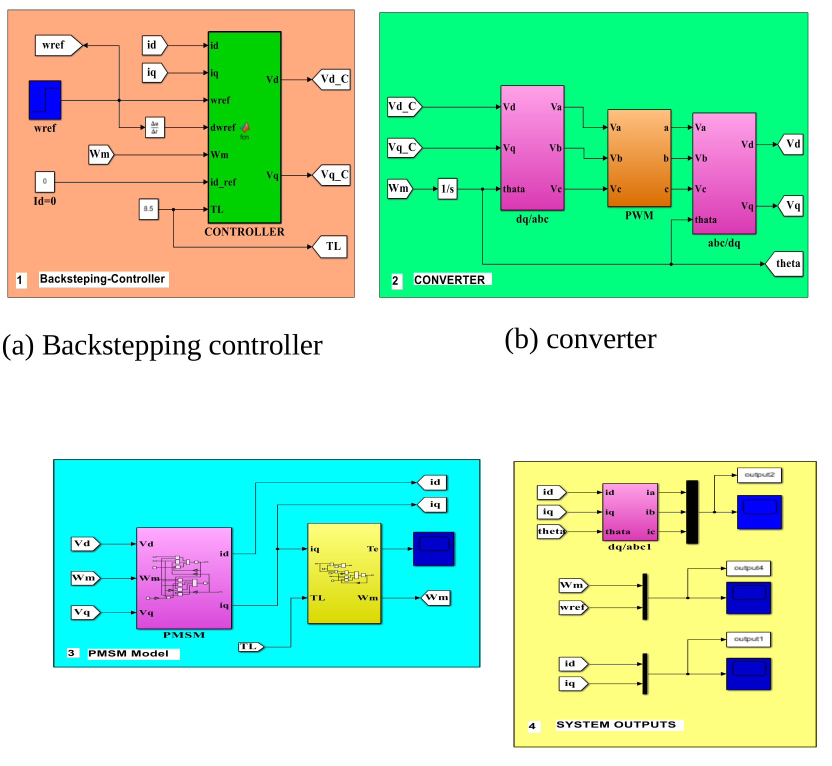
The relationship is perfectly simple: The motor's torque is almost directly proportional to the value of I_q. To get more torque, you

http://www.doi.org/10.62341/inad3258

command more $\boldsymbol{I_q}$. To reduce torque, you command less. It's very similar to how torque is controlled in a separate-excitation DC motor, which is why this method is so effective.

Simulation and result

The simulation of the overall system (PMSM) drive model was constructed and rigorously tested within the MATLAB/Simulink environment to validate the performance and robustness of the proposed Backstepping control strategy. The complete system architecture, as illustrated in figure. (2) integrates a PWM voltage inverter with the PMSM drive model, which is fed by the control voltages generated by the Backstepping controller.



(a) Backstepping controller (b) converter

(c) PMSM Model (d) System Outputs

Figure 2. MATLAB Simulink blocks of Backstepping for PMSM drive model

http://www.doi.org/10.62341/inad3258

The controller's core function is to calculate the required d-axis and q-axis voltages (v_d and v_q) to accurately track the desired speed reference (ω_{ref}) while maintaining the d-axis current (i_d) at zero for maximum torque per ampere operation. This process involves critical transformations, including measuring the three-phase stator currents (i_a, i_b, i_c) and converting them into the d-q reference frame using the rotor position (θ_r), and subsequently converting the computed d-q control voltages back to the three-phase voltages for the inverter.

The simulation was conducted using the specific PMSM parameters listed in table 1, such as a stator resistance of 3.59 Ω, stator inductance of 0.0435 H, and a rotor inertia of 0.015 kg.m^2. The performance was evaluated under challenging dynamic scenarios.

Table 1: specific PMSM parameters

Parameters	Symbol	Value
Rated stator voltage	V_s	380 V
Load Torque	T_L	6.45 N.m
Moment of inertia	J	0.015 kg.m^2
Stator resistance	R_s	3.59 Ω
Stator inductance	L_s	0.0435 H
Rated Frequency	F	60 Hz
Pole pairs	p	6
Nominal rotor speed	nn	125.66 rad/sec
Permanent magnet flux	λ_m	0.545 Vs
Direct-axis inductance	L_d	0.036 H
Quadrature-axis inductance	L_q	0.051 H
constant	K_E	0.148 V.rad/s

The gains for the Backstepping controller are selected as k_1 = 50, k_2 = 0.98, and k_3 = 40. The controller's performance was tested under various dynamic conditions.

As shown in figure (3), the model was subjected to a sudden speed increase from 100 rad/sec to 125.66 rad/sec at 0.1 seconds, with a load torque of 6.45 N.m. The actual speed converged to its reference within about 15.2 msec with no overshoot and a very small steady-state error 0.64%. At 0.02 sec, the speed showed a small transient

http://www.doi.org/10.62341/inad3258

drop but quickly recovered, demonstrating good disturbance rejection.

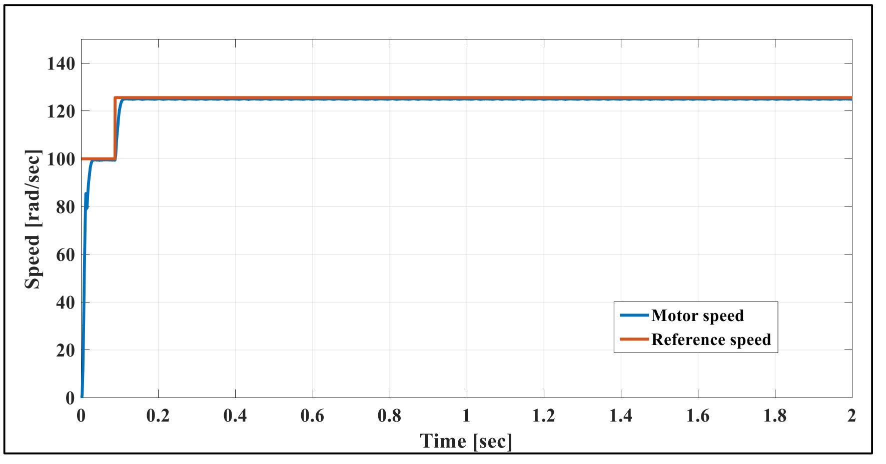


Figure3. Speed response of PMSM drive model with Backstepping controller

As depicted in figure (4) the i_q current exhibited a large but brief overshoot during startup, and it stable at 6.86 A, while the i_d current was quickly regulated to zero. The results demonstrated the controller's excellence.

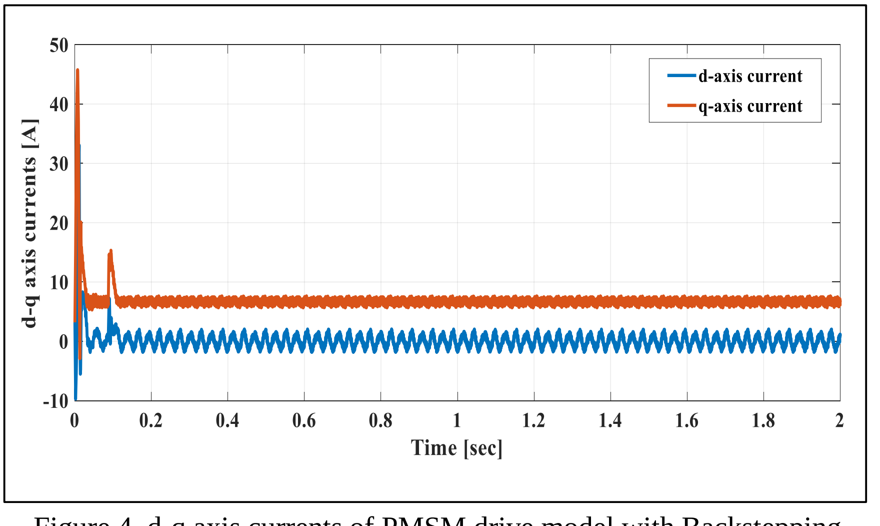
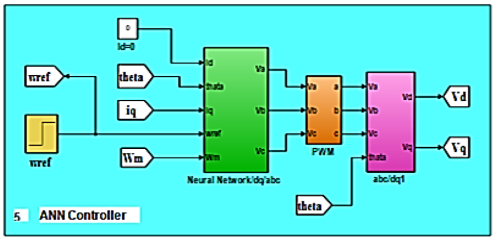


Figure 4. d-q axis currents of PMSM drive model with Backstepping controller

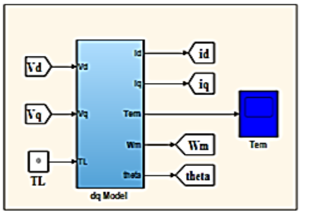
http://www.doi.org/10.62341/inad3258

Simulation of the PMSM Drive Model with a Neural Network (NN) controller

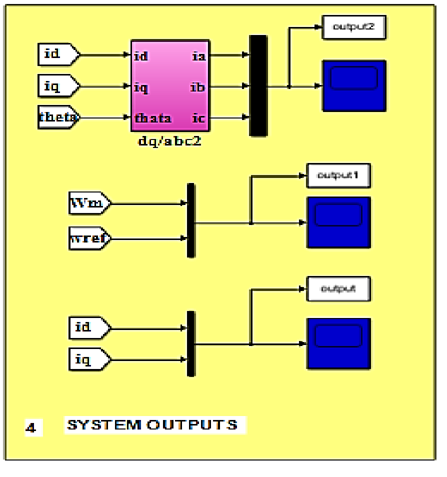
This work details the implementation and deployment of a neural network-based control architecture for a system that meets the specifications outlined in table 1. The established Backstepping controller is replaced with a Neural Network controller. This Neural controller is first trained offline via a simulated environment to optimize its performance against a defined cost function. Subsequently, the trained model is deployed onto dedicated hardware, and the final physical system is assembled and integrated as per the schematic in figure 5.



(a) ANN Controller



(b) PMSM Model



(c) System Outputs

Figure. 5. System with the (NN) controller

http://www.doi.org/10.62341/inad3258

Figure (6) illustrates that the performance of the system with the (NN) controller degraded severely, revealing a fundamental inability to handle disturbances. The most significant failure was the extremely high steady-state error of over 7 %, indicating that the motor speed dropped drastically and could not recover to the commanded setpoint when the load was introduced. While its rise and settling times were comparable to the other controllers, these metrics were irrelevant in the face of such a large regulation error. The controller also failed to mitigate the resulting electromagnetic torque fluctuations and could not overcome the nonlinear behavior induced by the load disturbance.

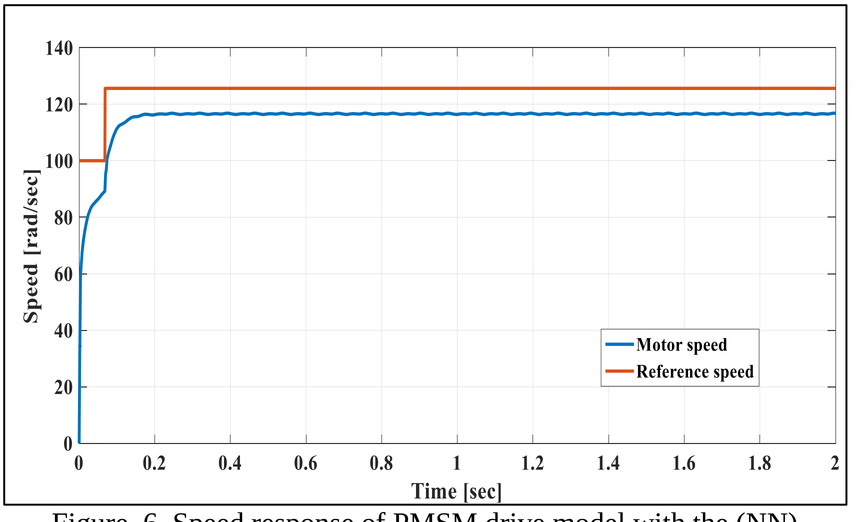


Figure. 6. Speed response of PMSM drive model with the (NN) controller

As illustrated in figure (7), the system startup transient was characterized by a significant yet brief overshoot in the i_q current, which subsequently stabilized at a steady-state value of 7.16 A. In contrast, the i_d current, while successfully regulated to zero, exhibited substantial oscillation during this period. This dynamic response in i_d presents a marked contrast to the more damped behavior observed for the same variable in the benchmark case of Figure 4, indicating a difference in transient performance that warrants further analysis from a control robustness perspective.

http://www.doi.org/10.62341/inad3258

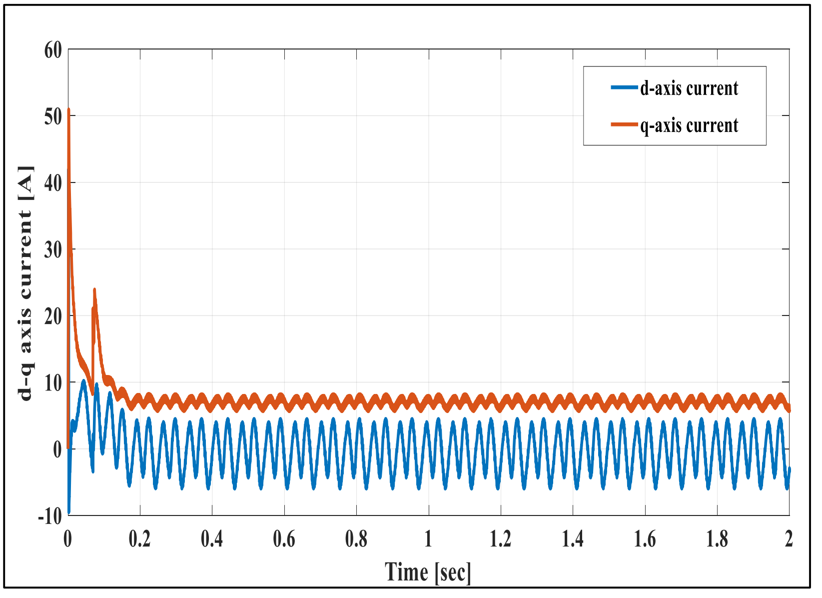


Figure.7. d-q axis currents of PMSM drive model with (NN) controller

Conclusion:

This paper presents rotor speed and current control for the permanent magnet synchronous motor using the Backstepping technique. The mathematical model of the machine is first established, followed by the design of Backstepping controllers based on the Lyapunov stability criterion. These approaches, encompassing conventional Backstepping and artificial Neural Network-based methods, are suitable for PMSM drives across diverse applications- particularly those involving PMSMs, which are pivotal in future green transportation systems. Accordingly, the results of this study are highly relevant to PMSM manufacturers, engineers, and researchers in power electronics and drives. As illustrated in preceding sections, the Backstepping controller delivers the fastest response and greatest efficiency, whereas the artificial Neural Network-based controller exhibits reduced model dependency. Analytical results demonstrate that, compared to artificial Neural Network control, the proposed strategy not only enhances response speed and reduces speed overshoot but also maintains speed control accuracy and dynamic performance under perturbations while improving system robustness.

http://www.doi.org/10.62341/inad3258

References

[1] Jin, J., 2020, "Backstepping Control Design Of PMSM Of Propeller Load System,". *International Core Journal of Engineering*, *6*(8), 281-286.

[2] Monadi, M., Nabipour, M., Akbari-Behbahani, F., & Pouresmaeil, E., 2024, "Speed control techniques for permanent magnet synchronous motors in electric vehicle applications towards sustainable energy mobility,": A review. *IEEE Access*.

[3] Lin, C. H., Chiang, P. H., & Tseng, C. S., 2010 June, Adaptive backstepping control for a permanent magnet synchronous motor drive using rnn uncertainty observer, In *2010 5th IEEE Conference on Industrial Electronics and Applications* (pp. 1293-1298). IEEE.

[4] Senhaji, A., Abdelouhab, M., Attar, A., & Bouchnaif, J., 2023, "Backstepping control of a permanent magnet synchronous motor,". *Materials Today: Proceedings*, *72*, 3730-3737.

[5] Duan, J., Wang, S., & Sun, L., 2022, "Backstepping sliding mode control of a permanent magnet synchronous motor based on a nonlinear disturbance observer,". *Applied Sciences*, *12*(21), 11225.

[6] Achour, H. B., Ziani, S., & El Hassouani, Y., 2023, A non-linear backstepping control of Permanent Magnet Synchronous Motor (PMSM), In *ITM Web of Conferences* (Vol. 52, p. 04005). EDP Sciences.

[7] George, R., & Mathew, A. S., 2015, "Speed Control of PMSM using Backstepping Method,". *International Journal of Engineering Research & Technology (IJERT)*, *4*(7), 609-612.

[8] Li, T., Liu, X., & Yu, H., 2021, "Backstepping nonsingular terminal sliding mode control for PMSM with finite-time disturbance observer,". *IEEE Access*, *9*, 135496-135507.

[9] Kendouci, K., Mazari, B., & Benhadria, M. R., 2010, "Speed Tracking Control of PMSM using Backstepping Controller-Simulation and Experimentation". *International Review of Electrical Engineering*, *5*(6).

[10] Kendouci, K., Bousserhane, I. K., Mazari, B., & Benhadria, M. R., 2010, PMSM Speed Controller based on Nonlinear Adaptive Backstepping, in proc. *International conference on Electrical, Electronics and Automatic (ICEEA), Nov. 2-4.*

http://www.doi.org/10.62341/inad3258

[11] Yahiaoui, M., Bousserhane, I. K., Saidi, Y., & Serraoui, M., 2019, “Adaptive Backstepping Controller of PMLSM,”. *Recent Innovations in Mechatronics*, *6*(1), 1-6.

[12] Wang, G., Wang, D., Lin, H., Wang, J., & Yi, X., 2024, “A DC error suppression adaptive second-order backstepping observer for sensorless control of PMSM,”. *IEEE Transactions on Power Electronics*, *39*(6), 6664-6676.

[13] Zhang, Y., Yan, Q., Huang, N., Wu, Z., Gong, H., & Du, G., 2023, “Fuzzy approximation-based backstepping control of permanent magnet synchronous motor,”. *Journal of Electrical Engineering & Technology*, *18*(3), 2115-2126.

[14] Nicola, M., & Nicola, C. I., 2020 June, Sensorless control of PMSM using backstepping control and ESO-type observer, In *2020 12th international conference on electronics, computers and artificial intelligence (ECAI)* (pp. 1-6). IEEE.

[15] Zheng, X., Xue, L., Wang, P., Li, J., & Shen, Z., 2021, Parameters adaptive backstepping control of PMSM using DTC method, In *E3S Web of Conferences* (Vol. 236, p. 04028). EDP Sciences.

[16] Mo, L., Fei, Y., Chen, X., & Chen, Z., 2021 December, Backstepping Terminal Sliding Mode Control for Surface Permanent Magnet Synchronous Motor, In *2021 IEEE 2nd International Conference on Information Technology, Big Data and Artificial Intelligence (ICIBA)* (Vol. 2, pp. 614-620). IEEE.

[17] Yahiaoui, M., Kechich, A., & Bouserhane, I. K., 2017, “Adaptive sliding mode control of PMLSM drive,”. *International Journal of Power Electronics and Drive Systems*, *8*(2), 639.

[18] Hongliang Yan, Jianan Zhang, Hulin Long., 2024, “PMSM Position Tracking Based On Improved Sliding Mode Reaching Law And Nonlinear Disturbance Observer,”. *Electric Measurement Technology*, *45*(13), 104-108.

[19] Djouadi, H., Ouari, K., Belkhier, Y., Lehouche, H., Bajaj, M., & Blazek, V., (2024), “Improved robust model predictive control for PMSM using backstepping control and incorporating integral action with experimental validation,”. *Results in Engineering*, *23*, 102416.

[20] Kirad, A., Groini, S., & Soufi, Y., 2022, “Improved sensorless backstepping controller using extended Kalman filter of a

http://www.doi.org/10.62341/inad3258

permanent magnet synchronous machine,”. *Bulletin of Electrical Engineering and Informatics*, *11*(2), 658-671.

[21] Zhang, L., Ma, J., Wu, Q., He, Z., Qin, T., & Chen, C., 2023, “Research on PMSM speed performance based on fractional order adaptive fuzzy backstepping control,”. *Energies*, *16*(19), 6922.

[22] Xu, Q., Cheng, X., Yang, H., Wei, Y., & Xue, H., 2020 December, Servo control system of permanent magnet synchronous motor based on feedforward control, In *2020 IEEE 9th Joint International Information Technology and Artificial Intelligence Conference (ITAIC)* (Vol. 9, pp. 1799-1804). IEEE.

[23] Qi, R., & Zhang, G., 2018 April, Permanent Magnet Synchronous Motor Vector Control System Based on the Fuzzy PID Controller, In *2018 3rd International Workshop on Materials Engineering and Computer Sciences (IWMECS 2018)* (pp. 379-382). Atlantis Press.

[24] Abdellah, B., Medjdoub, K., Hazzab, A., Trabelsi, H., Rezkallah, M., & Chandra, A., 2024 May, Control of PMSM drives for EV using nonlinear techniques and input-output linearization, In *2024 2nd International Conference on Electrical Engineering and Automatic Control (ICEEAC)* (pp. 1-4). IEEE.

[25] Lin, R., Huang, S. D., Cao, G. Z., & Wu, C., 2023 June, Model-Predictive-Control-Based Speed Control Strategies of Permanent Magnet Synchronous Motors, In *2023 IEEE International Conference on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)* (pp. 1-7). IEEE.

[26] Geethu, M., & Kunjumon, P. G., 2016 October, Sensorless adaptive PID speed control for permanent magnet synchronous motor drives, In *2016 International Conference on Emerging Technological Trends (ICETT)* (pp. 1-6). IEEE.

[27] Liu, Y., Li, J., Sun, Z. Y., & Chen, C. C., 2024, “A New Adaptive Control Design of Permanent Magnet Synchronous Motor Systems with Uncertainties,”. *Symmetry*, *17*(1), 2.

[28] Bekkour, E. H., Sakhri, Z., Mahfoud, S., Bossoufi, B., Merzouk, S., Mosaad, M. I., & Hussien, S. A., 2025, “An advanced sensorless control strategy using PS-EKF-based Integral Backstepping Controller for PMSM: Experimental validation using dSPACE DS1104,”. *Scientific African*, *29*, e02951.

http://www.doi.org/10.62341/inad3258

[29] Chen, C. X., Xie, Y. X., & Lan, Y. H., 2015, "Backstepping control of speed sensorless permanent magnet synchronous motor based on slide model observer,". *International Journal of Automation and Computing*, *12*(2), 149-155.

[30] Xuechun Hu, Yu Xia, Zsófia Lendek, Jinde Cao, & Radu-Emil Precup, 2025, "A novel dynamic prescribed performance fuzzy-neural backstepping control for PMSM under step load," *Neural Networks*,107627.