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Unified Flux Observer for Induction and Permanent Magnet Synchronous Machines

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Abstract—A new unified adaptive flux observer for induction machines (IMs) and permanent magnet synchronous machines (PMSMs) is proposed in this work. The proposed unified observer is created using both the well-known "Voltage Model" (VM) and the "Flux Model" (FM) in the estimated rotating synchronous frame. Under the time-scale separation assumption between the rotor flux dynamics and the stator current dynamics in the estimated rotor synchronous frame, the rotor flux can be considered a slowly varying signal for which an adaptation law has been designed. We showed that the proposed unified observer can be applied to IMs and PMSMs with minimum knowledge of motor parameters, requiring only information on the stator resistance and dq axis inductances. The stability of the proposed observer is proven using the Lyapunov theory based on the presented unified model. Finally, numerical simulations in MATLAB/Simulink and experimental tests on an IM and a PMSM are provided to illustrate the theoretical results.

Index Terms—ac machines, unified model, adaptive observer.

A. Nomenclature

The nomenclatures used in this paper are as follows:

v_s	Stator voltage vector $[v_{sd} \ v_{sq}]^T$
i_s	Stator current vector $[i_{sd} \ i_{sq}]^T$
ψ_s	Stator flux vector $[\psi_{sd} \ \psi_{sq}]^T$
Ψ_r	Rotor flux vector $[\Psi_{rd} \ \Psi_{rq}]^T$
ω	Synchronous angular speed
θ	Synchronous angular position
R_s	Stator resistance
L_d, L_q	PMSM direct and quadrature axis inductances
ψ_m	PMSM permanent magnet flux constant
L_s	IM stator inductance
σ	IM leakage factor
σL_s	IM total leakage inductance
ψ_{rd}	IM direct axis rotor flux
k_r	IM rotor coupling factor
τ_r	IM rotor time constant
R_r	IM T-model rotor resistance
R_{req}	IM Γ -model rotor equivalent resistance ($k_r^2 R_r$)
$\mathcal{L}_d, \mathcal{L}_q$	Unified direct and quadrature axis inductances

I. INTRODUCTION

In recent decades, the two most common ac electric machines, induction machines (IMs), also known as asynchronous machines, and permanent magnet synchronous machines (PMSMs), have been the focus of growing research since they are superior to their rivals in terms of reliability, efficiency, and ease of use [1]. The IM and PMSM have always been categorized as independent machines due to their distinct operating principles, rotor construction, and pole saliency effects, leading to great difficulty in unifying the ac machine models into one unified model [2]. The main differences between the two motor types can be summarized as follows:

- The machine's slip in IM is directly related to the torque. Whereas for PMSMs, the rotor rotates at a synchronous speed, meaning that there is no slip between the rotor position and its flux. [3].
- The rotor flux modulus of the PMSM is constant, while it depends on the stator current in IM due to the principle of induction [4].

For decades, the problem of sensorless control, which usually refers to the speed regulation of ac machines without the need for a speed sensor, was handled independently for each machine type [5]. After Boldea et al. [6] presented the concept of active flux, the ac machines equations were handled in a more unified way. The active flux concept transforms the salient machines into nonsalient machines and simplifies the observer design process. However, even though the voltage model (VM) can be written in a unified form, the current model (CM), which represents the rotor flux dynamics, still depends on the motor type [7]. This gives the path to different hybrid observer forms that combine both the VM and the CM of the machine, as in [8] and [9], where the rotor dynamics are still needed.

The flux observer design process for ac machines can be done either in the stator stationary frame or the rotor estimated

frame [10]. The advantage of the rotor estimated reference frame is that the rotor flux quantities can be treated as slowly varying signals. An advanced nonlinear state observer that operates in estimated rotor coordinates was systematically developed as early as the late 1980s [11]. Based on the equation of motion and the estimation error, the speed is estimated. Many different speed and position estimation models have been presented since this study. In [12] and [13], a voltage-model-based flux observer that functions in stator coordinates is coupled with a position-tracking loop. In [14], a speed adaptation loop is added to a state observer that functions in estimated rotor coordinates.

To address the challenge of creating distinct observers for each machine type, our goal in this work is to create a unified observer structure that can be utilized for both IMs and PMSMs. The contributions of this paper are as follows: first, by making use of the similarities between the two motor types, a unified model is developed in Section II. It is shown that the problem of rotor flux vector position estimation in IM is the same as estimating the PMSM rotor position. In Section III, a single unified flux observer is presented, showing that, despite their differences, it can be used to drive both motors without any modification. In this part, the Lyapunov theory is used to show the stability and the rotor flux adaptation law. Finally, the numerical simulation results reported in Section VI illustrate the performance of the flux observer when evaluated on both PMSMs and IMs. Lastly, in Section V experimental results performed on both machines validate our approach.

II. MOTOR MODEL

Given that the stator construction of all three-phase ac machines is the same, the stator VM equation is unified and it is given in the synchronous rotating dq frame as follows:

$$\dot{\psi}_s = v_s - R_s i_s - J\omega\psi_s \quad (1)$$

where $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$. The stator Flux Model (FM) of a three-phase ac machine can be generalized as follows:

$$\psi_{sd} = \mathbf{L}_d i_{sd} + \Psi_{rd} \quad (2a)$$

$$\psi_{sq} = \mathbf{L}_q i_{sq} + \Psi_{rq} \quad (2b)$$

where $\mathbf{L}_d = L_d, \mathbf{L}_q = L_q$ for PMSMs and $\mathbf{L}_d = \mathbf{L}_q = \sigma L_s$ for IMs. Depending on the type of machine, the rotor flux is written as:

$$\text{PMSM: } \Psi_{rd} = \psi_m, \quad \dot{\Psi}_{rd} = 0; \quad (3a)$$

$$\Psi_{rq} = 0 \quad (3b)$$

$$\text{IM: } \Psi_{rd} = k_r \psi_{rd}, \quad \dot{\Psi}_{rd} = \frac{-1}{\tau_r} \Psi_{rd} + R_{req} i_{sd}; \quad (3c)$$

$$\Psi_{rq} = 0. \quad (3d)$$

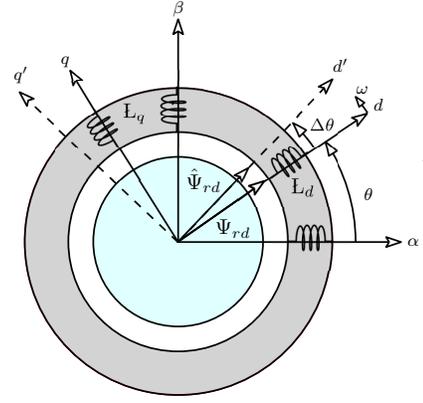


Fig. 1. Unified model in the estimated synchronous frame

From (1) and (2) the unified machine model is written as:

$$\begin{bmatrix} \dot{\psi}_{sd} \\ \dot{\psi}_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{\mathbf{L}_d} & \omega \\ -\omega & -\frac{R_s}{\mathbf{L}_q} \end{bmatrix} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} + \begin{bmatrix} \frac{R_s}{\mathbf{L}_d} & 0 \\ 0 & \frac{R_s}{\mathbf{L}_q} \end{bmatrix} \begin{bmatrix} \Psi_{rd} \\ \Psi_{rq} \end{bmatrix} \quad (4)$$

The following state space system can represent (4):

$$\begin{cases} \dot{x} = Ax + B_1 u + B_2 \Psi_r \\ i_s = Cx + D \Psi_r \end{cases} \quad (5)$$

where $x = [\psi_{sd} \ \psi_{sq}]^T$ is the state variable vector, $\Psi_r = [\Psi_{rd} \ \Psi_{rq}]^T$ is the rotor flux vector which can be treated as a disturbance, and $u = [v_{sd} \ v_{sq}]$ is the control input vector. The matrices A , B_1 , and B_2 are defined as follows:

$$A = \begin{bmatrix} -\frac{R_s}{\mathbf{L}_d} & \omega \\ -\omega & -\frac{R_s}{\mathbf{L}_q} \end{bmatrix}, \quad B_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad B_2 = \begin{bmatrix} \frac{R_s}{\mathbf{L}_d} & 0 \\ 0 & \frac{R_s}{\mathbf{L}_q} \end{bmatrix}$$

while C and D are defined as:

$$C = \begin{bmatrix} \frac{1}{\mathbf{L}_d} & 0 \\ 0 & \frac{1}{\mathbf{L}_q} \end{bmatrix}, \quad D = \begin{bmatrix} -\frac{1}{\mathbf{L}_d} & 0 \\ 0 & -\frac{1}{\mathbf{L}_q} \end{bmatrix}.$$

The rotor flux values in dq frame are treated as dc quantities, knowing that, given only the current and voltage measurements, our goal is to estimate ψ_s and Ψ_r without having information on the rotor flux dynamics.

III. UNIFIED OBSERVER DESIGN

This section presents the unified observer structure that can be used to drive both IMs and PMSMs. From (5), a unified flux observer in the synchronous rotating frame can be designed as follows:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + B_1 u + B_2 \hat{\Psi}_r + G\tilde{i}_s \\ \hat{i}_s = C\hat{x} + D\hat{\Psi}_r \\ \dot{\hat{\Psi}}_r = L\tilde{i}_s \end{cases} \quad (6)$$

where the observer state vector is $\hat{x} = [\hat{\psi}_{sd} \ \hat{\psi}_{sq}]^T$, $\tilde{i}_s = i_s - \hat{i}_s = [\tilde{i}_{sd} \ \tilde{i}_{sq}]^T$ is the current estimation error, and

$\hat{\Psi}_r = [\hat{\Psi}_{rd} \ \hat{\Psi}_{rq}]^T$ is the rotor flux estimation for which an adaptation law is to be designed. Note that L is the adaptation matrix to be computed and G is the observer matrix gain.

$$L = \begin{bmatrix} l_{11} & l_{12} \\ l_{21} & l_{22} \end{bmatrix}, \quad G = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \quad (7)$$

To study observer convergence, let's consider the following assumption:

Assumption 1. *The rotor flux dynamics can be treated as a slowly varying signal, i.e., $\dot{\Psi}_{rd} \simeq 0, \dot{\Psi}_{rq} \simeq 0$.*

This assumption is already true for Surface-mounted PMSM (SPMSM) and Interior-mounted PMSM (IPMSM), where the PM flux changes very slowly according to the temperature and aging of the machine. Regarding IM, this assumption remains true since the rotor time constant slows down the rotor flux dynamics from the stator current (see 3c). This permits us to treat the rotor flux as a slowly varying signal [15].

A. Stability Conditions

Proposition 1. *Consider the system (5) under Assumption 1. The proposed observer in (6) is globally asymptotically stable, i.e., $\lim_{t \rightarrow +\infty} |x(t) - \hat{x}(t)| = 0$, if the conditions below are satisfied:*

$$g_{11} < -R_s, \quad g_{22} < -R_s, \quad g_{12} = -\frac{\mathbf{L}_q}{\mathbf{L}_d} g_{21}$$

and

$$l_{11} = -\gamma(R_s + g_{11}), \quad l_{12} = -\gamma \frac{g_{12} \mathbf{L}_q}{\mathbf{L}_d}$$

$$l_{22} = -\gamma(R_s + g_{22}), \quad l_{21} = -\gamma \frac{g_{21} \mathbf{L}_d}{\mathbf{L}_q}$$

Proof. To prove the stability of the proposed observer and obtain the adaptation law, a Lyapunov candidate is to be defined. Writing down the estimation error dynamics, we obtain:

$$\dot{\psi}_s = (A - GC)\tilde{\psi}_s + (B_2 - GD)\tilde{\Psi}_r \quad (8)$$

where $\tilde{\psi}_s = [\tilde{\psi}_{sd} \ \tilde{\psi}_{sq}]^T$ is the stator flux error vector, and $\tilde{\Psi}_r = [\tilde{\Psi}_{rd} \ \tilde{\Psi}_{rq}]^T$ is the rotor flux estimation error vector. Let us define the following Lyapunov function:

$$V = \frac{1}{2} (\tilde{\psi}_s^T \tilde{\psi}_s + \frac{\tilde{\Psi}_r^T \tilde{\Psi}_r}{\gamma}) \quad (9)$$

where γ is a positive real number and $V(\tilde{\psi}_s, \tilde{\Psi}_r) > 0$ for all $\tilde{\psi}_s \neq 0$ and $\tilde{\Psi}_r \neq 0$. Using Assumption 1, the real rotor flux is assumed to be constant within a sampling interval. Differentiating the Lyapunov function, we obtain:

$$\dot{V} = \tilde{\psi}_s^T \dot{\tilde{\psi}}_s + \frac{1}{\gamma} \tilde{\Psi}_{rd} \dot{\tilde{\Psi}}_{rd} + \frac{1}{\gamma} \tilde{\Psi}_{rq} \dot{\tilde{\Psi}}_{rq}. \quad (10)$$

Substituting (11) in (10) gives us

$$\dot{V} = \tilde{\psi}_s^T (A - GC) \tilde{\psi}_s + \tilde{\psi}_s^T (B_2 - GD) \tilde{\Psi}_r + \tilde{\Psi}_{rd} \frac{\dot{\tilde{\Psi}}_{rd}}{\gamma} + \tilde{\Psi}_{rq} \frac{\dot{\tilde{\Psi}}_{rq}}{\gamma}. \quad (11)$$

Where

$$B_2 - GD = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

such that $a_{11} = \frac{R_s + g_{11}}{\mathbf{L}_d}$, $a_{12} = \frac{g_{12}}{\mathbf{L}_q}$, $a_{21} = \frac{g_{21}}{\mathbf{L}_d}$, $a_{22} = \frac{R_s + g_{22}}{\mathbf{L}_q}$. Knowing that C is always invertible, we substitute the stator flux estimation error vector in the second term of (11) by $\tilde{\psi}_s = C^{-1}(\tilde{i}_s - D\tilde{\Psi}_r)$ to obtain

$$\dot{V} = \tilde{\psi}_s^T (A - GC) \tilde{\psi}_s + (\mathbf{L}_d \tilde{i}_{sd} + \tilde{\Psi}_{rd})(a_{11} \tilde{\Psi}_{rd} + a_{12} \tilde{\Psi}_{rq}) + (\mathbf{L}_q \tilde{i}_{sq} + \tilde{\Psi}_{rq})(a_{21} \tilde{\Psi}_{rd} + a_{22} \tilde{\Psi}_{rq}) + \tilde{\Psi}_{rd} \frac{\dot{\tilde{\Psi}}_{rd}}{\gamma} + \tilde{\Psi}_{rq} \frac{\dot{\tilde{\Psi}}_{rq}}{\gamma}.$$

Rearranging the terms, we obtain

$$\dot{V} = \tilde{\psi}_s^T (A - GC) \tilde{\psi}_s + \tilde{\Psi}_{rd}(a_{11} \mathbf{L}_d \tilde{i}_{sd} + a_{11} \tilde{\Psi}_{rd} + a_{12} \tilde{\Psi}_{rq} + a_{21} \mathbf{L}_q \tilde{i}_{sq}) + \tilde{\Psi}_{rq}(a_{22} \mathbf{L}_q \tilde{i}_{sq} + a_{22} \tilde{\Psi}_{rq} + a_{21} \tilde{\Psi}_{rd} + a_{12} \mathbf{L}_d \tilde{i}_{sd}) + \tilde{\Psi}_{rd} \frac{\dot{\tilde{\Psi}}_{rd}}{\gamma} + \tilde{\Psi}_{rq} \frac{\dot{\tilde{\Psi}}_{rq}}{\gamma}.$$

Taking $g_{12} = -\frac{\mathbf{L}_q}{\mathbf{L}_d} g_{21}$, hence, $a_{12} = -a_{21}$, then the last equation becomes

$$\dot{V} = \tilde{\psi}_s^T (A - GC) \tilde{\psi}_s + \tilde{\Psi}_{rd}(a_{11} \mathbf{L}_d \tilde{i}_{sd} + a_{11} \tilde{\Psi}_{rd} + a_{21} \mathbf{L}_q \tilde{i}_{sq} + \frac{\dot{\tilde{\Psi}}_{rd}}{\gamma}) + \tilde{\Psi}_{rq}(a_{22} \mathbf{L}_q \tilde{i}_{sq} + a_{22} \tilde{\Psi}_{rq} + a_{12} \mathbf{L}_d \tilde{i}_{sd} + \frac{\dot{\tilde{\Psi}}_{rq}}{\gamma}).$$

The rotor flux-adaptation law can be obtained from the second and third terms as follows:

$$\dot{\tilde{\Psi}}_{rd} = -\gamma(a_{11} \mathbf{L}_d \tilde{i}_{sd} + a_{21} \mathbf{L}_q \tilde{i}_{sq})$$

$$\dot{\tilde{\Psi}}_{rq} = -\gamma(a_{22} \mathbf{L}_q \tilde{i}_{sq} + a_{12} \mathbf{L}_d \tilde{i}_{sd}).$$

Simplifying

$$\dot{V} = \tilde{\psi}_s^T (A - GC) \tilde{\psi}_s + a_{11} \tilde{\Psi}_{rd}^2 + a_{22} \tilde{\Psi}_{rq}^2.$$

Choosing $a_{11} < 0$ and $a_{22} < 0$, and since G is designed such that the matrix $A - GC$ is Hurwitz. We have $\dot{V} < 0$ for all $\psi_s \neq 0$ and all $\psi_r \neq 0$. Hence, from the Lyapunov stability theorem, the proposed adaptive observer is stable. \square

B. Tracking observer

The angular position and speed are estimated using a tracking observer. Knowing that the position error can be computed from the following relation

$$\Delta\theta = \theta - \hat{\theta} = \arctan \frac{\hat{\Psi}_{rq}}{\hat{\Psi}_{rd}}. \quad (12)$$

We can design the following extended state observer for estimating the angular position and speed:

$$\begin{cases} \dot{\hat{\theta}} = \hat{\omega} + k_1(\theta - \hat{\theta}) \\ \dot{\hat{\omega}} = \hat{z} + k_2(\theta - \hat{\theta}) \\ \dot{\hat{z}} = k_3(\theta - \hat{\theta}) \end{cases} \quad (13)$$

where $[k_1, k_2, k_3]^T$ is the observer gain vector. To simplify the parameter design, the observer's poles are chosen to be

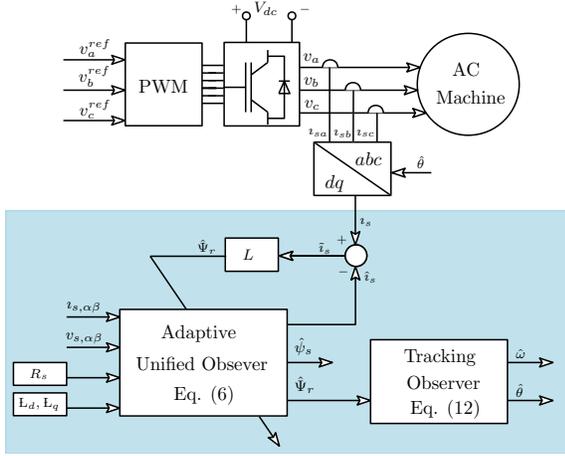


Fig. 2. Proposed unified observer structure.

equal. The gain vector is obtained by solving the following characteristic equation:

$$s^3 + k_1 s^2 + k_2 s + k_3 = (s + \omega_o)^3 \quad (14)$$

Hence, the tracking observer gains are then obtained as follows:

$$k_1 = 3\omega_o; \quad k_2 = 3\omega_o^2; \quad k_3 = \omega_o^3 \quad (15)$$

where ω_o is observer bandwidth. The complete block diagram of the proposed observer is shown in Fig. 2.

IV. NUMERICAL SIMULATIONS

We tested the proposed observer by numerical simulation in MATLAB/Simulink, for a three-phase 0.75 kW IM and a 3.5 kW PMSM whose parameters are presented in Table I. The observer parameters are designed as (IM: $\gamma = 100, \omega_o = 2\pi 50$, PMSM: $\gamma = 5, \omega_o = 2\pi 250$). All initial conditions of the motor and the observer are set to zero. The proposed observer was tested in an open-loop manner and compared to the real flux and position of the machines. The observer's fast convergence on IM is shown in Fig. 4, and the observer's error is converging to zero. The same observer was tested on PMSM in Fig. 5, where we can see that the observer converges to the permanent magnet flux constant. The PMSM's Lyapunov function variation with time is presented in Fig. 6. It is constantly decreasing, which confirms the theoretical conclusions.

V. EXPERIMENTAL RESULTS

Experiment tests were conducted on a real test bench that includes IM and PMSM whose parameters are the same as those used in the simulation (Table I). An Imperix fast prototyping controller system was used for testing the proposed unified observer (see Fig. 8). The observer was discretized by an 8 kHz sampling frequency using the forward Euler method. To test both machines under different circumstances, a predefined speed torque profile is chosen (see Fig. 3). The proposed observer was tested on IM and compared with the hybrid model observer [13], and the results for position and frequency estimation are shown in Fig. 9. It is seen that the position

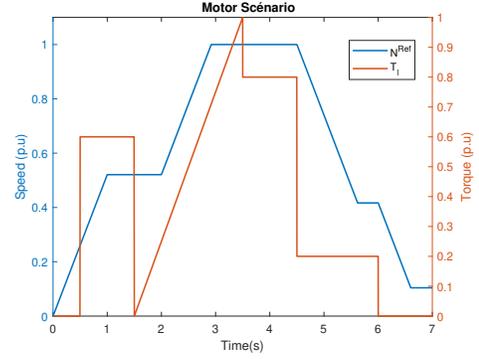


Fig. 3. The chosen speed-torque profile for testing both the IM and PMSM.

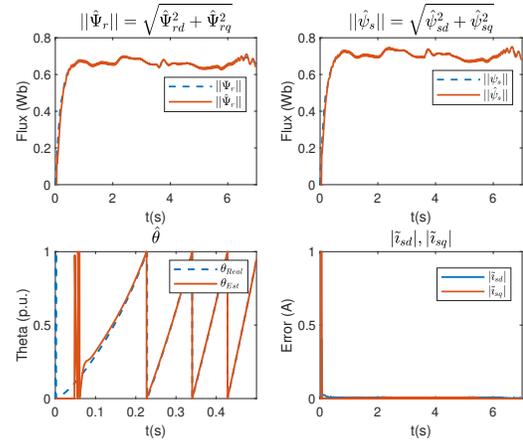


Fig. 4. Numerical simulation results for IM using the proposed observer.

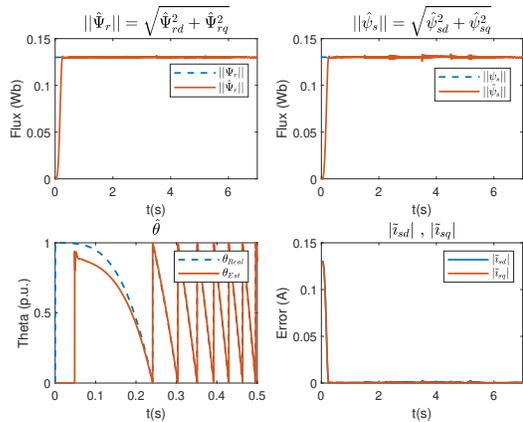


Fig. 5. Numerical simulation results for PMSM using the proposed observer.

TABLE I
MOTORS NAMEPLATE

	IM	PMSM
Rated Power	750 [W]	3500 [W]
Rated Speed	1440 [rpm]	3000 [rpm]
Rated Current	1.7 [A]	12.0 [A]
Rated Torque	5 [N.m]	12 [N.m]
Rated Frequency	50 [Hz]	250 [Hz]
n_p	2	5
R_s	9.165 [Ω]	0.250 [Ω]
R_r	4.5 [Ω]	-
L_{ls}	24.5 [mH]	-
L_{lr}	24.5 [mH]	-
L_m	850 [mH]	-
L_d	-	3 [mH]
L_q	-	3 [mH]
ψ_m	-	0.13 [Wb]

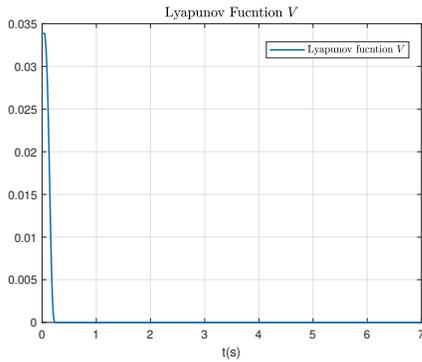


Fig. 6. The variation of the Lyapunov function $V(t)$ as a function of time.

error converges to zero even when a step torque disturbance is applied at 0.5 s. The flux estimation magnitude of the observer is shown in Fig. 11; where we can see that, without knowing the rotor time constant τ_r and rotor equivalent resistance R_{req} , the estimation of rotor flux by the observer is converging to the same values as the hybrid model observer. This shows that the proposed observer can be more robust since it doesn't take into consideration the rotor time constant, which varies a lot when the motor is operating. The second tested machine was the PMSM; in this case, the angular position and frequency estimation are compared with the encoder signals (see Fig. 10). The encoder signal and the estimated angular position have relatively little estimation error.

VI. CONCLUSION

In this paper, we propose a novel unified adaptive flux observer for AC machines that can be used to drive both IMs and PMSMs. The observer has the advantage that it only depends on the motor stator parameters: stator resistance R_s and the dq -axis inductance. The proposed unified observer was validated both in numerical simulation and experimental tests. It is shown that the unified observer rapidly converged to the real flux values in both machines without requiring information on the rotor flux dynamics. The convergence of the observer is not affected by torque load disturbance.



Fig. 7. Illustration of the motor test bench.

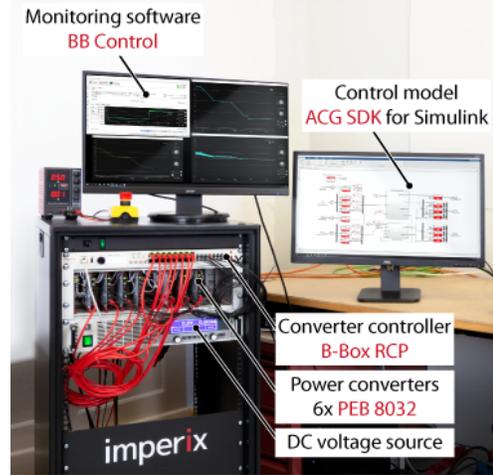


Fig. 8. Illustration of the rapid prototyping controller system from Imperix.

Although the proposed unified observer was proven to work on both IMs and PMSMs, there are a few important issues that need to be addressed:

- Study the observer's parameter sensitivity and its potential application to a saturated motor model.
- Testing the observer in a closed-loop manner for the aim of unified sensorless control of AC machines.
- Investigate the possibility of extending the observer for other motor types, such as SynRM and Pma-SynRM.

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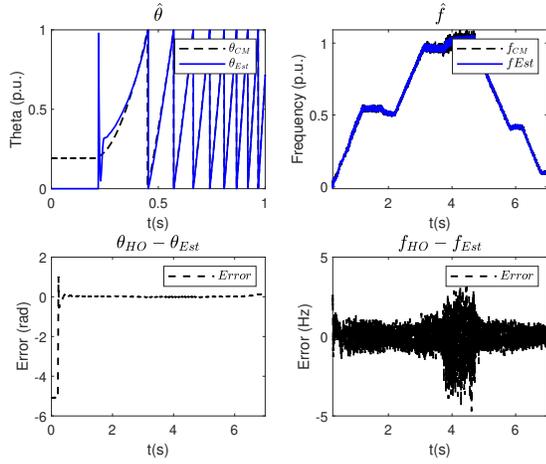


Fig. 9. IM observer experimental results for position and frequency estimation compared with hybrid observer (HO).

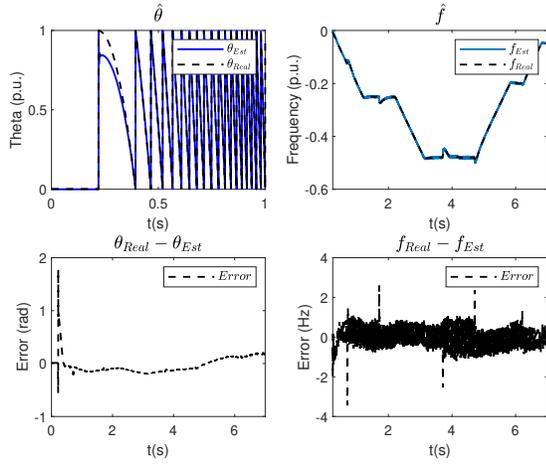


Fig. 10. PMSM experimental results for position and frequency estimation.

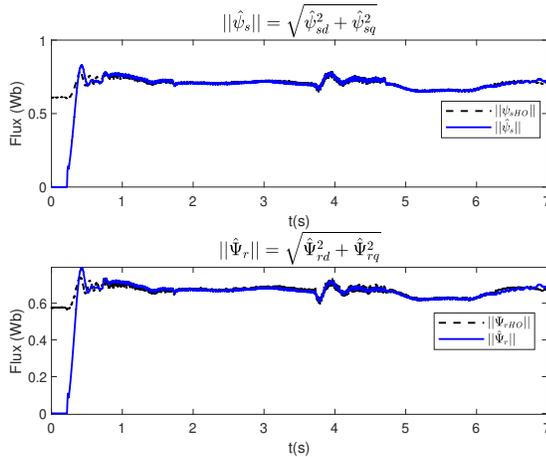


Fig. 11. IM experimental flux estimation results: comparison between the proposed observer and the combined model observer.

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