A Technology for Online Parameter Identification of Permanent Magnet Synchronous Motor

XiaoJun MA, Chao BI, *Senior Member, IEEE*

***Abstract*—Accuracy of the motor parameters is important in realizing high performance control of permanent magnet synchronous motor (PMSM). However, the inductance and resistance of motor winding vary with the change of temperature, rotor position and current frequency. In this paper, a technology based on circuit model is introduced for realizing online identification of the parameter of PMSM. In the proposed method, a set of nonlinear equations containing the parameters to be identified is established. Considering that it is very difficult to obtain the analytical solution of a nonlinear system of equations, Newton iterative method is used for solving the equations. Both the simulation and testing results confirm the effectiveness of the method presented.**

***Index Terms*—Online, PMSM, parameter identification, parameter measurement, electric machine theory**.

I. INTRODUCTION

PERMAGNET synchronous motor (PMSM) has been widely used in various fields because of its high torque density, simple structure and high efficiency [1]-[2]. The research on the parameter identification algorithms for PMSM has been motivated by improving the efficiency and reliability of control system. It is well known, the motor parameters are important factors affecting the performance of motor control. However, these parameters may vary with the change of rotor position and environment. For example, the winding inductance, L, may vary with the rotor position; the resistance of motor windings, R, varies with the change of temperature. PMSM is a high-order, strong coupling, nonlinear system with complex mathematical model and many control strategies depend on the precise parameters of the motor. For instance, Field oriented control (FOC) depends on the establishment of mathematical model of motor, which needs the establishment of stator resistance, motor flux and d-q axis inductance; direct torque control (DTC) requires motor flux to estimate the torque, etc. The mismatch between the control parameters and the actual parameters during the motor operation can affect the closed-loop characteristics of the regulator, resulting in the motor operation instability and performance degradation. Therefore, knowing precisely the parameters is very important in the high performance control of PMSM.

In recent years, different algorithms have been developed for the parameter identification and measurement, such as Extended Kalman filter (EKF) based identification approach, model reference adaptive system(MRAS) based approach, recursive least square method and artificial intelligence(AI) algorithm [3]. In applying the measurement approach based on Extended Kalman filter, Taylor series is used to linearize the nonlinear model of the motor, and state equations are used to describe the relationship between input and output. This approach needs complex matrix and vector operations, and it is difficult to design the algorithm for multi parameter measurement. [4] The basic idea of MRAS is to take the motor body as the reference model and the equations containing the parameters to be identified as the adjustable model. Under the same excitation input, the two models have the same physical output. Combining the output error between the two models and the adaptive law designed based on Lyapunov theory or Popov theory, the parameters are identified when the error tends to zero. The structure of the algorithm is simple, and the result is easy to converge, but it is difficult to be used in multi parameter identification/measurement of missing rank [5]-[7]. In recent years, AI algorithms are increasingly used in the parameter measurement, but the huge amount of calculation required by the complicated algorithm limits its application [8]-[9].

This paper presents an algorithm from PMSM circuit model for realizing the online measurement of stator inductance L, stator resistance R and inner power angle δ between the phase voltage U and phase back-emf. The algorithm focuses on the real-time detection of the parameters in the process of motor operation. The voltage equation and power equation containing the parameters to be identified are thus established based on PMSM theory. In the equations, as the 3-phase current and voltage are symmetrically sinusoidal, the amplitude of U and I can be obtained from the analysis of real-time values of the voltage and current. Besides, as it is difficult to get the numerical solution of nonlinear equations, Newton iterative method is used to obtain the numerical solution of the equations quickly. The identified parameters can thus be obtained from the solution, and then used in the motor control. These “real-time” parameters can reduce the control error induced by the variation of the parameters significantly. Both the simulation and testing results show the effectiveness of the mentioned method.

II. PMSM MODELING AND PARAMETER MEASUREMENT METHOD

A. Equivalent model of PMSM

In the analysis, the voltage, current and back EMF are assumed to be sinusoidal. The equivalent circuit diagram of PMSM is shown in Fig. 1.

Manuscript was submitted for review on 11, May, 2020;

The authors are with Machinery institute, University of Shanghai for Science and Technology, ShangHai, 200000, China. (e-mails:1160934915@qq.com; bichao@usst.edu.cn)

Digital Object Identifier 10.30941/CESTEMS.2020.00029

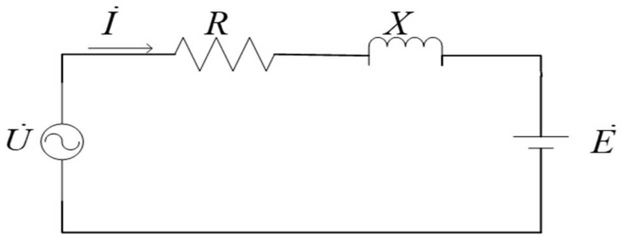

Fig. 1 The equivalent circuit diagram of PMSM

where, $\dot{U}$, $\dot{I}$, $\dot{E}$ are the phase voltage vector, phase current vector, phase back-emf respectively and R, X =2πωL are the resistance and impedance of the winding.

According to the equivalent circuit diagram, the phase voltage of PMSM can be expressed as follows:

$$\dot{U}=\dot{I}(\mathrm{R}+jX)+\dot{E} \tag{1}$$

The voltage equation at d-q axis is:

$$\dot{U}=\dot{E}+\dot{I}R+j\dot{I}_dX_d+j\dot{I}_qX_q\ . \tag{2}$$

According to the voltage equation at d-q axis, phasor diagram of PMSM can be built in Fig. 2.

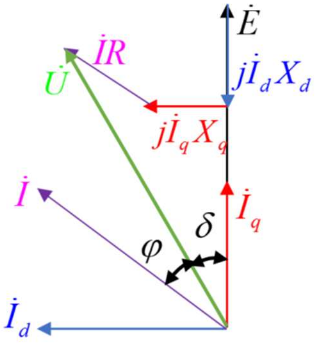

Fig. 2 The phasor diagram of PMSM

In Fig. 2, φ is the power factor angle between the voltage U and current I; and δ is the inner power angle between U and back-emf E.

B. Measurement of stator inductance, stator resistance and inner power angle δ

According to the phasor diagram, the voltage equation at d-axis and q-axis can be expressed as:

$$\begin{cases} U_d=U\sin\delta=I_dR+X_qI_q \\ U_q=U\cos\delta=I_qR-X_dI_d+E \end{cases} \tag{3}$$

And the current equation at d-axis and q-axis are:

$$\begin{cases} I_d=\dfrac{RU\sin\delta+X_q(E-U\cos\delta)}{R^2+X_dX_q} \\ I_q=\dfrac{X_dU\sin\delta-R(E-U\cos\delta)}{R^2+X_dX_q} \end{cases} \tag{4}$$

For the surface mounted PMSM $L_d=L_q$, using U as the reference, the voltage equation can be expressed as:

$$\begin{aligned} \dot{\mathrm{U}} &= \dot{I}(R+jX)+\dot{E} \\ &=\mathrm{I}[\mathrm{Cos}(\varphi)+j\,\mathrm{Sin}(\varphi)][R+jX]+E[\mathrm{Cos}(\delta)+j\,\mathrm{Sin}(-\delta)] \\ &=\mathrm{I}\cdot[\mathrm{R}\,\mathrm{Cos}(\varphi)-X\,\mathrm{Sin}(\varphi)]+E\,\mathrm{Cos}(\delta) \\ &\quad+\mathrm{j}\{I[R\cdot\mathrm{Sin}(\varphi)+X\,\mathrm{Cos}(\varphi)]-E\,\mathrm{Sin}(\delta)\} \end{aligned} \ . \tag{5}$$

Two equations related to the real part and imaginary part of the voltage can be established as follows:

$$\begin{cases} \mathrm{I}\cdot[\mathrm{R}\,\mathrm{Cos}(\varphi)+X\,\mathrm{Sin}(\varphi)]+E\,\mathrm{Cos}(\delta) &=\mathrm{U} \\ I\cdot[R\cdot\mathrm{Sin}(\varphi)\text{-}X\,\mathrm{Cos}(\varphi)]+E\,\mathrm{Sin}(\delta) &=0 \end{cases} \tag{6}$$

As three equations are necessary to solve these 3 unknowns, an equation related to power angle can be established and used. The active power absorbed by PMSM from power grid is $P=mUI\cos\varphi$. Part of the active power is the copper loss produced by the stator winding, and the rest is the electromagnetic power P_e including iron loss and mechanical loss. According to the phasor diagram, the active power can be expressed as:

$$P=mUI\cos\varphi=m(UI_d\sin\delta+UI_q\cos\delta)\ . \tag{7}$$

Combining (4), the active power can be expressed as:

$$\begin{aligned} P&=m(UI_d\sin\delta+UI_q\cos\delta) \\ &=m\frac{E\left(\text{-}E\cdot R+U\left(R\cos[\delta]+x\sin[\delta]\right)\right)}{R^2+X^2}+mI^2R \end{aligned} \ . \tag{8}$$

Equation (6) and (8) constitute a nonlinear simultaneous equations with three parameters to be identified. The voltage U, current I, power factor angle φ and back EMF E can be known from the real-time value of the current and voltage. By solving the equations, R, L and δ can be obtained, and then used in the motor control.

III. ALGORITHM FOR SOLVING EQUATIONS WITH PARAMETERS TO BE IDENTIFIED

A. Calculation of voltage, current and power factor angle

In the operation of the motor, it is not difficult to get the real-time value of the 3-phase voltage and the 3-phase current. The 3-phase current and voltage of PMSM are sine waves with phase difference of 120 °, which can be expressed as follows:

$$\begin{cases} u_a=U\sin(\beta) \\ u_b=U\sin(\beta-\frac{2}{3}\pi) \\ u_c=U\sin(\beta+\frac{2}{3}\pi) \end{cases} . \tag{9}$$

$$\begin{cases} i_a=I\sin(\alpha) \\ i_b=I\sin(a-\frac{2}{3}\pi) \\ i_c=I\sin(a+\frac{2}{3}\pi) \end{cases} . \tag{10}$$

The following results can thus be obtained from these instantaneous values:

$$U=\sqrt{\frac{2}{3}(u_a^2+u_b^2+u_c^2)}\ , \tag{11}$$

$$I=\sqrt{\frac{2}{3}(i_a^2+i_b^2+i_c^2)}\ . \tag{12}$$

Suppose the sum of the product of three-phase in-phase current and three-phase in-phase voltage is SM :

$$SM=u_ai_a+u_bi_b+u_ci_c=\frac{3}{2}UI\cos\varphi\ , \tag{13}$$

The sum of the products of current and voltage of different phases is:

$$DF1=u_bi_a+u_ci_b+u_ai_c=\frac{3}{4}UI(\sqrt{3}\,\mathrm{Sin}\,\varphi-\mathrm{Cos}\,\varphi)\ , \tag{14}$$

$$DF2=u_ci_a+u_ai_b+u_bi_c=-\frac{3}{4}UI(\mathrm{Cos}\,\varphi+\sqrt{3}\,\mathrm{Sin}\,\varphi) \tag{15}$$

Define

$$\begin{aligned}K1&=\frac{DF1}{SM}=\frac{1}{2}(\sqrt{3}\tan\varphi-1)\\ K2&=\frac{DF2}{SM}=\frac{1}{2}(-\sqrt{3}\tan\varphi-1)\end{aligned} \tag{16}$$

$$\begin{aligned}\tan\varphi_1&=(1+2K1)/\sqrt{3}\\ \tan\varphi_2&=-(1+2K2)/\sqrt{3}\end{aligned} \tag{17}$$

Then $\tan\varphi$ can be expressed as follows:

$$\tan\varphi=\frac{\tan\varphi_1+\tan\varphi_2}{2}=\frac{i_c(u_a-u_b)+i_a(u_b-u_c)+i_b(u_c-u_a)}{\sqrt{3}(i_au_a+i_bu_b+i_cu_c)} \tag{18}$$

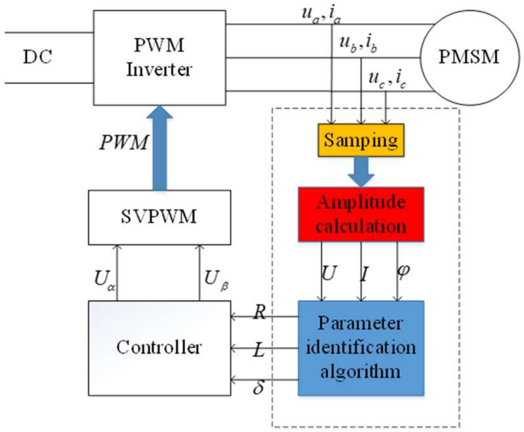

Fig. 3 The parameter measurement control system

In this way, the parameter measurement control system can be built as shown in Fig. 3.

B. Method for solving the nonlinear equations

It is very difficult to obtain an analytical solution of the third order nonlinear equations. In authors' research, Newton iterative method is used to solve the equations. The basic idea of Newton iterative method is to linearize the nonlinear equation, and then use the results of the linear equations in the next iterative step. The equations can be described as follows:

$$f=\begin{bmatrix}f_1(R,L,\delta)\\ f_2(R,L,\delta)\\ f_3(R,L,\delta)\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix}\ . \tag{19}$$

Suppose $x=[R,L,\delta]$ is the solution vector of the equations, applying Taylor expansion of f at $x_0=[R_0,L_0,\delta_0]$, and taking its linear term, the following equations can be obtained:

$$f=\begin{bmatrix}f_1(R_0,L_0,\delta_0)\\ f_2(R_0,L_0,\delta_0)\\ f_3(R_0,L_0,\delta_0)\end{bmatrix}+f'(x_{(0)})\begin{bmatrix}R_1-R_0\\ L_1-L_0\\ \delta_1-\delta_0\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix} \tag{20}$$

where,

$$f'(x_0)=\begin{bmatrix}\frac{\partial f_1}{\partial R} & \frac{\partial f_1}{\partial L} & \frac{\partial f_1}{\partial \delta}\\ \frac{\partial f_2}{\partial R} & \frac{\partial f_2}{\partial L} & \frac{\partial f_2}{\partial \delta}\\ \frac{\partial f_3}{\partial R} & \frac{\partial f_3}{\partial L} & \frac{\partial f_3}{\partial \delta}\end{bmatrix}\ . \tag{21}$$

Newton's iteration formula is:

$$\begin{bmatrix}R_{k+1}\\ L_{k+1}\\ \delta_{k+1}\end{bmatrix}=\begin{bmatrix}R_k\\ L_k\\ \delta_k\end{bmatrix}-\left[f'(x_k)\right]^{-1}\bullet\begin{bmatrix}f_1(R_k,L_k,\delta_k)\\ f_2(R_k,L_k,\delta_k)\\ f_3(R_k,L_k,\delta_k)\end{bmatrix} \tag{22}$$

When $k=0$, $x_0=[R_0,L_0,\delta_0]$ is the initial value given. An error $\Delta=x_{k+1}-x_k$ is set to decide when to stop iteration. If the set error is small enough, the approximate solution x_k can be regarded as the solution of equations. Newton iterative method has fast convergence speed, and when the given initial value is close to the actual value, only a very few iterations are needed to obtain the solution.

IV. SIMULATION AND TESTING RESULTS

Both simulation and testing are used for verifying the effectiveness of the algorithms introduced in the section- III. The parameters of the PMSM in simulation are shown in TABLE I.

TABLE I

Stator resistance	2.875Ω
Stator inductance	8.5mH
Rotor flux	0.3Wb
Pole pares	4

In simulation, the setting frequency is 50Hz. Three-phase current is shown in Fig. 4.

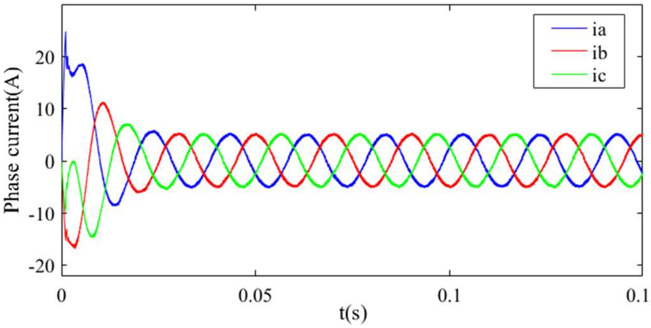

Fig. 4 3-phase current

The amplitude of phase current can be calculated according to equation 12. In order to verify the effectiveness of the algorithm in obtaining the amplitude of phase current, phase voltage and power factor angle, another approach related to Fourier series is used for comparison. The results of two different methods for calculating the current amplitude are shown in Fig. 5.

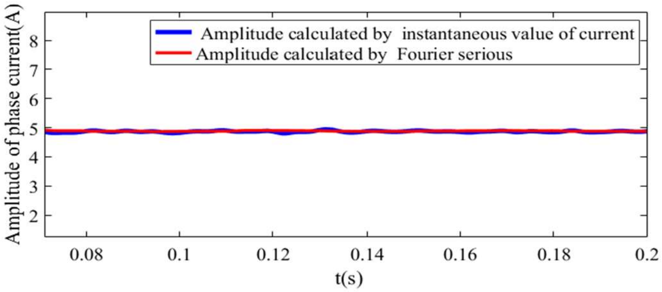

Fig. 5 Amplitude of phase current

Fig. 5 shows that, it is effective to obtain the amplitude of current through the instantaneous value of the 3-phase current. The voltage amplitude and power factor angle obtained by formula 13 and formula 20 are shown in the figure below:

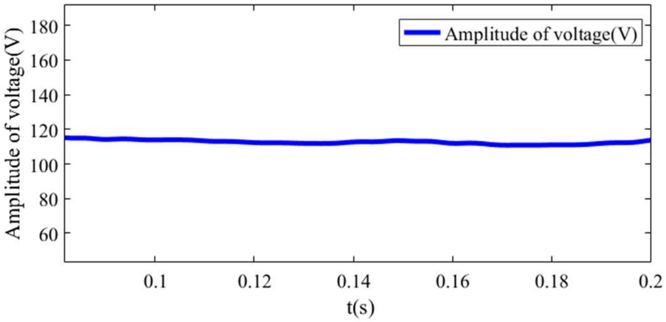

Fig. 6 Amplitude of phase voltage

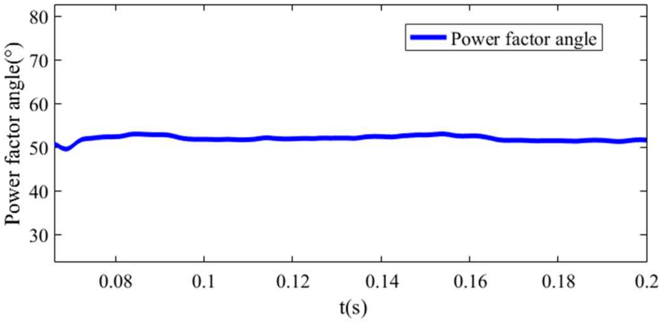

Fig. 7 Power factor angle

Fig. 8 to Fig. 10 show the identified amplitude of phase current, phase voltage and inner power angle.

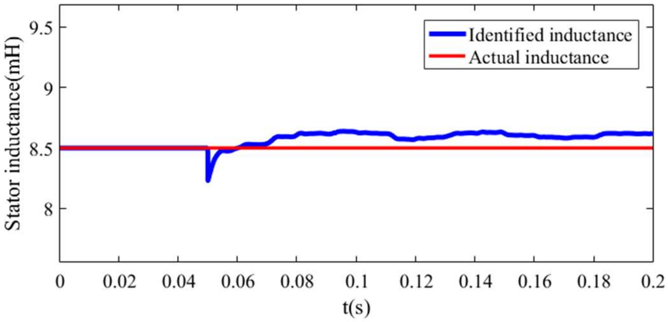

Fig. 8 Identified and actual value of stator inductance

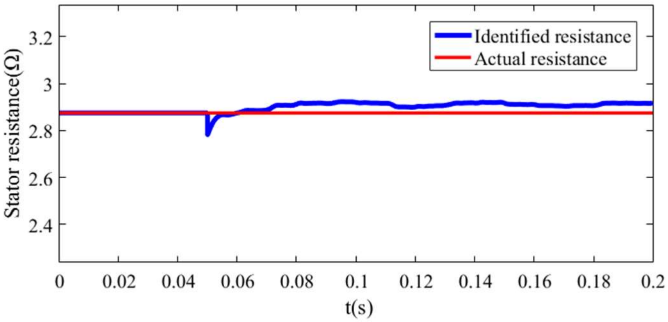

Fig. 9 Identified and actual value of stator resistance

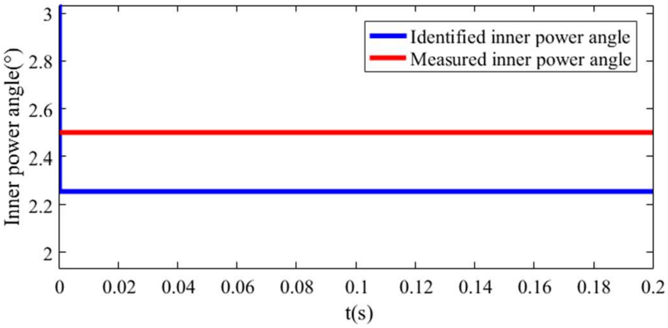

Fig. 10 Identified and actual value of inner power angle

According to the simulation results, the maximal error between the measurement value and actual value is less than 2%. The average error of inductance is 1.63%, the average error of resistance is 1.55%, and the error of inner power angle is 0.3°. All these show that the proposed technology is good in accuracy in the online measurement of the parameters of PMSM.

The testing experiment built is shown in Fig. 11. The motor is a 200W PMSM with surface mounted magnet on its rotor. In the test, the amplitude of the driving current is 0.65A.

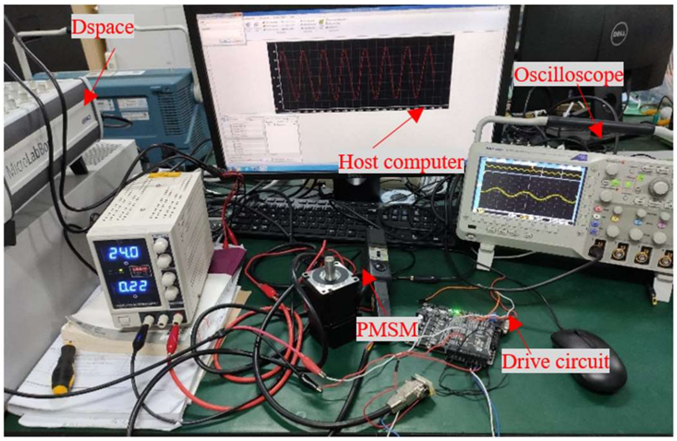

Fig. 11 Test bench used for online parameter identification

In the experiment, the identified parameter value of an electric period is taken and compare with the value measured by LCR. The test bench used for measuring with LCR is shown in Fig. 12.

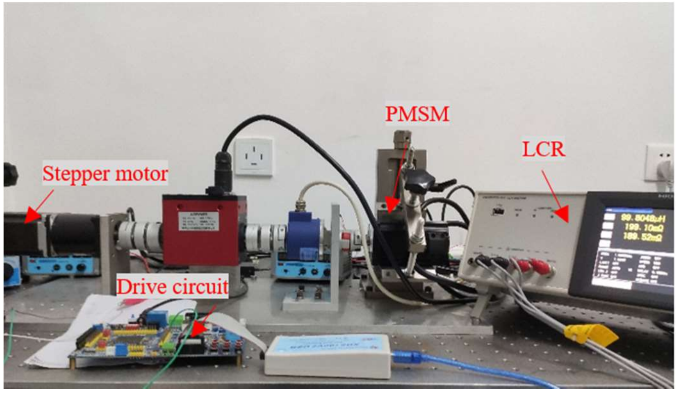

Fig. 12 Test bench used for offline parameter measurement with LCR

In the online measurement, the phase current and line-to-line voltage are shown as follows:

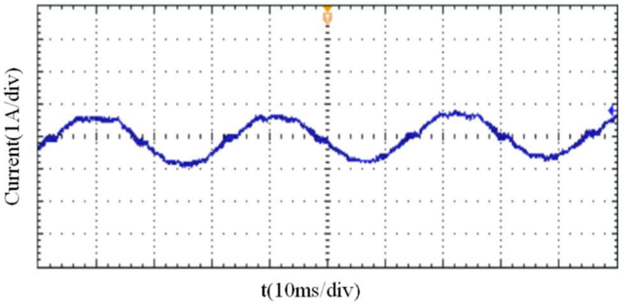

Fig. 13 Phase current

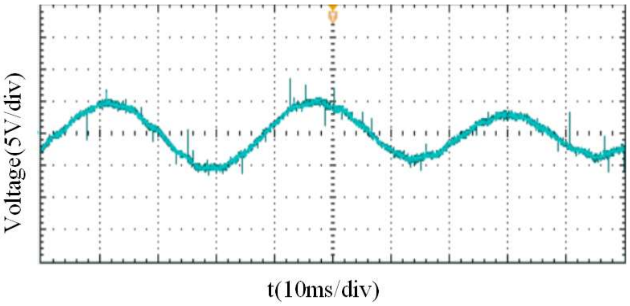

Fig. 14 Line-to-line voltage

The online identification results are shown as follows:

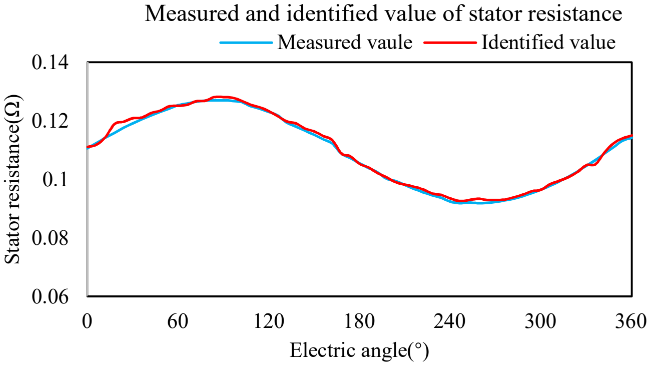

Fig. 15 Measured and identified value of stator resistance

According to Fig. 16 and Fig. 18, the average error of resistance is less than 2% and the average error of resistance is less than 1%.

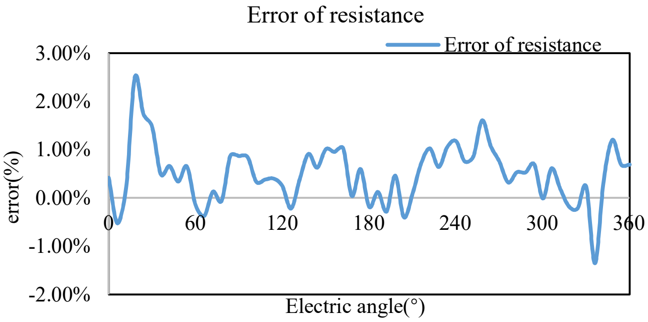

Fig. 16 Error of resistance.

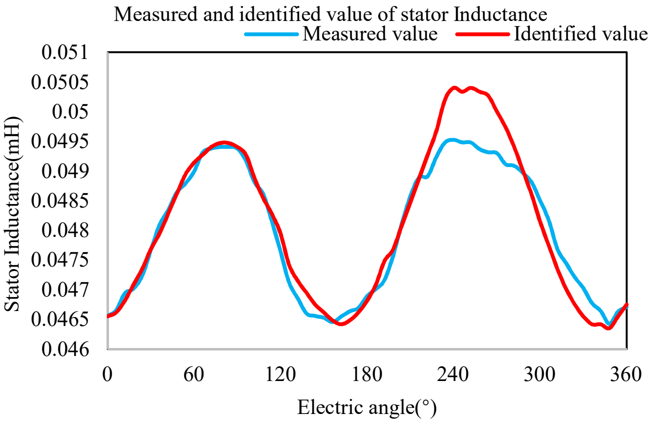

Fig. 17 Measured and identified value of stator Inductance

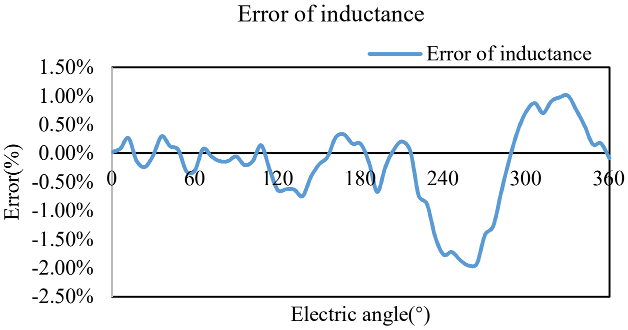

Fig. 18 Error of inductance

V. CONCLUSION

Knowing the accurate values of the motor parameters is important in PMSM control and applications. However, these parameters vary and change with many factors and are difficult to be measured accurately, not to mention the online measurement. The technology proposed in the paper can simplify significantly the procedure of the online measurement, and the accuracy of the results are good. In the measuring, only the real-time values of the current and voltage are required, and all these are not affect the other operations of the motor controller, and this is important to realize high performance control in many applications. This paper uses the model of PMSM to construct a nonlinear system of equations with parameters to be identified. Using numerical method to solve the equations, the parameters can be obtained effectively. Bothe the simulation and testing results confirm the effectiveness of the measurement method presented.

REFERENCES

[1] Honghao Guo, Bo Zhou, "Torque Estimation and Adaptive Inductance Identification for a Brushless DC Motor", *Proceedings of the CSEE*, vol. 31, pp. 151-158, 2011.

[2] Wenjing Fang, Zhonghua Wang, "Online identification of flux linkage of PMSM with unbalanced stator resistance", in *Proc. 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference*, 2018, pp. 820-823.

[3] Xinyue Li, Ralph Kennel, "Comparison of state-of-the-art estimators for electrical parameter identification of PMSM", IEEE, 2019.

[4] Y.shi, K.sun, "Online identification of permanent magnet flux based on Extended Kalman Filter for IPMSM drive with position sensorless control", *IEEE Transactions on Industrial Electronics*, vol. 59, no. 11, pp. 4169-4178, 2012.

[5] A.Piippo, M.Hinkkanen, "Adaptation of motor parameters in sensorless PMSM drives", *IEEE Transactions on Industry Applications*, vol. 45, no. 1, pp. 203-212, 2009.

[6] Yanqing Zhang, Zhonggang Yin, "Online identification Methods of parameters for permanent magnet Synchronous motors based on cascade MRAS", in *Proc. 2015 9th International Conference on Power Electronics-ECCE Asia*, 2015, pp. 345-350.

[7] Yanjing Ouyang, Yufei Dou , "Speed sensorless control of PMSM based on MRAS parameter identification", in *Proc. 2018 21st International Conference on Electrical Machines and Systems(ICEMS)*, 2018, pp. 1618-1622.

[8] ZhaoHua L, HuaLiang W, "Global identification of electrical and mechanical parameters in PMSM drive based on dynamic self-learning PSO", *IEEE Transactions on Power Electronics*, vol. 33, no. 12, pp. 10858-10871, 2018.

[9] Aliprantis D C, S.Audhoff D, Kuhn B T, "Genetic algorithm-based parameter identification of a hysteretic brushless exciter model", *IEEE Transactions on Energy Conversion*, vol. 21, no. 1, pp. 21-26, 2006.

Xiaojun Ma was born in Jiangsu province in China on July 1996. He received the B.Eng degree in electrical engineering from Nanjing University of Posts and Telecommunicatons, Nanjing,China in 2018. Currently, he is a Master student in the University of Shanghai for Science and Technology.

His research interests include parameters identification of PMSM and sensorless control of PMSM.

Chao Bi obtained the B.Eng degree from HeFei University of Technology in 1982, M.Eng degree from the Xian Jiaotong University in 1984, and Ph.D. degree from National University of Singapore in 1994.

Dr. Bi is presently the professor of University of Shanghai for Science and Technology. He is also the CTO of Fortior Technology. His research interests include the design, control and test of permanent-magnet motor, micro motor, electromagnetic field synthesis and analysis, optimization technology, and sustainable energy technology. He has published more than 190 conference and journal papers in these areas, and got National Technology Award (Singapore) in 2006 for his contributions in precision motor technology.