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ISTANBUL AYDIN UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

A COMPARISON STUDY BETWEEN EXTENDED KALMAN FILTER (EKF) AND IMMERSION & INVARIANCE (I&I) METHODS TO ESTIMATE THE SPEED OF PMSM MOTOR BASED ON THE STRUCTURE OF PORT-CONTROLLED HAMILTONIAN SYSTEM

MASTER'S THESIS

Enas Walid Ali Benzeglam

Department of Electrical and Electronics Engineering

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JULY, 2023

ONAY FORMU

DECLARATION

I hereby declare with the respect that the study "A Comparison Study between Extended Kalman Filter (EKF) and Immersion & Invariance (I&I) Methods to Estimate the Speed of PMSM Motor based on the structure of Port-Controlled Hamiltonian System.", which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the References. (…/…/2023)

Enas Walid Ali Benzeglam

FOREWORD

I wish to thank various people for their contribution to this project. I feel very fortunate to have Dr. Mohammed Alkrunz as my supervisor and want to express my appreciation for guiding me within the whole research process in a patient and effective manner. And for his willingness to give his time so generously has been very much appreciated.

I would also like to extend my thanks to all teachers and academic staff of our department for their efforts in teaching us. I also like to thank my family for encouraging me to study for a master's degree and also for teaching me to chase my dreams and never give up.

Finally, I would like to acknowledge the important contribution of Istanbul Aydin University to my academic background.

July, 2023 Enas Walid Ali Benzeglam

A COMPARISON STUDY BETWEEN EXTENDED KALMAN FILTER (EKF) AND IMMERSION & INVARIANCE (I&I) METHODS TO ESTIMATE THE SPEED OF PMSM MOTOR BASED ON THE STRUCTURE OF PORT-CONTROLLED HAMILTONIAN SYSTEM

ABSTRACT

Permanent Magnet Synchronous Motor (PMSM) is used increasingly in a wide range of industrial applications due to its advantageous features such as high efficiency, high torque to inertia ratio, low noise, and robustness. An accurate knowledge of motor parameters is essential in order to achieve a better performance. In this study, the problem of speed tracking of the PMSM motor considering uncertain speed is addressed. The model structure of the PMSM motor with uncertain speed is formulated in the structure of port-controlled Hamiltonian system in discrete-time setting. An adaptive discrete-time interconnection and damping assignment passivity based controller (IDA-PBC) for the uncertain PMSM motor is proposed. Besides, discrete-time immersion and invariance (I&I) based estimator is designed to estimate the uncertain motor speed. This estimated speed is used in the IDA-PBC controller to provide an automatic tuning for the motor speed. The asymptotic stability of the estimator is achieved based on Lyapunov theory. The proposed adaptive controller is applied to the PMSM motor where the controller performance is tested by Matlab/Simulink. The proposed I&I based estimation method is compared to the estimation method of Extended Kalman Filter (EKF). Simulation results show the productivity and effectiveness of the proposed method.

Keywords: PMSM, IDA-PBC, immersion and invariance (I&I), port-controlled Hamiltonian system, Adaptive Control, Extended Kalman Filter (EKF).

PORT KONTROLLÜ HAMILTON SISTEMININ YAPISINA DAYALI OLARAK PMSM MOTORUNUN HIZINI TAHMIN ETMEK İÇIN GENIŞLETILMIŞ KALMAN FILTRESI (EKF) ILE DALDIRMA VE DEĞIŞMEZLIK (I&I) YÖNTEMLERI ARASINDA BIR KARŞILAŞTIRMA ÇALIŞMASI

ÖZET

Permanent Mıknatıs Senkron Motor (PMSM), yüksek verimlilik, yüksek tork/inersiyon oranı, düşük gürültü ve sağlamlık gibi avantajlı özellikleri nedeniyle endüstriyel uygulamalarda giderek artan bir şekilde kullanılmaktadır. Daha iyi bir performans elde etmek için motor parametrelerinin doğru bir şekilde bilinmesi önemlidir. Bu araştırmada, belirsiz hızı dikkate alan PMSM motorunun hız takip problemi ele alınmaktadır. Belirsiz hızlı PMSM motorunun model yapısı, ayrık zamanlı port-kontrollü Hamilton sistem yapısında formüle edilmiştir. Belirsiz PMSM motoru için uyumlu ayrık zamanlı bağlantı ve sönümleme ataması geçişimsel temelli bir denetleyici (IDA-PBC) önerilmektedir. Ayrıca, belirsiz motor hızını tahmin etmek için ayrık zamanlı batma ve değişmezlik (I&I) temelli bir tahminleyici tasarlanmıştır. Bu tahminlenen hız, IDA-PBC denetleyicisinde kullanılarak motor hızı için otomatik bir ayarlama sağlar. Tahminleyicinin asimptotik kararlılığı, Lyapunov teorisi temelinde elde edilmektedir. Önerilen uyumlu denetleyici, denetleyici performansı Matlab/Simulink ile test edilen PMSM motoruna uygulanmıştır. Önerilen I&I temelli tahmin yöntemi, Extended Kalman Filtresi (EKF) tahmin yöntemiyle karşılaştırılmaktadır. Simülasyon sonuçları, önerilen yöntemin verimliliğini ve etkinliğini göstermektedir.

Anahtar Kelimeler: PMSM, IDA-PBC, I&I, port-kontrollü Hamilton sistem, Uyumlu Kontrol, Extended Kalman Filtresi (EKF).

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ABBREVIATIONS

PMSM : Permenant Magnet Synchrounius Motor

PCH : Port-Controlled Hamiltonian

I&I : Immersion & Invariance

EKF : Extended Kalman Filter

IDA-PBC : Interconnection and Damping Assignment Passivity-Based Control

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I. INTRODUCTION

The Permanent Magnet Synchronous Motor (PMSM) is the most commonly used motor in variable speed electric drive applications. It is favored for its superior full load efficiency, power factor, high torque/inertia ratio, and wide range of speed control (Balashanmugham et al, 2019). In PMSM drives, the vector control theory is applied in the d-q reference frame to independently control the flux and torque. For measuring the shaft position of the PMSM, an optimal encoder is employed. However, the speed signal obtained through discrete differentiation of the encoder position is noisy and exhibits inherent delay, which can negatively impact system performance (Balashanmugham et al, 2019; Liu et al, 2019). To address this issue, the speed can be estimated using different methods such as; the Extended Kalman Filter (EKF) and immersion and invariance (I&I) algorithms that will be discussed in the paper. However, the dynamic behavior of a PMSM can be influenced by factors like parameter uncertainties, variations in load conditions, and external disturbances.

Adaptive control techniques can be applied to PMSM drives to address these challenges and improve their performance. By using adaptive control algorithms, the control system can adapt to changes in the motor's characteristics or operating conditions in real-time (Jin et al, 2013). This allows the system to continuously optimize the control parameters or structure, compensating for uncertainties and disturbances, and achieving better performance. Adaptive control aims to enhance control performance and accommodate variations in the controlled system.

EKF is a state estimation algorithm commonly used in adaptive control systems. It enables the estimation of states, parameters, or other variables in real-time, even in the presence of nonlinearities and uncertainties (Ali et al, 2014). The estimated values obtained from EKF are used to update the control parameters or structure, facilitating adaptive control.

In summary, adaptive control techniques are utilized in PMSM drives to enhance their performance, address parameter uncertainties, and improve the system's ability to adapt and optimize control in real-time.

Extended Kalman filter (EKF) is heuristic for nonlinear filtering problem. It often works well (when tuned properly), but sometimes not widely used in practice. EKF is based on Linearizing dynamics and output functions at current estimateand propagating an approximation of the conditional expectation and covariance.

I&I, on the other hand, is a control framework that provides robustness against model uncertainties and disturbances (Donaire et al, 2012). It is particularly applicable to nonlinear systems. By employing I&I, the control system ensures the immersion of the system dynamics into a desired invariant manifold, allowing for robust and adaptive control.

Port Controlled Hamiltonian (PCH) systems are a framework for modeling and controlling a wide range of physical systems, including Permanent Magnet Synchronous Motors (PMSMs) (Liu et al, 2019).

In the context of PMSMs, the PCH framework provides a systematic and energy-based modeling approach. Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) is an approach used in the control of Port Controlled Hamiltonian (PCH) systems (Liu et al, 2019). PCH systems provide a unified framework for modeling and control ling a wide range of physical systems, including electrical circuits, mechanical systems, and multi-domain systems.

In the IDA-PBC approach, the control objective is to design a control law that achieves stability, good disturbance rejection, and desired performance in PCH systems. The approach is based on the concept of passivity, which ensures energy dissipation and stability in physical systems.

This study focuses on addressing the issue of tracking the speed of a PMSM motor under uncertain conditions. The model structure of the PMSM motor, considering uncertain speed, is developed based on the discrete-time port-controlled Hamiltonian system. To tackle this challenge, an adaptive discrete-time interconnection and damping assignment passivity based controller (IDA-PBC) is proposed for the PMSM motor with uncertain speed. Additionally, a discrete-time immersion and invariance (I&I) based estimator is designed to accurately estimate the uncertain motor speed. This estimated speed is utilized in the IDA-PBC controller to facilitate automatic tuning of the motor speed. The asymptotic stability of the estimator is established using Lyapunov theory. The proposed adaptive controller is implemented on the PMSM motor, and its performance is evaluated through simulations using Matlab/Simulink. Furthermore, the estimation method based on I&I is compared with the Extended Kalman Filter (EKF) estimation method. The simulation results demonstrate the effectiveness and productivity of the proposed approach.

II. LITERATURE REVIEW

The control of Permanent Magnet Synchronous Motors (PMSMs) has garnered significant attention due to their widespread usage in various industrial applications. Achieving accurate speed control in PMSM motors, especially under uncertain speed conditions, is crucial for ensuring optimal performance. In recent years, researchers have explored the application of adaptive control techniques, specifically the Discrete-time Adaptive Interconnection and Damping Assignment Passivity Based Control (IDA-PBC), within the framework of a port-controlled Hamiltonian system to address the challenges posed by uncertain speed in PMSM motors. This literature review aims to provide an overview of the existing research and developments in this area.

(Liu et al, 2019) represented a new control method for the PMSM drive system, called the speed-current single loop control method based on Port-Controlled Hamiltonian theory, is proposed instead of the conventional cascade controller. In order to enhance its resilience, a nonlinear disturbance observer method is employed to estimate and compensate for disturbances in the system. This approach allows for feed-forward compensation control. By utilizing this designed controller, stable speed control is achieved. Additionally, the controller exhibits favorable transient response and robustness against various disturbances, including parameter variations and external disruptions (Liu et al, 2019).

In the study of (Belkhier et al, 2022), a novel and robust IDA-PBC (Implicit Dissipative Approach - Port-Based Control) method with speed and load observer is applied to the PMSM (Permanent Magnet Synchronous Motor). The approach is based on the concept of passivity and utilizes the PCH (Port-Controlled Hamiltonian) model. The controller incorporates three important matrices: the interconnection matrix, representing the internal energy exchange ports within the PMSM; the damping matrix, accounting for all dissipation elements in the system; and the external interconnection matrix, capturing the energy exchanges between the PMSM and its external environment. The IDA-PBC stands out due to the adoption of the PCH structure in the closed loop, which allows for the determination of an energy function compatible with this model (Belkhier et al, 2022).

Besides, (Donaire et al, 2012) proposed a new approach for effectively managing the speed control of Permanent Magnet Synchronous Machines (PMSM) in this study. The machine's model is analyzed within the port-Hamiltonian framework, and a control strategy is developed using the concepts of immersion and invariance (I&I), which have been recently explored in existing literature. The suggested controller guarantees both the internal stability of the system and the accurate regulation of the output velocity. Additionally, it enforces integral action on non-passive outputs, ensuring a comprehensive and robust control solution (Donaire et al, 2012).

While (Ali et al, 2014) suggested a new approach for implementing a proportional-integral-derivative (PID) controller for a Permanent Magnet Synchronous Motor (PMSM) using a state observer known as Extended Kalman Filter (EKF). The proposed design introduces a novel implementation method for the PID controller. The method being suggested provides precise estimations of both speed and current. Furthermore, this approach effectively reduces any speed deviations caused by load disturbances and minimizes fluctuations in the control signal. It also enhances both the steady and transient responses.

Furthermore, in the study of (Maiti et al, 2009), a technique for speed estimation is introduced, which utilizes a model reference adaptive controller. The reactive power is employed as the functional candidate within the MRAS (Model Reference Adaptive System). The adaptation mechanism utilizes the instantaneous reactive power in the reference model and the steady-state reactive power in the adjustable model. By incorporating the steady-state reactive power, the need for derivative computation is eliminated, resulting in reduced sensitivity to noise. Additionally, this approach does not require back-emf estimation, which helps avoid issues related to integrator and improves the performance of the estimator, particularly at very low and zero speeds (Maiti et al, 2009).

(Lazi et al, 2019) presented a straightforward approach to estimate the speed and rotor position of PMSM (Permanent Magnet Synchronous Motor) drives using an adaptive controller. The proposed method introduces novel estimator equations and eliminates the need for a voltage probe, relying solely on direct and quadrature reference currents. The hardware implementation of these sensorless drives is achieved using the dSPACE DS11103 panel. The integration between the software and hardware setup is facilitated by dSPACE Real-Time Implementation (RTI) (Lazi et al, 2019).

In the study of (Akrad et al, 2007) the aim is to create a high-performance speed controller for a PMSM (Permanent Magnet Synchronous Motor) drive (Akrad et al, 2007). The controller is based on passivity and utilizes the energy shaping technique known as Interconnection and Damping Assignment. By making certain assumptions, a linear controller is derived in conjunction with a non-linear observer that estimates the unknown load torque. The key contribution of this paper lies in the demonstration of global stability, which is crucial for drive systems, particularly in embedded or transportation applications where reliability is of utmost importance. Simulation and experimental results are provided to validate the feasibility of this approach (Akrad et al, 2007).

In the study of (Jin et al, 2013) an adaptive and integral control scheme for permanent magnet synchronous motors (PMSM) within the port-controlled Hamiltonian (PCH) framework is introduced ((Jin et al, 2013). Initially, a speed tracking controller is designed using the IDA-PBC (Implicit Dissipative Approach - Port-Based Control) method for a nominal PMSM model. Subsequently, a second control term is developed to compensate for control errors arising from unknown or uncertain parameters. Finally, a third integral control term is introduced to address unknown disturbances. The stability of the closed-loop system is analyzed using passivity within the PCH framework. Simulation results are provided to validate the effectiveness of the proposed control scheme (Jin et al, 2013).

The paper of (Haisheng Yu, et al) introduces an innovative feedback control scheme for speed regulation of permanent magnet synchronous motors (PMSM) using a combination of energy-shaping and port-controlled Hamiltonian (PCH) systems theory (Yu et al, 2009). The closed-loop PMSM system is assigned a desired state error port-controlled Hamiltonian structure through feedback control. By employing the interconnection and damping assignment passivity-based control

(IDA-PBC) methodology, speed controllers are designed for scenarios where the load torque is both known and unknown (Yu et al, 2009).

Finally, the paper of (Naithan Peter) introduces a method introduced for estimating the mechanical parameters of a Permanent Magnet Synchronous Motor (PMSM) by utilizing the Forgetting Factor Recursive Least Squares (RLS) algorithm (Peter et al, 2023). These estimated parameters are then employed for adaptive feedforward control actions, considering that the mechanical parameters of a PMSM can undergo changes with varying loads and speeds. The proposed technique is simulated using MATLAB/Simulink® under various conditions. The results illustrate the effectiveness of the method in accurately estimating the mechanical parameters and improving the overall performance of the drive.

III. PRELİMİNARS

A. Port-Controlled Hamiltonian Systems

Port-Hamiltonian (PH) systems offer a framework to model, analyze, and control intricate dynamic systems. The complexity of these systems can arise from various factors such as the interaction of multiple physical phenomena, intricate spatial regions, and diverse nonlinear behaviors. One significant advantage of the PH representation is its clear expression of power interfaces, referred to as ports. These ports enable the interconnection of subsystems while preserving power, allowing for the flexible composition of modular multi-body systems (Kinon et al, 2023). An important advancement in the theory of port-Hamiltonian systems, compared to geometric mechanics, is the incorporation of energy-dissipating components that are not commonly found in traditional Hamiltonian systems (Van Der Schaft et al, 2014). In addition to providing a systematic and enlightening framework for modeling and analyzing multi-physics systems, port-Hamiltonian systems theory serves as a natural foundation for control. Particularly in nonlinear scenarios, it is widely acknowledged that the control design should leverage and adhere to the physical properties of the system, such as balance, conservation laws, and energy considerations. This approach enables the development of robust and physically interpretable control laws (Van Der Schaft et al, 2014).

In the context of port-based modeling, the overall physical system, which may be extensive in scale, is viewed as a composition of three fundamental types of ideal components: (1) elements for storing energy, (2) elements for dissipating energy (resistive elements), and (3) elements for routing energy.

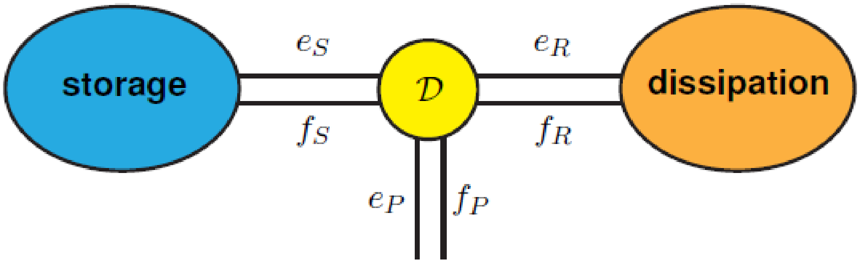


Figure 1 Port-Controlled Hamiltonian System (Van Der Schaft et al, 2014)

In the port-Hamiltonian formulation (Golo et al, 2003), the energy-storing elements are combined into a unified entity represented by S (referred to as 'storage'). Similarly, the energy-dissipating elements are consolidated into a single object represented by R (referred to as 'resistive'). Additionally, the interconnection of all energy-routing elements can be treated as a collective energy-routing structure denoted by D (formalized using the geometric concept of a Dirac structure).

Figure 1 illustrates three ports: the port (f_s, e_s) representing the connection to energy storage, the port (f_R, e_R) representing energy dissipation, and the external port (f_P, e_P), which facilitates interaction between the system and its environment, including controller actions.

The standard Hamiltonian equations for a mechanical system are given as (Van Der Schaft et al, 2006):

$$\dot{q} = \frac{\partial H}{\partial p}(q, p) \tag{3.1}$$

$$\dot{p} = -\frac{\partial H}{\partial q}(q, p) + F \tag{3.2}$$

The Hamiltonian $H(q, p)$ represents the overall energy of the system, where $q = [q_1, \ldots, q_k]^T$ denotes the generalized configuration coordinates for a mechanical system with k degrees of freedom, $p = [p_1, \ldots, p_k]^T$ represents the vector of generalized momenta, and F represents the vector of external generalized forces. The state space of equation (3.1) with local coordinates (q, p) is referred to as the phase space. From this, we can readily deduce the following energy balance:

$$\frac{d}{dt}H = \frac{\partial^T H}{\partial q}(q, p)\dot{q} + \frac{\partial^T H}{\partial p}(q, p)\dot{p} = \frac{\partial^T H}{\partial p}(q, p)F = \dot{q}^T F, \tag{3.3}$$

This implies that the growth in the system's energy is equivalent to the work input provided, emphasizing the conservation of energy. This leads to the definition of the system's output as $e = \dot{q}$, which represents the vector of generalized velocities (Van Der Schaft et al, 2006).

Another way to extend the analysis is to examine systems that are described using local coordinates,

$$\dot{x} = J(x)\frac{\partial H(x)}{\partial x} + g(x)f, \quad x \in \chi, f \in \mathbb{R}^m \tag{3.4}$$

$$e = g^T(x)\frac{\partial H(x)}{\partial x}, \; e \in \mathbb{R}^m \tag{3.5}$$

here, $J(x)$ is an $n \times n$ matrix, where the entries depend smoothly on x. It is assumed that $J(x)$ is skew-symmetric, meaning $J(x) = -J^T(x)$. Here, $x = [x_1, \ldots, x_n]^T$ represents local coordinates for an n-dimensional state space manifold X, which may not necessarily be even-dimensional as mentioned earlier. Due to the skew-symmetry of J, we can easily deduce the energy balance $\frac{d}{dt} H(x(t)) = e^T(t)f(t)$. We refer to equation (3.4) as a port-Hamiltonian system with the structure matrix $J(x)$, input matrix $g(x)$, and Hamiltonian H.

B. Interconnection and Damping Assignment Passivity-Based Control Technique

The Interconnection and Damping Assignment - Passivity-Based Control (IDA-PBC) approach was developed to combine the passivity characteristics of Port-Controlled Hamiltonian Systems (PCHS) with control through interconnection and energy-based methods. This technique has found applications in various domains, including mechanical systems, magnetic levitation systems, mass-balance systems, electric machines, and power converters (Van Der Schaft et al, 2014).

The fundamental concept behind IDA-PBC is that by leveraging the Hamiltonian framework, it is possible to solve the partial differential equation associated with the energy balance equation. This can be achieved by appropriately selecting the interconnection matrix J, the dissipation matrix R, and the energy function H for the desired closed-loop system (Van Der Schaft et al, 2014). These selected matrices and energy function are denoted by subscripts "d" to indicate their association with the desired closed-loop system: $J_d, R_d, and\ H_d$.

The aim of designing the interconnection and damping assignment passivity-based control (IDA-PBC) is to achieve a closed-loop system that has the following structure:

$$\dot{x} = [J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x}(x) \tag{3.6}$$

The desired interconnection and dissipation matrices are chosen such that they fulfill specific properties. The interconnection matrix, denoted as $J_d(x)$, is skew-symmetric, meaning it satisfies $J_d(x) = -J^T d(x)$. The dissipation matrix, denoted as $R_d(x)$, is symmetric and positive semi-definite, indicated by $R_d(x) = R_d^T(x)$ and $R_d(x) \geq 0$, respectively (Van Der Schaft et al, 2014).

$$[J(x) + J_a(x) - R(x) - R_a(x)] \frac{\partial H_d}{\partial x}(x) = [J_a(x) - R_a(x)] \frac{\partial H}{\partial x}(x) + g(x)u(x), \tag{3.7}$$

where $J_a(x) \coloneqq J_d(x) - J(x)$ and $R_a(x) \coloneqq R_d(x) - R(x)$

The control that satisfies the closed-loop control objective is given by:

$$u(x) = \left(g^T(x)g(x)\right)^{-1} g^T(x) \times ([J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x}(x) - [J(x) - R(x)] \frac{\partial H}{\partial x}(x) \tag{3.8}$$

The matching condition is solved to obtain the desired closed-loop Hamiltonian $H_d(x)$ and the desired interconnection and damping matrices.

$$g^{\perp}(x)[J(x) - R(x)] \frac{\partial H}{\partial x}(x) = g^{\perp}(x)[J_d(x) - R_d(x)] \frac{\partial H_d}{\partial x}(x), \tag{3.9}$$

There are three major approaches to solve the PDE’s of (3.9) (Van Der Schaft et al, 2014):

• **Non-parameterized IDA-PBC:** In this general form, $J_d(x)$ and $R_d(x)$ are fixed and the PDE's (3.9) are solved for the energy function $H_d(x)$.

• **Algebraic IDA-PBC:** The desired energy function $H_d(x)$. is fixed thus rendering (3.9) an algebraic set of equations in terms of the unknown matrices $J_d(x)$ and $R_d(x)$.

• **Parameterized IDA-PBC:** Here, the structure of the energy function $H_d(x)$ is fixed. This imposes constraints on the unknown matrices $J_d(x)$ and $H_d(x)$, which need to be satisfied by (3.9).

C. Immersion & Invariance Control Technique

I&I is a technique for designing control laws that can stabilize and adapt to nonlinear systems (Astolfi et al, 2003). This method relies on the concepts of system immersion and manifold invariance, and it doesn't necessarily require knowledge of a Lyapunov function for control purposes. The process of constructing the stabilizing control laws is similar to the approach used in nonlinear regulator theory, which involves determining the output zeroing manifold and its related components. This method is particularly useful when we have a stabilizing controller for a simplified model but want to enhance its robustness to account for higher order dynamics. To achieve this, a control law is designed to gradually incorporate the full system dynamics into the simplified model, eventually achieving asymptotic immersion (Astolfi et al, 2003).

Consider the following system (Astolfi et al, 2003):

$$\dot{x} = f(x) + g(x)u \qquad (3.9)$$

With state $x \in \mathbb{R}^n$and control $u \in \mathbb{R}^m$, with and equilibrium point $x^* \in \mathbb{R}^n$ to be stabilized. Let $p < n$ and assume mappings can be found

$\alpha(\cdot): \mathbb{R}^p \rightarrow \mathbb{R}^p$ $\quad$ $\pi(\cdot): \mathbb{R}^p \rightarrow \mathbb{R}^n$ $\quad$ $c(\cdot): \mathbb{R}^p \rightarrow \mathbb{R}^m$

$\phi(\cdot): \mathbb{R}^n \rightarrow \mathbb{R}^{n-p}$ $\quad$ $\psi(\cdot,\cdot): \mathbb{R}^{nx(n-p)} \rightarrow \mathbb{R}^m$

Such that the following hold.

H1) (*Target system*) The system

$$\dot{\xi} = \alpha(\xi) \tag{3.10}$$

with state $\xi \in \mathbb{R}^p$ has a globally asymptotically stable equilibrium at $\xi^* \in \mathbb{R}^p$ and $x^* = \pi(\xi^*)$.

H2) (*immersion condition*) for all $\xi \in \mathbb{R}^p$

$$f\big(\pi(\xi)\big) + g\big(\pi(\xi)\big)c\big(\pi(\xi)\big) = \frac{\partial \pi}{\partial \xi}\alpha(\xi). \tag{3.11}$$

H3) (*implicit manifold*) The following set identity holds

$$\{x \in \mathbb{R}^n | \phi(x) = 0\} = \{x \in \mathbb{R}^n | x = \ \pi(\xi)\}$$

for some $\xi \in \mathbb{R}^p$.

H4) (*Manifold attractivity and trajectory boundedness*) All trajectories of the system

$$\dot{z} = \frac{\partial \phi}{\partial x}[f(x) + g(x)\psi(x, z)] \tag{3.12}$$

$$\dot{x} = f(x) + g(x)\psi(x, z) \tag{3.13}$$

are bounded and satisfy

$$\lim_{t \to \infty} z(t) = 0. \tag{3.14}$$

Hence, the closed-loop system has a globally asymptotically stable equilibrium at point x^* (Astolfi et al, 2003).

D. Extended Kalman Filter Technique

If either the dynamics of the system state or the observation dynamics are nonlinear, the conditional probability density functions, which give the most accurate estimates with minimum mean-square error, are no longer Gaussian. In order to propagate and evaluate these non-Gaussian functions, the optimal non-linear filter requires a high computational effort. A suboptimal solution within the realm of linear filters is the Extended Kalman filter (EKF). The EKF employs a Kalman filter with system dynamics that are linearized based on the previous state estimates of the original non-linear filter (Ribeiro, 2004).

Consider the non-linear dynamics (Lewis et al, 2017:275). System model and measurment model

$$\dot{x} = a(x, u, t) + G(t)w \tag{3.15}$$

$$z = h(x, t) + v \tag{3.16}$$

$$x(0) \sim (\overline{x_0}, P_0), w(t) \sim (0, Q), v(t) \sim (0, R) \tag{3.17}$$

Assumptions

$\{w(t)\}$ and $\{v(t)\}$ are white noise processes uncorrelated with $x(0)$ and with each other.

Initialization

$$P(0) = P_0, \hat{x}(0) = \overline{x_0} \tag{3.18}$$

Estimate update

$$\dot{\hat{x}} = a(\hat{x}, u, t) + K[z - h(\hat{x})] \tag{3.19}$$

Error Covariance update

$$\dot{P} = A(\hat{x}, t)P + PA^T(\hat{x}, t) + GQG^T - PH^T(\hat{x}, t)R^{-1}H(\hat{x}, t)P \tag{3.20}$$

Kalman Gain

$$K = PH^T(\hat{x}, t)R^{-1} \tag{3.21}$$

Jacobians

$$A(x, t) = \frac{\partial a(x, u, t)}{\partial x} \tag{3.22}$$

$$H(x, t) = \frac{\partial h(x, t)}{\partial x} \tag{3.23}$$

E. Permenant Magnet Synchrounius Motor

The permanent-magnet synchronous motor (PMSM) offers several advantages compared to conventional machines used in AC servo drives. Unlike an induction motor (IM), the stator current of a PMSM only needs to generate torque since the magnetizing current is not required thanks to the presence of permanent magnets in the rotor (Pillay et al, 1989). This eliminates the need for supplying magnetizing current through the stator to maintain a constant airgap flux. Consequently, the PMSM operates at a higher power factor (due to the absence of magnetizing current) and is more efficient than the IM while delivering the same output.

The stator equations of the PMSM in the rotor reference frame are (Pillay et al, 1989):

$$v_q = Ri_q + p\boldsymbol{\lambda}_q + \boldsymbol{\omega}_s\boldsymbol{\lambda}_d \quad (3.24)$$

$$v_d = Ri_d + p\boldsymbol{\lambda}_d - \boldsymbol{\omega}_s\boldsymbol{\lambda}_q \quad (3.25)$$

where

$$\boldsymbol{\lambda}_q = \boldsymbol{L}_q\boldsymbol{i}_q \quad (3.26)$$

and

$$\boldsymbol{\lambda}_d = \boldsymbol{L}_d\boldsymbol{i}_d + \boldsymbol{\lambda}_{af} \quad (3.27)$$

The voltages on the d and q axes are represented by v_d and v_q, while the stator currents on the d and q axes are i_d and i_qThe d and q axis inductances are denoted as $\boldsymbol{L}_d$ and $\boldsymbol{L}_q$. The d and q axis stator flux linkages are $\boldsymbol{\lambda}_d$ and $\boldsymbol{\lambda}_q$, respectively. *R* represents the stator resistance, and $\boldsymbol{\omega}$ stands for the inverter frequency. $\boldsymbol{\lambda}_{af}$ represents the flux linkage resulting from the rotor magnets linking the stator.

IV. MAIN RESULTS

A. Introduction

In this chapter, we created a discrete-time port-controlled Hamiltonian system-based model structure for the PMSM motor that takes into account unknown speed. An adaptive discrete-time interconnection and damping assignment passivity based controller (IDA-PBC) for the PMSM motor considering unknown speed is proposed as a solution to this problem. To accurately estimate the ambiguous motor speed, a discrete-time immersion and invariance (I&I) based estimator is also created. The IDA-PBC controller uses this estimated speed to enable automatic motor speed adjusting. Lyapunov theory is used to prove the estimator's asymptotic stability.

The detailed calculations for the formulation of our system are provided, along with all the equations, in Section A. In Section B, a concise overview of the equations used in our structure, specifically in the port Hamiltonian IDA-PBC design, is presented. Section C elaborates on the equations that pertain to the I&I system, specifically in relation to our IDA-PBC adaptive control in discrete time, providing a thorough explanation.

B. System Formulation

The model of the PMSM can be written in synchronously rotating d-q reference frame as (Jin et al, 2013):

$$L_d \frac{di_d}{dt} = u_d - R_s i_d + n_p L_q i_q \omega \tag{4.1}$$

$$L_q \frac{di_q}{dt} = u_q - R_s i_q - n_p L_d i_d \omega - n_p \phi \omega \tag{4.2}$$

$$J\frac{d\omega}{dt} = \tau - \tau_L = n_p[(L_d - L_q)i_d i_q + \phi i_q] - \tau_L \tag{4.3}$$

where $D = diag\{L_d \quad L_q \quad J\}$, n_p is the number of pole pairs, i_d and i_q the direct and quadrature stator currents, The controllable inputs are the direct and quadrature voltages u_d and u_q, ω is the mechanical angular speed of the rotor, J is the moment of inertia, L_d and L_q are d-axis and q-axis stator inductances, respectively, R is the stator resistance per phase, τ and τ_L are the electromagnetic and load torque, ϕ is the rotor flux linking the stator.

The total stored energy represented as a Hamiltonian function in the continuous-time setting is (Jin et al, 2013):

$$H = \frac{1}{2}\left(\frac{1}{L_d}x_1^2 + \frac{1}{L_q}x_2^2 + \frac{1}{J}x_3^2\right) \tag{4.4}$$

where $x = [x_1 \quad x_2 \quad x_3]^T = [L_d i_d \quad L_q i_q \quad J\omega]^T$.

The PMSM model can be written as a PCHD system:

$$\dot{x} = [J(x) - R(x)]\frac{\partial H}{\partial x}(x) + g(x)u \tag{4.5}$$

$$y = g^T(x)\frac{\partial H}{\partial x}(x) \tag{4.6}$$

The state, input and output are defined as follows, respectively.

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \\ 0 & 0 & J \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ \omega \end{bmatrix} , \tag{4.7}$$

$$u = [u_d \;\; u_q \;\; -\tau_L]^T \;\; , \;\; y = [i_d \;\; i_d \;\; \omega]^T$$

The interconnection, dissipative and weight matrices can be described as:

$$J(x) = \begin{bmatrix} 0 & 0 & n_p x_2 \\ 0 & 0 & -n_p(x_1 + \phi) \\ -n_p x_2 & n_p(x_1 + \phi) & 0 \end{bmatrix} \tag{4.8}$$

$$R = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad g = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4.9}$$

Assigning to a closed-loop energy function:

$$H_d = \frac{1}{2}\left(\frac{1}{L_d}(x_1 - x_1^*)^2 + \frac{1}{L_q}(x_2 - x_2^*)^2 + \frac{1}{J}(x_3 - x_3^*)^2\right) \tag{4.10}$$

Where the desired equilibrium $x^* = [x_2^* \ x_2^* \ x_3^*]^T = \left[0 \ \ \frac{L_q \tau_L^*}{n_p \phi} \ \ J\omega^*\right]^T$, according to the principle of maximum torque per ampere. Under a feedback control $u = \alpha(x)$ finding $J_a$and $R_a$satisfying $J_d = J(x) + J_a(x) \quad R_d = R(x) + R_a(x) = R_d^T(x) > 0$, the system (4.5) can be transformed to zero energy gradient dissipative Hamiltonian system.

$$\dot{x} = [J_d(x) - R_d(x)]\frac{\partial H_d}{\partial x}(x) \tag{4.11}$$

The following represents $J_a(x)$ and $R_a(x)$:

$$J_a(x) = \begin{bmatrix} 0 & -J_{12} & J_{13} \\ J_{12} & 0 & -J_{23} \\ -J_{13} & J_{23} & 0 \end{bmatrix} \qquad R_a(x) = \begin{bmatrix} r_1 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4.12}$$

Where $J_{12}, J_{13}, J_{23}, r_1, r_2$ are the interconnection and damping parameters to be designed, and $r_1, r_2 > 0$. According to the standard procedure of IDA-PBC (Petrovic et al, 2001) with the chosen parameters $J_{12} = 0$, $J_{23} = -n_p L_d i_d$, $J_{13} = -n_p L_q i_q$(Jin et al, 2013), we can receive the controller as

$$u_d = -r_1 i_d - n_p L_q i_q \omega \tag{4.13}$$

$$u_q = -r_2\left(i_q - \frac{\tau_L^*}{n_p \phi}\right) + n_p L_d i_d \omega + \frac{R_s \tau_L^*}{n_p \phi} + n_p \phi \omega^* \tag{4.14}$$

the desired speed estimator system in discrete-time is:

$$x^+ - x = T[J - R]\overline{\nabla} H(\bar{x}) + Tg(\bar{x})u \tag{4.15}$$

In order to estimate the speed, assume that:

$$\overline{\nabla}H(\bar{x}) = \begin{bmatrix} \frac{1}{L_d}x_1 \\ \frac{1}{L_q}x_2 \\ \frac{1}{J}x_3 \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{1}{L_d}x_1 \\ \frac{1}{L_q}x_2 \\ 0 \end{bmatrix}}_{\overline{\nabla}H_{Kn}(\bar{x})} + \underbrace{\left[\underbrace{\begin{bmatrix} 0 \\ 0 \\ \frac{1}{J} \end{bmatrix}}_{\pi}\right] \underbrace{[x_3]}_{\theta_{est}}}_{\overline{\nabla}H_{un}(\bar{x})} \tag{4.16}$$

$$x^{+} - x = [J(\bar{x}) - R]\overline{\nabla}H_{Kn}(\bar{x}) + [J(\bar{x}) - R]\pi\theta_{est} + Tg(\bar{x})u \tag{4.17}$$

where $\bar{x} = \frac{3x - x^{-}}{2}$ as proposed in (Yalçın and Sümer, 2015; Alkrunz and Yalçın, 2021).

C. Design of discrete-time IDA-PBC controller:

$$[J_d - R_d]\overline{\nabla}H_d(\bar{x}) = [J - R]\overline{\nabla}H(\bar{x}) + g(x)u \tag{4.18}$$

$$g(x)u = [J_d - R_d]\overline{\nabla}H_d(\bar{x}) - [J - R]\overline{\nabla}H(\bar{x}) \tag{4.19}$$

$$u = (g^T g)^{-1} g^T([J_d - R_d]\overline{\nabla}H_d(\bar{x}) - [J - R]\overline{\nabla}H(\bar{x})) \tag{4.20}$$

By considering (4.18), (4.19) and (4.20), then we can obtain the adaptive control law as:

$$u = ([J_d - R_d]\overline{\nabla}H_d(\bar{x}) - [J - R]\overline{\nabla}H(\bar{x})) \tag{4.21}$$

$$\overline{\nabla}H(\bar{x}) = \overline{\nabla}H_{Kn}(\bar{x}) + \overline{\nabla}H_{un}(\bar{x}) \tag{4.22}$$

Therefore,

$$\dot{x} = [J(x) - R][\overline{\nabla}H_{Kn}(\bar{x}) + \overline{\nabla}H_{un}(\bar{x})] + g(x)u \tag{4.23}$$

$$\dot{x} = [J(x) - R]\overline{\nabla}H_{Kn}(\bar{x}) + [J(x) - R]\pi\theta_{est} + g(x)u \tag{4.24}$$

$$u_{est} \equiv ([J_d - R_d]\overline{\nabla}H_d(\bar{x}) - [J(x) - R]\overline{\nabla}H_{Kn}(\bar{x}) - [J(x) - R]\pi\theta_{est} \tag{4.25}$$

D. Design of parameter estimator using I&I technology

In this section, the desired PMSM system in discrete-time is considered as (Alkrunz and Yalçın, 2021). Let us recall the uncertain system formulation in (4.17):

$$x^{+} - x = T[J - R]\overline{\nabla}H(\bar{x}) + Tg(\bar{x})u \tag{4.26}$$

$$x^{+} - x = [J(\bar{x}) - R]\overline{\nabla}H_{Kn}(\bar{x}) + [J(\bar{x}) - R]\pi\theta_{est} + Tg(\bar{x})u \tag{4.27}$$

where $\bar{x} = \frac{3x - x^{-}}{2}$ (Alkrunz and Yalçın, 2021).

The parameter estimation error can be defined as:

$$z = \theta_{est} - \theta = \underbrace{\hat{\theta} + \beta(x^{-})x}_{\theta_{est}} - \theta \tag{4.28}$$

$$z^{+} = \hat{\theta}^{+} + \beta(x)x^{+} - \theta \tag{4.29}$$

where $\beta(x)$ is a free design function to be selected such that the estimator is asymptotic Lyapunov stable.

By taking the difference equation of (4.28) and (4.29), and replacing $x^{+}$by (4.27) then:

$$\begin{aligned} z^{+} - z \equiv \hat{\theta}^{+} - \hat{\theta} - \beta(x^{-})x + \beta(x)(T[J(\bar{x}) - R]\overline{\nabla}H_{Kn}(\bar{x}) \\ + T[J(\bar{x}) - R]\pi\theta_{est} + Tg(\bar{x})u + x \end{aligned} \tag{4.30}$$

$$\begin{aligned} z^{+} - z \equiv \hat{\theta}^{+} - \hat{\theta} - \beta(x^{-})x + \beta(x)(T[J(\bar{x}) - R]\overline{\nabla}H_{Kn}(\bar{x}) + Tg(\bar{x})u \\ + x) + \beta(x)(T[J(\bar{x}) - R]\pi\theta_{est}) \end{aligned} \tag{4.31}$$

By selecting the update law as:

$$\begin{aligned} \hat{\theta}^{+} = \hat{\theta} + \beta(x^{-})x - \beta(x)(T[J(\bar{x}) - R]\overline{\nabla}H_{Kn}(\bar{x}) + Tg(\bar{x})u + x) \\ - \beta(x)(T[J(\bar{x}) - R]\pi\theta_{est}) \end{aligned} \tag{4.32}$$

Therefore, the dynamics of the estimation error is given as:

$$z^+ - z = \beta(x) \underbrace{T[J(\bar{x}) - R]\pi}_{A} \underbrace{(\theta - \theta_{est})}_{-Z} \tag{4.33}$$

$$z^+ - z = -\beta(x)Az \tag{4.34}$$

$$z^+ = z - \beta(x)Az = (1 - \beta(x)A)z \tag{4.35}$$

Assume that, the free design function $\beta(x)$

$$\beta(x) = \frac{kA^T}{A^TA + 1} \tag{4.36}$$

By using the equation in (4.16) and (4.33), the matrix A can be expressed as:

$$A = T[J(\bar{x}) - R]\pi = \begin{bmatrix} \frac{Tn_p\overline{x_2}}{J} \\ \frac{-Tn_p(\overline{x_1}+\phi)}{J} \\ 0 \end{bmatrix} \tag{4.37}$$

As a result, the free design function $\beta(x)$ is given as:

$$\beta(x) = k[\frac{J}{Tn_p\overline{x_2}} \quad \frac{-J}{Tn_p(\overline{x_1} + \phi)} \quad 0] \tag{4.38}$$

where $k > 0$ is free design parameter.

Proof:

By considering the dynamics of the uncertain motor speed in discrete-time described in (4.26), by defining the estimator dynamics as in (4.28) and (4.29), by selecting the parameter update rule as in (4.32), and by selecting the free parameter function $\beta(x)$ as in (4.38), then:

$$z^+ = z - \beta(x)Az = [1 - \beta(x)A]z = \rho z \tag{4.39}$$

where, $\rho = 1 - \beta(x)A$ and $0 < k < 1$, then ρ satisfies $0 < \rho < 1$

Let us select the Lyapunov candidate function as:

$$V_z = z^2 \tag{4.40}$$

Then, the time difference of V_z is:

$$\Delta V_z = V_{z^+} - V_z = \rho^2 z^2 - z^2 = z^2 \left[\underbrace{\rho}_{0<\rho<1}{}^2 - 1 \right] < 0 \tag{4.41}$$

Thus, asymptotic stability of the estimator is proved.

V. SİMULATİONS AND RESULTS

This section showcases the outcomes of numerical simulations aimed at tackling the challenge of monitoring the velocity of a PMSM motor in uncertain circumstances. The suggested adaptive controller is applied to the PMSM motor, and its effectiveness is assessed through simulations employing Matlab/Simulink. Additionally, the estimation method based on I&I is compared with the Extended Kalman Filter (EKF) estimation method. The simulation outcomes convincingly exhibit the efficacy and efficiency of the proposed methodology.

A. Table of system parameters

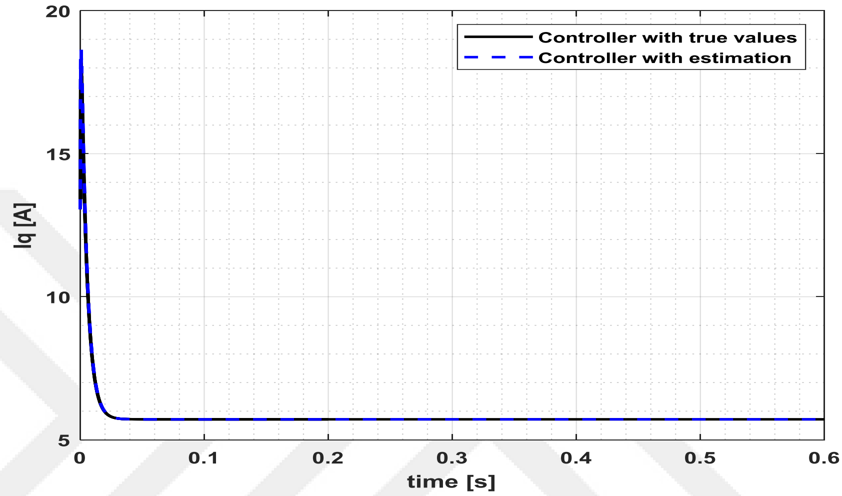
The system parameters are considered as listed in Table 1:

Table 1: PMSM system parameters

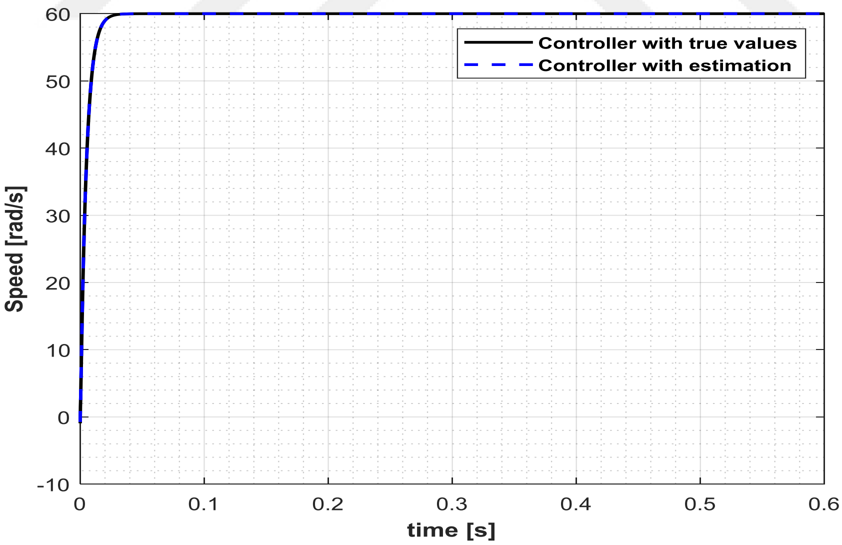
Variable	Value
Armature Resistance (Rs)	2.875 Ω
Armature Inductance (Ls)	0.00085 H
Moment of Inertia (J)	0.00085 kg·m^2
Rotor Flux (ϕ)	0.175 wb
Poles (P)	4
Load Tourqe (T_L)	4 N·m
Desires speed (ω_d)	60 rad/s

The parameters of the desired energy function are assumed as: $r_1 = 0.1$ and $r_2 = 0.1$. The parameter of the free design function is assumed as: $k = 1$. The simulations are performed under sampling time, $T = 5e - 5s$.

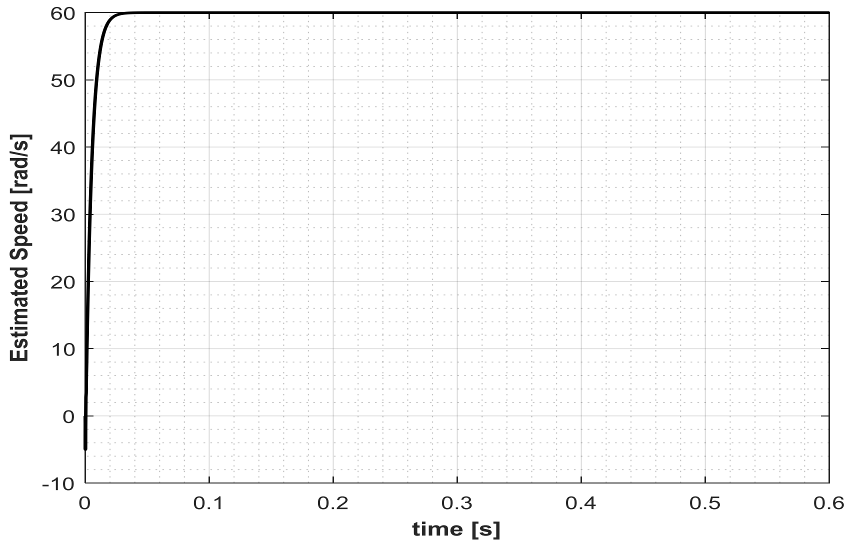
The simulation results are shown in the Figures 2 to 7. Figure 2 shows the closed-loop dynamics of PMSM by applying the proposed adaptive IDA-PBC controller. Figure 2a and Figure 2b show the dynamics of the current i_q and the speed respectively under adaptive and non-adaptive control. Namely, the controller with true values (non-adaptive) and with estimated values (adaptive). Besides, Figure 2c shows the dynamics of the estimated speed based on I&I method. According to the principle of maximum torque per ampere, desired $i_d = 0$.



a)



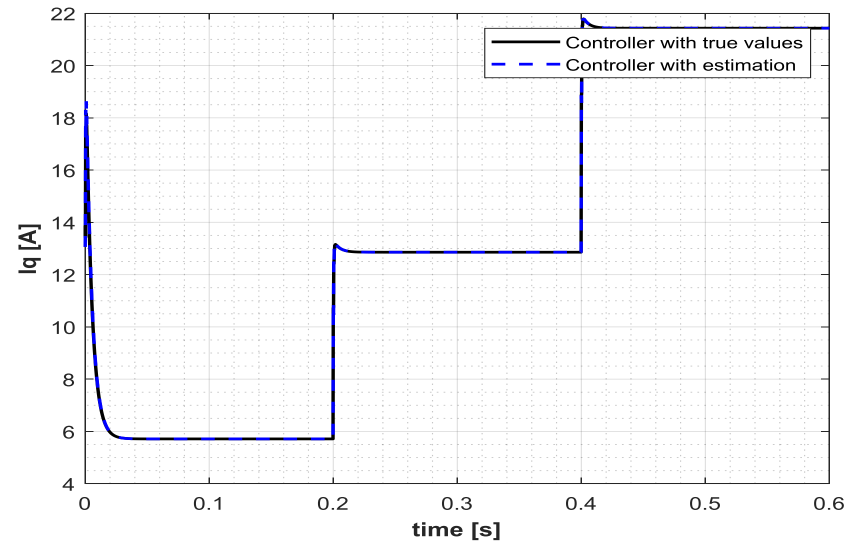
b)



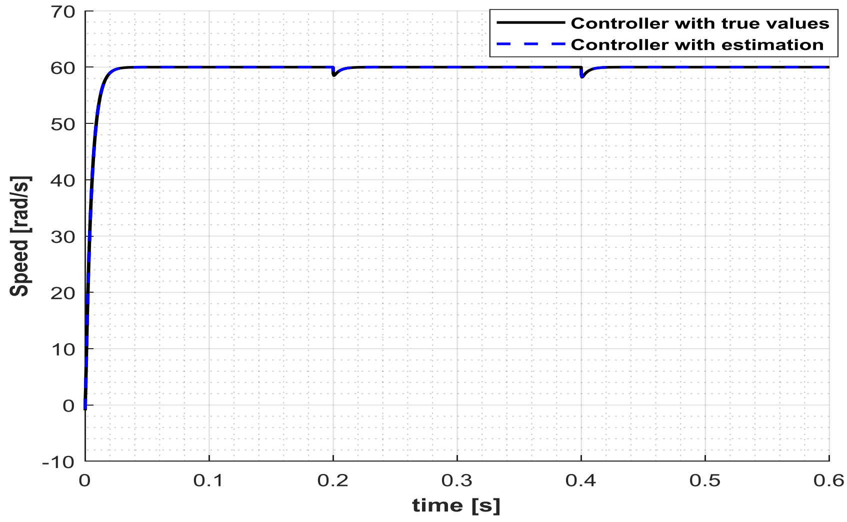
c)

Figure 2 The closed loop dynamics of PMSM by applying the proposed adaptive IDA-PBC controller: (a) Current i_q (b) Speed (c) I&I based estimated speed

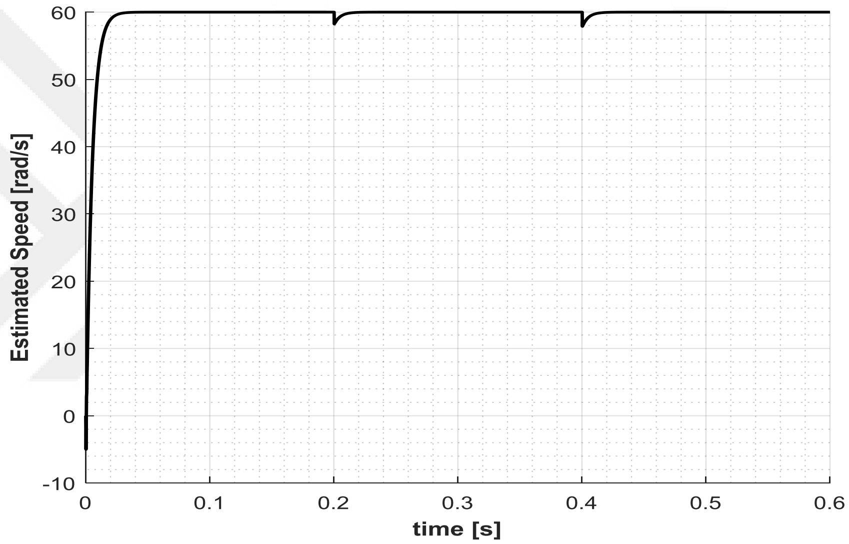
At $t = 0.2s$, the load torque changes from 4 $N.m$ to 5 $N.m$, and at $t = 0.4s$ the load torque changes from 5 $N.m$ to 6 $N.m$. The adaptive proposed controller is applied and the simulation results in Figure 3a show the dynamics of i_q using the controller with true values and estimated values. Figure 3b shows the dynamics of speed using the controller with true values and estimated values, and Figure 3c shows the estimated speed.



a)



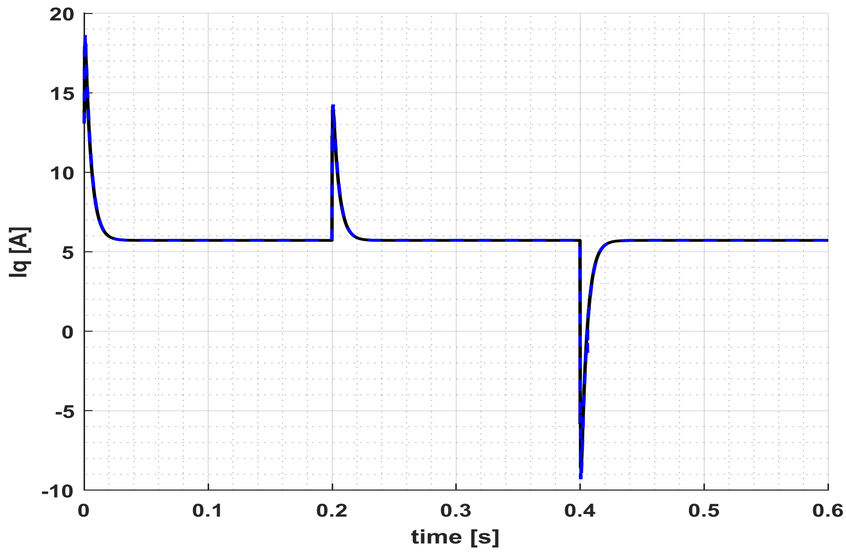
b)



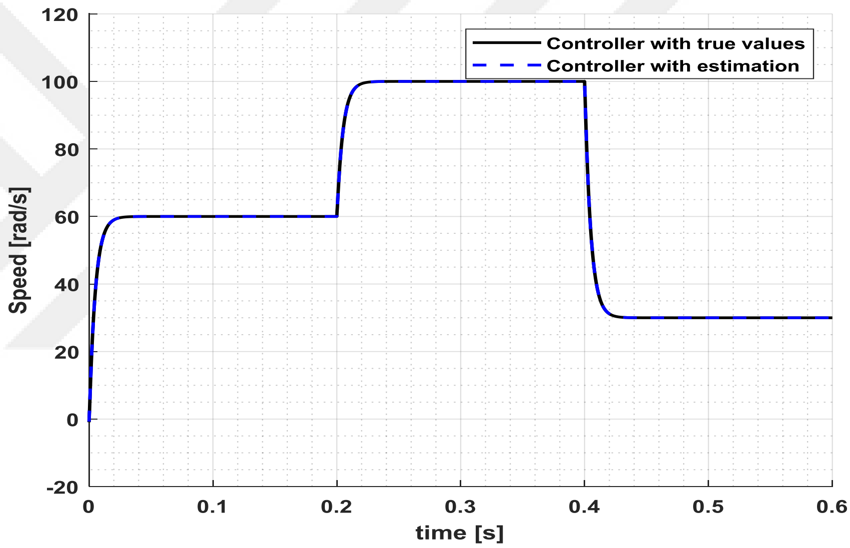
c)

Figure 3 The effect of the step changing in load torque at $t = 0.2s$ and $t = 0.4s$

In order to track the speed, the speed is step changed as shown in Figure 4. At $t = 0.2s$, the speed changes from $60\,rad/s$ to $100\,rad/s$, and at $t = 0.4s$ the speed changes from $100\,rad/s$ to $30\,rad/s$. The adaptive proposed controller is applied and the simulation results shown in Figure 4a show the dynamics of i_q using the controller with true values and estimated values, Figure 4b shows the dynamics of speed using the controller with true values and estimated values and Figure 4c shows the estimated speed.


Iq [A]
20
15
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
0.6
time [s]

a)


Controller with true values
Controller with estimation
Speed [rad/s]
120
100
80
60
40
20
0
-20
0
0.1
0.2
0.3
0.4
0.5
0.6
time [s]

b)

c)

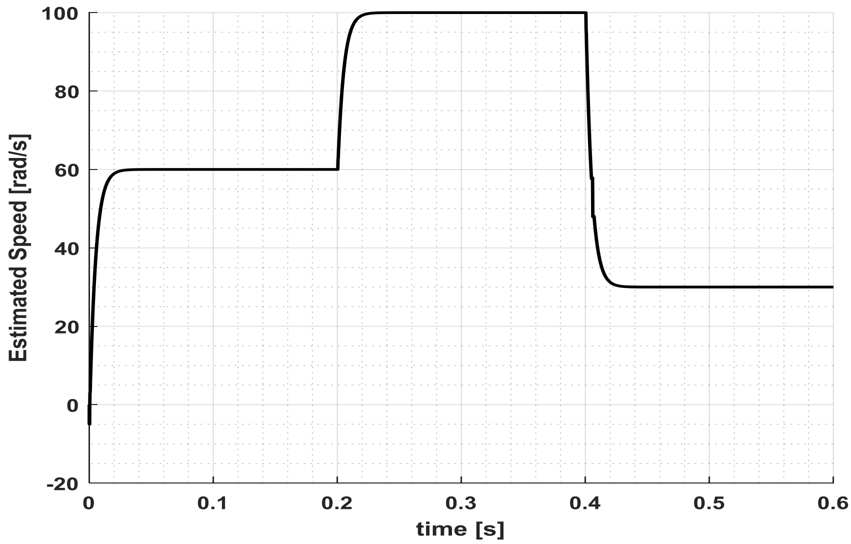


Figure 4 The effect of the step changing in the speed at $t = 0.2s$ and $t = 0.4s$

B. Comparision between I&I and EKF

Since EKF is nonlinear, Trial and error in the context of the EKF is an approach to refine the parameter settings, it has some disadvantages, such as:

a) Time-consuming and resource-intensive.
b) Lack of systematic guidance.
c) Sensitivity to initial parameter values.
d) Limited exploration of parameter space.
e) Difficulty in evaluating performance objectively.

On the other hand, I&I method can achieve speed estimation and show robustness against parameter uncertainties and disturbances.

Secondly, the computational complexity differs between the two methods. The I&I method involves formulating the estimation problem within the port-controlled Hamiltonian system framework, which may have certain computational requirements. The EKF, being a recursive Bayesian filter, involves iterative updates and matrix calculations, which can also have computational complexity.

Additionally, the performance of the two methods may vary depending on the specific motor and operating conditions. Factors such as noise levels, available sensor measurements, and the accuracy of the motor model can impact the estimation accuracy of both methods.

In summary, the choice between the I&I method and the EKF for speed estimation in a PMSM motor depends on factors such as the motor dynamics, computational complexity considerations, and the specific requirements and constraints of the application. Comparative analysis and evaluation under specific conditions can help determine the most suitable method for a given scenario.

The following figures show a comparision between the EKF using in the following paper (Ali et al, 2014) and I&I method. The simulation results using EKF in Figure 5 shows The dynamics of i_q using the controller with true values and estimated values a) using EKF and b) using I&I. Figure 6 shows The dynamics of speed using the controller with true values and estimated values a) using EKF and b) using I&I. and Figure 7 shows the estimated speed a) using EKF and b) using I&I. According to the principle of maximum torque per ampere, desired $i_d = 0$.

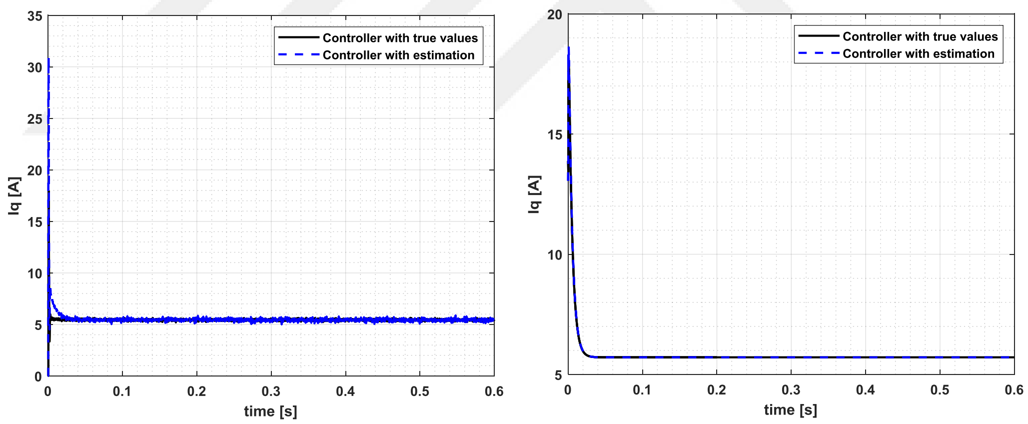
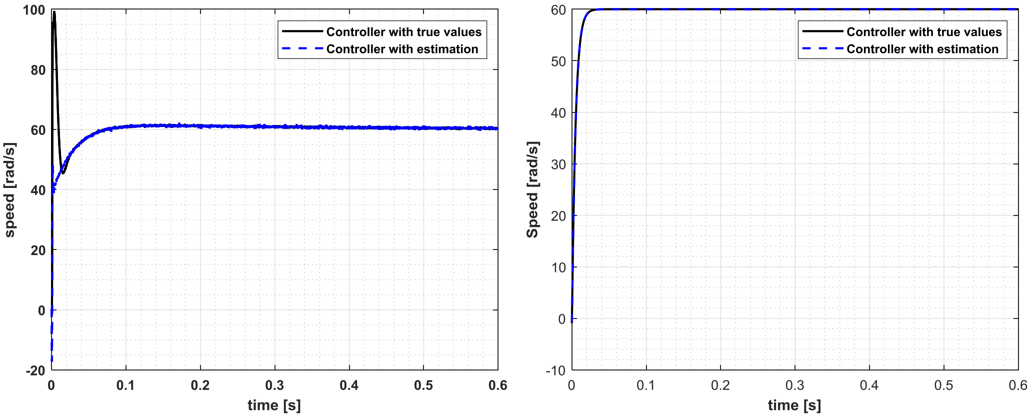
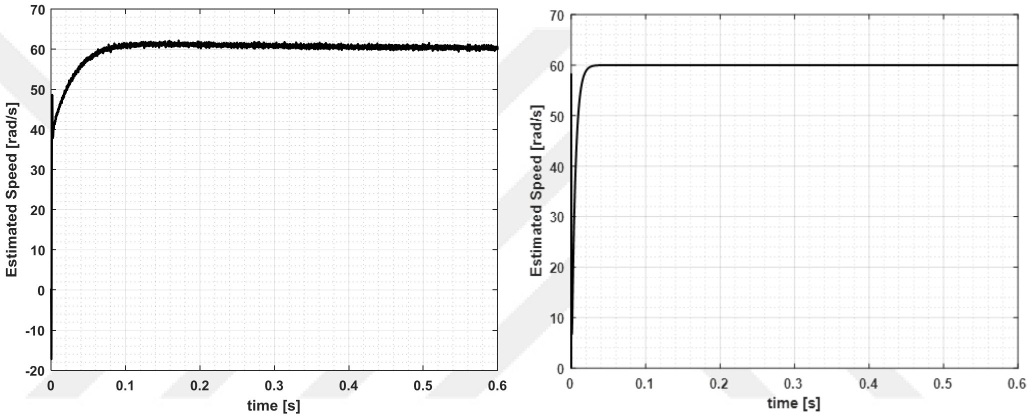


Figure 5 The dynamics of i_q by applying the adaptive and non-adaptive control under different estimation methods a) using EKF and b) using I&I.



a) b)

Figure 6 The dynamics of speed by applying the adaptive and non-adaptive control under different estimation methods a) using EKF and b) using I&I.



a) b)

Figure 7 The estimated speed a) using EKF and b) using I&I.

VI. CONCLUSİON

The application of discrete-time Adaptive IDA-PBC control for PMSM motors with uncertain speed within the structure of a port-controlled Hamiltonian (PCH) system has shown significant promise in addressing the challenges associated with speed control. The combination of adaptive control techniques, such as IDA-PBC, with the underlying PCH system has provided a robust framework for achieving accurate and robust speed tracking in PMSM motors.

This study focuses on addressing the challenge of tracking the speed of a PMSM in the presence of uncertainties. To achieve this, a model for the PMSM motor with uncertain speed using the port-controlled Hamiltonian system in a discrete-time framework is developed.

An adaptive discrete-time interconnection and damping assignment passivity-based controller (IDA-PBC) is then proposed to control the uncertain PMSM motor. Additionally, a discrete-time immersion and invariance (I&I) based estimator is designed to estimate the uncertain motor speed. This estimated speed is integrated into the IDA-PBC controller to automatically adjust and fine-tune the motor speed.

To ensure the stability of the estimator, Lyapunov theory is employed, which guarantees asymptotic stability. The proposed adaptive controller is applied to the PMSM motor, and its performance is tested using Matlab/Simulink.

Furthermore, the effectiveness of the proposed I&I based estimation method with the Extended Kalman Filter (EKF) estimation method is compared. Simulation results demonstrate the productivity and effectiveness of the proposed method. Overall, the research in this field has paved the way for the development of advanced control solutions that can effectively handle uncertain speed conditions in PMSM motors. The combination of adaptive control techniques, estimation methods, and the utilization of the PCH system structure holds reasonable potential for achieving optimal performance and stability in PMSM motor control applications.

The discrete-time adaptive IDA-PBC control within the framework of a PCH system provides a valuable contribution to the field of speed control for PMSM motors with uncertain speed, offering improved performance, adaptability, and robustness.

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VII. APPENDICES

A. Actual discrete system for theta

```
function [out] = Actual_sys_disc(inputs)

x1 = inputs(1);

x2 = inputs(2);

x3 = inputs(3);

xe1 = inputs(4);

xe2 = inputs(5);

xe3 = inputs(6);

xd1 = inputs(7);

xd2 = inputs(8);

xd3 = inputs(9);

xde1 = inputs(10);

xde2 = inputs(11);

xde3 = inputs(12);

Tld = inputs(13);

x1_disc = (3*x1 - xe1)/2;

x2_disc = (3*x2 - xe2)/2;

x3_disc = (3*x3 - xe3)/2;

xd1_disc = (3*xd1 - xde1)/2;

xd2_disc = (3*xd2 - xde2)/2;

xd3_disc = (3*xd3 - xde3)/2;
```

```
% Define variables
np          = 4;
Ld          = 8.5e-4;        % [H] d-axis inductance
Lq          = 8.5e-4;        % [H] q-axis inductance
flux        = 0.175;
Rs          = 2.875;         % ohm
j           = 0.00085;
% Tl        = 4;
J13         = -np*x2_disc;
J23         = -np*x1_disc;
J12         = 0;
r1          = 0.1;
r2          = 0.1;
wd          = 60;
% Tld       = 4;
i_qr        = Tld/(np*flux);
T           = 5e-05;
J = [0, 0, np*x2_disc; 0, 0, -np*(x1_disc + flux); -np*x2_disc, np*(x1_disc + flux), 0];
R = [Rs, 0, 0; 0, Rs, 0; 0, 0, 0];
g = eye(3);
Ja = [0, -J12, J13; J12, 0, -J23; -J13, J23, 0];
Ra = [r1, 0, 0; 0, r2, 0; 0, 0, 0];
Jd = J+Ja;
Rd = R+Ra;
```

```
xd1_desired = 0;

xd2_desired = Lq*i_qr;

xd3_desired = j*wd;

grad_H = [(1/Ld)*x1_disc;(1/Lq)*x2_disc;(1/j)*x3_disc];

grad_Hd = [(1/Ld)*(xd1_disc - xd1_desired);(1/Lq)*(xd2_disc -
xd2_desired);(1/j)*(xd3_disc - xd3_desired)];

u = (Jd - Rd)*grad_Hd - (J - R)*grad_H;

x = [x1;x2;x3];

xd = [xd1;xd2;xd3];

x_plus = T*(J - R)*grad_H + T*g*u + x;

xd_plus = T*(Jd - Rd)*grad_Hd + xd;

y = grad_H;

out = [x_plus;xd_plus;y(3)];

end
```

B. Actual discrete system for estimation

```
function [out] = Estimation(inputs)

x1 = inputs(1);

x2 = inputs(2);

x3 = inputs(3);

xe1 = inputs(4);

xe2 = inputs(5);

xe3 = inputs(6);

xee1 = inputs(7);

xee2 = inputs(8);
```

```
xee3 = inputs(9);
theta_head = inputs(10);
Tld = inputs(11);
x1_disc = (3*x1 - xe1)/2;
x2_disc = (3*x2 - xe2)/2;
x3_disc = (3*x3 - xe3)/2;
xe1_disc = (3*xe1 - xee1)/2;
xe2_disc = (3*xe2 - xee2)/2;
xe3_disc = (3*xe3 - xee3)/2;
if x2_disc<0.001 && x2_disc>=0
    x2_disc = 0.001;
end
if x2_disc>-0.001 && x2_disc<0
    x2_disc = -0.001;
end
if xe2_disc<0.001 && xe2_disc>=0
    xe2_disc = 0.001;
end
if xe2_disc>-0.001 && xe2_disc<0
    xe2_disc = -0.001;
end
% Define variables
np          = 4;
Ld          = 8.5e-4;       % [H] d-axis inductance
Lq          = 8.5e-4;       % [H] q-axis inductance
```

```
flux            = 0.175;
Rs              = 2.875;            % ohm
j               = 0.00085;
%Tl             = 4;
J13             = -np*x2_disc;
J23             = -np*x1_disc;
J12             = 0;
r1              = 0.1;
r2              = 0.1;
wd              = 60;
%Tld            = 4;
i_qr            = Tld/(np*flux);
% T             = 5e-05;
T               = 2e-04;
J = [0, 0, np*x2_disc; 0, 0, -np*(x1_disc + flux); -np*x2_disc, np*(x1_disc + flux),
0];
R = [Rs, 0, 0; 0, Rs, 0; 0, 0, 0];
g = eye(3);
Ja = [0, -J12, J13; J12, 0, -J23; -J13, J23, 0];
Ra = [r1, 0, 0; 0, r2, 0; 0, 0, 0];
Jd = J+Ja;
Rd = R+Ra;
xd1_desired = 0;
xd2_desired = Lq*i_qr;
xd3_desired = j*wd;
```

```
%grad_H = [(1/Ld)*x1_disc;(1/Lq)*x2_disc;(1/j)*x3_disc];

grad_H_kn = [(1/Ld)*x1_disc;(1/Lq)*x2_disc;0];

PI = [0;0;(1/j)];

x = [x1;x2;x3];

k = 1;

Beta = k*[(j/(T*np*x2_disc)) (-j/(T*np*(x1_disc + flux))) 0];

Beta_e = k*[(j/(T*np*xe2_disc)) (-j/(T*np*(xe1_disc + flux))) 0];

theta_est = theta_head + Beta_e*x;

grad_Hd = [(1/Ld)*(x1_disc - xd1_desired);(1/Lq)*(x2_disc -
xd2_desired);(1/j)*(theta_est - xd3_desired)];

u = (Jd - Rd)*grad_Hd - (J - R)*grad_H_kn - (J - R)*PI*theta_est;

theta_head_plus = theta_head + Beta_e*x - Beta*(T*(J - R)*grad_H_kn + T*g*u +
x) - Beta*T*(J - R)*PI*theta_est;

x_plus_est = T*(J - R)*grad_H_kn + T*(J - R)*PI*theta_est + T*g*u + x;

w_est =  theta_est/j;

out = [x_plus_est;theta_head_plus;w_est];

end
```

RESUME

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PUBLICATIONS

➢ Enas Walid Benzeglam., 2023. *Discrete-time Adaptive IDA-PBC Control for PMSM Motor with Uncertain Speed in the Structure of Port-controlled Hamiltonian System*. 8th International New York Academic Research Congress on Life, Engineering and Applied Sciences.