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# On-line Parameter Identification for Vector Controlled PMSM Drives Using Adaptive Algorithm

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***Abstract*—In advanced PI type and sensorless control systems of motors, the precise determination of permanent magnet synchronous motor (PMSM) parameters is of great significance. By means of the field orientation control principle of PMSM and *Popov* super stability theory, a novel adaptive online identification method of motor parameters is proposed in this paper. Resistance, inductance and PM flux of PMSM are achieved in the presented model. PMSM *d*, *q*-axis voltage, current and their errors are used to obtain the adaptive laws of parameters. *Popov* stability theory guarantees the convergence of the estimated parameters under certain conditions. The simulation results as well as experimental ones illustrate the validity and efficiency of the proposed method.**

***Keywords* — PMSM; Vector control; Parameter identification; Adaptive control; Simulation and experiment**

## I. INTRODUCTION

Duo to the high efficiency and good controllability, PMSM drives are largely used in many industrial applications [1]. At the present, classic PID control is mostly adopted, whose performance is affected dramatically by parameters of motors [2]. In addition, in order to reduce cost and avoid the limitation of mechanical sensor, people proposed sensor-less techniques which are arousing great interest [3]. They aim at eliminating the mechanical sensor, which are rather expensive and delicate, especially if accurate mounting and calibration are necessary, and at obtaining rotor position and angular velocity from the measurement of only electrical quantities [4]. But the precision of position estimation often depends on motor's parameters [5]. Naturally, the precise determination of PMSM parameters is of great significance.

Many identification methods of motor' parameters are proposed to increase the performance of controllers and precision of position estimation [6-9]. S. Bolognani and his partners [6] presented the recursive parameter identification (RPI) method to estimate parameters of PMSM on-line. The model of adaptive identification of PMSM parameters based on predictive current control was designed in [7]. Inductance and PM flux were obtained by this method, but resistance was ignored. Reference [8] gave an adaptive identification method to get electromagnetic and mechanical parameters of PMSM. The identification model of resistance and inductance was built on stationary condition, thus, sinusoidal *d*, *q*-axis voltage inputs were necessary to ensure convergence of the algorithm. Also, the identification of flux, resistance and inductance were designed in different models, which added the complexity.

This paper proposes an on-line identification method of PMSM electromagnetic parameters based on model reference adaptive control. By means of *Popov* super stability theory, the adaptive laws are derived with *d*, *q*-axis voltages, currents and their errors in the rotor reference frame. The model which runs in parallel with vector control can track the electromagnetic parameters rapidly.

## II. FIELD ORIENTATION CONTROL SYSTEM OF PMSM WITH ADAPTIVE PARAMETER IDENTIFICATION

The complete block schematic of the system considered in this paper is shown in Fig. 1. The power stage of the system consists of a sinusoidal isotropic PMSM, fed by a voltage source PWM inverter with space vector (SV) modulation technique. Two Hall-effect current sensors remain the control feedback is required, indispensable also for diagnostic and alarm purpose; rotor angular velocity is obtained using an encoder mounted on the shaft. The speed close loop produces a *q*-axis current reference $i_{qref}$, which is the input to the Field Orientation Control (FOC) in order to produce a reference voltage space vector, whose components in the $\alpha\beta$ reference frame are $u_{\alpha ref}$ and $u_{\beta ref}$ respectively. Finally, a space vector PWM routine generates the switching commands for the inverter.

The adaptive parameter identifier in parallel with FOC requires *d*, *q*-axis voltages, currents and rotor angular speed, which are measured and calculated. Indeed, in order to reduce the sensors, phase voltages are usually obtained by means of the measurement of DC bus voltage. For a voltage source inverter as shown in Fig. 2, if $s_a$, $s_b$ and $s_c$ are respectively used to describe the switch state of power transistor, then, the switch state vector $\boldsymbol{s}$ can be written as:

$$\boldsymbol{s} = [s_a \quad s_b \quad s_c]^{\mathrm{T}} \tag{1}$$

with:

$$s_a, s_b, s_c = \begin{cases} 1 & \text{when the up transistor is on} \\ 0 & \text{when the up transistor is off} \end{cases} \tag{2}$$

Then, the relationship between phase voltage vector and switch state vector can be described by:

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$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix} \tag{3}$$

*Clarke* and *Park* transforms are used to derive *d*, *q*-axis voltages and currents [10].

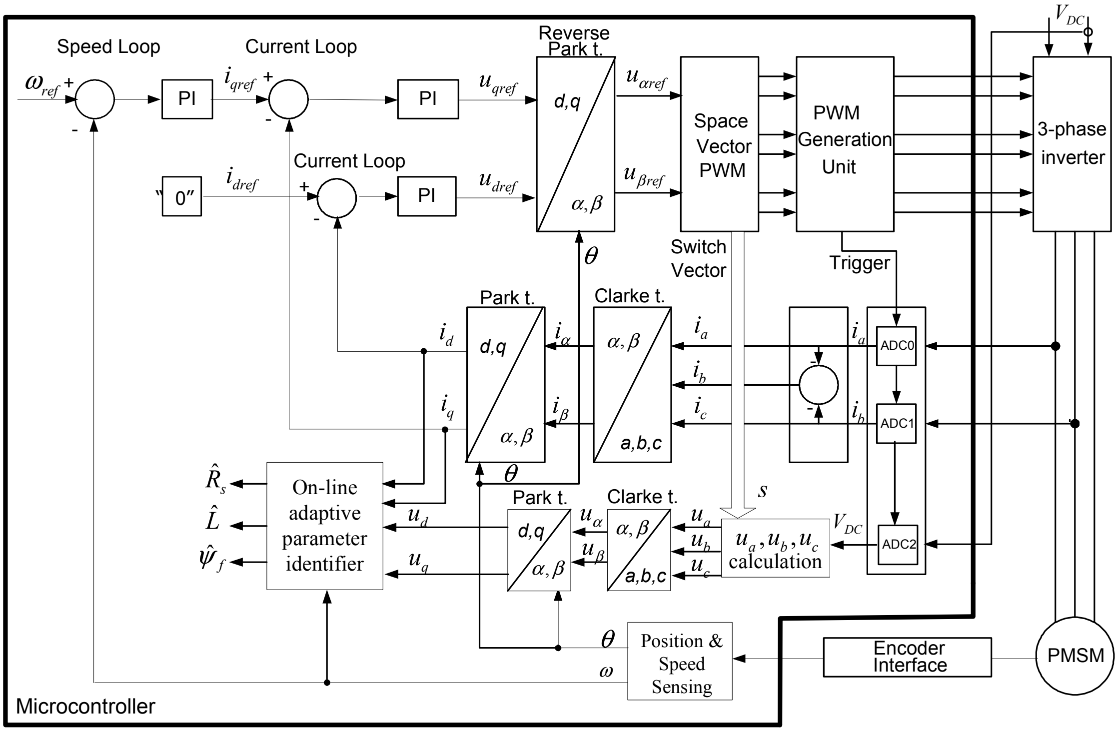



Fig. 1 The schematic of FOC-PMSM with adaptive parameter identification

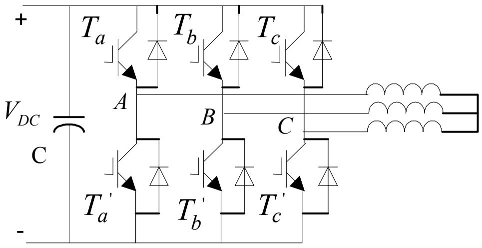



Fig. 2 Voltage source PWM inverter

## III. MODEL OF PARAMETER IDENTIFICATION

PMSM is a complex nonlinear system with multi-variables and strong coupling. In order to reduce the analysis, we suppose that the spatial distribution of the stator winding and PM field is sinusoidal, and no cage is on the rotor. Also the saturation and damping effects are neglected [11].

By choosing *d*, *q*-axis currents as states variables, the state space equation of PMSM is given by:

$$\mathrm{P}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega \\ -\omega & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_d} & 0 \\ 0 & -\frac{1}{L_q} \end{bmatrix} \begin{bmatrix} u_d \\ u_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\omega \frac{\psi_f}{L_q} \end{bmatrix} \tag{4}$$

Where $i_d$, $i_q$, $u_d$, $u_q$, $L_d$ and $L_q$ are *dq* frame currents, voltages and inductances respectively. $R_s$ is stator resistance, $\omega$ is electrical angular velocity of rotor and $\psi_f$ is rotor PM flux. P differential operator and P=d/d*t*.

For surface PMSM, no saliency effect is considered, thus $L_d$=$L_q$=$L$.

Suppose:

$$a = R_s / L \tag{5}$$

$$b = 1 / L \tag{6}$$

$$c = \psi_f / L \tag{7}$$

Then, the state space equation of (1) can be written as:

$$\mathrm{P}\boldsymbol{i} = \boldsymbol{A}\boldsymbol{i} + \boldsymbol{B}\boldsymbol{u} + \boldsymbol{C} \tag{8}$$

Where, current state vector $\boldsymbol{i} = [i_d \quad i_q]^{\mathrm{T}}$ ; voltage state vector $\boldsymbol{u} = [u_d \quad u_q]^{\mathrm{T}}$ ; $\boldsymbol{A} = \begin{bmatrix} -a & \omega \\ -\omega & -a \end{bmatrix}$; $\boldsymbol{B} = \begin{bmatrix} b & 0 \\ 0 & b \end{bmatrix}$; $\boldsymbol{C} = [0 \quad -\omega c]^{\mathrm{T}}$ .

Rotor velocity $\omega$ is supposed to be a constant in one sampling period. According to the state space equation (8), the adjustable parameter model is given by:

$$\mathrm{P}\hat{\boldsymbol{i}} = \hat{\boldsymbol{A}}\hat{\boldsymbol{i}} + \hat{\boldsymbol{B}}\boldsymbol{u} + \hat{\boldsymbol{C}} + \boldsymbol{G}(\hat{\boldsymbol{i}} - \boldsymbol{i}) \tag{9}$$

Where $\hat{\boldsymbol{i}} = [\hat{i}_d \quad \hat{i}_q]^{\mathrm{T}}$ is state vector of the model. $\hat{\boldsymbol{A}} = \begin{bmatrix} -\hat{a} & \omega \\ -\omega & -\hat{a} \end{bmatrix}$, $\hat{\boldsymbol{B}} = \begin{bmatrix} \hat{b} & 0 \\ 0 & \hat{b} \end{bmatrix}$ and $\hat{\boldsymbol{C}} = [0 \quad -\omega\hat{c}]^{\mathrm{T}}$

and where $\hat{a} = \hat{R}_s / \hat{L}$ （$\hat{R}_s$ and $\hat{L}$ are the estimated value of $R_s$ and $L$）, $\hat{b} = 1/\hat{L}$ , $\hat{c} = \hat{\psi}_f / \hat{L}$ （$\hat{\psi}_f$ is the estimated value of $\psi_f$ ）, $\boldsymbol{G}$ is the proportional gain matrix to be chosen so as to achieve prespecified error characteristics and $\boldsymbol{G}=\begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}$, where $k_1$ and $k_2$ are limited positive real.

The state space equation (8) as reference model is subtracted by adjustable parameter model (9), then:

$$\text{P}\boldsymbol{e}=(\boldsymbol{A}+\boldsymbol{G})\boldsymbol{e}+\Delta\boldsymbol{A}\hat{\boldsymbol{i}}+\Delta\boldsymbol{B}\boldsymbol{u}+\Delta\boldsymbol{C} \tag{10}$$

Where $e$ is error vector and $\boldsymbol{e}=i-\hat{i}$ ; $\Delta\boldsymbol{A}=\boldsymbol{A}-\hat{\boldsymbol{A}}$ ; $\Delta\boldsymbol{B}=\boldsymbol{B}-\hat{\boldsymbol{B}}$ ; $\Delta\boldsymbol{C}=\boldsymbol{C}-\hat{\boldsymbol{C}}$ .

Define $\boldsymbol{w}=-(\Delta\boldsymbol{A}\hat{\boldsymbol{i}}+\Delta\boldsymbol{B}\boldsymbol{u}+\Delta\boldsymbol{C})$, equation (10) can be written as:

$$\text{P}\boldsymbol{e}=(\boldsymbol{A}+\boldsymbol{G})\boldsymbol{e}-\boldsymbol{w} \tag{11}$$

From above equations, the adaptive identification system of PMSM parameters can be described as a standard system which composed of linear forward block and nonlinear feedback one varying with time, shown in Fig. 3.

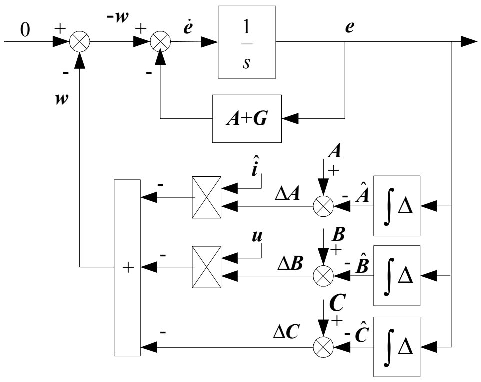



Fig. 3 The equivalent feedback structure of PMSM adaptive parameter dentification

## IV. ADAPTIVE LAWS

The global stability of model reference adaptive control system designed using *Popov* super stability theory is easily guaranteed. Also, this system has a less adjustable parameters, transparent structure and flexible adaptive laws [12]. Based on *Popov* stability theory, the above system composed of linear forward block and nonlinear feedback one is stable, if the following conditions are satisfied:

(1) Transfer function matrix of the linear forward block is positive real strictly.

(2) The nonlinear feedback block meets *Popov* integral inequation.

The gain matrix $\boldsymbol{G}$ is designed using the method proposed in reference [13] so as to ensure the forward block positive real.

$$F(s)=(s\boldsymbol{I}-\boldsymbol{A}-\boldsymbol{G})^{-1} = \begin{bmatrix} s+a-k_1 & -\omega \\ \omega & s+a-k_2 \end{bmatrix}^{-1}$$

Then, we consider the condition (2). *Popov* integral inequation:

$$\int_0^t \boldsymbol{w}^{\mathrm{T}}\boldsymbol{e}\,\mathrm{d}\tau \ge -\gamma_0^2 \tag{12}$$

Where $\gamma_0^2$ is a limited positive constant independent from $t$, when any $t\ge 0$ .

Based on adaptive control theory, state error $e$ can tend to zero by means of parameters adjustable model using special adaptive laws when the system is stable. In order to prevent adjustment effects from disappearing along with state error $e$ tending to zero, the adaptive laws are often designed as PI style. So, the adaptive laws of parameters are written as:

$$\hat{a}=\int_0^t f_1(\tau)\mathrm{d}\tau+f_2(t)+\hat{a}(0) \tag{13}$$

$$\hat{b}=\int_0^t g_1(\tau)\mathrm{d}\tau+g_2(t)+\hat{b}(0) \tag{14}$$

$$\hat{c}=\int_0^t h_1(\tau)\mathrm{d}\tau+h_2(t)+\hat{c}(0) \tag{15}$$

Where $\hat{a}(0)$ , $\hat{b}(0)$ and $\hat{c}(0)$ are the initial value of $\hat{a}$ , $\hat{b}$ and $\hat{c}$ respectively.

Using the equations of $\hat{a}$ , $\hat{b}$ and $\hat{c}$ derived from equation (13), (14) and (15) and the lemma given in the appendix, the adaptive laws of parameters are obtained from

$$\begin{aligned}
&-\int_0^t(\hat{i}_d e_d+\hat{i}_q e_q)\left[\int_0^t f_1(\tau)\mathrm{d}\tau+\hat{a}(0)-a+f_2(t)\right]\mathrm{d}t \\
&+\int_0^t(u_d e_d+u_q e_q)\left[\int_0^t g_1(\tau)\mathrm{d}\tau+\hat{b}(0)-b+g_2(t)\right]\mathrm{d}t \\
&-\int_0^t \omega e_q\left[\int_0^t h_1(\tau)\mathrm{d}\tau+\hat{c}(0)-c+h_2(t)\right]\mathrm{d}t \\
&\ge -\gamma_0^2
\end{aligned} \tag{16}$$

Where $e_d=i_d-\hat{i}_d$ and $e_q=i_q-\hat{i}_q$ are the current errors of $d$ and $q$-axis respectively.

Parameters adaptive laws are described by:

$$\begin{cases} \hat{a}=-(K_{f2}+K_{f1}/s)(\hat{i}_d e_d+\hat{i}_q e_q)+\hat{a}(0) \\ \hat{b}=(K_{g2}+K_{g1}/s)[u_d e_d+u_q e_q]+\hat{b}(0) \\ \hat{c}=-(K_{h2}+K_{h1}/s)\omega e_q+\hat{c}(0) \end{cases} \tag{17}$$

*Popov* super stability theory decides that the system composed of adaptive model and laws above is stable, and its structure is shown as Fig. 4.

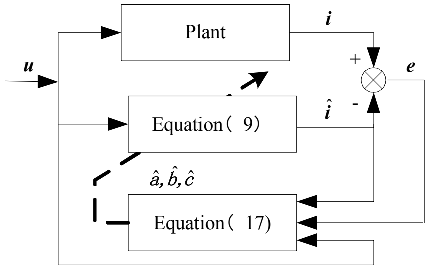



Fig. 4 The diagram of adaptive parameter identification

The adjustable parameters track ones in the plant. And when the system is stable, the adjustable parameters can be as the identified results. Using the value of $\hat{a}$ , $\hat{b}$ and $\hat{c}$ , the stator winding resistance $\hat{R}_s$ , the stator winding inductance $\hat{L}$, and the PM flux $\hat{\psi}_f$ are obtained employing equation (5), (6) and (7).

## V. SIMULATION RESULTS

Adaptive parameters identification model of PMSM under vector control using Matlab/Simulink is shown in Fig. 5. Parameters of the motor in the model are listed in Table I.

Fig. 6 to Fig. 10 report the simulation results. Fig. 6 is rotor speed in r/min. The *d*, *q*-axis current errors between plant and model are shown in Fig. 7 and Fig. 8. Fig. 9 is the identification behaviours of resistance, inductance and PM flux respectively. Table II shows simulation parameter values obtained using adaptive laws. Tracking capability of the adaptive identification algorithm when parameters vary is shown in Fig. 10 and the identified values are shown in Table Ⅲ. Here, resistance and inductance of the plant increase 10% and PM flux decreases 5%. We can see that the identified values are converging to the actual values, because the model parameters are changing to coincide with the plant parameters.

TABLE I
SIMULATION CONDITION

| | |
|---|---|
| Stator winding resistance | $R_s$=3.5Ω |
| Stator winding *d*, *q*-axis inductance | $L_d$=$L_q$=11.5mH |
| Rotor PM flux | $\psi_f$=0.178Wb |
| Combined inertia | $J$=4.4×10$^{-4}$kg·m$^2$ |
| Number of pole pairs | $n_p$=3 |
| Speed give | 300r/min |
| DC voltage | 300V |
| Switch frequency | 10kHz |
| Load torque | 2N·m |

TABLE II
SIMULATION RESULTS

| | |
|---|---|
| Stator winding resistance | $R_s$=3.502Ω |
| Stator winding *d*, *q*-axis inductance | $L_d$=$L_q$=11.50mH |
| Rotor PM flux | $\psi_f$=0.1776Wb |

TABLE III
SIMULATION RESULTS WHEN CONDITIONS VARY

| | |
|---|---|
| Stator winding resistance | $R_s$=3.862Ω |
| Stator winding *d*, *q*-axis inductance | $L_d$=$L_q$=10.38mH |
| Rotor PM flux | $\psi_f$=0.1688Wb |

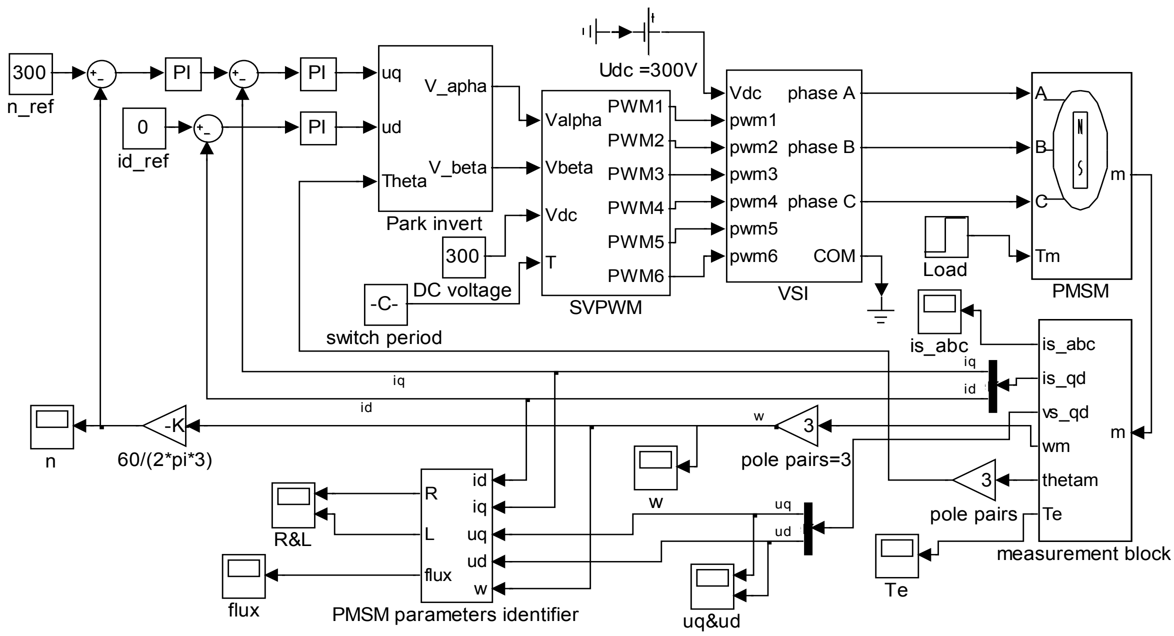



Fig. 5 The simulation model of PMSM parameters adaptive identification

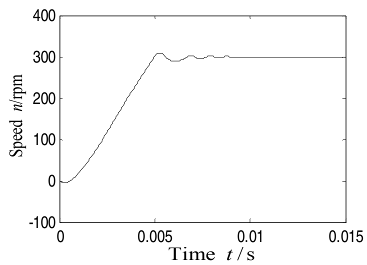



Fig. 6 Rotor speed of PMSM

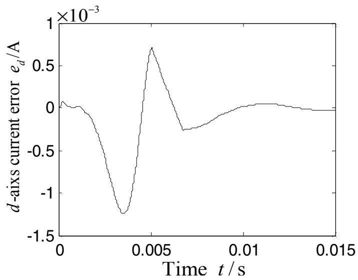



Fig. 7 *d*-axis current error

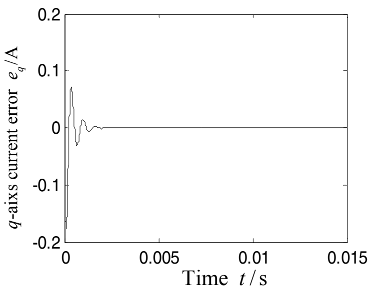
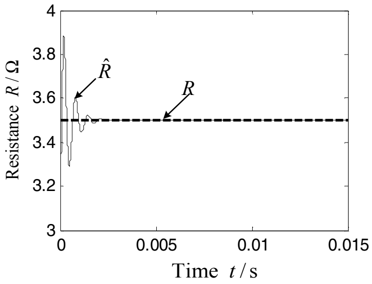
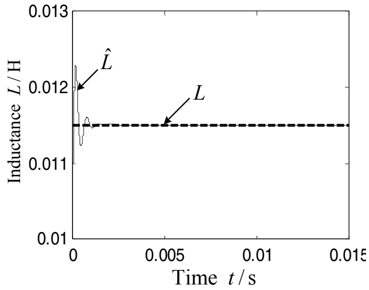


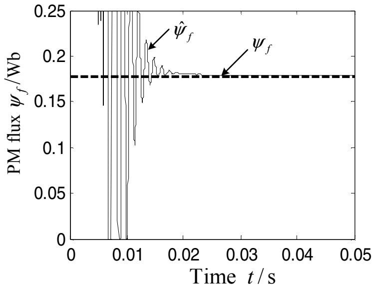

Fig. 8 *q*-axis current error




(a) Identified and actual value of resistance

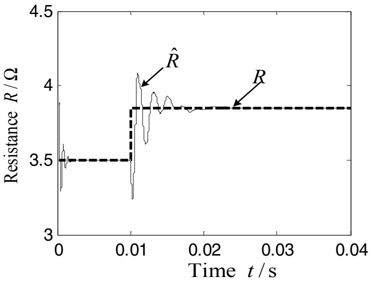



(b) Identified and actual value of inductance

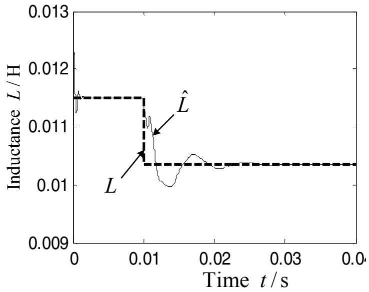



(c) Identified and actual value of PM flux

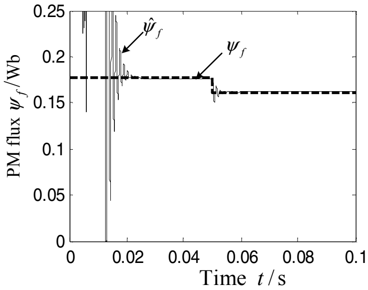
Fig. 9 Time-behaviours of parameter Identification




(a) Resistance




(b) Inductance




(c) PM flux

Fig. 10 Tracking capability of the adaptive identification algorithm when parameters vary

## VI. EXPERIMENTAL RESULTS

Field orientation control system of PMSM is implemented by using TMS320LF2407A DSP of TI Company as core chip, shown in Pig. 11. Hall-effect sensors are used to measure DC voltage and phase currents, and a 2500-line encoder mounted on the shaft of the motor is used to determine position of rotor. Experimental results are shown in Fig. 12, Fig. 13 and Fig. 14. From these curves we can confirm that each parameter converged to a constant value due to variation of the adaptive laws, and all parameters can be identified within a short time.

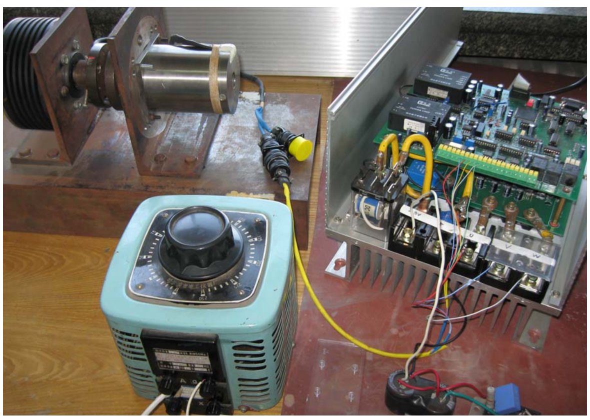


Fig. 12 Identified value of resistance

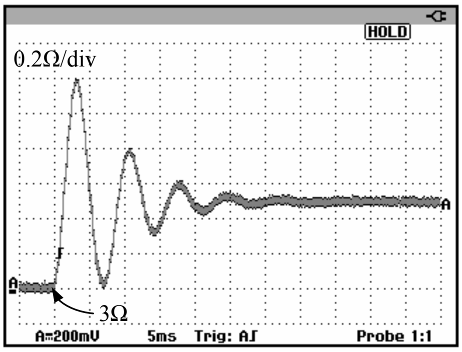



Fig. 12 Identified value of resistance

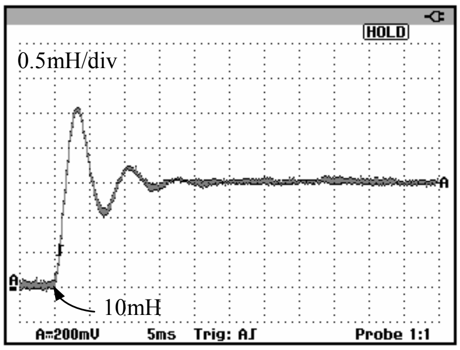



Fig. 13 Identified value of inductance

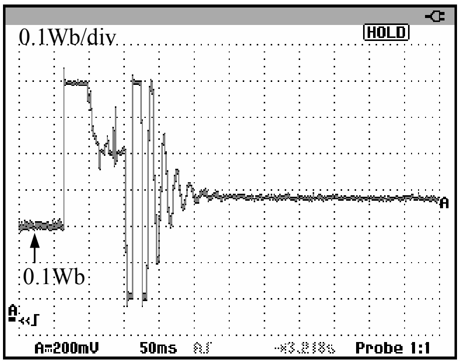



Fig. 14 Identified value of PM flux

## VII. CONCLUSION

An adaptive on-line identification method of motor parameters is proposed in this paper. Resistance, inductance and PM flux of PMSM are achieved at the same time in the presented model. It is based on field orientation control principle of PMSM and *Popov* super stability theory, which simplifies the model. *Popov* stability theory guarantees the convergence of the estimated parameters when certain conditions are satisfied. Simulation and experimental bench were built, and the results illustrate the validity and efficiency of the proposed method.

## APPENDIX

Lemma:

Define:

$$\psi(t,\tau) = k(t-\tau) f(\tau)$$

Where $k(t-\tau)$ is a positive definite scalar integral core, whose Laplace transform is a positive real transfer function with a pole in $s=0$. Then, the following inequation is tenable:

$$\eta(0,t_1) = \int_0^{t_1} f(t)\left[\psi(0) + \int_0^t \psi(t,\tau)\mathrm{d}\tau\right]\mathrm{d}t \ge -r^2 \quad (r^2 < \infty)$$

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