Direct torque control without speed sensor using extended kalman filter for permanent magnet synchronous motor

Choayb BOUSNOUBRA[1] ,Yacine DJEGHADER[2] and Selma ALLELE[3]

[1,2,3]Department of Electrical Engineering, University of Mohamed-Cherif Messaadia ,Souk Ahras, ALGERIA ; BP 1553 Annaba Road 41000 Souk Ahra, Algeria.

[1,3]LEER Laboratory University of Mohamed-Cherif Messaadia ,Souk Ahras, ALGERIA;

[1]Corresponding. Author: c.bousnoubra@univ-soukahras.dz

Abstract – In this paper, a control without speed sensor with extended Kalman filter (EKF) for command a permanent magnet synchronous motor (PMSM) speed rotor position estimation is proposed. The direct torque control (DTC) technique for permanent magnet synchronous motor (PMSM) is receiving increasing attention due to the significant advantages of low dependence on motor parameters compared to other motor control techniques. The Kalman filter is an observer of linear and nonlinear systems and is based on stochastic intromission, in other words, noise. The PMSM is powered by an electronic power converter. Simulation tests performed for different operating conditions have confirmed the robustness of the whole system

Keywords – Permanent Magnet Synchronous Motor (PMSM), Direct Torque Control (DTC), Extended Kalman Filter (EKF).

I. INTRODUCTION

The demand for highly dynamic electrical drives, characterized by high quality torque control, in a wide variety of applications has grown tremendously during the past decades.

Permanent magnet synchronous motor (PMSM) has the advantages of high efficiency, high power density, simple control, and small size, and it has become an important development direction for the electric propulsion system. The speed control techniques for PM are well studied, and many techniques such as the field-oriented control (FOC) and direct torque control (DTC) have been proposed in the literature. In general, FOC has following disadvantages: complex control structure, requires coordinate trans formation, and pulse width modulator (PWM) signal generators.

Hence, the challenge is to adapt and modifying the available techniques of speed control, proposed for industrial applications.

Compared to FOC, DTC does not need current regulators and can provide extremely high transient torque control performance with very simple structure. However, the DTC technique has some drawbacks like high torque ripple, flux ripple, high stator current distortion, and variable switching frequency, the authors propose a predictive scheme with low computational complexity and low parameter sensitivity, which diminish both the torque and flux ripples in a PMSM drive.

To improve the performance of the classical DTC, This paper presents the modeling, analysis, design and experimental validation of a robust sensorless control method for permanent magnet synchronous motor (PMSM) based on Extended Kalman Filter (EKF) to accurately estimate speed and rotor position. The extended Kalman filter (EKF) has an excellent state estimation capability for nonlinear systems, and can still estimate the state of the system especially in the case of noise and measurement bias errors. EKF is widely used in the motor position less control system. has adopted the stator flux, motor speed and rotor position, and designed the permanent magnet synchronous motor position less DTC control system. The aim of this paper is to study the use of the Extended Kalman filer (EKF) for sensorless control of a permanent magnet synchronous motor (PMSM) drive controlled by direct torque control (DTC). In contrast to the vector control, the DTC allows for better compensation of the dead-time effects, however, it also needs to run with much shorter sampling period. The challenge for the EKF is to minimize its execution time. This is achieved by using state space model of the drive with only two state variables, the rotor speed and the rotor position, which will be known as the reduced model. We show in simulations and experiments, that the EKF with this reduced model has the same performance as the four-dimensional full order model at much lower computational cost. This allows to use the EKF even in DTC with very short sampling time and take full advantage of the dead-time compensation. Due to better reconstruction of the voltage vector, the sensorless DTC is able to operate the drive at lower speed than the vector control with the same estimator.[1][2][3]

II. DIRECT TORQUE CONTROL OF PMSM

A- Mathematical model of PMSM

A-1 Electrical equations:

$$\begin{cases} V_d = R_s I_d + \dfrac{d}{dt}\varphi_d - \omega_r \varphi_q \\ V_q = R_s I_q + \dfrac{d}{dt}\varphi_q + \omega_r \varphi_d \end{cases} \tag{1}$$

A-2 Magnetic equations:

$$\begin{aligned} \varphi_d &= L_d I_d + \varphi_f \\ \varphi_q &= L_q I_q \end{aligned} \tag{2}$$

The PMSM model can be written as follows:

$$\begin{cases} V_d = R_s I_d + L_d \dfrac{d}{dt} I_d - \omega_r L_q I_q \\ V_q = R_s I_q + L_q \dfrac{d}{dt} I_q + \omega_r (L_d I_d + \varphi_f) \end{cases} \tag{3}$$

$$\begin{cases} \dfrac{d}{dt} I_d = -\dfrac{R_s}{L_d} I_d - \omega_r \dfrac{L_q}{L_d} I_q + V_d \\ \dfrac{d}{dt} I_q = -\dfrac{R_s}{L_q} I_q - \omega_r \dfrac{L_d}{L_q} I_d - \dfrac{1}{L_q} \varphi_f \omega_r + V_q \end{cases} \tag{4}$$

A-3 Expression of the electromagnetic torque:

$$T_e = \frac{3}{2} P[\varphi_d I_q - \varphi_q I_d] \tag{5}$$

After assigning the necessary operations we can write:

$$T_e = \frac{3}{2} P[(L_d - L_q] I_d I_q + I_q \varphi_f)] \tag{6}$$

A-4 Mechanical equations:

$$T_e - T_r - f\Omega = J \frac{d\Omega}{dt} \tag{7}$$

A-5 Model of PMSM:

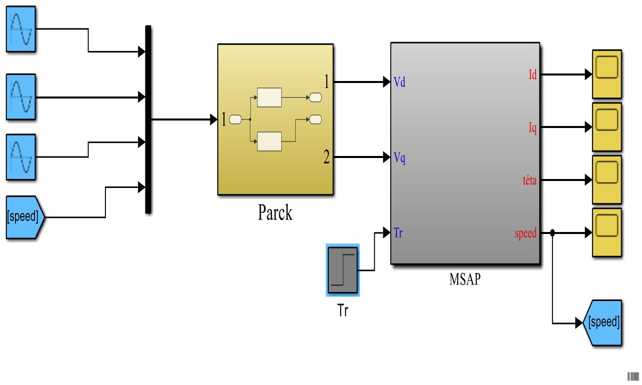


Fig.1. Model of PMSM

A-5 Characteristics of the PMSM:

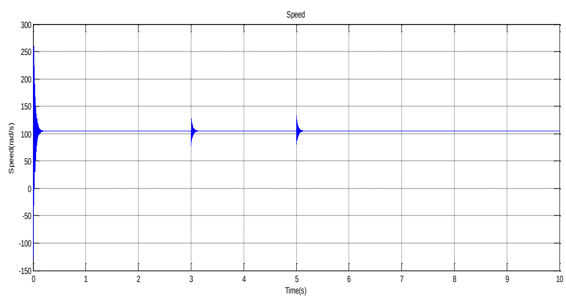


Fig.2. Speed

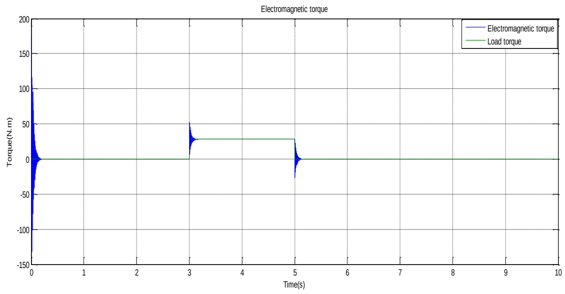


Fig.3. Electromagnetic and load torque

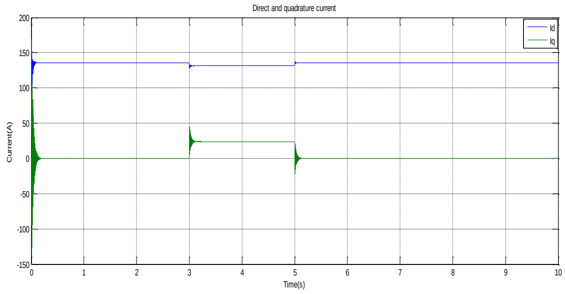


Fig.4. Direct and quadrature current

B- DTC classic

The DTC control of a permanent magnet synchronous machine is based on the direct determination of the control sequence applied to the switches of a voltage inverter. This choice is generally based on the use of hysteresis comparators whose function is to control the state of the system, i.e. the amplitude of the stator flux and the electromagnetic torque. A voltage inverter allows to reach seven distinct positions in the phase plane, corresponding to the eight sequences of the voltage vector at the output of the inverter.[4][5]

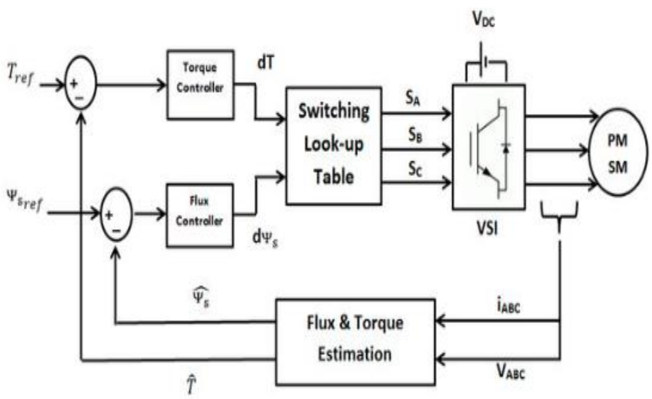


Fig.5. Synoptic diagram of the DTC control.

B-1- Estimation of stator flux and electromagnetic torque

B-1-1 Control of stator flux

Basing on the PMSM model in stationary frame, the stator flux equation can be expressed as follows

$$\hat{\varphi}s\alpha = \int (Vs\alpha - Rs \cdot Is\alpha)dt \qquad (8)$$

$$\hat{\varphi}s\beta = \int (Vs\beta - Rs \cdot Is\beta)dt$$

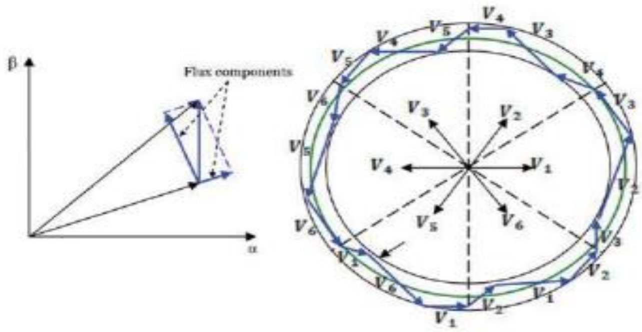


Fig.6 Evolution of stator flux vector in the complex plan

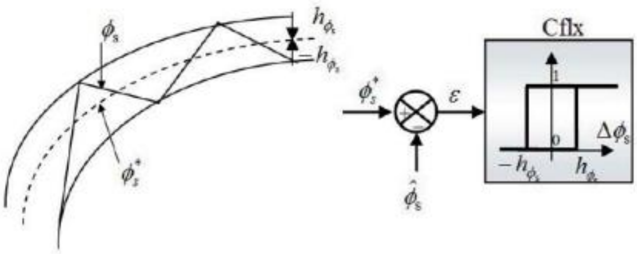


Fig.7 Two-level hysteresis comparator for stator flux control.

The logical outputs of the flux controller are defined as:

Clfx=1 if $\Delta\varphi s > h\varphi s$

Clfx=0 if $\Delta\varphi s \leq -h\varphi s$

Where $h\varphi s$ is hysteresis band of stator flux.

The stator flux error is defined by the difference between the reference value of flux and the actual estimated value: [5][6]

$$\Delta\varphi s = |\varphi s *| - |\varphi s|$$

B-1-2 Control of electromagnetic torque

The electromagnetic torque is proportional to the vector product between the stator and rotor flux vectors stator and rotor flux vectors as follows:

Ce=K($\overline{\varphi s}$*$\overline{\varphi' r}$)*sin $\delta = K\|\overline{\varphi s}\|\,\|\overline{\varphi' r}\| \sin\delta$

such as : K=P/Lq

with :

$\overline{\varphi s}$: is the stator flux vector .

$\varphi' r$: *is the rotor flux vector returned to the stator.*

δ: is the angle between the stator and rotor flux vectors

The torque therefore depends on the amplitude of the two vectors and their relative position. If we manage to control the flow perfectly $\overline{\varphi s}$ (from ($\overline{Vs}$) in modulus and position, so we can control its amplitude, and the electromagnetic torque.[5][6]

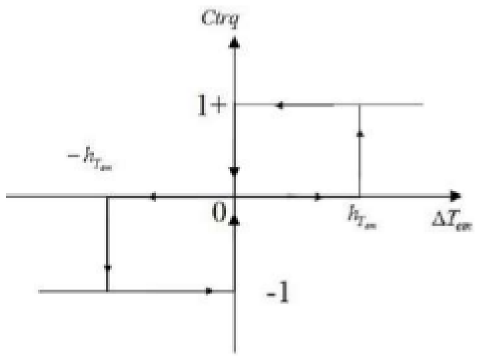


Fig.8 Three-level hysteresis comparator for stator flux control.

Ctfx=1 if $\Delta Te > hTe$

Ctrq=0 if $\Delta Te \leq \Delta Te \leq hTe$

Ctrq=-1 if $Te < -hTe$

where hTe is hysteresis band of torque.

The torque error is defined by the difference between the references values of the torque and the actual estimated values:

ΔTe = Te*-Te

B-2 Choice of voltage vectors

The choice of the vector ($\overline{Vs}$) depends:

- On the position of $\overline{\varphi s}$ in the fixed reference frame (α,β).
- Of the desired variation for the modulus of $\overline{\varphi s}$.
- Of the desired variation for the torque .
- Of the direction of rotation of $\overline{\varphi s}$.

When the flux is in a zone i, control of the flux and torque can be provided by selecting one of the following eight voltage vectors:

- If $\overline{V\iota}$+1 is selected then $\overline{\varphi s}$ grows and Ce grows
- If $\overline{V\iota}$+2 is selected then $\overline{\varphi s}$ decreases and Ce grows ;
- If $\overline{V\iota}$-1 is selected then $\overline{\varphi s}$ grows and Ce decreases ;
- If $\overline{V\iota}$-2 is selected then $\overline{\varphi s}$ decreases and Ce decreases ;

If $\overline{V0}$ and $\overline{V7}$ are selected then the rotation of the flux $\overline{\varphi s}$ is stopped; hence the torque decreases while the modulus of the flux $\overline{\varphi s}$ remains unchanged[5]

B-3 Estimation of stator flux and electromagnetic torque

B-3-1 Stator flux estimation

The amplitude of the stator flux is estimated from its two-phase components $\varphi s\alpha$ and $\varphi s\beta$:

$$\varphi s = \sqrt{\varphi s\alpha^2 + \varphi s\beta^2}$$

he area or sector in which the vector $\overline{\varphi s}$ lies is determined from the components φsα and φsβ. The angle θs between the stator reference frame and the vector is equal to:

$$\theta s = \tan^{-1}\frac{\hat{\varphi} s\beta}{\hat{\varphi} s\alpha}$$

B-3-2 **Electromagnetic torque estimation**

The produced electromagnetic torque of the induction motor can be determined using the cross product of the stator quantities (i.e., stator flux and stator currents). The torque formula is expressed as the following:

$$\widehat{Te} = \frac{3}{2} p[\hat{\varphi} s\alpha * Is\beta - \hat{\varphi} s\beta * Is\alpha]$$

B-4 Switching table construction and control algorithm design

For each sector, the vectors (Vi and V3+i) are not considered because both of them can increase or decrease the torque in the same sector according to the position of flux vector on the first or the second sector. If the zero vectors V0 and V7 are selected, the stator flux will stop moving, its magnitude will not change, and the electromagnetic torque will decrease, but not as much as when the active voltage vectors are selected. The resulting look-up table for DTC which was proposed by Takahashi is presented in Table 1. [6]

Flux	Torque	1	2	3	4	5	6	Comparator
Cflx = 1	Ctrq = 1	V_2	V_3	V_4	V_5	V_6	V_1	Two-level
	Ctrq = 0	V_7	V_0	V_7	V_0	V_7	V_0	
	Ctrq = −1	V_6	V_1	V_2	V_3	V_4	V_5	Three-level
Cflx = 0	Ctrq = 1	V_3	V_4	V_5	V_6	V_1	V_2	Two-level
	Ctrq = 0	V_0	V_7	V_0	V_7	V_0	V_7	
	Ctrq = −1	V_5	V_6	V_1	V_2	V_3	V_4	Three-level

Table.1. Look-up table for basic direct torque control.

B-5 Global scheme of conventional direct torque control

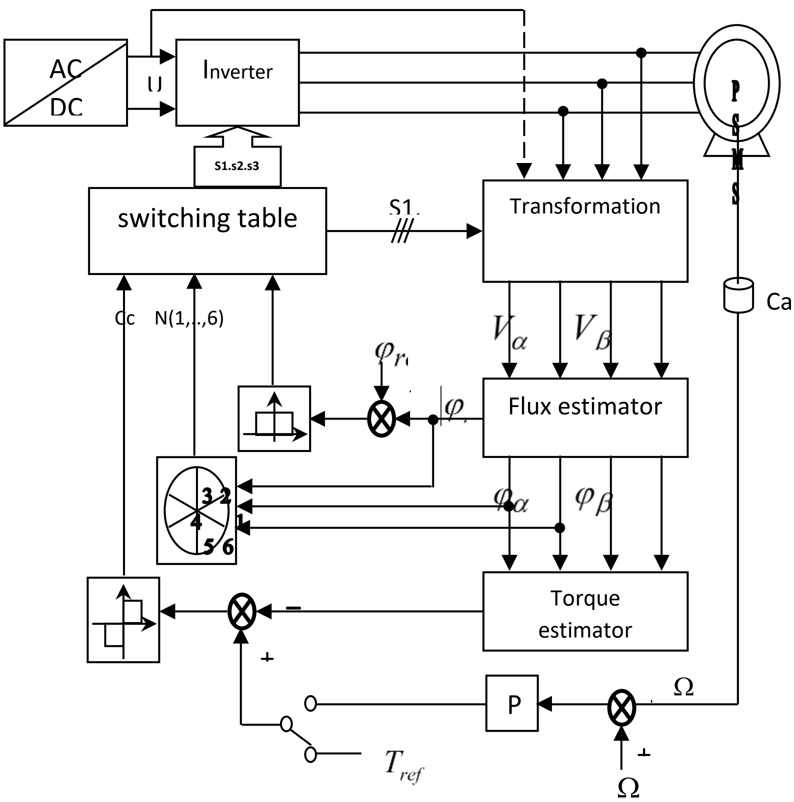


Fig.9. Global control scheme of basic direct torque control

B-6 Simulation results:

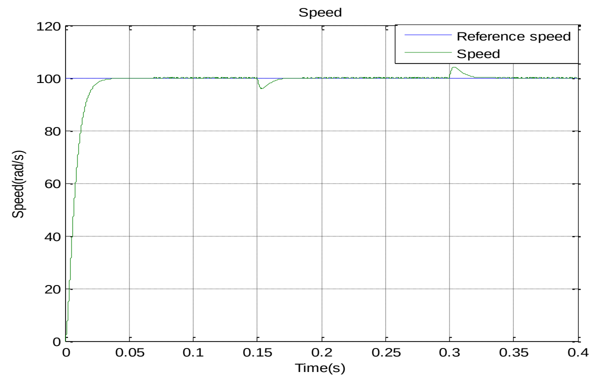


Fig 10.Speed and its reference

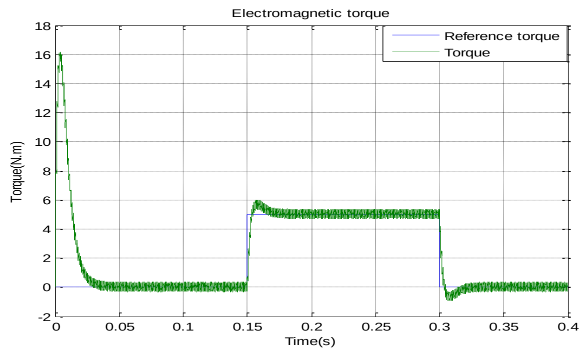


Fig 11.Electromagnetic torque and its reference

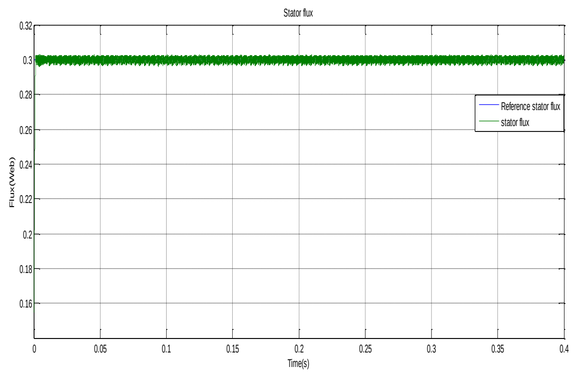
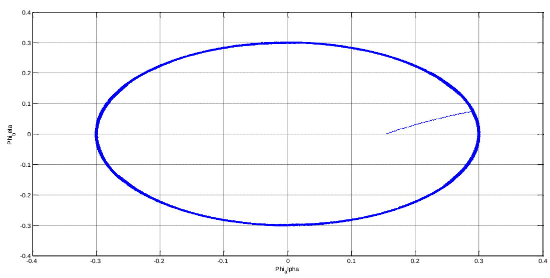


Fig 12.Stator flux and its reference



(a) $\varphi s\beta = f\ (\varphi s\alpha)$

Fig.13 Simulation results of the DTC control

III. DESIGN OF EKF OBSERVER

Accurate and robust estmation of motor variables Which are not measured is crucial for high performnmance scnsorless drves. A multitude of observers have been proposed, but only a few are able to sustain persistent and accurate Wide speed range Sensorless operation. At very low speed, theirs performances are poor One of the reasons is the high sensitivity of the observers to unmodcled nonlineaire, disturbance and model parameters detuning. The Kalman filter provides a solution that dircetly cares for the effects of disturbance noises including system and measurement noises. The errors in parameters will also normally be handled as noise . The dynamic sate model for non non linear stochastic machine is as follows where all symbols in the formulations denote matrices or vector.

X(k+1)= f (X(k),u(k))+W(k) = Ad X(k) +Bd U(k) +W(k)

Y(k) =h X(k) +V(k) = Cd X(k) +V(k)

With :

$$A_k=\frac{\partial f}{\partial X}\Big|X(k)=\hat{X}(k)$$

$$B_k=\frac{\partial f}{\partial X}\Big|X(k)=\hat{X}(k)$$

$$C_k=\frac{\partial h}{\partial X}\Big|X(k)=\hat{X}(k)$$

A- Application of the extended Kalman filter (EKF) on the PMSM:

A-1 Model of permanent magnet synchronous motor

$$\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \\ \Omega \\ \theta \end{bmatrix}=\begin{bmatrix} -\frac{R_s}{Ld} & P\Omega\frac{L_q}{Ld} & 0 & 0 \\ -P\Omega\frac{L_d}{L_q} & -\frac{R_s}{L_q} & -P\frac{\varphi_f}{L_q} & 0 \\ 0 & 0 & -\frac{f}{J} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ \Omega \\ \theta \end{bmatrix}+\begin{bmatrix} \frac{1}{L_d} \\ \frac{1}{L_q} \\ -\frac{1}{J} \\ 0 \end{bmatrix}\begin{bmatrix} V_d \\ V_q \\ Tr \\ 0 \end{bmatrix}$$

Where:

$$\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \end{bmatrix}=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ \Omega \\ \theta \end{bmatrix}$$

A-2 Discretization of the permanent magnet synchronous motor model

The corresponding discrete time model is given by:

$$X(_{k+1})=A_d.X_{(k)}+B_d.u_{(k)}$$

$$y_{(k+1)}=C_d.X_{(k)}$$

The conversion is done by the following approximation:

$$A_d=e^{At}=I+ATs$$

$$B_d=\int_0^t e^{A\xi}Bd\xi=B.Ts$$

$$C_d=C$$

We assume that time Ts is very small compared to the system dynamics. The discrete model of the step engine is given:

$$\frac{d}{dt}\begin{bmatrix} I_d \\ I_q \\ \Omega \\ \theta \end{bmatrix}=\begin{bmatrix} 1-Ts\frac{R_s}{Ld} & P\Omega Ts\frac{L_q}{Ld} & 0 & 0 \\ -P\Omega Ts\frac{L_d}{L_q} & 1-Ts\frac{R_s}{L_q} & -PTs\frac{\varphi_f}{L_q} & 0 \\ 0 & 0 & 1-Ts\frac{f}{J} & 0 \\ 0 & 0 & Ts & 1 \end{bmatrix}\begin{bmatrix} I_d \\ I_q \\ \Omega \\ \theta \end{bmatrix}+\begin{bmatrix} Ts\frac{1}{L_d} \\ Ts\frac{1}{L_q} \\ -Ts\frac{1}{J} \\ 0 \end{bmatrix}\begin{bmatrix} V_d \\ V_q \\ Tr \\ 0 \end{bmatrix}$$

The nonlinear dynamic system of step motor is shown :

$$f=\begin{bmatrix} \left(1-Ts\frac{R_s}{Ld}\right)I_d+\left(P\Omega Ts\frac{L_q}{Ld}\right)I_q+Ts\frac{1}{L_d}V_d \\ \left(-P\Omega Ts\frac{L_d}{L_q}\right)I_d+\left(1-Ts\frac{R_s}{L_q}\right)I_q-\left(Ts\frac{\varphi_f}{L_q}\right)P\Omega+\left(Ts\frac{1}{L_q}\right)V_q \\ PTs\frac{Ld-Lq}{J}I_dI_d+PTs\frac{\varphi}{J}I_q+\left(1-Ts\frac{f}{J}\right)\Omega-\left(Ts\frac{1}{J}\right)Tr \\ \Omega \end{bmatrix}$$

Determination of the F and H matrix:

The linearization matrices F and H allow us to linearize the system at each operating time. They are given as follows[5][6][7]

$$\frac{\partial F}{\partial t}=\begin{bmatrix} 1-Ts\frac{R_s}{Ld} & P\Omega Ts\frac{L_q}{Ld} & TsP\frac{L_q}{Ld}I_q & 0 \\ -P\Omega Ts\frac{L_d}{L_q} & 1-Ts\frac{R_s}{L_q} & -\frac{Ts}{L_q}P\left(L_dI_d+\varphi_f\right) & 0 \\ PTs\frac{Ld-Lq}{J}I_q & PTs\left(\frac{Ld-Lq}{J}+\frac{\varphi_f}{J}\right) & 1-Ts\frac{f}{J} & 0 \\ 0 & 0 & Ts & 1 \end{bmatrix}$$

$$h = \begin{bmatrix} I_d \\ I_q \end{bmatrix} \qquad \frac{\partial H}{\partial X} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

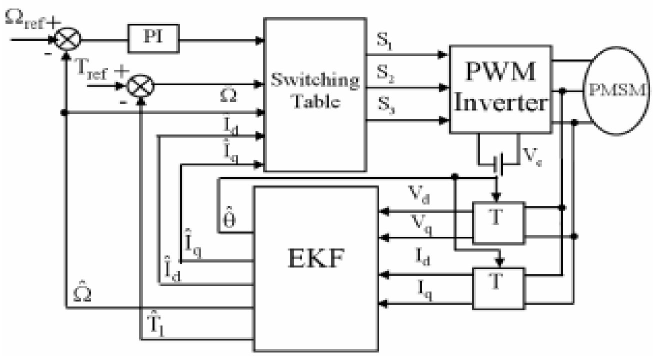


Fig 14: System of typical DTC-PMSM drive with an EFK

IV. SIMULATION RESULTS

In following figures, we present the simulations results of the DTC control using the FEE in the start with reversal of rotation direction at t=0.2s

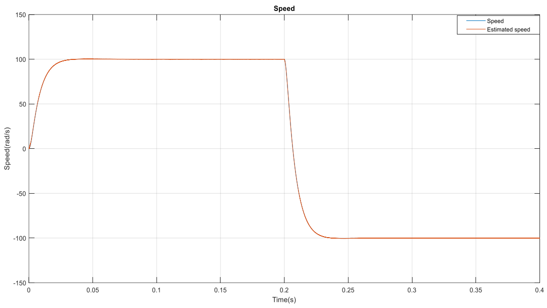


Fig 15. Speed

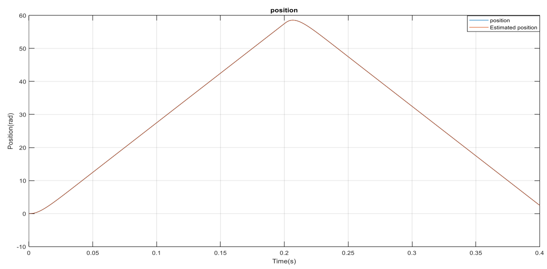


Fig 16.Position

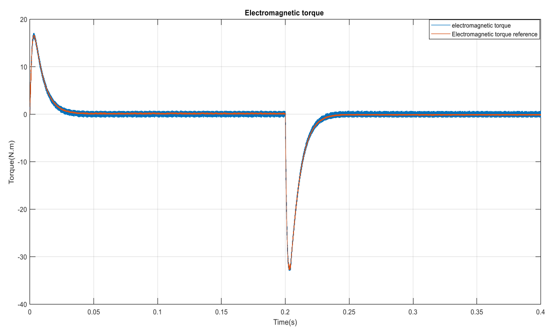


Fig 17.Electromagnetic torque and its reference

we notice that the torque perfectly follows its reference value with a negligible effect on the speed which is quickly restored to follow its reference.

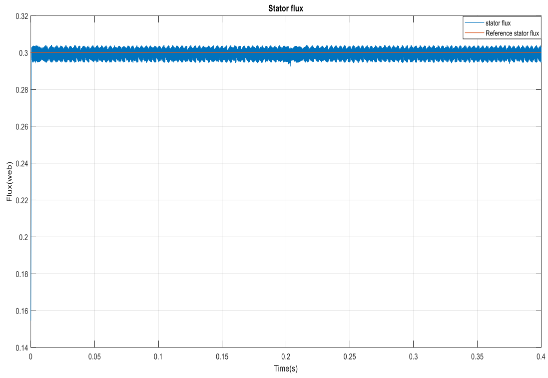


Fig 18.Stator flux

we found that the flux was not affected by the variation in the load, and the flux always follows its reference without overshoot.

Conclusion

In this paper, the direct torque control (DTC) of the MSAP with association of the inverter is presented using the Kalman filter extended for the control of mechanical speed of rotation, the electrical position of the rotor, the load torque and the stator resistance. The simulation results obtained are performed in discrete time to examine the robustness of this filter as well as the complete drive system in different operating modes. In fact , the simulation results show that this studied filter has a great robustness when applying the load torque and reversing the direction of rotation.

References

[1] Shuai Yin* , Wei Xu, and Chunlei Yu j, " Direct Torque Control of Permanent Magnet Synchronous Motor in Ship Propulsion System Based on Memory Attenuation Kalman Filter ", , *Journal of Coastal Research 2020*

[2] Amit Kumar Singh, Kashyap Kumar Prabhakar, C. Upendra Reddy, and Praveen Kumar, " A Lookup Table-Based Reference Flux Linkage Selection of Direct Torque Control Induction Motor Drive for Electric Vehicle Applications ", *An Offline Strategy 2020*

[3] Gang Yang, Xiao Jiang, Shuaishuai, " Model Predictive Direct Torque Control of Permanent Magnet Synchronous Motor (PMSM) with Online Parameter Estimation Based on Extended Kalman Filter International Journal of Communications, Network and System Sciences, July 2022

[4] Fateh Benchabane Abdenacer Titaouine, Ouafae Bennis, Khaled Yahia, Djamel Taibi, Abderazak Guettaf Sensorless direct torque control for salient-pole PMSM based on extended Kalman filter fed by AC/DC/AC converter ", *HAL open science 24.10.2012*

[5] Bousnoubra Choayb " DTC control of a permanent magnet synchronous motor with speed estimation using the KALMAN filter ", *university Larbi ben m'hidi oum el bouaghi, 2020*

[6] Fatma Ben Salem " , Direct Torque Control Strategies of Electrical Machines *"*, Book PUBLISHED January 20th, 2021

[7] Zhen Chen , Liang Wang , Xiangdong Liu " Sensorless Direct Torque Control of PMSM using Unsected Kalman Filter " T*he* 18th World Congress The International Federation of Automatic Control Milano (Italy) August 28 - September 2, 2011