Sensorless Control of Low Inductance Coreless AFPM Machines for Fault-tolerant Operation of Propulsion Systems

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***Abstract*—In motor-drive systems utilized in safety-critical applications and demanding conditions like electric aircraft propulsion systems, the reliability of the system is greatly affected by position sensors, given their susceptibility within the motor-drive system. Consequently, there is a need to eliminate sensors in vector-controlled motor drives to decrease overall hardware complexity and expenses, bolster the mechanical durability and dependability of the drive system. In this paper, a fault-tolerant sensorless control system for low inductance coreless axial flux PM (AFPM) machines, integrated into electric aircraft propulsion systems, is introduced. The proposed control system spans a wide operating range, from zero to ultra-high speed, all without the need for a position sensor, enhancing fault tolerance. The system is capable of accelerating the motor from standstill to a certain speed where fundamental signals become available for a flux observer. This observer estimates the rotor position and speed, which are then fed into a field-oriented control scheme. The effectiveness of the introduced control scheme was experimentally verified using a prototype coreless AFPM machine with a PCB stator as a case study.**

***Index Terms*—Sensorless control, estimation, PMSM drives, vector control, field-oriented control, flux observer, AFPM machines, coreless machines.**

I. Introduction

The coreless (air-cored) stator axial flux permanent magnet (AFPM) machine configuration offers unique advantages compared to their conventional cored counterparts by eliminating the stator core and associated losses, such as zero cogging torque, diminished audible noise and vibration, as well as reduced mass and volume. These characteristics potentially enhance torque, power density, and efficiency [1]. Coreless machines eliminate the primary factor contributing to frequency-dependent power losses, namely stator core losses. As a result, they emerge as highly suitable candidates for applications requiring ultra-high speeds, such as electric aircraft propulsion systems [2].

Modern power electronic drives are based on advanced simulation and modeling techniques to analyze the complex behavior and operation under different conditions [3]. To leverage the full potential of electric machines, high-performance electric drive systems are required. Field-oriented control (FOC) is a widely used technique for regulating the output torque and speed of high-performance motor-drive systems by adjusting the stator phase currents in a rotational direct and quadrature reference frame. In this approach, the stator currents undergo transformation into flux and torque components, represented as dc waveforms. These components can be independently regulated by typically proportional-integral (PI) controllers to achieve predetermined objectives. To carry out all the necessary reference frame transformations within FOC like Park, accurate real-time rotor position information is essential. The torque and speed control loops also require shaft speed information, typically obtained by taking the derivative of the measured rotor position.

The measurement of rotor position and speed can be achieved through various methods, including electromagnetic resolvers or digital means utilizing incremental or absolute encoders. Among these, optical encoders stand out as one of the most commonly employed position sensors. Electromagnetic resolvers are also favored for rotor position measurement due to their robust construction and capacity to operate at higher temperatures [4].

In motor-drive systems operating in hostile environments, such as electric aircraft propulsion systems, position sensors significantly impact system reliability, as they are among the most vulnerable parts of a motor-drive system [4]. Therefore, to reduce total hardware complexity and costs, enhance the mechanical robustness and reliability of the drive system, and improve noise immunity, it is desirable to eliminate sensors in motor drive systems employing field-oriented control schemes. Such motor drive systems, i.e., sensorless drives, also reduce maintenance requirements [5], [6].

There are two main categories of sensorless control schemes: model-based methods generally applied in the high-speed range and saliency-based methods typically employed in the low-speed range. The model-based method can be implemented using the electromotive force (back-EMF) or flux associated with the fundamental frequency excitation, and it can be subdivided into open-loop methods and closed-loop methods [6]–[8].

Two rotor position estimation methods for surface mounted PM machines including rotor flux observer and sliding mode observer for FOC-based drive systems were introduced and in [9]. A novel flux observer with DC component and harmonics attenuation capability was proposed for PMSM sensorless control in [10]. This observer effectively reduces the adverse

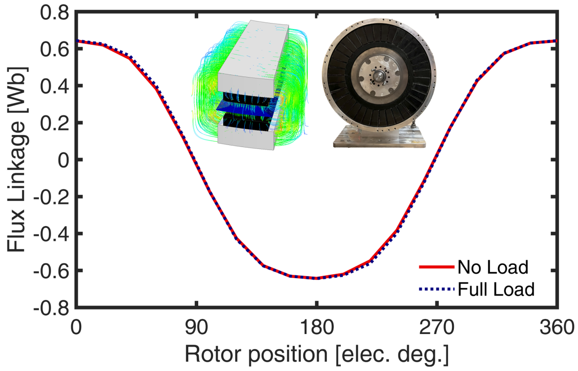


Fig. 1. Flux linkage of a phase winding for the coreless AFPM machine at both no-load and full-load conditions derived from finite element analysis.

effects of non-zero integral initial value, parameter mismatch, and converter non-linearities on conventional flux observers based on second-order integrator and frequency-locked loops. A highly accurate and resilient sensorless control system for induction machines, relying on an enhanced stator flux identification method, was introduced in [11]. This system utilized a dc offset voltage estimator alongside a noise compensator to produce clean voltage and current signals, serving as inputs to the stator flux estimator.

In this paper, leveraging the inherent characteristics of coreless AFPM machines, such as ultra-low phase inductance, a flux-observer-based sensorless control method is introduced. This method is intended to serve as a redundancy for rotor position sensors, aiming to enhance the reliability and fault tolerance of electric aircraft propulsion systems. The analytically described method was experimentally tested using a prototype integral horsepower coreless axial flux machine to demonstrate the effectiveness of this approach.

II. Proposed Sensorless Control Method

Real-time computation devices, such as digital signal processors (DSPs), are reaching a satisfactory level of maturity. Therefore, speed and position estimation can be achieved using software-based state estimation techniques, where stator voltage and/or current measurements are utilized. These drives are labeled as "sensorless", even though it specifically refers to position or speed sensors. It's important to note that there are still other sensors in the drive system, including current sensors. In certain applications where cost is not the primary constraint but reliability is crucial, such as in electric aircraft propulsion systems, sensorless control schemes are utilized in conjunction with position sensors as a redundancy measure. This is implemented to enhance fault-tolerance and overall system reliability.

The primary sensorless control techniques for PM synchronous motor drives include open-loop estimators utilizing the fundamental motor signals, position estimators based on back-EMF, saliency-based methods involving high-frequency (HF) signal injection, and observer-based estimators (such as Kalman and Luenberger). The choice of technique or a combination thereof for estimating rotor position and speed in

TABLE I
Specifications and main dimensions of the prototype coreless AFPM machine considered as a case study.

Parameter	Value	Unit
Rated power	4.18	kW
Rated speed	2,100	rpm
Torque density (natural cooling)	6.6	Nm/L
Airgap (rotor to stator)	1.3	mm
Stator thickness	6.0	mm
Rotor inner/outer diameter	208/304	mm
Stator inner/outer diameter	202/310	mm
No. of rotor/stator poles	36/36	-
Phase inductance	32.3	μH

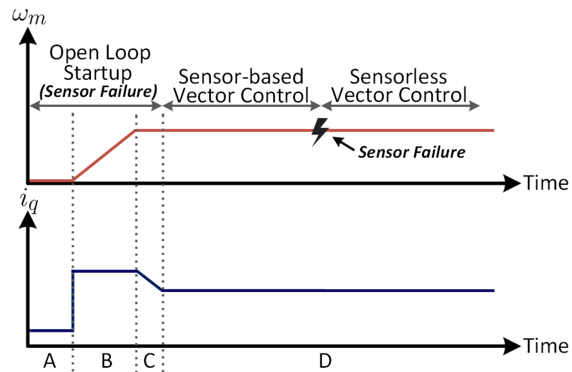


Fig. 2. The timeline of the proposed fault-tolerant sensorless control scheme. The rotor flux observer becomes active in the absence of a rotor position sensor due to a fault condition to cover the full range of operation.

sensorless control depends on intrinsic machine characteristics, application requirements, available signals and processing hardware [6], [11], [12].

Coreless axial flux PM machines fall into the category of non-salient motors. Consequently, saliency-based methods—those relying on variations in inductance due to geometrical effects—are not applicable to their sensorless drive systems. The absence of a magnetic core introduces unique features such as low armature reaction, indicating that even under high electric loading, the magnetic field produced by the stator current has minimal impact on the main magnetic field generated by the PMs, as shown in Fig. 1, based on finite element analysis results.

Due to the absence of a magnetic core, there is no nonlinearity in the phase inductances and torque constant [13]. It's essential to highlight that coreless machines typically exhibit ultra-low phase inductance, a factor that requires strict consideration in the design of the drive system [14]. The phase inductance for the prototype machine under study is reported in Table I. It is worth mentioning that due to the absence of slot protection, stator windings are directly exposed to flux variations, leading to high vulnerability to another type of frequency-dependent power loss, namely, eddy current losses. Researchers have proposed effective approaches to significantly reduce eddy current losses through the optimization and meticulous design of coil shapes, as presented in [2], [15].

Given the unique advantages mentioned earlier for coreless

AFPM machines, this study introduces a rotor flux observer for estimating the rotor position and speed within a sensorless field-oriented control of coreless AFPM machines. This technique is computationally efficient and all the required calculations can be performed within switching periods even at ultra-high speeds. Mathematical equations, advantages, challenges, and more details are provided in the next section.

Most rotor position estimation techniques based on the machine fundamental signals, i.e., phase currents, and back-EMFs, do not demonstrate satisfactory performance at low speeds due to a low signal-to-noise (SNR) ratio in this operational region [4]. Moreover, they also fail in estimating the initial rotor position at standstill, which is imperative in field-oriented control schemes [11]. To address these issues, researchers have proposed different approaches, mainly by taking advantage of variations in the inductance values due to saturation and the geometry of the machine, relying on HF-signal injection [6]. None of these techniques is applicable to the non-salient pole coreless AFPM machines.

Therefore, there is a need for an encoder or resolver to measure rotor position at standstill and low speeds. Furthermore, in the case of sensor failure, there is a need for an open-loop startup strategy to run the motor from standstill to a certain speed at which the rotor flux observer can accurately estimate the rotor position information. In fact, to establish a fault-tolerant drive system, the sensorless control scheme has to cover a wide operational range from standstill to ultra-fast speeds, all in the absence of a position sensor. The timeline of the proposed fault-tolerant sensorelss control scheme is presented in Fig. 2. A prototype PCB stator coreless AFPM machine with the specifications listed in Table I was considered as a case study.

Within this control scheme, an open-loop startup strategy and rotor flux observer are employed to cover the full range of operation in the absence of rotor position information due to a malfunction. If there is no information from the position sensor at zero speed, the open-loop strategy starts by applying a pulse to phase A only, aligning the rotor with the d-axis corresponding to $\theta_e = 0$. It should be noted that coreless AFPM machines are typically designed with a high pole count, like the machine under study, which has 36 poles. Therefore, the rotor movement caused by the instantaneous current mentioned is negligible for most applications, including electric aircraft propulsion systems. In the presented timeline in Fig. 2, this stage is determined by "A".

In the second stage marked with "B" in Fig. 2, the motor accelerates from standstill to a certain speed. A constant current reference is applied to the q-axis of the synchronous reference frame, while the d-axis current is set to zero. The speed is determined by a speed ramp command, and the position is obtained by integrating this speed command. In the subsequent phase, denoted as "C", the speed remains constant, and the q-axis current in the synchronous reference frame is reduced to guarantee precise rotor position estimation and a seamless transition to the closed-loop FOC mode. It should be noted that within this range (from "A" to "C"), closed-loop vector control can be executed if the rotor position information is available from the sensor.

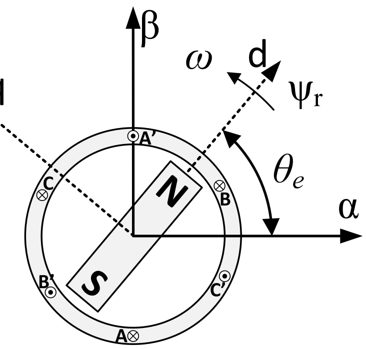


Fig. 3. Vector diagram of a PM synchronous machine demonstrating rotor flux vector.

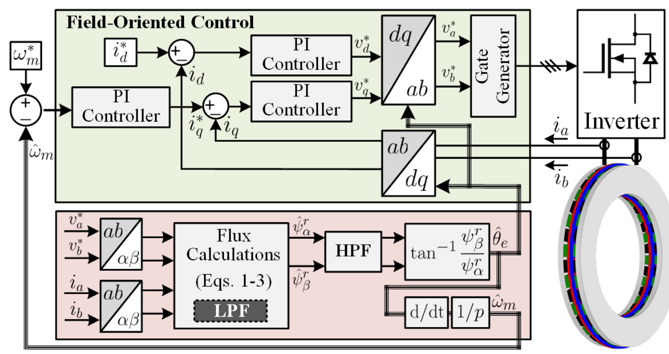


Fig. 4. The block diagram of the introduced sensorless FOC based on a rotor flux observer.

Throughout the region "D", there is a need for a closed loop vector control. In this operational domain, the introduced flux-observer based estimator serves as a redundancy for the position sensor, activating only in the event of a sensor malfunction. This feature enhances the fault tolerance of the motor-drive system. This sensorless approach is presented in the next section.

III. Position and Speed Estimation based on Rotor Flux Observer

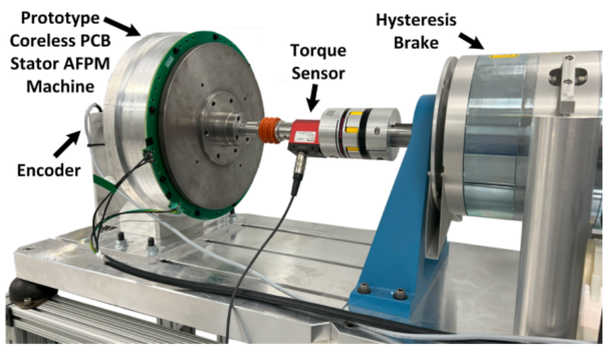
The application of rotor flux observers is common in direct torque control (DTC) implementations. Their primary role in DTC is to accurately estimate stator flux and torque for feedback to the algorithms. In this study, rotor flux observers are utilized to extract rotor position and corresponding speed.

The voltage equations of PMSMs can be described as

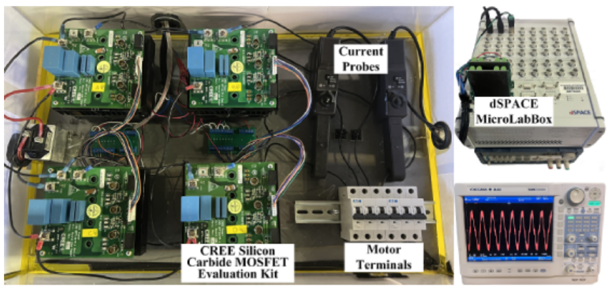
$$v_\alpha = R_s i_\alpha + \frac{\mathrm{d}\psi^s_\alpha}{\mathrm{d}x} \ ; \quad v_\beta = R_s i_\beta + \frac{\mathrm{d}\psi^s_\beta}{\mathrm{d}x} \quad , \tag{1}$$

where $\psi^s_{\alpha\beta}$ and $\psi^r_{\alpha\beta}$ represent the stator and rotor fluxes, respectively, and can be expressed as

$$\psi^s_{\alpha\beta} = \psi^r_{\alpha\beta} + L_s i_{\alpha\beta}, \ ; \quad \psi^r_{\alpha\beta} = \psi_{PM} \cdot \begin{bmatrix} \cos\theta_e \\ \sin\theta_e \end{bmatrix} \tag{2}$$



(a)



(b)

Fig. 5. The assembled prototype machine mounted on the test bench (a). The machine was coupled to a hysteresis brake as a fully controllable mechanical load. Two independent single-phase inverters connected to PCB stators (b). The dSPACE MicroLabBox was used to control the hardware-in-loop (HIL) system, i.e., gate signal generation and feedback.

From (1) and Fig. 3, it can be concluded that the rotor flux encompasses rotor position information. Hence,

$$\begin{aligned}\hat{\psi}^r_\alpha &= \int (v_\alpha - i_\alpha R_s)\mathrm{d}t - L_s i_\alpha,\\ \hat{\psi}^r_\beta &= \int (v_\beta - i_\beta R_s)\mathrm{d}t - L_s i_\beta,\end{aligned} \tag{3}$$

$$\hat{\theta}_e = \mathrm{atan2}(\hat{\psi}^r_\beta, \hat{\psi}^r_\alpha), \tag{4}$$

$$\hat{\omega}_e = \frac{\mathrm{d}\hat{\theta}_e}{dt}, \tag{5}$$

where L_s, R_s, θ_e, and ω_e are stator inductance, resistance, estimated rotor electrical position, and estimated rotor electrical speed respectively.

The presence of a DC component in the measured currents is inevitable. Hence, utilizing a pure integrator to calculate the rotor flux results in saturation. To address this issue, a first-order low-pass filter (LPF) is utilized as an integrator, with a relatively low cut-off frequency. The low-pass filter remains unsaturated and the position estimator effectively works at high and medium speeds. A first-order high-pass filter (HPF) is also incorporated at the output stage to eliminate the integration constant resulting from initial conditions and the input DC offset.

The block diagram depicting the introduced flux observer-based sensorless FOC for a coreless AFPM machine is illustrated in Fig. 4. It's worth noting that the low-pass filter introduces limitations on the flux observer at low speeds due to phase shift, resulting in speed oscillation. It can be solved by employing dynamic phase compensation techniques [11].

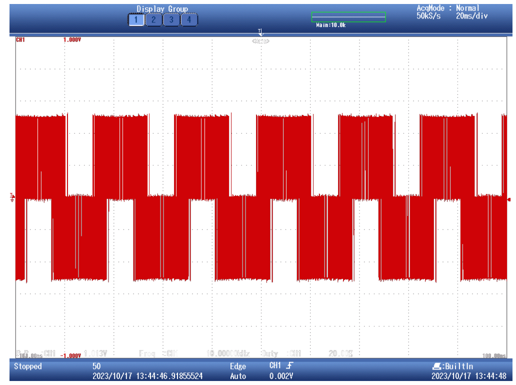


Fig. 6. The measured phase voltage of the two-phase machine that are used in the introduced flux observer calculations.

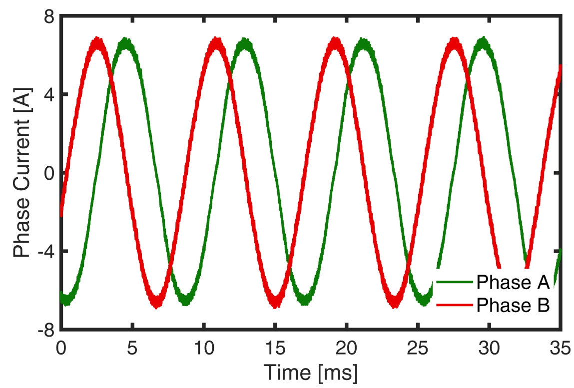
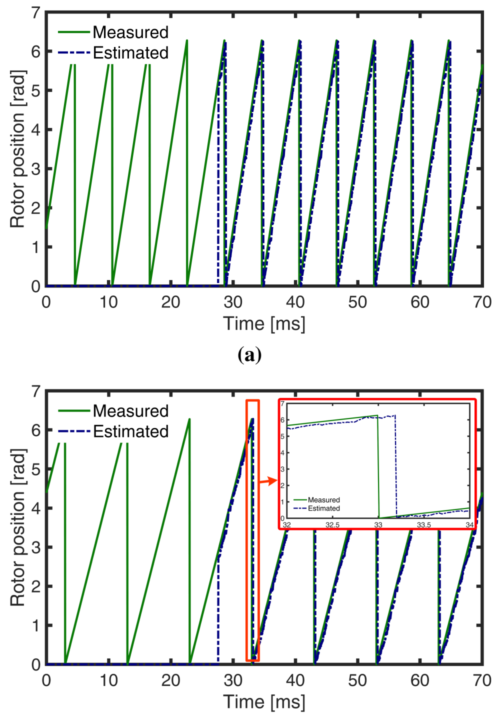


Fig. 7. The measured phase currents of the two-phase machine that are used in the introduced flux observer calculations.

IV. Experimental Results

The performance of the introduced sensorless drive for the two-phase coreless AFPM machine was evaluated through experimental testing on the test bench depicted in Fig. 5a. The prototype four-leg two-phase 10kW inverter, based on SiC switches, is shown in Fig. 5b. The measured phase voltage applied to the machine terminal is illustrated in Fig. 6. The required phase voltages in (3) is calculated based on the inverter reference voltages. The measured two-phase currents fed into the equations exhibit nearly sinusoidal waveforms with negligible ripple, thanks to a high switching frequency of 65kHz, as illustrated in Fig. 7.

To replicate a fault scenario, the flux observer was enabled at two distinct speeds and arbitrary moments. The estimated position was then compared with the measured position, as depicted in Fig. 8a and Fig. 8b. The estimated speed, derived by taking the derivative of position, was also compared with the measurements, as depicted in Fig. 9. The results indicate a satisfactory level of accuracy, especially at high speeds. In the zoomed-in view shown in Fig. 8b, the discussed phase delay caused by the LPF as an integrator is visible.



(a)

(b)

Fig. 8. The measured and estimated rotor position at two different speeds (a) and (b). To replicate a fault scenario, the flux observer was activated at two distinct speeds and arbitrary moments.

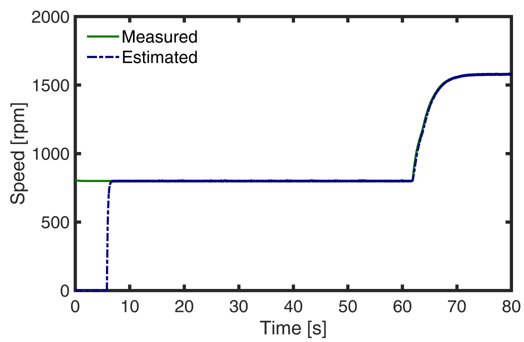


Fig. 9. The measured and estimated speeds during a sensor fault occurrence and speed change. A sensor failure was emulated at second 6, and the proposed sensorless method successfully estimated the shaft speed. The results also demonstrate that the rotor flux observer has a good performance during transients.

V. Conclusion

In this paper, a sensorless control scheme for coreless AFPM machines aiming to improve the reliability and fault tolerance of propulsion systems was proposed. The method relies on a rotor flux observer, taking advantage of the lack of magnetic core saturation effects and low armature-reaction in coreless machines, making such observers highly suitable for sensorless control schemes. An open-loop startup strategy was also introduced to accelerate the machine from standstill in the absence of a position sensor. At medium and high speeds, a flux observer was employed to estimate rotor position, which feeds into a FOC scheme. A fault scenario was emulated, and the results demonstrated that the proposed sensorless method can immediately estimate accurate rotor position. The experimental results indicate a satisfactory level of accuracy, highlighting the effectiveness of the flux observer as a computationally-efficient state estimator.

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