

Hybrid Adaptive Backstepping Sliding Mode Controller of Permanent Magnet Linear Synchronous Motors

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Abstract—This paper tackles the tracking position control dilemma of permanent magnet linear synchronous motors with parameter uncertainties and load force disturbance. Adaptive nonlinear backstepping control augmented with sliding mode control (SMC) is proposed to solve the problem of load force distribution. The backstepping is a recursive control technique where its stability is ensured at each step. However, its sensitivity to uncertainties, disturbances, and electromagnetic noise leads to unwanted performances. SMC is a well-known nonlinear robust approach for uncertain dynamical systems and reduces its parametric adaptive laws. However, implementing this technique in real-time applications is stopped by its main shortcoming, the undesirable chattering phenomenon. The saturation function is used to reduce the chattering phenomenon. The incorporation of these approaches is a promising solution to provide a suitable position tracking of PMLSM in the presence of parameter uncertainties and load force disturbance. The simulation tests have been performed on the PMLSM system to prove the effectiveness and robustness of the proposed controller law. The results highlighted satisfactory position tracking performance in transient conditions and steady-state and under different load force disturbances.

Keywords—Adaptive Control, Backstepping Sliding Mode Controller, Hybrid Controller, Position Control, Permanent Magnet Linear Synchronous Motors

I. INTRODUCTION

Electric motors (EMs) are essential to many different industries because they transform electrical energy into mechanical power that powers everything from industrial machines to electric cars [1]-[4]. Permanent-magnet linear synchronous motors (PMLSMs), one of the many varieties of EMs, are especially well-known for their exceptional accuracy and efficiency. These EMs' performance characteristics are greatly improved by the use of permanent magnets in the rotor, which guarantee synchronized magnetic fields with the stator [5]-[8]. Nevertheless, since PMSMs are nonlinear, coupled, and multivariable, they are fundamentally

complicated despite their benefits. To attain optimal performance, this complexity calls for the creation of sophisticated control systems [9]-[13]. PMLSMs have traditionally been managed using conventional control techniques like field-oriented control (FOC). To maximize EM performance, FOC works by separating the torque and flux components. Although it works well in many situations, FOC may have trouble being resilient when faced with changes in parameters and outside disruptions [14]-[17]. Scholars are developing sophisticated control strategies that combine reliability, optimization, and nonlinear control to overcome these constraints. These methods include adaptive control, backstepping control (BC), sliding mode control (SMC), feedback linearization, and other clever methods. These techniques' main goal is to improve PMLSMs' general efficacy by efficiently controlling their nonlinear dynamics and reducing uncertainty [18]-[20].

The direct drive design of mechanical applications based on a PMLSM is a potential candidate to meet the increasing demands for higher contouring accuracy at high machine speeds [21], [22]. The direct drive design based on PMLSM has the following advantages over its indirect counterpart: no backlash and less friction, high speed and high precision in long-distance locations, simple mechanical construction resulting in higher reliability and frame stiffness, and high thrust force however, many control methods are employed to achieve the good performance [23]-[25].

The conventional control methods for linear motors are faced with a challenge because of the existence of system parameter perturbation and edge effect etc. [26]-[28]. New advanced control schemes have been proposed to reduce disruption and attain good performance. Ref. [29], [30] used an SMC of surface-mount PMLSM based on an error model with an unknown load, and [31] proposed a nonlinear optimal control approach for PMLSMs. Ref. [32] implemented the speed SMC of PMLSM with load force observer [33]

developed and realized the adaptive nonlinear disturbance observer using double loop self-organizing recurrent wavelet-neural-network for two-axis motion control system, and [34] proposed research on predictive functional control based on disturbance observer for PMLSM speed system, and [35], [36] proposed adaptive SMC with nonlinear disturbance observer for uncertain nonlinear system based on backstepping method, and [37] realized a sensorless vector control of PMLSM based on self-adaptive super-twisting SMC, Implementation on adaptive SMC position of PMLSM was proposed in [38], recurrent function all ink based fuzzy neural network controller with improved particle swarm optimization for a linear synchronous motor drive, in [39], and FPGA-realization of adaptive fuzzy controller for the linear x-y table in [40].

It is, well known that the control performance of the PMLSM is sensitive to the load disturbance and mass variation because the motor mover drives directly moving parts or the load force is directly applied to the motor, so that's forced to find control strategies to solve these problems. In this paper, we have presented hybrid control, adaptive backstepping SMC with estimated load force to overcome this problem and find a good performance in all driving conditions.

II. PMLSM SYSTEM

The dynamics model of PMLSM can be described as follows [41]-[43]:

$$\frac{di_d}{dt} = -\frac{R_s}{L_d}i_d + \frac{L_q\pi}{L_d\tau}vi_q + \frac{1}{L_d}u_d \quad (1)$$

$$\frac{di_q}{dt} = -\frac{R_s}{L_q}i_q - \frac{L_d\pi}{L_q\tau}vi_d - \frac{\psi\pi}{L_q\tau}v + \frac{1}{L_q}u_q \quad (2)$$

$$\frac{dv}{dt} = \frac{3\pi}{2\tau M}i_q(\psi + (L_d - L_q)i_d) - \frac{F_L}{M} - \frac{B_m}{M}v \quad (3)$$

III. DESIGNING OF ADAPTIVE BACKSTEPPING SLIDING MODE CONTROLLER

The objective is to design adaptive position control in the overall operating system.

A. Step 1

For a position tracking system, the position tracking error can be defined as:

$$e_1 = x_{ref} - x \quad (4)$$

Its derivative is:

$$\dot{e}_1 = \dot{x}_{ref} - v \quad (5)$$

The Lyapunov stability function is defined as:

$$V_1 = \frac{1}{2}e_1^2 \quad (6)$$

And the derivative of V_1 is:

$$\dot{V}_1 = e_1(\dot{x}_{ref} - v) = -k_1e_1^2 \quad (7)$$

where k_1 is a strictly positive constant.

The virtual speed control functions can be defined as:

$$v = \dot{x}_{ref} + k_1e_1 \quad (8)$$

B. Step 2

The error speed can be defined as:

$$e_2 = v_{ref} - v \quad (9)$$

Where v_{ref} is the virtual speed of the previous step

$$e_2 = \dot{x}_{ref} + k_1e_1 - v \quad (10)$$

For the recursive control and according to (5) and (10), the \dot{e}_1 can be rewritten as:

$$\dot{e}_1 = e_2 - k_1e_1 \quad (11)$$

From (11) and (3), the time derivative of the tracking error e_2 rewritten as:

$$\dot{e}_2 = \ddot{x}_{ref} + k_1(e_2 - k_1e_1) - Ai_q + \frac{F_r}{M} + \frac{f_c}{M}v \quad (12)$$

The Lyapunov candidate function V_2 is selected:

$$V_2 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 \quad (13)$$

According to (12) and (13), the derivative of V_2 can be rewritten as:

$$\dot{V}_2 = -k_1e_1^2 + e_2 \left(\begin{array}{l} \dot{x}_{ref} + (1 - k_1^2)e_1 \\ +k_1e_2 - Ai_q + \frac{F_r}{M} + \frac{f_c}{M}v \end{array} \right) \quad (14)$$

The virtual current control functions of i_d and i_q can be defined as:

$$\begin{cases} i_d = 0 \\ i_q = \frac{1}{A} \left[\begin{array}{l} \ddot{x}_{ref} + (1 - k_1^2)e_1 + \\ (k_1 + k_2)e_2 + \frac{F_r}{M} + \frac{f_c}{M}v \end{array} \right] \end{cases} \quad (15)$$

Substituting equation (15) into (14), we obtain:

$$\dot{V}_2 = -k_1e_1^2 - k_2e_2^2 < 0 \quad (16)$$

C. Step 3

In this step and for the adaptation law the reference currents are defined as:

$$\begin{cases} i_{dref} = 0 \\ i_{qref} = \frac{1}{A} \left[\begin{array}{l} \ddot{x}_{ref} + (1 - k_1^2)e_1 \\ + (k_1 + k_2)e_2 + \frac{\hat{F}_r}{M} + \frac{f_c}{M}v \end{array} \right] \end{cases} \quad (17)$$

Were $\hat{F}_r = F_r + \tilde{F}_r$, F_r the nominal value, \tilde{F}_r the error between the estimated value and the nominal value, and \hat{F}_r the estimated value. The error currents are defined as:

$$\begin{cases} e_3 = i_{qref} - i_q \\ e_4 = i_{dref} - i_d \end{cases} \quad (18)$$

For the recursive control and according to (12), (17) and (18), the \dot{e}_2 can be rewritten as:

$$\dot{e}_2 = Ae_3 - e_1 - k_2e_2 - \frac{\tilde{F}_r}{M} \quad (19)$$

The sliding mode surface equation can be designed as:

$$S = \dot{e}_2 + \lambda e_2 \quad (20)$$

The derivative \dot{S} rewritten as:

$$\begin{aligned} \dot{S} = & \ddot{x}_{ref} - k_1^2(e_2 - k_1 e_1) + \\ & (k_1 + \lambda)(Ae_3 - e_1 - k_2 e_2 - \frac{\tilde{F}_r}{M}) \\ & + \frac{\dot{\tilde{F}}_r}{M} + \frac{f_c}{M} \dot{v} - A\varphi_2 - \frac{A}{L} u_q \end{aligned} \quad (21)$$

The derivative error \dot{e}_4 rewritten as:

$$\dot{e}_4 = -\varphi_1 - \frac{1}{L} u_d \quad (22)$$

To design the adaptive backstepping sliding mode controller, the Lyapunov function is selected as:

$$V_3 = \frac{1}{2} e_1^2 + \frac{1}{2} e_2^2 + \frac{1}{2} e_4^2 + \frac{1}{2} S^2 + \frac{1}{n} \tilde{F}_r^2 \quad (23)$$

According to the equations (11), (19), (21), and (22) the derivative Lyapunov function is rewritten as:

$$\begin{aligned} \dot{V}_3 = & -k_1 e_1^2 - k_2 e_2^2 - k_3 e_4^2 + Ae_3 e_2 - e_2 \frac{\tilde{F}_r}{M} \\ & + e_4 \left[-\varphi_1 - \frac{1}{L} u_d + k_3 e_4 \right] \\ & + S \left[\ddot{x}_{ref} - k_1^2(e_2 - k_1 e_1) + (k_1 + \lambda) \right. \\ & \left. \left(Ae_3 - e_1 - k_2 e_2 - \frac{\tilde{F}_r}{M} \right) + \frac{\dot{\tilde{F}}_r}{M} \right. \\ & \left. + \frac{f_c}{M} \dot{v} - A\varphi_2 - \frac{A}{L} u_q \right. \\ & \left. + \frac{1}{n} \tilde{F}_r \dot{\tilde{F}}_r \right] \end{aligned} \quad (24)$$

To find $\dot{V}_3 < 0$, the backstepping sliding-mode control and adaptive laws are designed as:

$$u_q = \frac{L}{A} \begin{bmatrix} \ddot{x}_{ref} - k_1^2(e_2 - k_1 e_1) + (k_1 + \lambda)(Ae_3 - e_1) \\ -k_2 e_2 + \frac{\dot{\tilde{F}}_r}{M} + \frac{f_c}{M} \dot{v} - A\varphi_2 \\ + k_q \text{sat}(S) \end{bmatrix} \quad (25)$$

$$u_d = L[-\varphi_1 + k_3 e_4]$$

$$\dot{\tilde{F}}_r = n \int \left(\frac{e_2}{M} + (k_1 + \lambda) \frac{S}{M} \right) \quad (26)$$

According to equation (19), the estimated load force is rewritten as:

$$\hat{F}_r = n \int \left(\frac{(1 + (\lambda - k_2)(k_1 + \lambda))}{M} e_2 + \frac{(k_1 + \lambda)}{M} (Ae_3 - e_1 - \frac{\tilde{F}_r}{M}) \right) \quad (27)$$

Where k_1, k_2, k_3, k_q and n are constants positives gain. Substituting (25) and (26) into (24), one can obtain:

$$\dot{V}_3 = -k_1 e_1^2 - k_2 e_2^2 - k_3 e_4^2 \quad (28)$$

Since \dot{V}_3 is negative definite.

IV. RESULTS AND DISCUSSIONS

A simulation platform with MATLAB-SIMULINK software environments is used to validate the proposed

adaptive backstepping sliding mode controller using the motor parameters listed in Table 1.

Table 1. PMLSM PARAMETERS

Primary Winding Resistance	1.32Ω
Direct-Axis Primary Inductance	11mH
Quadrature-Axis Primary Inductance	11mH
Permanent Magnet Flux	0.65Wb
Mass of the Primary Part	20kg
Polar Pitch	30mm
Viscous Damping Coefficient	2Ns/m

Fig. 1 a-d shows the responses of the motor position, current, and load force when force load changes from 0N to 100N and 100N to 0N at $t=3s$ and $t=7s$, respectively under the condition that the reference position is a triangular wave.

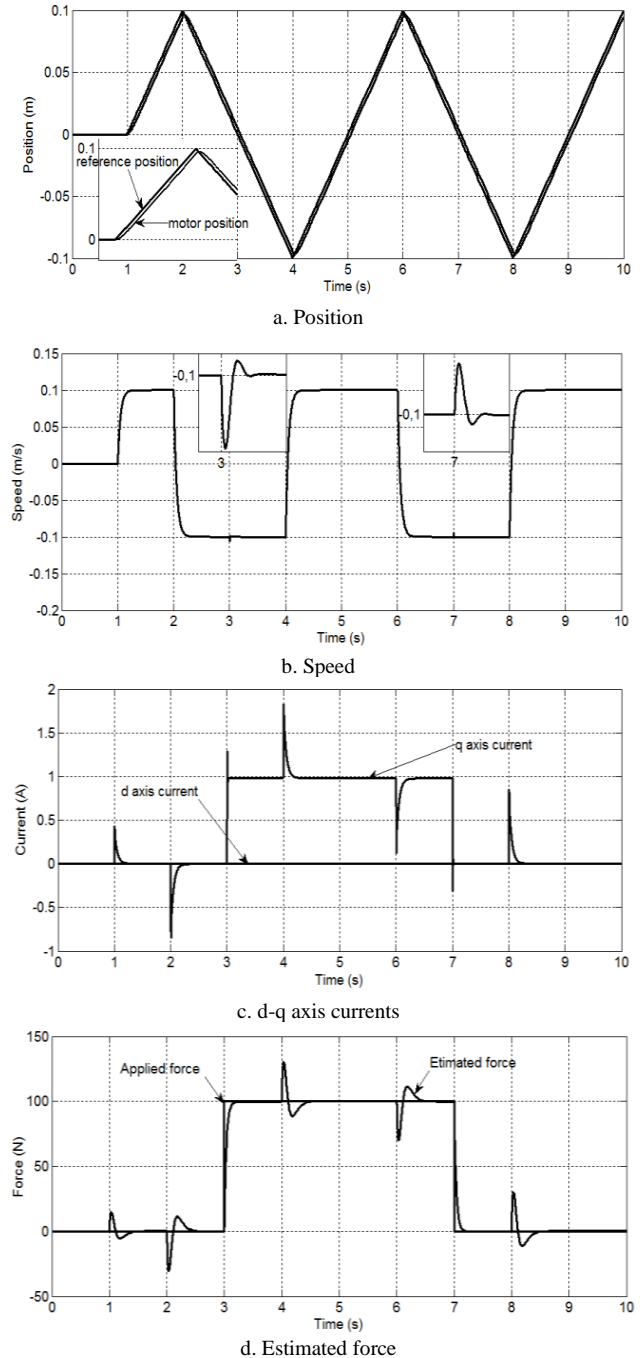


Fig. 1. Responses of the motor position, current, and load force when force load changes from 0N to 100N and 100N to 0N at $t=3s$ and $t=7s$

Fig. 1 a plots the reference and the actual position with respect to time. It is observed that the good matching of the reference position with good accuracy. Fig. 1 b shows the motor speed. We notice a very good load disturbance rejection during 0.4s. The stator current components are shown in Fig. 1 c. For vector-controlled PMLSM drive, the q-axis stator current is directly proportional to the electromagnetic force, and the d-axis stator current should be zero. Fig. 1 d plots the real and estimated load force. The estimated load force takes 0.868s to follow the disturbance load without going beyond and with good matching.

Fig. 2 a-d shows the control in position for triangular-wave reference trajectory and the load force was set to 100 Nm. Fig. 2 a shows the actual and reference positions, which overlap each other indicating a good matching of the reference position and motor position without going beyond. Fig. 2 b shows the speed. It is observing the good dynamic. Fig. 2 c shows the d-q axis currents the d-axis stator current should be maintained at zero and the q-axis stator current is directly proportional to the electromagnetic force. Fig. 2 d shows the load force estimated and the applied force. It is observed that the estimated load force takes 76 ms to follow the applied load force without going beyond. It is observed that the control law presents a good dynamic with no steady-state error.

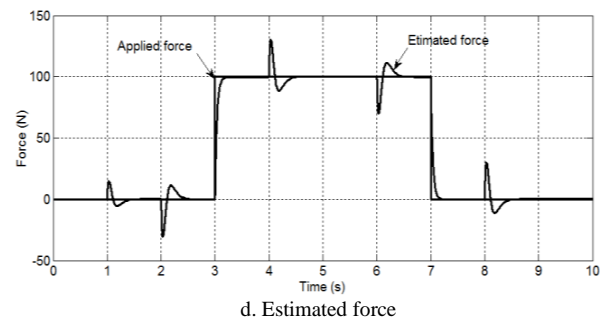
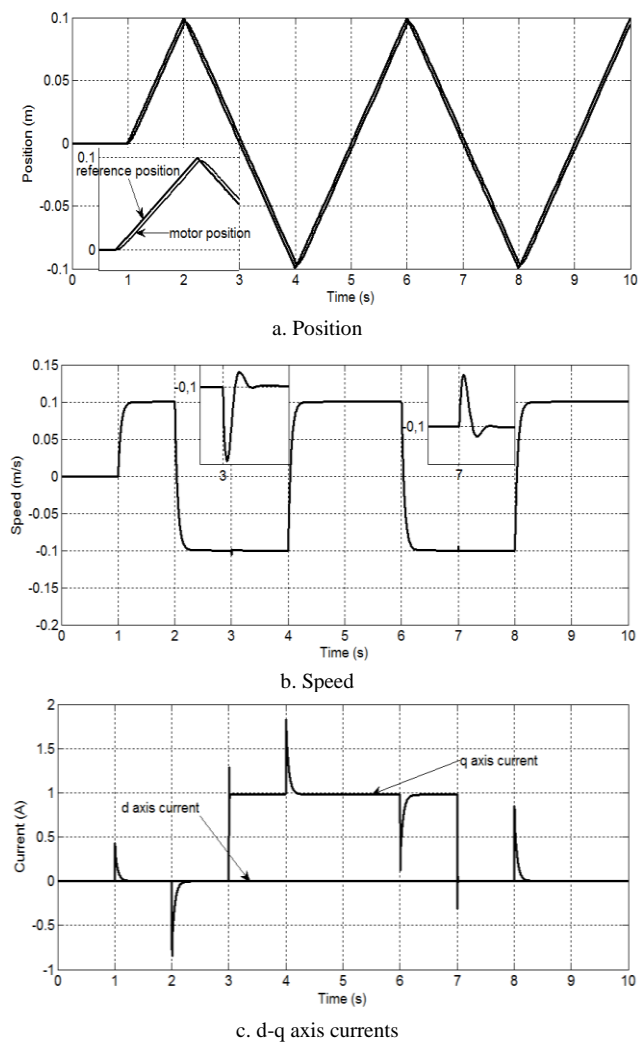


Fig. 2. Control in position for triangular-wave reference trajectory and the load force was set to 100 Nm

V. CONCLUSION

A new adaptive backstepping SMC for PMLSM drive position control is studied and investigated in this paper, through to the property of the SMC in front of the variation of the motor parameters and the efficiency of the backstepping controller in the stability of the overall system and according to the simulations results we can say that the proposed controller is robust. The simulated parameters were position, speed, dq axis currents, and estimated force. The simulated results prove the role of the proposed controller in terms of steady-state error, settling time, and fast response.

REFERENCES

- [1] Z. Li, K. T. Wang, J. S. Wang, Z. H. Zhang, X. Q. Guo, and H. X. Sun, "Cross-coupling control strategy based on intelligent adaptive control for cross-shaped dual-axis linear motors," *IET Electric Power Applications*, vol. 17, no. 9, pp. 1212–1224, 2023, <https://doi.org/10.1049/elp2.12336>.
- [2] M. M. Mahmoud, "Improved current control loops in wind side converter with the support of wild horse optimizer for enhancing the dynamic performance of PMSG-based wind generation system," *International Journal of Modelling and Simulation*, vol. 43, no. 6, pp. 952–966, 2023, <https://doi.org/10.1080/02286203.2022.2139128>.
- [3] H. Miloudi *et al.*, "Electromagnetic Compatibility Characterization of Start-Capacitor Single-Phase Induction Motor," *IEEE Access*, vol. 12, pp. 2313–2326, 2024, <https://doi.org/10.1109/ACCESS.2023.3349018>.
- [4] V. Kumar *et al.*, "A Novel Hybrid Harris Hawk Optimization–Sine Cosine Algorithm for Congestion Control in Power Transmission Network," *Energies*, vol. 17, no. 19, p. 4985, 2024, <https://doi.org/10.3390/en17194985>.
- [5] D. Fu and X. Zhao, "A Novel Robust Adaptive Nonsingular Fast Integral Terminal Sliding Mode Controller for Permanent Magnet Linear Synchronous Motors," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 2, pp. 1672–1683, 2023, <https://doi.org/10.1109/JESTPE.2022.3229904>.
- [6] M. M. Mahmoud *et al.*, "Application of Whale Optimization Algorithm Based FOPI Controllers for STATCOM and UPQC to Mitigate Harmonics and Voltage Instability in Modern Distribution Power Grids," *Axioms*, vol. 12, no. 5, p. 420, 2023, <https://doi.org/10.3390/axioms12050420>.
- [7] B. S. Atia *et al.*, "Applications of Kepler Algorithm-Based Controller for DC Chopper: Towards Stabilizing Wind Driven PMSGs under Nonstandard Voltages," *Sustainability*, vol. 16, no. 7, p. 2952, 2024, <https://doi.org/10.3390/su16072952>.
- [8] B. K. Ponukumati *et al.*, "Evolving fault diagnosis scheme for unbalanced distribution network using fast normalized cross-correlation technique," *PLoS One*, vol. 19, no. 10, p. e0305407, 2024, <https://doi.org/10.1371/journal.pone.0305407>.
- [9] F. Wang, K. Chen, S. Zhen, H. Zheng, X. Chen, and F. Chen, "Optimal design of Udawadia–Kalaba theory-based adaptive robust control for permanent magnet linear synchronous motor," *Journal of Vibration and Control*, vol. 30, no. 3–4, pp. 616–631, 2024, <https://doi.org/10.1177/10775463221149086>.

- [10] M. Nicola, C. I. Nicola, and D. Selișteanu, "Improvement of PMSM Sensorless Control Based on Synergetic and Sliding Mode Controllers Using a Reinforcement Learning Deep Deterministic Policy Gradient Agent†," *Energies*, vol. 15, no. 6, p. 2208, 2022, <https://doi.org/10.3390/en15062208>.
- [11] M. Awad *et al.*, "A review of water electrolysis for green hydrogen generation considering PV/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application," *Alexandria Engineering Journal*, vol. 87, pp. 213–239, 2024, <https://doi.org/10.1016/j.aej.2023.12.032>.
- [12] B. Benbouya, "Dynamic Assessment and Control of a Dual Star Induction Machine State Dedicated to an Electric Vehicle Under Short-Circuit Defect," *International Journal of Robotics and Control Systems*, vol. 4, no. 4, pp. 1731–1745, 2024, <https://doi.org/10.31763/ijrcs.v4i4.1557>.
- [13] S. R. K. Joga *et al.*, "Applications of tunable-Q factor wavelet transform and AdaBoost classifier for identification of high impedance faults: Towards the reliability of electrical distribution systems," *Energy Exploration & Exploitation*, 2024, <https://doi.org/10.1177/01445987241260949>.
- [14] L. Wang, J. Zhao, Z. Yu, Z. Pan and Z. Zheng, "High-Precision Position Control of PMLSM Using Fast Recursive Terminal Sliding Mode With Disturbance Rejection Ability," *IEEE Transactions on Industrial Informatics*, vol. 20, no. 2, pp. 2577–2588, 2024, <https://doi.org/10.1109/TII.2023.3295570>.
- [15] M. M. Mahmoud, M. K. Ratib, M. M. Aly, and A. M. M. Abdel-Rahim, "Wind-driven permanent magnet synchronous generators connected to a power grid: Existing perspective and future aspects," *Wind Engineering*, vol. 46, no. 1, pp. 189–199, 2022, <https://doi.org/10.1177/0309524X211022728>.
- [16] M. M. Mahmoud *et al.*, "Evaluation and Comparison of Different Methods for Improving Fault Ride-Through Capability in Grid-Tied Permanent Magnet Synchronous Wind Generators," *International Transactions on Electrical Energy Systems*, vol. 2023, no. 1, pp. 1–22, 2023, <https://doi.org/10.1155/2023/7717070>.
- [17] A. Fatah *et al.*, "Design, and dynamic evaluation of a novel photovoltaic pumping system emulation with DS1104 hardware setup: Towards innovative in green energy systems," *PLoS One*, vol. 19, no. 10, p. e0308212, 2024, <https://doi.org/10.1371/journal.pone.0308212>.
- [18] D. Karboua, T. Belgacem, Z. H. Khan, and C. Kellal, "Robust performance comparison of PMSM for flight control applications in more electric aircraft," *PLoS One*, vol. 18, no. 7, p. e0283541, 2023, <https://doi.org/10.1371/journal.pone.0283541>.
- [19] N. F. Ibrahim *et al.*, "Operation of Grid-Connected PV System With ANN-Based MPPT and an Optimized LCL Filter Using GRG Algorithm for Enhanced Power Quality," *IEEE Access*, vol. 11, pp. 106859–106876, 2023, <https://doi.org/10.1109/ACCESS.2023.3317980>.
- [20] O. M. Kamel, A. A. Z. Diab, M. M. Mahmoud, A. S. Al-Sumaiti, and H. M. Sultan, "Performance Enhancement of an Islanded Microgrid with the Support of Electrical Vehicle and STATCOM Systems," *Energies*, vol. 16, no. 4, p. 1577, 2023, <https://doi.org/10.3390/en16041577>.
- [21] Y. Kung, "Design and implementation of a high-performance PMLSM drives using DSP chip," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 3, pp. 1341–1351, 2008, <https://doi.org/10.1109/TIE.2007.909736>.
- [22] I. E. Maysse *et al.*, "Nonlinear Observer-Based Controller Design for VSC-Based HVDC Transmission Systems Under Uncertainties," *IEEE Access*, vol. 11, pp. 124014–124030, 2023, <https://doi.org/10.1109/ACCESS.2023.3330440>.
- [23] F. Lin, J. Hwang, P. Chou and Y. Hung, "FPGA-Based Intelligent-Complementary Sliding-Mode Control for PMLSM Servo-Drive System," *IEEE Transactions on Power Electronics*, vol. 25, no. 10, pp. 2573–2587, 2010, <https://doi.org/10.1109/TPEL.2010.2050907>.
- [24] M. M. Mahmoud *et al.*, "Voltage Quality Enhancement of Low-Voltage Smart Distribution System Using Robust and Optimized DVR Controllers: Application of the Harris Hawks Algorithm," *International Transactions Electrical Energy Systems*, vol. 2022, no. 1, pp. 1–18, 2022, <https://doi.org/10.1155/2022/4242996>.
- [25] H. Boudjemai *et al.*, "Application of a Novel Synergetic Control for Optimal Power Extraction of a Small-Scale Wind Generation System with Variable Loads and Wind Speeds," *Symmetry*, vol. 15, no. 2, p. 369, 2023, <https://doi.org/10.3390/sym15020369>.
- [26] D. M. Alter and T. C. Tsao, "Control of linear motors for machine tool feed drives: Design and implementation of H_∞ optimal feedback control," *Journal of Dynamic Systems, Measurement, and Control*, vol. 118, no. 4, pp. 649–656, 1996, <https://doi.org/10.1115/1.2802339>.
- [27] M. M. Mahmoud, B. S. Atia, A. Y. Abdelaziz, and N. A. N. Aldin, "Dynamic Performance Assessment of PMSG and DFIG-Based WECS with the Support of Manta Ray Foraging Optimizer Considering MPPT, Pitch Control, and FRT Capability Issues," *Processes*, vol. 10, no. 12, p. 2723, 2022, <https://doi.org/10.3390/pr10122723>.
- [28] N. Benalia *et al.*, "Enhancing electric vehicle charging performance through series-series topology resonance-coupled wireless power transfer," *PLoS One*, vol. 19, no. 3, p. e0300550, 2024, <https://doi.org/10.1371/journal.pone.0300550>.
- [29] B. Wang and J. Wang, "Sliding mode control of surface-mount permanent-magnet synchronous motor based on error model with unknown load," *Journal of Software*, vol. 6, no. 5, pp. 819–825, 2011, <https://www.jssoftware.us/vol6/jsw605-8.pdf>.
- [30] M. K. Ratib *et al.*, "Applications of hybrid model predictive control with computational burden reduction for electric drives fed by 3-phase inverter," *Ain Shams Engineering Journal*, vol. 14, no. 8, p. 102028, 2023, <https://doi.org/10.1016/j.asej.2022.102028>.
- [31] G. Rigatos, P. Siano, F. Marignetti and I. Gros, "A nonlinear optimal control approach for PM Linear Synchronous Motors," *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)*, pp. 453–458, 2018, <https://doi.org/10.1109/INDIN.2018.8472019>.
- [32] L. Yu, J. Huang, W. Luo, S. Chang, H. Sun, and H. Tian, "Sliding-Mode Control for PMLSM Position Control—A Review," *Actuators*, vol. 12, no. 1, p. 31, 2023, <https://doi.org/10.3390/act12010031>.
- [33] F. F. M. El-Sousy and K. A. Abuhasel, "Adaptive Nonlinear Disturbance Observer Using a Double-Loop Self-Organizing Recurrent Wavelet Neural Network for a Two-Axis Motion Control System," *IEEE Transactions on Industry Applications*, vol. 54, no. 1, pp. 764–786, 2018, <https://doi.org/10.1109/TIA.2017.2763584>.
- [34] Z. Lei, L. Jian and H. Jia-cai, "Research on predictive functional control based on disturbance observer for PMLSM speed system," *2017 36th Chinese Control Conference (CCC)*, pp. 4650–4653, 2017, <https://doi.org/10.23919/ChiCC.2017.8028088>.
- [35] T. Chen, D. Cao, J. Yuan, and H. Yang, "Observer-based adaptive neural network backstepping sliding mode control for switched fractional order uncertain nonlinear systems with unmeasured states," *Measurement and Control*, vol. 54, no. 7–8, pp. 1245–1258, 2021, <https://doi.org/10.1177/00202940211021107>.
- [36] A. M *et al.*, "Prediction of Optimum Operating Parameters to Enhance the Performance of PEMFC Using Machine Learning Algorithms," *Energy Exploration & Exploitation*, 2024, <https://doi.org/10.1177/01445987241290535>.
- [37] Z. Li, S. Zhou, Y. Xiao and L. Wang, "Sensorless Vector Control of Permanent Magnet Synchronous Linear Motor Based on Self-Adaptive Super-Twisting Sliding Mode Controller," *IEEE Access*, vol. 7, pp. 44998–45011, 2019, <https://doi.org/10.1109/ACCESS.2019.2909308>.
- [38] J. Yang, S. Wang, W. Yu, and L. Yang, "Implementation on adaptive sliding mode position controller of permanent magnet linear synchronous motor," *2007 International Conference on Electrical Machines and Systems (ICEMS)*, pp. 468–471, 2007, <https://doi.org/10.1109/ICEMS12746.2007.4412008>.
- [39] F. J. Lin, S. Y. Chen, L. T. Teng, and H. Chu, "Recurrent functional-link-based fuzzy neural network controller with improved particle swarm optimization for a linear synchronous motor drive," *IEEE Transactions on Magnetics*, vol. 45, no. 8, pp. 3151–3165, 2009, <https://doi.org/10.1109/TMAG.2009.2017530>.
- [40] Y. Kung, L. T. V. Anh and S. Jou, "FPGA-Realization of Adaptive Fuzzy Controller for the Linear X-Y Table," *2008 Eighth International Conference on Intelligent Systems Design and Applications*, pp. 89–94, 2008, <https://doi.org/10.1109/ISDA.2008.10>.
- [41] H. Sun *et al.*, "Research on dual-mode switching fuzzy PID servo algorithm based on micro-linear motor," *The Journal of Engineering*, vol. 2019, no. 23, pp. 8927–8931, 2019, <https://doi.org/10.1049/joe.2018.9150>.
- [42] X. Zhang and J. Pan, "Nonlinear Robust Sliding Mode Control for PM Linear Synchronous Motors," *2006 CES/IEEE 5th International Power*

- Electronics and Motion Control Conference*, pp. 1-5, 2006, <https://doi.org/10.1109/IPEMC.2006.4777988>.
- [43] M. Chebaani, M. M. Mahmoud, A. F. Tazay, M. I. Mosaad, and N. A. Nouraldin, "Extended Kalman Filter design for sensorless sliding mode predictive control of induction motors without weighting factor: An experimental investigation," *PLoS One*, vol. 18, no. 11, p. e0293278, 2023, <https://doi.org/10.1371/journal.pone.0293278>.