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Developed Permanent Magnet Synchronous Motor Control using Numerical Algorithm and Backstepping

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Abstract

Permanent magnet synchronous motors with high-performance electric actuation require sophisticated control systems due to their complex motions. These methodologies for control typically result in algorithms best utilized digitally, employing robust microprocessors. To address the issue of adaptive control of low-power permanent magnet synchronous motors, we provide a solution in this paper. By using numerical algorithms and backstepping, efficient control schemes may be developed while still requiring little computational resources. Static and dynamic qualities are both satisfactory, and the system is relatively insensitive to external disturbances and parameter uncertainties.

Keywords: Control, Backstepping, Lyapunov, Stability, Numerical

1. Introduction

The vast majority of the physical systems we encounter daily are nonlinear. Over their helpful operating range, these nonlinearities are typically either negligible or invisible. More accurate modeling allows for responses across a broader spectrum of operations due to the ongoing drive to boost the effectiveness of controlled systems. At this juncture, non-linearities become manifest, rendering obsolete the linear field's analysis and synthesis tools for control laws, which were previously adequate for describing most but not all phenomena. As a result, studying how to regulate nonlinear systems has been a hot topic of study for a while now.

P, PI, or PID controllers can control the speeds. Yet regulators are developed with control strategies designed for linear models.

Historically, the linear approximation around an operational point or a trajectory has been used as a solution; in other words, one first reduces this complexity in linearization before defining a system as nonlinear. Even if the linearized system can have measurable and/or controlled parameters, the domain of validity of the linear approximation must be enlarged since, following linearization, the physical parameters can lose their interpretation and, consequently, their measurability around the interesting operational points. This is where we are first introduced to the idea of adaptive control; wherein control is considered adaptive if it employs parameters that can be adjusted in reareal-timether than predetermined in advance. The state might diverge infinitely for a finite amount of time during transitions of the estimated parameters, highlighting instability as the most challenging issue for this category of systems. Thus, the nonlinear triangular shape that we will depict later will be the nonlinear system for which the adaptive control proposed in this study provides a solution to this type of problem. Adaptive control is necessary in nonlinear systems due to the prevalence of explosive instability, which directly impacts the expected performance of control systems. The concept of linear approximation has to be broadened.

These modern adaptive control techniques include backstepping. Kanellakopoulos et al.[1] created it after being influenced by several researchers [2-3]. With this technique's recursive design process, the formulation of the control law [4]. and the associated Lyapunov function is systematic, which is a key innovation for lower triangular systems. While traditional linearization techniques necessitate precise models and frequently cancel out some valuable nonlinearities, backstepping provides a design tool by avoiding cancellations at the nonlinear system level. In what follows, we propose introducing the backstepping algorithm. The first stage is to select the conditions that let this technique be applied, and the second step is to choose nonlinear functions that may make use of this control method. At last, we'll use the proper numerical algorithms described in this research to perform direct numerical modeling of the permanent magnet synchronous motor model.

2. Research method

In this part, we will describe the research approaches and

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the modeling of the synchronous motor PMSM. Meanwhile, the assumptions that will promote simplification are provided [5].

2.1. Model

The Permanent magnet synchronous motor model in the reference frame (d-q) is shown below:

$$\begin{cases} \frac{d_{id}}{dt} = -\frac{R_s}{L_d} i_d + p\frac{L_q}{L_d}\Omega i_q + \frac{v_d}{L_d} \\ \frac{d_{iq}}{dt} = -\frac{R_s}{L_q} i_q - p\frac{L_d}{L_q}\Omega i_d - p\frac{\Omega\varphi_f}{L_q} + \frac{v_q}{L_q} \\ \frac{d\Omega}{dt} = \frac{p}{J}\left(L_d - L_q\right) i_d i_q - \frac{f}{J}\Omega + \frac{P}{J}\varphi_f i_q - \frac{C_r}{J} \end{cases} \quad (1)$$

Where:
R_s: Stator resistance (Ω)
L_d, L_q: d,q axis self-inductance (H)
φ_f: Mutual flux due to permanent magnetic (Wb)
i_d, i_q: d,q axis currents (A)
Ω Angle speed (rad/s)
J: Moment of inertia (kg.m^2)
f: damping constant (N/rad/s)
p: Number of pole pairs
C_r: load torque (N.m)

The equations presented above suggest that PMSM is a nonlinear dynamic system owing to the bend that arises between both the equations that describe the state of the electrical current and the speed. It is essential to keep in mind that all incredibly different depending on the operating conditions, the much more notable of which are the fluctuations in heating, the saturating effects, and the disturbances in torque generated by the applied load. Therefore, if high-performance speed control of PMSM is necessary, the design of the controller must take into consideration any and all nonlinearities, parameter uncertainties, and unknown external disturbances [6].

2.2. Performed Backstepping control

The main goal of the central control is to make an asymptotically stable speed-tracking controller for PMSM that can keep an eye on the reference trajectory even if there are errors or changes in the parameters and an unknown change in the load torque disturbance. This goal can be reached by ensuring that the speed-tracking controller is not affected by any disruptions caused by PMSM or load torque. As a direct result, it is necessary to have an adaptive online estimate of all the parameters and external disturbances. One of the objectives of utilizing adaptive backstepping is to identify a virtual control state and then coerce that state into performing the role of a stabilizing function. This is one of the purposes. The output of this method will be an error variable structured in a suitable manner [7]. Consequently, the error variable can be more stable by implementing Lyapunov's stability theory [8]. It is possible to create the overall control design by working through the following three steps in the following order:

Step 1: Define the reference speed as Ω^* and Ω^* as continuous second − order dérivatves . Moreover, the speed tracking error can be defined as:

$$z_\Omega = \Omega^* - \Omega + k_\Omega{}' \int_0^t (\Omega^* - \Omega)dt \quad (2)$$

So: $z_\Omega = e_\Omega + z_\Omega{}'$

Where: $e_\Omega = \Omega^* - \Omega$ and $z_\Omega{}' = k_\Omega{}' \int_0^t (\Omega^* - \Omega)dt$: is the integral action added to the backstepping order to ensure convergence-tracking error towards zero despite uncertainties of type piecewise constant at each step of the algorithm?
So by using model (1), we find:

$$\dot{z}_\Omega = \dot{\Omega}^* - \dot{\Omega} + k_\Omega{}'(\Omega^* - \Omega) = \dot{\Omega}^* \begin{bmatrix} \frac{p}{J}\left(L_d - L_q\right) i_d i_q - \frac{f}{J}\Omega + \\ \frac{P}{J}\varphi_f i_q - \frac{C_r}{J} \end{bmatrix} + k_\Omega{}'(\Omega^* - \Omega) \quad (3)$$

Consider the first Lypanov function as:

$V_\Omega = \frac{1}{2} z_\Omega^2$ and the derivative of V_Ω is :

$$\dot{V}_\Omega = z_\Omega \dot{z}_\Omega = -K_\Omega z_\Omega^2$$

Then:

$$\dot{z}_\Omega = -K_\Omega z_\Omega = \dot{\Omega}^* - i_{q,ref}\left[\left(L_d - L_q\right) i_d + \varphi_f\right]\frac{P}{J} + \frac{f}{J}\Omega + \frac{C_r}{J} + k_\Omega{}'(\Omega^* - \Omega) \quad (4)$$

Finally, the virtual control $i_{q,ref}$ is given by the following equation:

$$i_{q,ref} = \frac{J}{p(\left(L_d - L_q\right) + \varphi_f)}\left[\dot{\Omega}^* + \frac{C_r}{J} + \frac{f}{J}\Omega + K_\Omega z_\Omega + k_\Omega{}'(\Omega^* - \Omega)\right] \quad (5)$$

Given that it does not offer accurate simulations, we will no longer employ integral proportional regulation when controlling the currents. This choice has been made as it is inefficient.

Step 2: The i_q current tracking error can be defined to develop their dynamic:

$$z_q = i_{q,ref} - i_q$$

So:

$$\dot{z}_q = \dot{i}_{q,ref} - \dot{i}_q$$

Define the second Lypanov function as:

$$V_q = V_\Omega + \frac{1}{2} z_q^2$$

Then by using model (1), we find::

$$\dot{V}_q = -K_\Omega z_\Omega^2 + z_q\left[\dot{i}_{q,ref} - \dot{i}_q\right]$$

Thus:

$$\dot{V}_q = -K_\Omega z_\Omega^2 + z_q\left[\dot{i}_{q,ref} - \dot{i}_q\right]$$

So, we get:

$$\dot{V}_q = -K_\Omega z_\Omega^2 + z_q\left[\dot{i}_{q,ref} + \frac{R_s}{L_q} i_q + \frac{p\Omega}{L_q}\left(L_d i_d + \frac{\varphi_f}{L_q}\right) - \right.$$

$$\left.\frac{v_{q,ref}}{L_q}\right] \tag{6}$$

Where:

$$v_{q,ref} = L_q\left[K_q z_q + \dot{i}_{q,ref} + \frac{R_s}{L_q} i_q + \frac{p\Omega}{L_q}\left(L_d i_d + \varphi_f\right)\right]$$

Step 3: The i_d current tracking error can be defined to develop their dynamic:

$$z_d = i_{d,ref} - i_d$$

So: $z_d = e_d$

Where:

$$e_d = i_{d,ref} - i_d$$

Define the third Lypanov function as:

$$V_d = \frac{1}{2} z_d^2$$

Then:

$$\dot{V}_d = z_d \dot{z}_d$$

And by choosing: $i_{d,ref} = 0$

So, we get:

$$\dot{V}_d = -\dot{i}_d z_d = -z_d\left(-\frac{R_s}{L_d} i_d + p\frac{L_q}{L_d}\Omega i_q + \frac{v_{d,ref}}{L_d}\right)$$

By using model (1) we find:

$$\dot{V}_d = -z_d\left(-\frac{R_s}{L_d} i_d + p\frac{L_q}{L_d}\Omega i_q + \frac{v_{d,ref}}{L_d}\right) \tag{7}$$

And finally:

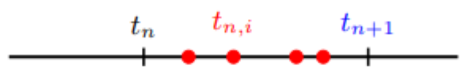
$$v_{d,ref} = L_d\left[K_d z_d + \frac{R_s}{L_d} i_d - p\frac{L_q}{L_d}\Omega i_q\right] \tag{8}$$

2.3. Numerical Algorithm

With numerical approaches, the function F is evaluated repeatedly at each subdivision interval, making the process a one-step affair. The idea is, of course, to obtain precision and order.

$$\begin{cases} \forall\, 1 \le i \le s, \begin{cases} t_{n,i} = t_n + C_i \Delta t, \\ Y_{n,i} + \Delta t \sum_{j=1}^{i-1} a_{ij} F\left(t_{n,i}, Y_{n,i}\right), \end{cases} \\ Y_{n+1} = Y_n + \Delta t \sum_{j=1}^{i-1} b_i F\left(t_{n,i}, Y_{n,i}\right) \end{cases} \tag{9}$$

Where, Here, the temporal discretization is demonstrated to be dissolved.



We considered five interconnected differential equations, making up a nonlinear system due to our considerations. Two fundamental functions, AlgoPaper and Algo, were defined throughout the Python implementations of numeric resolving. The finalized script is demonstrated in Fig. 1.

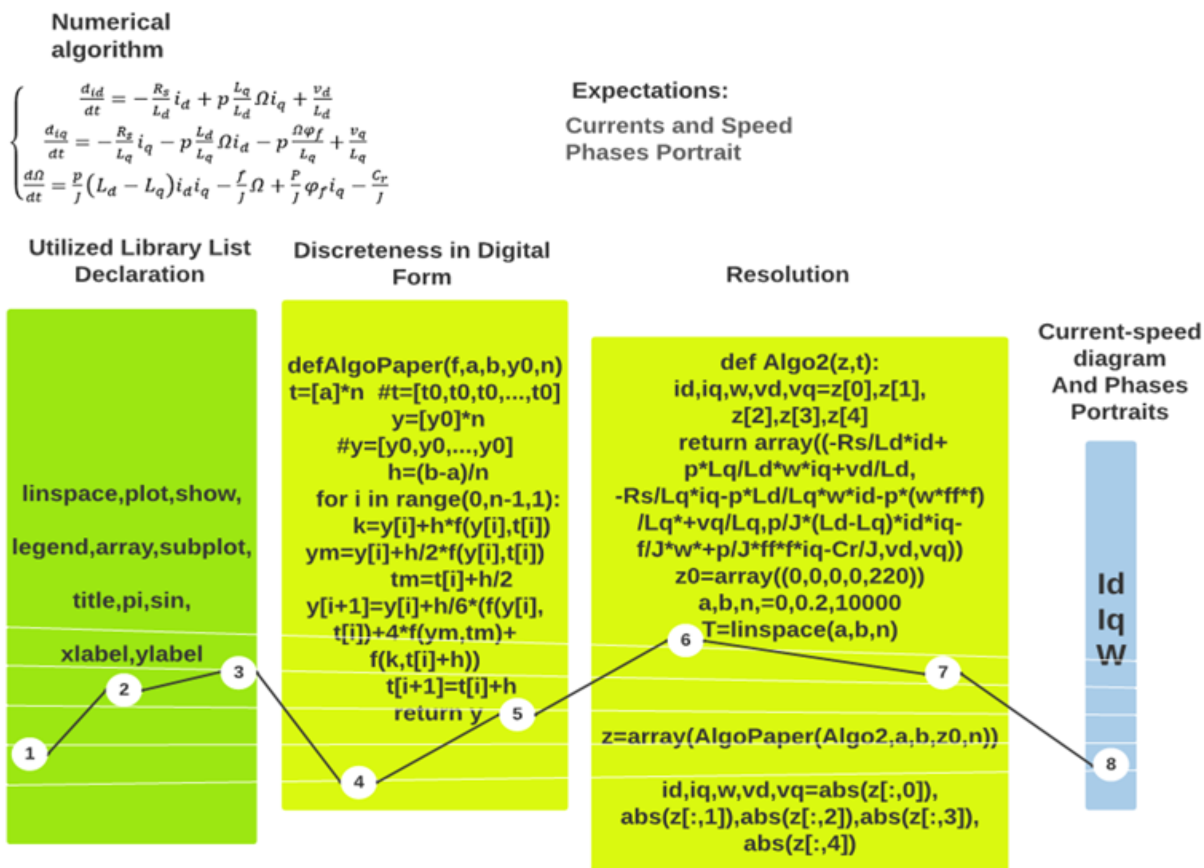


Fig. 1. Algorithm

3. Results and discussion

This section summarizes the research findings while also providing a complete discussion.

3.1. Nominal parameters of the PMSM

The ratings and nominal parameters of the PMSM used in the simulations are given in Table 1 :

Table 1. The nominal parameters

Parameters	Value
P	3
R_s	$0.2377[\Omega]$
L_d	0.0733[H]
L_q	0.0728[H]
φ_f	0.29562[Web]
J	$0.025942[N.mS^2/rad]$
f	0.02124

3.2. Simulation Results

The methodologies outlined in the preceding sections were validated using numerical simulations based on precise synchronous motor data, as shown in Table 1. The gains for each of the six gains are shown in alphabetical order in Table 2. Additional simulations support each of these numbers. To demonstrate the quality of the control, figures depicting asymptotically converged speeds and currents, as well as the electromagnetic torque's reaction to overloads, will be presented. In order to eliminate undesirable harmonics, a synchronous motor model and a number of bandpass filters have been added to the Simulink model's converter output. The effect of this series of filters was increased in the event of overheating by saturation effect in a real-time simulation. Using a temperature sensor on an Arduino, constant temperature readings can be obtained.

Table 2. Gain values

Parameters	Value
Kd	800
kq	800
Kw	800
Kdd	16
Kqq	8
Kww	10

3.2.1. Response Speed and d-q Currents Using Backstepping

The following figures illustrate the findings of the command by backstepping with integral action applied at the PMSM. The results are obtained with a perturbation due to the nominal load torque of amplitude 5N.m.The objective is to control the closed-loop system's operation by first varying the rotational speed reference. The following figures provide simulation results demonstrating the command's efficiency and performance. The efficiencies and robustness of the control are shown by the curves, which show the effect of changing the load torque, the resistance, and the inductance by 100%.

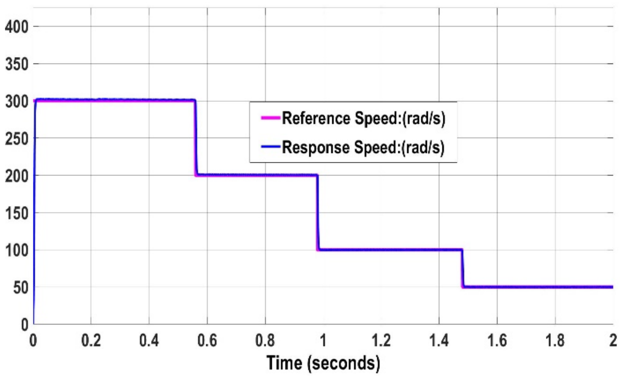


Fig. 2 Reference and Response Speed

Fig. 2 and Fig. 3 demonstrate that the speed converges towards the reference, and the decoupling of the currents is preserved when all parameters are altered. Fig. 4 illustrates the electromagnetic torque Cem.

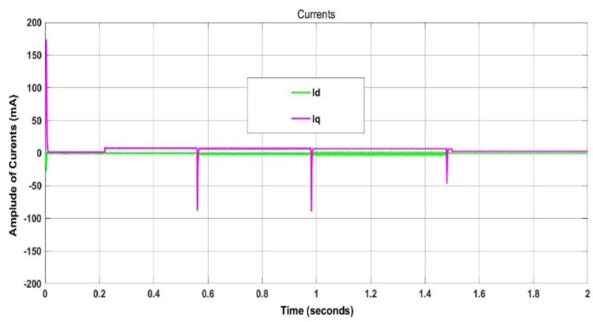


Fig. 3. D-Q Currents

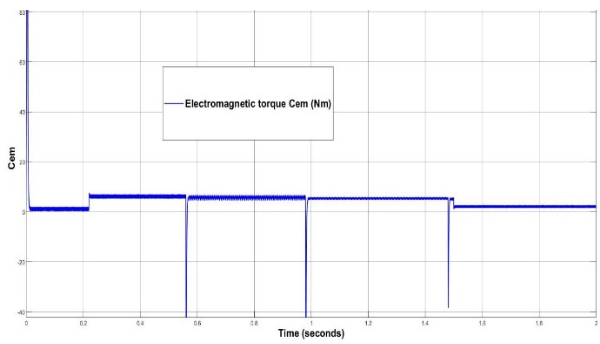


Fig. 4. Electromagnetic torque.

3.2.2. Response Speed and d-q Currents Using Numerical algorithm

Timelines of d-q-currents, and response speed with their associated phase portraits, are shown in Fig. 5(a,b), Fig. 6(a,b), and Fig. 7(a,b).

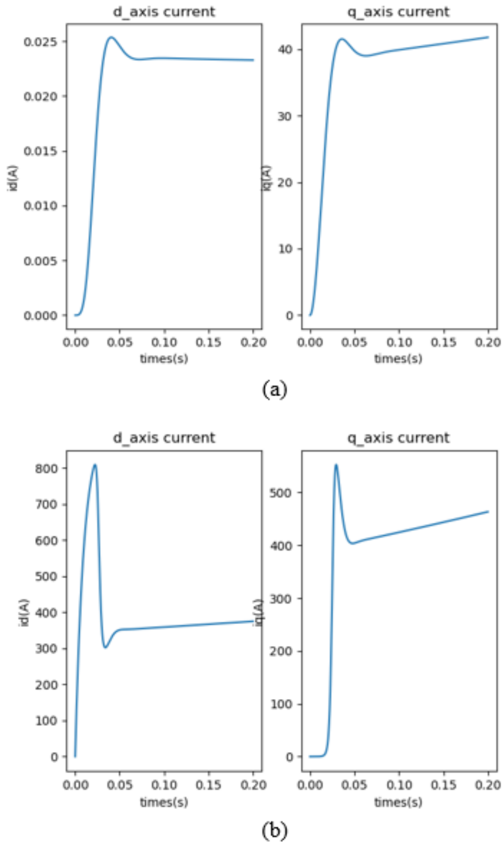


Fig. 5. Id and Iq Currents. (a): vd=0_vq=220, (b): vd=220_vq=0.

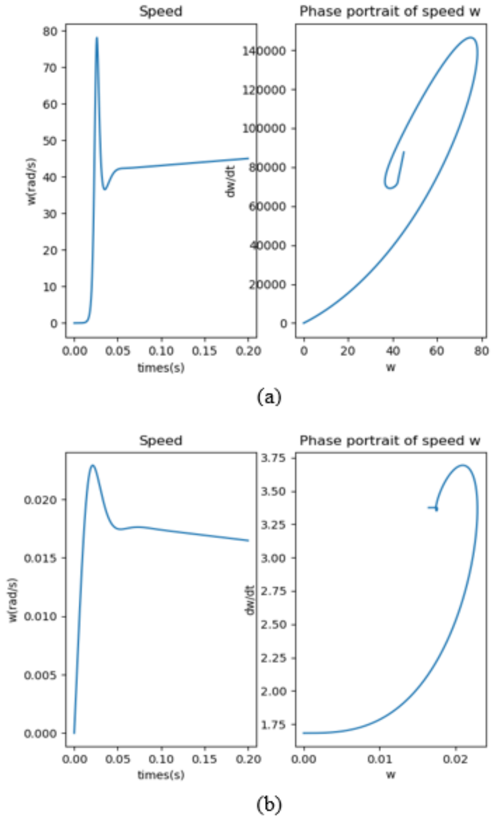


Fig. 7. Response Speed and Phase portrait. (a): vd=0_vq=220, (b): vd=220_vq=0.

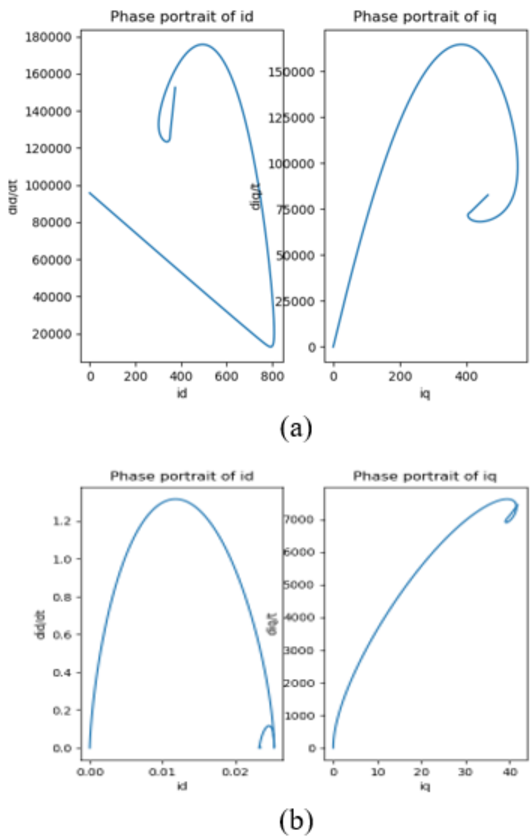


Fig. 6. Phases portraits of D-Q Currents. **(**a) vd=0_vq=220, (b): vd=220_vq=0.

3.2.3. Discussion of results

As noted in Section 2.2, it is critical to ensure that the time derivative of the Lyapunov function candidate is negative semi-definite in order to maintain the asymptotic stability of the entire control system. This essentiality is assured if the parameter and load torque disturbance estimate errors converge to zero or a constant value, since their time derivatives are equal to zero. The total control system's asymptotic stability is then ensured. The simulation findings indicate that this essentiality is guaranteed in both circumstances. The proposed control's performance was evaluated using simulations for the classic adjustment of an PMSM supplied by a two-level voltage inverter, with a PI regulator facing a reference speed ranging from 100 to 300 (rad / s), followed by the application of a resistive torque of 5 (Nm) at a period of [1.27s], between t = 0.22 (s) and 1.449 (s) (s). We denote a diligent pursuit of the reference speedas shown in Figure 2. The simulation results in Figure 3 demonstrate that the decoupling is maintained regardless of the load variation (in the steady-state). Due to the fact that the inverter generates fluctuations that are reduced by the cascaded bandpass filters, they are not felt strongly at the torque level. After the transitory regime expires, the current Id value reverts to zero. The rate of change is rapid, with very little overshoot and no static inaccuracy. Additionally, disturbance rejection is quick, with an ideal rising time of 0.06 seconds (s). Additionally, they have a significant effect on the estimation of other parameters.

Fig. 4 illustrates the tracking errors and their convergence to zero under all parameter uncertainties/perturbations and variations in load torque disturbance. Figures 5, 6, and 7 show that the controller maintains a high-reliability level. Although the system is non-linear, the equations describing the machine's behavior are intricate. The direct numerical resolution of model (1) by integrating only two additional equations is emphasized as the primary contribution of this work. The asymptotic convergence shown in the numerically-obtained phase pictures is also underlined; this is a surprising and promising result.

The second additional value of this study is the restriction on the potential values of the gains Kww, Kqq, and Kdd, which affect the stability, speed, and precision of the dilemma. For example, a large value of k results in a big overshoot. However, as illustrated in Figure 8, we observe an exceptional degree of accuracy and an optimal rise time. Additionally, it is found that as the load torque grows, a big value of the gains may yield a stunning pseudo-periodic transient regime with a singularity. As seen in Fig. 8 and Fig. 9.

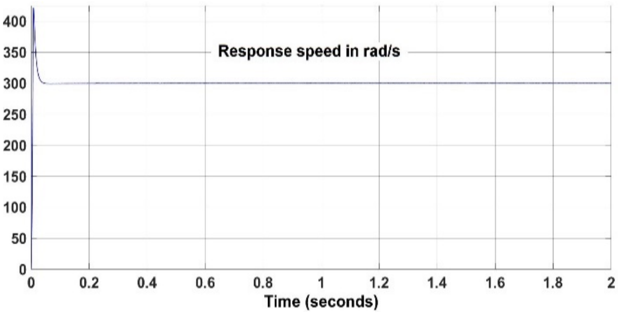


Fig. 8 . Overshoot for Kww=160;Kqq=8;Kdd=10;

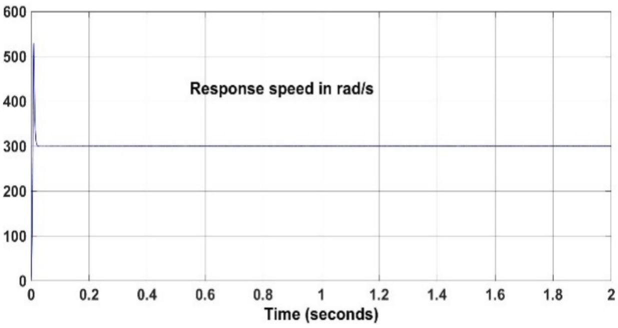


Fig. 9. Pseudo-periodic transient regime, for :Kww=800; Kqq=8; Kdd=100.

What is critical to emphasize is that the integral action PI must be performed on all parameters: speeds and currents, or else the results will be skewed. The figures 10 and Figure 11 clearly illustrate the enormous overshoot and significant spread of the transient regime, which exceeded 0.02 seconds for kdd = Kqq = 0, but exceeded 0.4 seconds for Kww = 0.

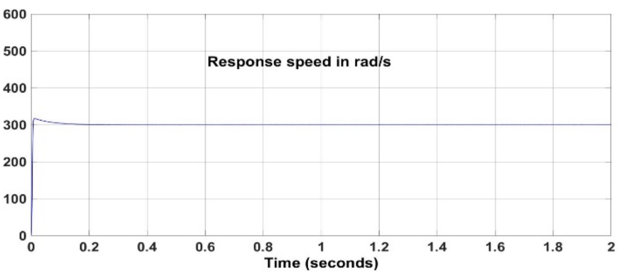


Fig.10 . Response speed for:Kww=16;Kdd=0;Kqq=0;

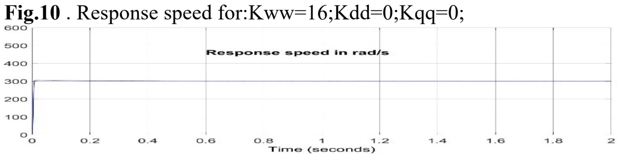


Fig. 11. Response speed for:Kww=0;Kdd=5;Kqq=5;

Our work created an adaptive backstepping technique to improve the control's dynamic performance. The steps of the algorithm and the stability analysis have been explained in detail. This method shows how useful it is by letting the stator resistance, load torque, and inductors be changed even when the parameters for the stator, load torque, and inductors are unknown. The simulation results match what was expected, demonstrating that the method works. Compared to previous research [9], [10–18], and [19], the proposed methodology has no static error and the best rising time. It is said that the results of this study could be improved by using a new algorithm for mobile energy optimization that gives a heuristic solution based on the device's tasks [20–23]. The authors of [24] investigate the optimization of processing time and computing resources in a mobile edge computing node. Lastly, the results of this study show how integrated data analysis techniques like ICA-NMF-SVD-PCA [25–27] and [28–32] , which are often used in biomedical signal processing, can be used with wavelets to make the methods even more effective.

4. Conclusion

This work highlights numerous significant and outstanding outcomes, which can be summed up as follows:

1. The pi controller's method is not impacted by any parameters or disturbances in the load torque of a PMSM.
2. The yardstick provided by the numerical control algorithm can handle all parameter uncertainties and disturbances.
3. The numerical resolution can be made in the backstepping command, which means that the algorithm can be used in real-time with the best execution time.

This can be exploited in the industrial world, especially in the computer industry. electric cars.

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References

1. Xingcheng, W., "Ship Steering Nonlinear Control Based on Backstepping Design Approach". In: *Proceedings of the 6th World Congress on Intelligent Control and Automation*, Dalian, China: IEEE, 2006, pp. 6265-6268.
2. Yueneng, Y. and Ye, Y., "Backstepping sliding mode control for uncertain strict-feedback nonlinear systems using neural-network-based adaptive gain scheduling". *Journal of Systems Engineering and Electronics*, vol. 29, no. 3, June 2018, pp. 580-586.
3. Sun, L.Y., Tong, S., Liu, Y., "Adaptive Backstepping Sliding Mode H∞ Control of Static Var Compensator". *IEEE Transactions*

on Control Systems Technology, vol. 19, no. 5, 2011, pp. 1178-1185,

4. Li, T., Liu, X., Yu, H., "Backstepping Nonsingular Terminal Sliding Mode Control for PMSM with Finite-Time Disturbance Observer". *IEEE Access*, vol 9, 2021, pp. 135496–135507.
5. Liang, B., Zheng, B.S., Ahn, .C.K., Liu, F., "Adaptive Fuzzy Control for Fractional-Order Interconnected Systems with Unknown Control Directions". *IEEE Transactions on Fuzzy Systems*, 2022, vol. 30, no. 1, pp. 75–87.
6. Rebouhl, S., Kaddouri, S.A., Abdessemed, R., Haddoun, A., "Nonlinear control by input-output linearization scheme for EV permanent magnet synchronous motor". In: *Proceedings of the 2007 Vehicle Power and Propulsion Conference*,: IEEE 2007 pp. 185–190.
7. Hamida, M.A., Glumineau. A., De Leon, J., Loron, M., "Robust adaptive high order sliding-mode optimum controller for sensorless interior permanent magnet synchronous *motors" Mathematics and Computers in Simulation*, vol. 105, 2014, pp. 79–104.
8. Zhoua, J., Wang, J.Y., "Real-time nonlinear adaptive backstepping speed control for a PM synchronous motor". *Control Engineering Practice*, vol. 13, no. 10, 2005, pp. 1259–1269.
9. Weng, Y., Nan, D., Wang, F., "Data-Driven Backstepping Sliding-Mode Control of Disturbed QUAVs". *IEEE Access*, vol. 10, 2022, pp. 81713–81721.
10. Ye, H., Song, Y., "Backstepping Design Embedded With Time-Varying Command Filters". *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 69, no. 6, June 2022, pp. 2832-2836,
11. Gao, H., et al., "Automatic Parking Control of Unmanned Vehicle Based on Switching Control Algorithm and Backstepping". *IEEE/ASME Transactions on Mechatronics,* vol. 27, no. 3, 2022, pp. 1233–1243.
12. Truong, N.T., et al.,"A backstepping global fast terminal sliding mode control for trajectory tracking control of industrial robotic manipulators". *IEEE Access,* vol. 9, 2021, pp. 31921–31931.
13. Wang, M., et al., "A Novel Framework for Backstepping-Based Control of Discrete-Time Strict-Feedback Nonlinear Systems with Multiplicative Noises". *IEEE Transactions on Automatic Control*, vol. 66, no. 4, 2021, pp. 1484–1496.
14. Mazenc, F., et al., "Backstepping Design for Time-Delay Nonlinear Systems". *IEEE Transactions on Automatic Control,* vol. 51, no. 1, 2006, pp. 149–154.
15. Benachour, H., Ziani, S., Chaou, Y., El Hassouani, Y., Daoudia, A., "Permanent Magnet Synchronous Motor PMSM Control by Combining Vector and PI Controller". *WSEAS Transactions on Systems and Control,* 2022. vol. 17, p. pp. 244-249.
16. Chaou, Y., et al., "Nonlinear Control of the Permanent Magnet Synchronous Motor PMSM using Backstepping Method". *WSEAS Transactions on Systems and Control,* vol. 17, 2022, p. pp. 56-61.
17. Ziani, S., El Ghmary, M., Youssef, A.Z., "Permanent magnet synchronous motor control performed using PI-backstepping with a model of harmonics reduction". International Journal of Power Electronics and Drive Systems, Vol. 14, No. 1, 2023, pp. 199~208.
18. Ziani, S., El Hassouani, Y., Farhaoui, Y., "An NMF Based Method for Detecting RR Interval". In: *Farhaoui, Y., Moussaid, L. (eds) Big Data and Smart Digital Environment,* Studies in Big Data, vol 53, 2019, pp 342–346.
19. Ziani, S., El Hassouani, Y., "Fetal-Maternal Electrocardiograms Mixtures Characterization Based on Time Analysis". *5th International Conference on Optimization and Applications (ICOA),* Morocco: IEEE, 2019, pp. 1-5.
20. Ziani, S., et al., "QRS complex characterization based on non-negative matrix factorization NMF". *4th International Conference on Optimization and Applications (ICOA),* Morocco: IEEE, 2018, pp. 1-5.
21. Ziani, S., et al., "Blind Maternal-Fetal ECG Separation Based on the Time-Scale Image TSI and SVD – ICA Methods". *Procedia Computer Science*, Volume 134, 2018, pp. 322-327.
22. ElGhmary, M., et al., "Energy and Computational Resources Optimization in a Mobile Edge Computing Node". In: Proceedings of *9th International Symposium on Signal, Image, Video and Communications*, Morocco: IEEE,, 2019, pp. 323–328.
23. ElGhmary, M., et al., "Efficient multi-task offloading with energy and computational resources optimization in a mobile edge computing node". *International Journal of Electrical and Computer Engineering,* vol. 9, no. 6, 2019, pp. 4908–4919.
24. Ziani, S., El Hassouani, Y., "Fetal Electrocardiogram Analysis Based on LMS Adaptive Filtering and Complex Continuous Wavelet 1-D". *Lecture Notes in Networks and Systems,* vol. 81, 2020, pp. 360–366.
25. Ziani, S., et al., "Fetal electrocardiogram characterization by using only the continuous wavelet transform CWT". *International Conference on Electrical and Information Technologies (ICEIT),* Morocco: IEEE, 2017, pp. 1-6.
26. Ziani, S., ElHassouani, Y., "A new approach for extracting and characterizing fetal electrocardiogram". *Traitement du Signal,* 2020, Vol. 37, No. 3, pp. 379-386.