Sensorless control for PMSM in underwater propeller based on improved phase-locked loop

Qingjun Zeng¹ and Yaowei Chen¹, a)

Abstract As the core part of underwater propeller, the performance of permanent magnet synchronous motor (PMSM) affects the thrust of it. In the operation of a PMSM, when the speed of PMSM is reversed, a position error of 180° will be generated by the traditional phase-locked loop (PLL). In this paper, an improved PLL based Luenberger observer is proposed to resolve this problem. The back electromotive force (EMF) was obtained by the Luenberger observer. In contrast to the traditional PLL, the improved PLL has a different phase discriminator to tackle rotor position errors. Results of simulation and experiments show the effective convergence of the proposed improved PLL for rotor position errors and that the trust of propeller meets the requirements.

Keywords: underwater propeller, thrust, phase-locked loop (PLL), Luenberger observer, phase discriminator, convergence, rotor position errors

Classification: Circuits and modules for electronic instrumentation

1. Introduction

In the last decade, underwater robot, surface unmanned vehicle, and other vehicles have been greatly developed. Increasingly, the complex of vehicles has been designed. Thus, the higher requirements of propulsion system would be expected to match. Currently, underwater propulsion systems are divided into two categories [1]: thermal propulsion systems [2] and Electric propulsion systems [3]. The electric propulsion systems are gradually making thermal propulsion obsolete due to their better control and higher efficiency. With the development of Electric propulsion systems, integrated underwater propeller has seen rapid adoption by placing the motor directly in the position where torque is required, eliminating the need for drive shafts and gears [4]. In the choice of motor, due to the special environment of the ocean, there are strict restrictions on sound [5], so permanent magnet synchronous motor (PMSM) has high power density and efficiency. The characteristics of high and quiet operation have been widely studied by scholars.

Fig. 1 shows the structure of an integrated underwater propeller, mainly including duct, propeller, magnetic coupler, and PMSM. The rotor of the PMSM is connected to the input shaft of the magnetic coupler. The motor drives the magnetic coupler to rotate, and the output shaft of the magnetic coupler is connected to the propeller, so as to realize the synchronous rotation of the propeller and the rotor of the motor. The electric drive of the propeller. The duct can convert the trailing vortex of the blade into the attached vortex of the duct, which effectively plays a rectifying role and effectively increases the thrust. The magnetic coupler can effectively isolate the seawater and realize the static sealing of the underwater propeller.

The thrust of the underwater propeller determines the movement posture of the vehicles. Wanting to accurately control the attitude, it need to control the thrust, and the core power of the underwater propeller is the PMSM. Among the many dynamic motor parameters obtained, the speed is the easiest data to obtain and control. Therefore, it is only necessary to establish the relationship between the speed and thrust through experiments, and the thrust of the propeller can be controlled through precise control of the speed.

PMSM has been widely used in the industrial area. Most PMSMs used position sensors as a part of the control method to acquire rotor position and speed after the sensorless control method appeared. Although the sensor provided accurate information, it increased cost and had unreliability in degraded work environments. To enhance reliability and reduce cost, the position sensorless control method has been widely studied by global researchers and academics since the 1980s [6, 7]. Accurate information on rotor position and speed is essential to sensorless control. Therefore, many approaches to speed/position estimation have been investigated.

In general, these approaches can be classified into two main categories: Saliency-based sensorless control applied in the low-speed range and model-based sensorless control applied in the high-speed range [8]. The first approach can be implemented using high-frequency signal injection or fundamental pulse-width modulation (PWM) excitation (FPE)-based methods [9, 10, 11, 12, 13]. The latter one is always used for the surface PMSMs. Thanks to containing information of rotor position and speed in the EMF, its methods are based on the back electromotive force (EMF) or the flux linkage, including observer-based method, Artificial intelligence-based method, and

¹ School of Electrical Information, Jiangsu University of Science and Technology, Zhenjiang 212000, China
a) just_magicyw@163.com

DOI: 10.1587/exlex.18.20210111
Received March 5, 2021
Accepted April 1, 2021
Published May 17, 2021
Copyedited June 10, 2021

Copyright © 2021 The Institute of Electronics, Information and Communication Engineers
so on [14, 15, 16, 17, 18]. But the limit of hardware, observer-based sensorless control is widely applied in the product, such as Sliding mode observer, Luenberger observer, Kalman filter observer, etc [19, 20, 21, 22, 23].

The EMF can be estimated by the aforementioned methods. Hence, the rotor position and speed can be extracted from it with some methods. In [24], the rotor position is obtained by the arc-tangent function method directly. Although the method is simple to implement, the unreliability of position value will be raised when the variable value of arc-tangent is approaching zero. In order to improve the performance of the estimated position, a phase-locked loop (PLL) algorithm was proposed in [25], called traditional PLL in this paper. It improves the reliability, but only applying in a single rotated direction. Because, as the direction is reversed, traditional PLL will decline the accuracy of the estimated rotor position, resulting in a position error of 180°. In [26, 27], a reason was demonstrated that the sign of back EMF has effects the sign of the equivalent position error. And a new PLL was proposed to resolve the problem, based on the tangent function. So it is vulnerable to noises and harmonics.

![Fig. 2](image)

**Fig. 2** Structure of sensorless control for PMSM

To improve the estimated accuracy of position and speed information, Fig. 2 shows the sensorless control method. Speed controller and current controller are all designed as PI controllers. The back EMF is estimated through Luenberger observer, and it is made the input of improved PLL. Finally, information on rotor position and speed is obtained by the improved PLL.

2. **Mathematical model of the PMSM**

In the paper, surface PMSM is the subject. So, the model is taking the counterclockwise direction as the positive direction of the motor rotation, and established with the principle of the motor. Since the mathematical model of the PMSM in the three-phase frame is a multivariable, strongly coupled, and nonlinear system, it is difficult to control. Therefore, the mathematical model of PMSM in αβ stationary reference frame transformed it is expressed as [28]

\[
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix}
= \begin{bmatrix}
R_s & 0 \\
0 & R_s
\end{bmatrix}
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix}
+ \begin{bmatrix}
L_s & 0 \\
0 & L_s
\end{bmatrix}
\begin{bmatrix}
\alpha \\
\beta
\end{bmatrix}
+ \begin{bmatrix}
e_{\alpha} \\
e_{\beta}
\end{bmatrix}
\tag{1}
\]

where \(u_\alpha\) and \(u_\beta\) are the \(\alpha\) and \(\beta\) axis voltages, respectively; \(i_\alpha\) and \(i_\beta\) are the \(\alpha\) and \(\beta\) axis currents, respectively; \(R_s\) is the stator phase resistance; \(L_s\) is the stator phase inductance; \(e_{\alpha}\) and \(e_{\beta}\) are the \(\alpha\) and \(\beta\) axis back EMFs, satisfying

\[
e_{\alpha} = -\psi_T \omega_e \sin \theta_e, \quad e_{\beta} = \psi_T \omega_e \cos \theta_e
\tag{2}
\]

where \(\psi_T\) is PM flux linkage; \(\omega_e\) is electrical rotor speed; \(\theta_e\) is rotor position.

3. **Design of Luenberger observer**

Luenberger observers have shown superiority, both considering robustness and performance, in several comparative studies [29, 30]. The observer adds a correction to the model by its feedback of the measurable states to enhance the dynamic performance, primarily at low-range speed.

The establishment of the Luenberger observer generally adopts the progressive state observer with output error feedback, estimates the state variables according to the input and output signal of the system, finally reconstructing the observed system. The error between the observed state variables \(\hat{x}\) and the actual state variables \(x\) will be reflected in the error of the measured output \(y\) and the estimated output \(\hat{y}\), which will be fed back to the input of the observer through the error feedback matrix \(K\), and the observer state will be adjusted to make it approach the actual state of the system with a certain speed and accuracy.

To obtain the back EMFs, the mathematic model shown in Equations (1) and (2) is organized into the current model and \(e_\alpha, e_\beta\) are differentiated, so it is expressed in the matrix as

\[
\begin{bmatrix}
i_\alpha \\
i_\beta \\
\dot{e}_\alpha \\
\dot{e}_\beta
\end{bmatrix}
= \begin{bmatrix}
\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} & 0 \\
0 & -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} \\
0 & 0 & 0 & -\omega_e \\
0 & 0 & \omega_e & 0
\end{bmatrix}
\begin{bmatrix}
i_\alpha \\
i_\beta \\
e_\alpha \\
e_\beta
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_s} \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
u_\alpha \\
u_\beta
\end{bmatrix}
\tag{3}
\]

According to Fig. 1, the currents and back EMFs are taken as state variables, then Luenberger observer is represented as

\[
\begin{bmatrix}
\dot{i}_\alpha \\
\dot{i}_\beta \\
\dot{e}_\alpha \\
\dot{e}_\beta
\end{bmatrix}
= \begin{bmatrix}
-\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} & 0 \\
0 & -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} \\
0 & 0 & 0 & -\omega_e \\
0 & 0 & \omega_e & 0
\end{bmatrix}
\begin{bmatrix}
i_\alpha \\
i_\beta \\
e_\alpha \\
e_\beta
\end{bmatrix}
+ \begin{bmatrix}
\frac{1}{L_s} \\
0 \\
0 \\
0
\end{bmatrix}
\begin{bmatrix}
u_\alpha \\
u_\beta
\end{bmatrix}
+ K \begin{bmatrix}
i_\alpha - \hat{i}_\alpha \\
i_\beta - \hat{i}_\beta
\end{bmatrix}
\tag{4}
\]

where \(\hat{i}_\alpha\) and \(\hat{i}_\beta\) are the estimated currents in \(\alpha\beta\) stationary reference frame; \(\hat{e}_\alpha\) and \(\hat{e}_\beta\) are the estimated back EMFs in \(\alpha\beta\) stationary reference frame; \(K\) is the Luenberger observer gain matrix.

4. **Design of improved PLL**

Generally, the rotor position and speed can be acquired by the back EMFs estimated by the aforementioned Luenberger observer through the arc-tangent function (5) directly.
\[ \dot{\theta}_e = -\arctan\left(\frac{\dot{\theta}_e}{\dot{\theta}_e}\right), \quad \dot{\omega}_e = \frac{d\theta_e}{dt} \quad (5) \]

As function (5) shown, the estimated rotor position and speed are vulnerable to noise and harmonics. Particularly, \( \dot{\theta}_e \) is equal to zero, emerging an obvious error. So the phase-locked loop was proposed.

### 4.1 Analysis of traditional PLL

Ordinarily, PLL has three parts: Phase discriminator, oscillator, and loop filter. And in the structure of the traditional PLL shown in Fig. 3, the phase discriminator produces the phase error \( \Delta \theta \). The oscillator is an integrator that estimates the rotor position, followed by the computation of \( \sin(\varphi) \) or \( \cos(\varphi) \). The loop filter is a simple proportional-integral controller.

There is an assumption that the rotor is running in a positive direction. \( \dot{\varphi} \) and \( \dot{\varphi} \) are expressed in Equations (2). Then, the position error \( \Delta \varphi \) can be written as

\[ \Delta \varphi = \sin(\theta_e - \hat{\theta}_e) \approx \theta_e - \hat{\theta}_e \quad (6) \]

The transfer function of the traditional PLL can be represented as

\[ G(s) = \frac{K_P s + K_I}{s^2 + K_P s + K_I} \quad (7) \]

where \( K_P \) is the proportional gain, \( K_I \) is the integral gain.

Then, the dynamic equations of the traditional PLL can be represented as

\[ \frac{d\varphi}{dt} = \varphi, \quad \frac{d\varphi}{dt} = -K_P \cos(\varphi)\varphi - K_I \sin(\varphi) \quad (8) \]

where \( \varphi = \theta_e - \dot{\theta}_e, \varphi = \omega_e - \dot{\omega}_e. \)

In order to confirm the stabilities of the traditional PLL in the system, the Jacobian matrix for Equations (8) is represented as

\[ J(\varphi, \varphi) = \begin{bmatrix} 0 & 1 \\ K_P \sin(\varphi)\varphi - K_I \cos(\varphi) & -K_P \cos(\varphi) \end{bmatrix} \quad (9) \]

Supposed that \( K_I > 0, K_P > 0 \), the result of Equations (9) in \((\varphi, \varphi) = (0,0)\) is expressed as

\[ J(0,0) = \begin{bmatrix} 0 & 1 \\ -K_I & -K_P \end{bmatrix} \quad (10) \]

According to the Lyapunov stability criterion, the calculation of eigenvalues is \( \lambda_1 < 0, \lambda_2 < 0 \). So that point belongs to a stable point which means a convergent point. By the same logic, Substituting and \((\varphi, \varphi) = (\pm \pi, 0)\) into Equations (9) respectively, the expression is the same at two points.

\[ J(\pm \pi, 0) = \begin{bmatrix} 0 & 1 \\ K_I & K_P \end{bmatrix} \quad (11) \]

The calculation of eigenvalues is \( \lambda_1 > 0, \lambda_2 > 0 \). That means that two points belong to saddle points. Therefore, \( \varphi = e_\varphi \) and \( \varphi = e_\varphi \) are converged to \((0, 0)\) in a limited time, running in a positive direction.

However, if the direction was reversed to a negative direction, the situation would be changed. Firstly, the \( \dot{\varphi} \) and \( \dot{\varphi} \) are transformed into Equations (12).

\[ e_\varphi = \psi_F \varphi \sin \varphi, \quad e_\varphi = -\psi_F \varphi \cos \varphi \quad (12) \]

Meanwhile, the position error \( \Delta \varphi \) is turned as

\[ \Delta \varphi = \sin(\hat{\varphi}_e - \varphi_e) = -(\theta_e - \hat{\theta}_e) \quad (13) \]

By the same thing, the dynamic equations of the traditional PLL in the negative direction can be represented as

\[ \frac{d\varphi}{dt} = \varphi, \quad \frac{d\varphi}{dt} = K_P \cos(\varphi)\varphi + K_I \sin(\varphi) \quad (14) \]

Continuing to analyze the stabilities, the Jacobian matrix for Equations (14) is represented as

\[ J(\varphi, \varphi) = \begin{bmatrix} 0 & 1 \\ -K_P \sin(\varphi)\varphi + K_I \cos(\varphi) & K_P \cos(\varphi) \end{bmatrix} \quad (15) \]

Similarly supposed that \( K_I > 0, K_P > 0 \), the result of Equations (15) in \((\varphi, \varphi) = (0,0)\) is expressed as

\[ J(0,0) = \begin{bmatrix} 0 & 1 \\ K_I & K_P \end{bmatrix} \quad (16) \]

According to the Lyapunov stability criterion, the calculation of eigenvalues is \( \lambda_1 > 0, \lambda_2 > 0 \). In other words, \((\varphi, \varphi) = (0,0)\) changes into a saddle point from a stable point. On the contrary, \((\varphi, \varphi) = (\pm \pi, 0)\) the two points become stable points.

The aforementioned analysis explains that the system produces a position estimation error of 180° since the \( K_P \) and \( K_I \) parameters of PLL are set for one direction of rotation, which the estimation of the rotor position is correct for this direction only. Although this problem can be solved by resetting the gains of the PI controller, it is difficult to implement in the real-time control system. Therefore, the traditional PLL cannot apply in the requirements where the motor needs to switch the direction of rotation.

### 4.2 Analysis of improved PLL

To resolve the issue that traditional PLL brings. In this paper, the improved PLL is designed. Fig. 4 shows the structure of the improved PLL.

Comparing to the structure of the traditional PLL, the phase discriminator is mainly altered.
In this structure, the position error $\Delta \theta$ can be written as

$$\Delta \theta = \frac{1}{2} \sin(2(\theta - \hat{\theta}))$$

(17)

Whatever the rotor direction is, the dynamic equations of the improved PLL are represented as

$$\frac{de_\theta}{dt} = e_\omega, \quad \frac{de_\omega}{dt} = \frac{1}{2} [-K_P \cos(2e_\theta)2e_\omega - K_I \sin(2e_\theta)]$$

(18)

Similarly, the Jacobian matrix for Equations (18) is represented as

$$J(e_\theta, e_\omega) = \begin{bmatrix} 0 & 1 \\ 2K_P \sin(2e_\theta) e_\omega - K_I \cos(2e_\theta) & -K_P \cos(2e_\theta) \end{bmatrix}$$

(19)

Suppose that $K_I > 0, K_P > 0$, the results of Equations (19) in $(e_\theta, e_\omega) = (0, 0)$ and $(e_\theta, e_\omega) = (\pm \pi, 0)$ are expressed as

$$J(0, 0), (\pm \pi, 0) = \begin{bmatrix} 0 & 1 \\ K_I & K_P \end{bmatrix}$$

(20)

The calculation of eigenvalues is expressed as

$$\lambda_1 = \frac{-K_P + \sqrt{K_P^2 - 4K_I}}{2}, \quad \lambda_2 = \frac{-K_P - \sqrt{K_P^2 - 4K_I}}{2}$$

(21)

According to (21) and the assumption, $\lambda_1 < 0, \lambda_2 < 0$ can be obtained. So, three points all belong to stable points. By selecting the appropriate gains of the PI controller, $e_\theta$ and $e_\omega$ will converge to the origin. That means the motor can switch the rotor direction steadily by adopting the improved PLL.

5. Results of simulation and experiments

The proposed design method for a controller is tested in simulation. The PMSM parameters include the output power 1500W, the input voltage 48V, pole pairs 5, rated speed 1500/(r/min), max speed 1800/(r/min), stator phase resistance 0.9585Ω, stator phase inductance 5.25mH, permanent magnet flux linkage 0.1827Wb, and moment of inertia 0.0063 kg · m².

The key technical parameters of underwater propeller include the torque 6.5/N · m, the weight 10/kg, the max thrust 350/N, the rated voltage 48/V, the rated speed 1500/(r/min), the max speed 1800/(r/min).

5.1 Analysis of simulation results

Under the simulated condition that load torque equal to 5N · m, the given speed is 1500/r/min when the PMSM starts. In the time $t = 0.15s$, the given speed is altered to $-1500/r/min$.

Fig. 5 shows responses that the traditional PLL used in PMSM. During a time of $0 \sim 0.15s$, the rotor direction is positive, and the PMSM was worked normally with the normal dates. However, in the time $t = 0.15s$, the direction was reversed. The PMSM did not work after the speed passed zero points.

Indeed, Fig. 6 shows the estimated speed of PMSM passed zero points in the time $t = 0.184s$, and in the time, the back EMFs were normally estimated. But, in the time $t = 0.188s$, the rotor position was wrongly estimated. The estimated back EMFs came after it happened in the time $t = 0.19s$. Finally, it results in the motors did not work.

Fig. 7 shows responses that the improved PLL used in PMSM. Comparing to the traditional one, it normally worked all-time in similar conditions. It still worked even the direction changed and the zero points passed. According to the data, the errors of rotor position have 10 deg values, and the errors of speed has a maximum of 100r/min values in a short time, which is ensuring normally work for PMSM.

5.2 Analysis of experiment results

In order to verify the effectiveness of the proposed method,
a hardware platform is built for experimental verification as shown in Fig. 8. The experimental subject is the PMSM with following parameters equal to parameters of simulation.

The experiment results are shown in Fig. 9 and Fig. 10. The Fig. 9(a) and Fig. 9(b) show the actual rotor position and estimated rotor position with the improved PLL at given 1500r/min in two direction. It can estimate the rotor position with improved PLL when the direction was reversed. And PMSM did not work in the negative direction with the traditional PLL.

The Fig. 10(a) and Fig. 10(b) show reference rotor speed and estimated rotor speed with the improved PLL at given 1500r/min in two direction. Meanwhile, the actual speed is singly obtained to the measurement instrument. The Fig. 10(c) and Fig. 10(d) show the errors of speed. The errors is limited with ±50 r/min in all directions. So, the improved PLL proposed in Luenberger observer has a good performance in the experiment.

The above results verified the effectiveness, and then the thrust of underwater propeller experiments was conducted to obtain the relationship of speed and thrust. The underwater thrust experiment of the propeller was carried out in the pool. The underwater propeller was installed on a special experimental device. The thrust output of the propeller was increased by continuously increasing the speed, and the thrust force was measured by a dynamometer. The curves of the thrust and torque of the underwater propeller with the rotation speed are drawn from the data in the table as shown in Fig. 11. It can be seen from the figure that the designed underwater thruster control system can make the thrust of the thruster reach the technical requirements of 343N. The characteristics of the forward and reverse rotation of the motor make a slight difference in the thrust and torque of the forward and reverse rotation, and the characteristics of the forward and reverse rotation are also different.

6. Conclusion

To solve the problem of errors that the traditional PLL can estimate the rotor position for this direction only, since the parameters of it are set for one direction of rotation. An improved PLL is proposed, and its combined Luenberger observer applies in sensorless control for PMSM in underwater propeller. Indeed, the issue is settled by the improved PLL, mainly owed to the structure of the phase discriminator. The position error is changed.

According to the results of the simulation and experiments, the main findings are as followed. The proposed method can estimate the rotor position without affected by the reversed direction of rotation. Additionally, the errors of position have an effective convergence in a limited time. And the propeller has a good performance on thrust to fulfill requirements of vehicles. Nevertheless, the method lacks experimental results. The parameters of PMSM may be varied in the actual running, such as stator phase resistance raised by rising temperature. In this condition, the effectiveness of the improved PLL should be tested and verified.

Acknowledgments

The work was financially supported by the National Natural Science Foundation of China (11574120).

References

[1] G. Liu, et al.: “Study on counter-rotating dual-rotor permanent magnet motor for underwater vehicle propulsion,” IEEE Trans. Appl. Supercond. 28 (2018) 1-5 (DOI: 10.1109/TASC.2018.2802482).
[2] F. Giulii Capponi: “Recent advances in axial-flux permanent-magnet machine technology,” IEEE Trans. Ind. Appl. 48 (2012) 2190 (DOI: 10.1109/TIA.2012.2226854).
[3] P. Jin, et al.: “3-D analytical magnetic field analysis of axial flux permanent-magnet machine,” IEEE Trans. Magn. 50 (2014) 1 (DOI: 10.1109/TMAG.2014.2323573).
[4] T.D. Batzel and K.Y. Lee: “Electric propulsion with sensorless permanent magnet synchronous motor: implementation and performance,” IEEE Trans. Energy Convers. 20 (2005) 575 (DOI: 10.1109/TEC.2005.852956).
[5] C.M. Orndorff and C.J. Egan: “Electric propulsion: fleet readiness at affordable costs,” IEEE AEROSPACE AND ELECTRONICS SYSTEMS MAGAZINE 11 (1996) 27 (DOI: 10.1109/62.494185).
[6] D. Liang, et al.: “Adaptive second-order sliding-mode observer for PMFS sensorless control considering VSI nonlinearity,” IEEE Transactions on Power Electronics. 33 (2018) 8994 (DOI: 10.1109/TPEL.2017.2839290).
[7] M.-H. Park and H.-H. Lee: “Sensorless vector control of permanent magnet synchronous motor using adaptive identification,” 15th Annual Conference of IEEE Industrial Electronics Society 1 (1989) 209 (DOI: 10.1109/IECON.1989.69636).
[8] G. Wang, et al.: “Position sensorless permanent magnet synchronous machine drives—a review,” IEEE Transactions on Industrial Electronics. 67 (2020) 5830 (DOI: 10.1109/TIE.2019.2955409).
[9] X. Zhang, et al.: “Improved initial rotor position estimation for PMSM drives based on HF pulsating voltage signal injection,” IEEE Transactions on Industrial Electronics 65 (2018) 4702 (DOI: 10.1109/TIE.2017.2772204).
[10] G. Zhang, et al.: “Pseudorandom-frequency sinusoidal injection based sensorless IPMSM drives with tolerance for system delays,” IEEE Transactions on Power Electronics. 34 (2019) 3623 (DOI: 10.1109/TPEL.2018.2865802).
[11] G. Wang, et al.: “Sensorless control of IPMSM drives using a pseudo-random phase-switching fixed-frequency signal injection scheme,” IEEE Transactions on Industrial Electronics. 65 (2018) 7660 (DOI: 10.1109/TIE.2018.2798590).
[12] G. Wang, et al.: “Sensorless control scheme of IPMSMs using HF orthogonal square-wave voltage injection into a stationary reference frame,” IEEE Transactions on Power Electronics. 34 (2019) 2573 (DOI: 10.1109/TPEL.2018.2844347).
[13] C. Li, et al.: “Saliency-based sensorless control for SynRM drives with suppression of position estimation error,” IEEE Transactions on Industrial Electronics. 66 (2019) 5839 (DOI: 10.1109/TIE.2018.2874585).
[14] A. Andersson and T. Thiringer: “Motion sensorless IPMSM control using linear moving horizon estimation with Luengerberger observer state feedback,” IEEE Transactions on Industrial Electronics. 4 (2018) 464 (DOI: 10.1109/TIE.2018.2790709).
[15] M. Hassani and A. Shoulouie: “Sensorless load and position estimation in linear reluctance actuators,” IEEE/IEICE Electronics Express 11 (2014) 2030908 (DOI: 10.1587/elex.10.20130908).
[16] Y. Lee and S. Sul: “Model-based sensorless control of an IPMSM with enhanced robustness against load disturbances based on position and speed estimator using a speed error,” IEEE Transactions on Industry Applications. 54 (2018) 1448 (DOI: 10.1109/TIA.2017.2777390).
[17] R. Antonello, et al.: “Enhanced low-speed operations for sensorless anisotropic PM synchronous motor drives by a modified back-EMF observer,” IEEE Transactions on Industrial Electronics. 65 (2017) 3069 (DOI: 10.1109/TIE.2017.2748042).
[18] S. Bolognani, et al.: “Model sensitivity of fundamental-frequency-based position estimators for sensorless pm and reluctance synchronous motor drives,” IEEE Transactions on Industrial Electronics. 65 (2018) 77 (DOI: 10.1109/TIE.2017.2716902).
[19] D. Liang, et al.: “Sensorless control of permanent magnet synchronous machine based on second-order sliding-mode observer with online resistance estimation,” IEEE Transactions on Industry Applications. 53 (2017) 3672 (DOI: 10.1109/TIA.2017.2690218).
[20] Z. Chen, et al.: “New adaptive sliding observers for position- and velocity-sensorless controls of brushless DC motors,” IEEE Transactions on Industry Applications. 47 (2001) 582 (DOI: 10.1109/41.847899).
[21] Z. Xu and M.F. Rahman: “An adaptive sliding stator flux observer for a direct torque controlled IPM motor drive,” IEEE International Conference on Electric Machines and Drives (2005) 704 (DOI: 10.1109/IEMDC.2005.195800).
[22] S. Bolognani, et al.: “Extended Kalman filter tuning in sensorless PMSM drives,” IEEE Transactions on Industry Applications. 39 (2003) 1741 (DOI: 10.1109/TIA.2003.818991).
[23] Y. Liu, et al.: “Instantaneous torque estimation in sensorless direct torque controlled brushless DC motors,” Fourth IAS Annual Meeting Conference Record of the 2005 Industry Applications Conference 2005 3 (2005) 2140 (DOI: 10.1109/IAS.2005.1518743).
[24] J. Lee, et al.: “Sensorless control of surface-mount permanent-magnet synchronous motors based on a nonlinear observer,” IEEE Transactions on Power Electronics. 25 (2010) 290 (DOI: 10.1109/TPEL.2009.2025276).
[25] G. Wang, et al.: “Quadrature PLL-based high-order sliding-mode observer for IPMFS sensorless control with online MTPA control strategy,” IEEE Transactions on Energy Conversion. 28 (2013) 214 (DOI: 10.1109/TIE.2012.2228484).
[26] C. Olivieri, et al.: “A full-sensorless permanent magnet synchronous motor drive with an enhanced phase-locked loop scheme,” 2012 International Conference on Electrical Machines (2012) 2202 (DOI: 10.1109/IECom.2012.6350188).
[27] C. Olivieri and M. Tursini: “A novel PLL scheme for a sensorless PMSM drive overcoming common speed reversal problems,” International Symposium on Power Electronics Power Electronics, Electrical Drives, Automation and Motion (2012) 1051 (DOI: 10.1109/SPEEDAM.2012.6264468).
[28] W. Kang and H. Li: “Improved sliding mode observer based sensorless control for PMSM,” IEICE Electronics Express. 14 (2017) 20170934 (DOI: 10.1587/elex.14.20170934).
[29] C. Afri, et al.: “State and parameter estimation: a nonlinear Luengerberger observer approach,” IEEE Transactions on Automatic Control. 62 (2017) 973 (DOI: 10.1109/TAC.2016.2566804).
[30] A. Andersson and T. Thiringer: “Motion sensorless IPMSM control using linear moving horizon estimation with Luengerberger observer state feedback,” IEEE Transactions on Industrial Electronics. 4 (2018) 464 (DOI: 10.1109/TIE.2018.2790709).