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Natural Speed Observer for Sensorless Nonsalient Permanent Magnet Synchronous Motors

Jiahao Chen, *Member, IEEE*, Jie Mei, *Member, IEEE*, Xin Yuan, *Member, IEEE*,
Yuefei Zuo, *Member, IEEE*, Christopher H. T. Lee, *Senior Member, IEEE*

Abstract—This letter addresses experimental validation of the reduced-order natural speed observer design for position sensorless drive with nonsalient permanent magnet synchronous motor. The natural speed observer and the active flux estimator are connected in a cascaded fashion, which results in a simple speed observer design that needs only to tune a pair of proportional-integral gains in load torque update rule. Experimental results of high speed reversal test, zero speed stopping test and slow speed reversal test are included, where the practice of applying non-zero d -axis current near zero speed has shown to be effective to help the sensorless drive to survive zero speed operation. With the aid of the active flux concept, the proposed sensorless design is also applicable to other types of electric motors.

Index Terms—natural observers, permanent magnet motor drives, sensorless control, active flux.

I. SENSORLESS DRIVE REVIEW: A NEW PERSPECTIVE

THE LITERATURE of sensorless motor drives has been developed for decades, and there has been a trend of unifying sensorless control for different motor types [1]–[3]. When it comes to literature review of different sensorless drives, the widely accepted classification is to divide sensorless drives into model based drives and magnetic asymmetry based drives (see, e.g., [4], [5]). This letter, however, attempts to provide a new perspective in terms of how speed estimation and position estimation are related, and to categorize the existing sensorless drives into groups of three design patterns.

A. Coupled Position and Speed Acquisition

The first design pattern is to get both speed $\hat{\omega}$ and rotor d -axis position $\hat{\theta}_d$ from one full-order observer. This relies on the fact that both $\hat{\omega}$ and $\hat{\theta}_d$ can be obtained from observer's output error, i.e., estimated current error—more specifically, $\hat{\omega}$ from q -axis current error, and $\hat{\theta}_d$ from d -axis current error [6]. Typical example is the direct field oriented controlled sensorless induction motor drive [7]. There are only a few papers in the field of sensorless permanent magnet (PM) motor drives following this design pattern, and a recent one [8] devises speed adaptive full-order observer based on extended emf model and elaborates its gain design with the aid of linear system tools.

The observer designs that are previously applied to induction motors should also be applicable to synchronous motors. For example, motivated by the “known regressor model” in [9], we can replace extended emf e with a new state variable

$\chi = -e - \omega J L_d i$. This results in new PM motor dynamics in which the regressor of speed consists of known signals:

$$\begin{aligned} L_d p i &= u - R i + \chi + (2L_d - L_q) \omega J i \\ p \chi &= -\omega J (u - R i) + \omega^2 (L_d - L_q) i \end{aligned} \quad (1)$$

for which one can design speed adaptive high gain observer [10] or speed update rule with filtered regressor [9] to get $\hat{\omega}$, and at the same time obtains $\hat{\theta}_d$ from the estimate of χ .

B. Position Independent Speed Acquisition

The second design pattern is to first estimate speed $\hat{\omega}$ and then calculate the rotor d -axis position with an integrator as $\hat{\theta}_d = \frac{1}{p} (\hat{\omega} + \omega_{sl}^*)$, with ω_{sl}^* the commanded slip angular speed. Typical examples include the sensorless indirect field oriented controlled PM motor drive (with $\omega_{sl}^* = 0$) [11], induction motor drive (see e.g., [9]) and those sensorless drives based on emf calculation [12]–[14]. Particularly, the emf e that provides rotor position by $\hat{\theta}_d = \text{atan}(\frac{-e_\alpha}{e_\beta})$, is calculated in a controller d - q frame that depends on $\hat{\theta}_d$, which forms an algebraic loop problem and needs to be properly dealt with, as is discussed in [2].

C. Speed Independent Position Acquisition

The third design pattern is exclusively targeted for synchronous motors (i.e., PM and synchronous reluctance motors) as it directly estimates the rotor d -axis position $\hat{\theta}$ from which the speed information $\hat{\omega}$ is later extracted. Typical examples include high frequency signal injection based drives [15], emf based drives [1], [4], [16] and flux based drives [3], [17].

The high frequency injection method estimates $\hat{\theta}_d$ utilizing the *rotor saliency* on the q -axis using invasive injection of high frequency voltage. The resulting practical issues such as limited current control bandwidth and audible noise can be resolved by increasing injection frequency to PWM frequency [15], while the theoretical development can be found in [18].

Active flux is defined in complex notations as $\psi_{\text{Active}} = K_{\text{Active}} e^{j\theta_d}$, with $K_{\text{Active}} = K_E + (L_d - L_q) i_d$. Extended emf is defined as $e = [\omega K_{\text{Active}} - (L_d - L_q) p i_q] e^{j\theta_d}$, and it becomes $\omega \psi_{\text{Active}}$ if $p i_q = 0$, i.e., at steady state.

The extended emf e was estimated by Gopinath reduced-order observer [1]. For non-salient PM motors, the emf was estimated by sliding mode observer [4], [16]. The dynamics of active flux involve pure integration, which are also known as the critical stable voltage model in induction motor drive context. In the PM motor drive context, as an instance, to

stabilize the active flux estimation, a disturbance observer was designed to estimate the presumed low frequency ac disturbance in the emf and a flux limiter design is proposed for motor startup in [17]. In [5], the stator flux estimator was corrected under the PM flux amplitude constraint, of which the stability property was found to be distinct at different speeds.

With the information of θ_d , e , or ψ_{Active} available, a speed estimator is then devised, e.g., Luenberger observer [15], I&I technique [5], model reference adaptive system [1], [16], phase-locked-loop [3] and type-2 system [17].

It is worth mentioning that the $\hat{\theta}_d$ estimation process in [1], [17] “weakly” depends on the estimated speed $\hat{\omega}$. That is, it has been shown with frequency analysis in [17] that an erroneous speed is not a big issue for active flux estimation, while in [1], the H_∞ norm of the transfer function from estimated speed error to extended emf error is minimized by properly placing observer poles.

D. Contribution of This Letter

The contribution of this letter is, by following the third design pattern, to propose and experimentally validate a motor motion dynamics based speed observer with the aid of natural observer concept and active flux concept. The 4th-order active flux estimator gives $\hat{\theta}_d$ without knowledge of $\hat{\omega}$; and by using $\hat{\theta}_d$, a 3rd-order reduced-order natural speed observer potentially provides consistent estimate of $\hat{\omega}$ even during speed transient conditions. The proposed sensorless scheme is simple to implement, and has potential for high performing sensorless motor drive as it removes the constant speed assumption.

II. REDUCED-ORDER NATURAL SPEED OBSERVER WITH ACTIVE FLUX CONCEPT

A. PMSM Model in Synchronous d - q frame

Let p denote the differentiation operator, and the 3rd-order dynamics of PMSM in rotor field oriented frame are

$$u_d = Ri_d + pL_d i_d - \omega L_q i_q \quad (2a)$$

$$u_q = Ri_q + pL_q i_q + \omega L_d i_d + \omega K_E \quad (2b)$$

$$\frac{J_s}{n_{pp}} p\omega = \underbrace{\frac{3}{2} n_{pp} (K_E + (L_d - L_q) i_d) i_q}_{T_{em}} - T_L \quad (2c)$$

where u_d, u_q denote the d -axis, q -axis voltages, i_d, i_q are d -axis, q -axis currents, L_d, L_q designate the d -axis, q -axis inductances, ω is the electrical rotor speed, R the stator resistance, $K_E \in \mathbb{R}_+$ the permanent magnet flux linkage, J_s the shaft inertia, T_{em} the electromagnetic torque, T_L the load torque, and n_{pp} the pole pair number.

B. The Natural Speed Observer

The natural observer originally discussed in [19] is applicable to dc motor and ac induction motor. By noticing the fact that PM motor in dq frame is identical to that of a dc motor, we propose the 3rd-order reduced-order natural speed

observer that is simply a copy of (2b) and (2c) plus a load torque identifier:

$$L_q p \hat{i}_q = u_q - R \hat{i}_q - \hat{\omega} (K_E + L_d i_d) \quad (3a)$$

$$p \hat{\omega} = J_s^{-1} n_{pp} \left[\frac{3}{2} n_{pp} (K_E + (L_d - L_q) i_d) \hat{i}_q - \hat{T}_L \right] \quad (3b)$$

$$\hat{T}_L = K_P \varepsilon + K_I \frac{1}{p} \varepsilon \quad (3c)$$

where $K_P, K_I \in \mathbb{R}_+$, a hat $\hat{\cdot}$ at the top of a symbol indicates estimated value, and ε is the active power error defined as

$$\varepsilon = \text{sign}(u_q) u_q (\hat{i}_q - i_q) \quad (4)$$

The stability of (3) and (4) can be proved via finding Lyapunov function using Krasovskii's stability technique [20]. The implementation of (3) and (4) relies on the information of rotor d -axis position $\hat{\theta}_d$, to calculate the d - q frame quantities:

$$\begin{aligned} i_d &= i_\alpha \cos \hat{\theta}_d + i_\beta \sin \hat{\theta}_d \\ i_q &= -i_\alpha \sin \hat{\theta}_d + i_\beta \cos \hat{\theta}_d \\ u_q &= -u_\alpha \sin \hat{\theta}_d + u_\beta \cos \hat{\theta}_d \end{aligned} \quad (5)$$

where u_α, u_β are substituted with voltage commands in stationary α - β frame, and i_α, i_β are obtained by applying amplitude invariant Clarke transformation to measured phase currents.

C. The Output Error based Estimator for Active Flux and $\hat{\theta}_d$

Motivated by the sliding mode flux estimator by Lascu and Andreescu [21], the 4th-order output error corrected active flux estimator can be written as follows

$$\begin{aligned} p\psi_1 &= \mathbf{u} - R\mathbf{i} + \left(k_p + k_i \frac{1}{p}\right) (\mathbf{i} - \hat{\mathbf{i}}) \\ \hat{\theta}_d &= \arctan2(\psi_{\beta 1} - L_q i_\beta, \psi_{\alpha 1} - L_q i_\alpha) \\ \hat{i}_\alpha &= L_q^{-1} \left(\psi_{\alpha 1} - K_{\text{Active}} \cos \hat{\theta}_d \right) \\ \hat{i}_\beta &= L_q^{-1} \left(\psi_{\beta 1} - K_{\text{Active}} \sin \hat{\theta}_d \right) \end{aligned} \quad (6)$$

where stator flux estimate $\psi_1 = [\psi_{\alpha 1}, \psi_{\beta 1}]^T$, stator current $\mathbf{i} = [i_\alpha, i_\beta]^T$, stator voltage $\mathbf{u} = [u_\alpha, u_\beta]^T$, $k_p, k_i \in \mathbb{R}_+$, and $K_{\text{Active}} = K_E + (L_d - L_q) i_d$ with i_d defined in (5). The rotor d -axis position $\hat{\theta}_d$ is extracted from the active flux estimate $\hat{\psi}_{\text{Active}} = (\psi_1 - L_q \hat{\mathbf{i}})$. In this estimator, only the amplitude of the voltage model flux estimate is corrected by the active flux amplitude K_{Active} .

D. Discussion on Active Flux Concept and Generalization

The active flux is a concept introduced in [3]. By properly redefining direct-axis and quadrature-axis inductances, L_d, L_q , six types of electric machines can be described as the following nonsalient model in *active flux d - q frame*:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + (p\mathbf{I} + \mathbf{J}\omega) \left(L_q \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} K_{\text{Active}} \\ 0 \end{bmatrix} \right) \quad (7)$$

$$J_s n_{pp}^{-1} p\omega = \underbrace{\frac{3}{2} n_{pp} K_{\text{Active}} i_q}_{T_{em}} - T_L \quad (8)$$

which is equivalent to (2), where $\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $\mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$.

In other words, by introducing the active flux concept, the sensorless scheme proposed in this section is generally applicable to other types of electric machines. In fact, successful application to induction motor has been reported in [20].

III. EXPERIMENTAL RESULTS

The test motor is a 750 W, 3 Arms, 2.4 Nm, $n_{pp} = 4$ pole pair surface mounted PM motor. The test motor is driven by a voltage source SiC inverter that receives gate signals from the digital signal processor of TMS320F28377D. The carrier signal frequency of the space vector pulse width modulation is 10 kHz, and the current sampling period and code execution period are 1×10^{-4} s. A dc power supply is used as the dc bus. An encoder with 2500 ppr is used for verification purpose.

A. Voltage Error Issues

The active flux estimate ψ_{Active} is prone to be erogenous due to voltage error at low speeds, so it is important to remove the drift in dc bus voltage measurement as well as compensate inverter nonlinearity.

When measuring the inverter's voltage and current characteristics at standstill, it should be emphasized that instead of applying α -axis current, the dc current should be applied at β -axis such that the phase U current (i.e., i_α) is null and phase V and phase W have the same current amplitude with opposite signs. Otherwise, by regulating i_α , the current amplitude of phase U is two times as large as the amplitude of phase V or W , so the distorted phase voltage that is a nonlinear function of phase current cannot be acquired. Finally, multiplying a scaling factor of $\sin(-\frac{2\pi}{3})$ to β -axis quantities gives phase quantities.

B. Load Motor Manipulation

The shaft of the test motor is coupled with another servo motor as load. The load motor is controlled with some speed command and its speed loop output limit is set to 2.1 A.

In Fig. 1, the speed command for the load motor is 0 rpm, so the q -axis current has the same sign of the speed at steady state. The overall load torque that includes friction is estimated to be about 1.5 Nm, which equals 62.5% of the motor rated torque.

In Fig. 2 and Fig. 3, in order to test the sensorless drive for various operating conditions, the speed command of the load motor is set to -300 rpm. This means that when the speed is positive, the test motor is motoring; while the test motor is regenerating when the speed is negative.

C. Natural Speed Observer based Sensorless Drive

1) *Sensorless High Speed Fast Reversal*: According to Fig. 1, it takes 0.04 s for the drive to step from -1500 rpm to 1500 rpm. There exists oscillation in $\hat{i}_q$ during the fast speed reversal when the actual value i_q is almost constant, which results in estimated speed error during speed reversal transients. However, the actual speed trace is a straight line during speed reversal transients, which implies the field orientation is maintained.

2) *Sensorless Zero Speed Stopping Test*: In order to stabilize zero speed operation when the motor is loaded, we propose to excite the motor with d -axis current, i.e., $i_d = 2$ A. Note this nonzero i_d is not an effort to "mitigate" the influence of the inverter nonlinearity, as the motor is loaded and i_q is large. The reason is that, in a detuned controller frame, the nonzero i_d helps to pull the rotor d -axis back to align with

Fig. 1. Sensorless high speed reversal test under step speed command. The tuning used is $K_P = 1$, $K_I = 6$, $k_p = 1.0$, $k_i = 2.0$ (all in SI units).

Fig. 2. Sensorless zero speed stopping test under step speed command. The tuning used is $K_P = 1$, $K_I = 6$, $k_p = 0.1$, $k_i = 0.02$ (all in SI units).

the controller d -axis. In Fig. 2, at zero speed operation, one can observe that i_q and θ_d are slowly deviating even though the load motor outputs constant load torque. In this case, the nonzero i_d helps to "lock" the shaft at zero speed if $\theta_d \neq \theta_d$.

In Fig. 2, the speed ripples are found to have vanished at zero speed. After applying nonzero i_d , the speed ripples become more apparent at 100 rpm, and are found to have the same frequency of the mechanical speed of 6.67 Hz (i.e., 100 rpm). Note the speed estimate $\hat{\omega}$ even tracks the speed ripples in ω at 100 rpm steady state. How to reduce the speed ripples is beyond the scope of this letter.

3) *Sensorless Slow Speed Reversal*: The point of a slow speed reversal test is to keep decreasing the acceleration rate of the ramp speed command until the sensorless drive shows some undesired behaviors. In our case, the acceleration is ± 50 rpm/s in Fig. 3. At a glance, one might consider Fig. 3 shows a successful slow speed reversal test. However, there exist problems of "zero speed locked-up", "detuned field orientation", and "loss of speed control" as annotated in Fig. 3.

Zero speed locked-up occurs when the actual motor speed ω becomes zero regardless of the speed command during speed reversal near zero speed. Detuned field orientation essentially

Fig. 3. Sensorless slow speed reversal test with ramping speed command. The tuning used is $K_P = 1$, $K_I = 6$, $k_p = 0.1$, $k_i = 0.02$ (all in SI units).

means $\hat{\theta}_d$ from the active flux estimator deviates from θ_d . In a sensorless drive, a clear indicator for loss of field orientation is that i_q deviates from its desired value, as shown in Fig. 3, at $t = 4$ s when the motor escapes from zero speed locked-up, and at $t = 9$ s when the motor is locked up at zero speed. A severer consequence of loss of field orientation is loss of speed control at $t = 4$ s when the actual speed reaches over -100 rpm when the speed command is about -30 rpm. During loss of speed control, the actual speed diverges from speed command, and as $\hat{\theta}_d$ converges, the speed control is attained again.

As a comparison, the sensorless drive in [13, Fig. 7], which follows the second design pattern in Section I, shows severe speed oscillation at zero speed. Another difference is that the sensorless drive in [13, Fig. 7] loses the speed control at the very beginning of the slow speed reversal.

IV. CONCLUSION

After categorizing existing sensorless drives into groups of three design patterns, this letter proposes a simple load torque-adaptive natural speed observer using the active flux concept, which follows the third design pattern. The experimental results show improved performance in slow speed reversal, as compared to an existing sensorless drive that follows second design pattern. High speed fast reversal and loaded zero speed operation are also found possible.

By introducing the active flux concept, the proposed sensorless design is applicable to different types of ac electric motors. It is worth pointing out that the slow speed reversal test done by a natural speed observer based sensorless induction motor drive can go down to 5 rpm/s acceleration [20]. The future work should investigate the influence of the inverter nonlinearity on the drive's performance at low speeds.

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