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# Research Article
# An Extended Kalman Filter Algorithm for a PMSM: Experimental Results

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## Abstract
**Background and Objective:** In this study, a fifth-order Discrete-time Extended Kalman Filter (DEKF) approach is introduced for on-line estimation of speed, torque and rotor position in a Permanent Magnet Synchronous Motors (PMSM). **Methodology:** In order to verify the effectiveness of the estimation, the DEKF scheme has been implemented and validated in real-time on a test bench, which is composed of a synchronous machine, a powder brake completed by current and voltage sensors. **Results:** The satisfying experimental results carried out on a 1.6 kW PMSM demonstrate the excellent performance of the proposed DEKF against measurement noises and perturbations. **Conclusion:** The interesting results obtained on the PMSM show that this estimation method can be to use for the reconstitution of the speed and position in the industrial applications.

Key words: PMSM model, sensorless control, extended Kalman filter, observation, test bench

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Data Availability: All relevant data are within the paper and its supporting information files.

## INTRODUCTION

In recent years, PMSM are widely used in low and mid power applications such as computer peripheral equipments, robotics and adjustable speed drives. The high efficiency and simple controller of the PMSM drives[1,2] compared with the induction motors make them a good alternative in certain applications namely automobiles and aerospace technology. However, its control is proved very difficult since the dynamic systems are nonlinear, because some parameters (inductance or resistance) drift with the temperature of the rotor current frequency.

The PMSM non-linear structure induces the use of robust feedback linearization method[3,4] in order to permit a good dynamic stability of the PMSM variables in a field-oriented (d, q) coordinate.

However, this feedback control technique requires the knowledge of certain variables (speed or position), which are not usually measurable or difficult to access. Also, parameters variations (resistance or load torque variation) can involve a performance degradation of the system.

In order to achieve better system dynamic performance, the approach proposed in this study consists to design an extended observers allowing an on-line estimation of speed and position in presence of noises.

Accurate estimation of speed in the presence of system noise and parameter variations is a challenging task. Extended Kalman Filter (EKF) presented[5,6] is one of the most well-known and often used tools for stochastic estimation by comparison with the sliding mode observer[7,8].

Thus, after a brief review of the PMSM model, the central idea of this study consists to validate the simulations results presented in the study[9] by the implementation in real-time of this proposed fifth-order DEKF method carried out on a 1.6 kW PMSM drive system.

## MATERIALS AND METHODS

**General test bench description:** This study, conducted in the Laboratory of ESATIC Abidjan (Côte d'Ivoire) from June 2015-March 2016 by a theoretical work, has been implemented and validated in real-time on a test bench (Fig. 1, 2), which is composed of electrical fittings, as follows:

- A synchronous motor "Leroy-Somer" equipped with an incremental encoder resolution of 4096 points per mechanical revolution, used by the control (1)
- An identical second motor (2), intended to simulate a load, controlled by a controller (4) and equipped with a resolver completed by an acquisition currents (5) card using three sensors LEM
- A PC-board (3) which contains the Dspace software ("Cockpit, Trace...") and Matlab-Simulink environment (DSPACE 1104 using a TMS320 processor)
- An ASIC card used as communication interface between the PC and a 15 kW three-phase static inverter (7) supplied by a voltage source which provides (6) about 0-400 V with current limitation of about 6 A

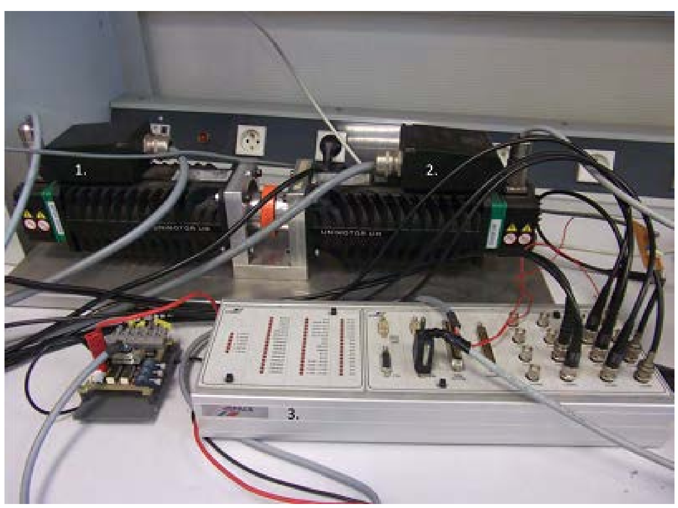


Fig. 1: A view of the test bench: Part control and mechanical 1-3


Fig. 2: Test bench: Party power and instrumentation 4-7

**PMSM model:** The dynamic model for the PMSM in the (d-q) transformed rotor reference frame is given in state space as follow[2,5]:

$$\begin{cases} \dot{X} = F(X) + G.U \\ Y = H(X) = [h_1(X)\ \ h_2(X)]^T = [I_d\ \ I_q]^T \end{cases} \tag{1}$$

with $X = [\ I_d\ I_q\ \Omega\ \theta]^T$, $U = [\ V_d\ V_q\ ]^T$

$$F(X) = \begin{bmatrix} f_1(X) \\ f_2(X) \\ f_3(X) \\ f_4(X) \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} I_d + \frac{L_q}{L_d} p.I_q.\Omega \\ -\frac{R_s}{L_q} I_q - \frac{L_d}{L_q} p.I_d.\Omega - \frac{p.\Phi_f}{L_q}\Omega \\ -\frac{f}{J}.\Omega + \frac{p.\Phi_f}{J} I_q - \frac{T_L}{J} \\ p.\Omega \end{bmatrix}; \quad G = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

In order to preserve the reliability and robustness stability under the load torque variation and noises, this study uses a full fifth-order DEKF method to provide an on-line estimatin of currents, speed, rotor position and load torque for the PMSM drive.

**Model of extended Kalman filter:** For parameter estimation using a full order EKF, the model structure (Eq. 1) is discretized directly using Euler approximation (1st order) proposed by Gowda *et al.*[10]. Furthermore, the state vector is extended to the load torque. Thus, choosing the currents ($I_{d,}$ $I_q$), speed (), rotor position (θ) and load torque ($T_L$) as state variables, the voltages ($V_d$, $V_q$) as inputs, the new discrete-time and Stochastic fifth-order nonlinear dynamic model for the PMSM is described by equations:

$$\begin{cases} X_e(k+1) = f\left(X_e(k), U(k)\right) + w(k) \\ \qquad\qquad\ = X_e(k) + T_e.Q\left(x_e(k), U(k)\right) + w(k) \\ Y_e(k) = h\left(X_e(k)\right) + v(k) \end{cases} \tag{2}$$

where, $X_e(k) = [\ I_d(k)\ I_q(k)\ \Omega(k)\ \theta(k)\ T_L(k)\ ]^T$, $U(k) = [\ V_d(k)\ V_q(k)\ ]^T$.

$$Q\left(X_e(k), U(k)\right) = \begin{bmatrix} -\frac{R_s(k)}{L_d} I_d(k) + \frac{L_q}{L_d} p.I_q(k).\Omega(k) + \frac{1}{L_d} V_d \\ -\frac{R_s(k)}{L_q} I_q(k) - \frac{L_d}{L_q} p.I_d(k).\Omega(k) - \frac{p.\Phi_f}{L_q}\Omega(k) + \frac{1}{L_q} V_q \\ -\frac{f}{J}.\Omega(k) + \frac{p.\Phi_f}{J} I_q(k) - \frac{T_L(k)}{J} \\ p.\Omega(k) \\ 0 \end{bmatrix}$$

$$Y_e(k) = \begin{pmatrix} I_d \\ I_q \end{pmatrix} = h\left(X_e(k)\right) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}.X_e(k) = H.X_e(k)$$

The resulting output vector $Y_e(k)$ consists of the estimated motor current in a rotor reference frame being compared to the measured current. The difference is used to correct the state vector of the system model.

The $X_e(k)$ and $Y_e(k)$ are the state vector and output, respectively at the k-th sampling instant, i.e., $t = k.T_e$ with $T_e$ the adequate sampling period chosen without failing the stability and the accuracy of the discrete-time model. The w(k) represents the random disturbance input; it is the sum of modeling uncertainty, the discretization errors and the system noise. The v(k) is the measurement noise. Both w(k) and v(k), are assumed to be white Gaussian noise with zero mean and covariance matrix Q and R respectively. Consider that:

- $\hat{X}_e(k)$ = The estimate of $X_e(k)$ and $K(k+1)$ = EKF gain
- $\hat{X}_e(k+1|k)$ = The linear minimum mean square estimate of $X_e(k+1)$
- $P(k+1|k)$ = State prediction covariance error
- $P(k+1|k+1)$ = State estimation covariance error
- Initialization givens: $\hat{X}_e(0|0) = \hat{X}_e(0)$ and $P(0|0) = P(0)$

The steps of the proposed fifth-order EKF algorithm are as follows:

$$\left\{\begin{array}{l}
1.\quad \hat{X}_e(k+1|k) = f\left(\hat{X}_e(k|k),\ U(k)\right) \\
2.\quad F(k) = \left.\dfrac{\partial f\left(\hat{X}(k),\ U(k)\right)}{\partial \hat{X}(k)}\right|_{X_e(k) = X_e(k|k)} \\
3.\quad P(k+1|k) = F(k).P(k|k).F^T(k) + Q \\
4.\quad K(k+1) = P(k+1|k).H^T\left[H.P(k+1|k).H^T + R\right]^{-1} \\
5.\quad \Delta Y_e(k+1|k) = Y_e(k+1) - H.\hat{X}_e(k+1|k) \\
6.\quad \hat{X}_e(k+1|k+1) = \hat{X}_e(k+1|k) + K(k+1).\Delta Y_e(k+1|k) \\
7.\quad P(k+1|k+1) = \left[I - K(k+1).H\right].P(k+1|k) \\
8.\quad \text{Increment } k \text{ and Go to step } 1
\end{array}\right\} \tag{3}$$

The EKF algorithm consists of repeated use of step 1-8 for each measurement. The F(k) is the Jacobian matrix of partial derivatives of f(·) with respect to $X_e(k)$. From Eq. 2, we obtain:

$$F(k) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} + T_e. \begin{bmatrix} -\dfrac{R_s(k)}{L_d} + p.\Omega(k) + p.I_q(k) - \dfrac{I_d(k)}{L_d} + \dfrac{1}{L_d}V_d \\ -\dfrac{R_s(k)}{L_q} - p.\Omega(k) - p.I_d(k) - \dfrac{p.\Phi_f}{L_q} - \dfrac{I_q(k)}{L_q} + \dfrac{1}{L_q}V_q \\ -\dfrac{f}{J} + \dfrac{p.\Phi_f}{J} - \dfrac{1}{J} \\ p \\ 0 \end{bmatrix}$$

## RESULTS AND DISCUSSION

**Experimental results and analyses:** Finally, the implementation in real-time of the proposed scheme, carried out on a testing bench is given by the Fig. 3. The nominal electrical parameters of the PMSM are given in the Table 1.

Figure 3 is composed of a 1.6 kW PMSM, a powder brake with load torque measurements, three LEM current sensors and a 4096 points incremental encoder. A PC-board and a Dspace 1104 card using MATLAB/SIMULINK are used to implement PWM function, control and observation algorithms. The PWM and the position measurement work at 10 kHz. In order to verify the accuracy of the DEKF (which is implanted in a function using C-language and operates using a sampling period Te = 1 msec), an information feedback is required. A series of sensors accomplishes this task:

- The measurements of stator currents are given by the measurements of the phase current via Hall sensors
- A voltage sensor providing the DC bus voltage and an acquiring a resolver motor position
- An incremental encoder safeguarding the load position
- A torque sensor giving the frictional torque measurement applied by the powder brake

It should be noted that satisfying simulations results[9] carried out on this 1.6 kW PMSM demonstrated the excellent performance and high robustness of the proposed DEKF against parameter variations, modeling uncertainty and measurement noise.

The work presented in this study, shows only the experimental results set-up.

Two kinds of tests have been performed (without and with load torque) in order to evaluate the performances and effectiveness of the DEKF algorithm against modeling uncertainty. The comparisons between the observed state variables and the real ones have been realized for several operating conditions with the presence of load torque.

The first one (Fig. 4) illustrates the results where several step changes in the motor position (or speed) reference has been made without load torque ($T_l \cong 0$ N m).

Table 1: Nominal parameters of the PMSM

| | | |
|---|---|---|
| $P_{mn}$ = 1.6 kW/p = 3 | $U_n$ = 220/380 V | $f_n$ = 0.0162 N m sec $rad^{-1}$ |
| $T_{Lnom}$ = 5.09 (N m) | $W_n$ = 1000 rpm | $J_n$ = 0.0049 kg $m^2$ |
| $R_{sn}$ = 2.06 W | $Phif_n$ = 0.29 Wb | $L_{qn} = L_{dn}$ = 9.15 mH |

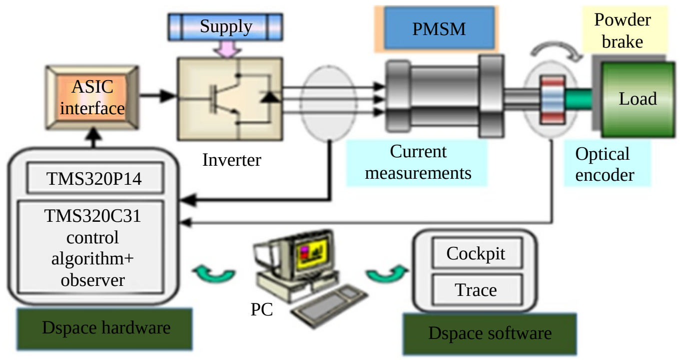


Fig. 3: Experimental configuration diagram

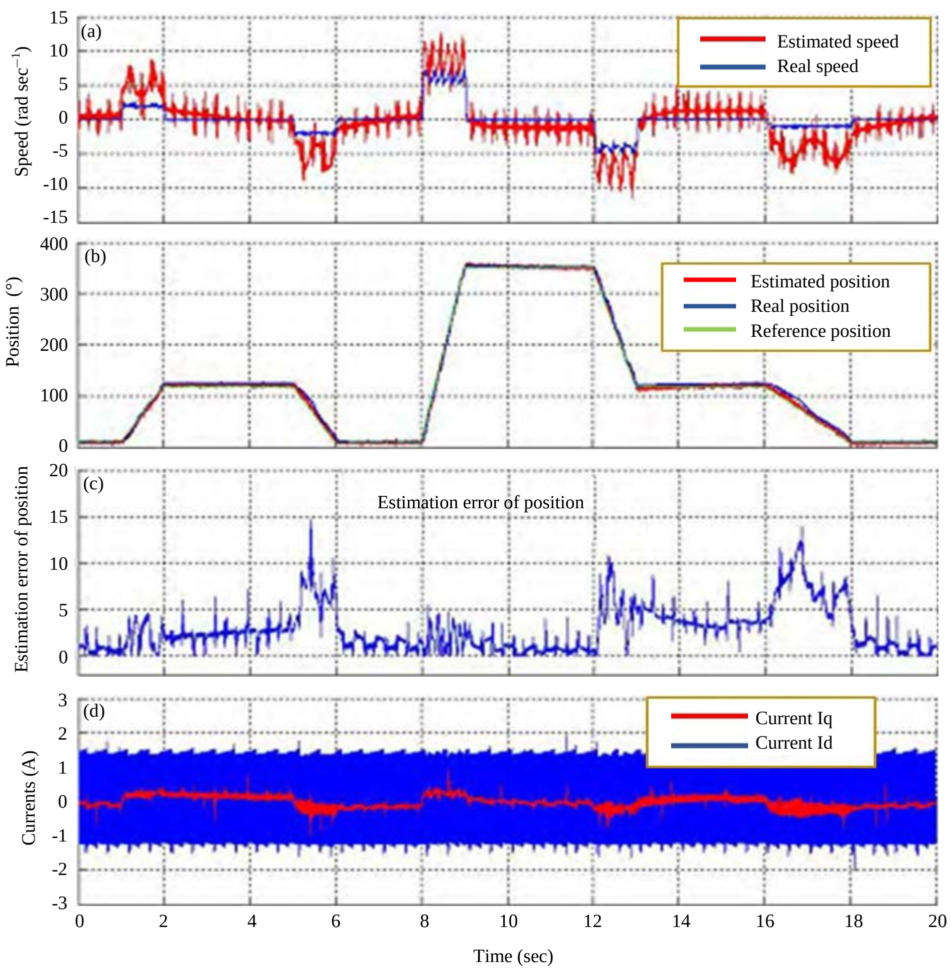


Fig. 4(a-d): Experimental results without load torque $T_l \cong 0$ N m

In the second one (Fig. 5), the motor speed is regulated with the presence of load torque $T_l$ (about 20% of nominal torque).

For each test, real and observed values have been registered and have been compared to reference values. The weak perturbations on the experimental values are probably tied to the inverter noises. In both cases the machine speed slows slightly but the observer continues to follow perfectly. The estimated values of speed and rotor position converge very well to their real values. The estimation error of the

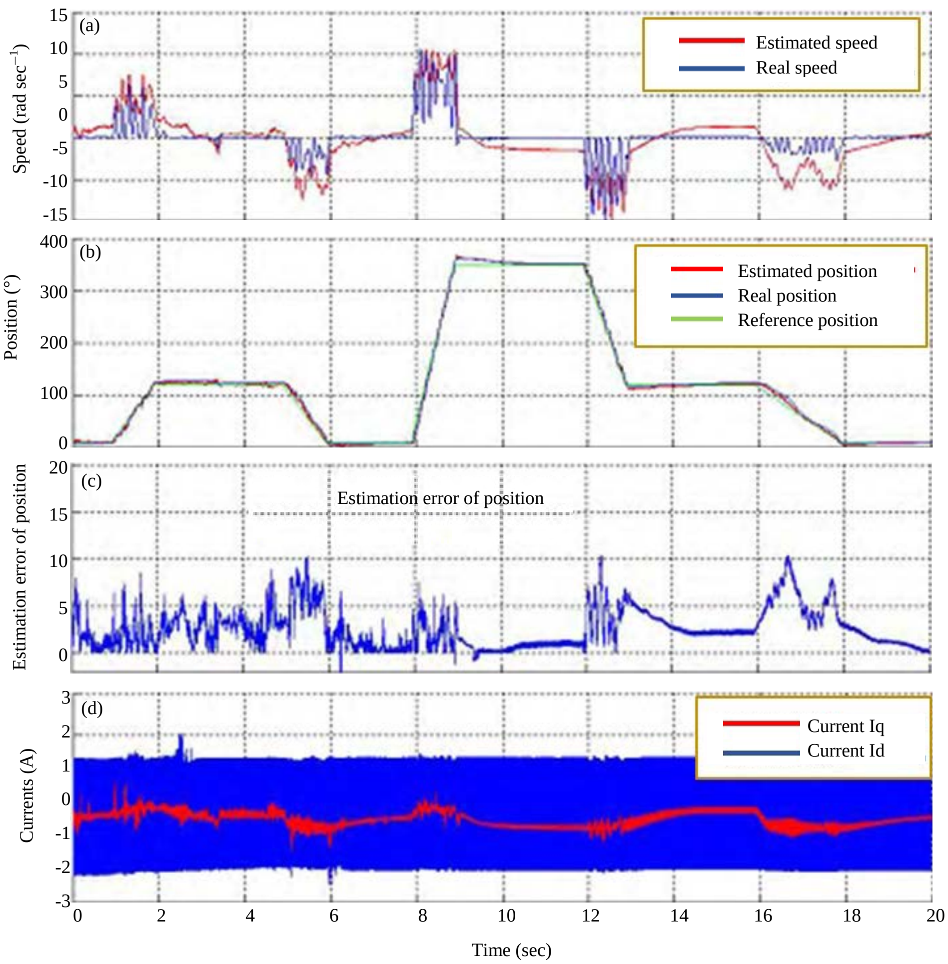


Fig. 5(a-d): Experimental results with the presence of load torque ($T_l \cong 20\% \times T_{Lnom}$)

position is acceptable which is due to a favorable position estimation. The experimental estimated current (Fig. 4, 5) is in good agreement with the real value.

Thus better estimation performance yielded by the proposed DEKF method against perturbations is well verified from the experimental results. The agreement between the experimental dynamic performance and the estimated ones is demonstrated.

## NOMENCLATURE

| | | |
|---|---|---|
| p, J, f | : | p: Pole number, J: Inertia (kg m$^2$), f: Damping coefficient (N m sec rad$^{-1}$) |
| $L_d$, $L_q$ | : | (d, q)-axis inductances (H) |
| $R_s$, $T_e$ | : | Stator resistance (Ω) and sampling period (sec) |
| $T_l$ | : | Load torques (N m) |
| $I_d$, $I_q$ | : | (d, q)-axis stator currents (A) |
| $V_d$, $V_q$ | : | D-axis and q-axis stator voltage (V) |
| $\Phi_f$, θ | : | $\Phi_f$: Rotor magnet flux linkage (Wb), θ: Rotor position at electrical angle (rpm) |
| $\omega_r$, Ω | : | $\omega_r$: Rotor electrical radian speed, Ω: Mechanical rotor speed (rad sec$^{-1}$) |

## CONCLUSION

A new approach for speed and position estimation in high-performance PMSM drive, namely, in sensorless control, was presented in this study. It is based on a DEKF approach.

The proposed DEKF was successfully implemented in real-time on a testing bench (1.6 kW PMSM) in order to provide certain variables estimations (speed and position) which are difficult to access, measure in practice or its transducers are expensive.

A series of experimental tests have been achieved on the 1.6 kW PMSM. It can be seen that the experimental waves are quite similar to the estimation ones. Thus the results obtained have demonstrated a good performance of this DEKF strategy against noises and load torque.

Thus, one will appreciate very well the experimental implementation of this robust estimator for the reconstitution of the speed and position in the industrial applications.

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