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# SENSORLESS DIRECT TORQUE CONTROL OF RUSHLESS AC MACHINE USING LUENBERGER OBSERVER

**[1]Khalil. Nabti,[2]K. Abed, [3]H. Benalla**
[1,2]Student, [3]Prof. Department of Electrical Engineering, Faculty of Engineering Sciences, Ain El Bey, Constantine ,25000ALGERIA
E-mail: Idor2006@yahoo.fr, Khoudir.abed@Laposte.net, benalladz@yahoo.fr

## ABSTRACT

The sensorless DTC of Brushless AC (BLAC) machine using Luenberger observer is proposed in this paper. In Direct Torque Control (DTC), accurate rotor position information is not essential. The speed is estimated by Luenberger observer, which used to improve the performance of dynamic tracking and accuracy of the whole system. The speed regulation is realized by a conventional PI regulator. Simulation results shows small overshooting and good dynamic of the speed and torque, low ripples in torque and flux. So we verify the effectiveness of the proposed observer to monitor the drive.

**Keywords:** Sensorless BLAC, Direct Torque Control, Luenberger Observer, PI regulator.

## 1. INTRODUCTION

The PMSM control difficulty resides in the coupling of control variables such as flux and electromagnetic torque. Two principal strategies were developed almost at the same time in two different research centers, Direct Torque Control strategy was first introduced by I. Takahashi, in 1986 [1]. M. Depenbrock, develop a similar idea in 1988 under the name of Direct Self Control [2]. The DTC is one of the recent researches control schemes which are based on the decoupled control of stator flux and torque providing a quick and robust response with a simple implementation in AC drives. DTC has the advantages of simplicity, good dynamic performance, and insensitive to motor parameters except the stator resistance. In DTC strategy the speed sensor is not essential for the flux and torque estimation. Basically Direct Torque Control employs two hysteresis controllers to regulate the stator flux and torque, which results in approximate decoupling between the flux and the torque control. The key issue of DTC design is how to choose the suitable stator voltage vector to keep the stator flux and torque in their hysteresis band. The principal disadvantages of conventional DTC are: the high torque ripples and the slow transient response during start-up and during load disturbance.

In most control schemes; closed-loop control is based on the measurement of speed or position of the motor using an encoder. However, in some cases it is difficult to use sensors for speed measurement. There are several disadvantages of encoder such as higher number of connection between motor and its driver, additional cost, susceptibility to noise and vibrations, extra space, volume and weight on the motor.

Some techniques were proposed in literature. These techniques are generally based on the state observer or Luenberger observer [3], MRAS method [4]-[5], and Kalman filters [6]-[7].

In Speed sensorless strategies, the motor speed is estimated and used as a feedback signal for closed-loop speed control. In any control strategy we cannot obtain a much satisfactory response under the moment of inertia or load torque variation which generally happens, adding to sensorless drive using this kind of observer we can estimate the load torque and its variation which used to ameliorate the performance of the whole system. Luenberger observer is a special type of observer which provides optimal estimation and high performances. Simulation results showing that the method improves the Direct Torque Control system performances.

## 2. MOTOR EQUATIONS IN α,β REFERENCE FRAME

In the stationary $\alpha$-$\beta$ reference frame, the motor model can be expressed as [8]:

$$u_\alpha = R_s.i_\alpha + \frac{d\psi_\alpha}{dt}$$
$$u_\beta = R_s.i_\beta + \frac{d\psi_\beta}{dt} \qquad (1)$$

$$\begin{bmatrix}\psi_\alpha \\ \psi_\beta\end{bmatrix} = \begin{bmatrix}\cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r\end{bmatrix} . \begin{bmatrix}\psi_d \\ \psi_q\end{bmatrix} \tag{2}$$

$$\begin{aligned}\psi_d &= L_d.i_d + \psi_m \\ \psi_q &= L_q.i_q\end{aligned} \tag{3}$$

$$\begin{bmatrix}\psi_\alpha \\ \psi_\beta\end{bmatrix} = \begin{bmatrix}L_d.i_\alpha \\ L_q.i_\beta\end{bmatrix} + \psi_m . \begin{bmatrix}\cos\theta_r \\ \sin\theta_r\end{bmatrix} \tag{4}$$

The mechanical equation is given by:

$$\frac{d\omega}{dt} = \frac{1}{J}\left( p.i_{s\beta}\left( \left(L_d - L_q\right) i_{s\alpha} + \sqrt{\frac{3}{2}}.\psi_m \right) - T_L - B_m\omega \right) \tag{5}$$

If $L_d = L_q$, for smooth poles machine. The electromagnetic torque is given by:

$$T_{em} = p.i_{s\beta}\sqrt{\frac{3}{2}}.\psi_m \tag{6}$$

Where $(u\alpha, u\beta)$, $(i\alpha, i\beta)$ and $(\psi s\alpha, \psi s\beta)$ are the stator voltages, stator currents, and stator flux linkages in $\alpha$, $\beta$ reference frame, $L_d$, $L_q$ are the $d,q$ axes inductance, $R_s$ is the stator resistance. $\psi_m$ is the flux linkage of permanent magnet, $p$ is the number of pole pairs, $T_{em}$ is the electromagnetic torque, $T_L$ is the load torque, $B_m$ is the damping coefficient, $\omega_r$ is the rotor speed and $J$ is the moment of inertia.

## 3. DIRECT TORQUE CONTROL PRINCIPLES

### Flux and torque estimation and control

In stationary reference frame, the machine stator voltage space vector is represented as follows:

$$V_s = R_s \cdot i_s + \frac{d\psi_s}{dt} \tag{7}$$

$$V_s = u_{s\alpha} + j.u_{s\beta} = \sqrt{\frac{2}{3}}\left[ V_{aN} + V_{bN}\cdot e^{\left(j\cdot\frac{2\pi}{3}\right)} + V_{cN}\cdot e^{\left(j\cdot\frac{4\pi}{3}\right)} \right] \tag{8}$$

Where: $R_s$, $i_s$, $\psi_s$ stator resistance, current and flux respectively. $V_{aN}$, $V_{bN}$, $V_{cN}$ the three phase voltage inverter outputs are given as follows:

$$\begin{aligned} V_{aN} &= V_{sa} = \frac{U_c}{3}\left(2\cdot C_1 - C_2 - C_3\right) \\ V_{bN} &= V_{sb} = \frac{U_c}{3}\left(2\cdot C_2 - C_1 - C_3\right) \\ V_{cN} &= V_{sc} = \frac{U_c}{3}\left(2\cdot C_3 - C_2 - C_1\right) \end{aligned} \tag{9}$$

*Uc* is the inverter DC supply voltage, *C1, C2, C3* are the switching table outputs, and they are relevant to the switching strategy.

From (7) we can estimate the stator flux as follow:

$$\psi_s = \psi_{s0} + \int\left(v_s - R_s.i_s\right)dt \tag{10}$$

$$\left\|\psi_s\right\| = \sqrt{\psi_{s\alpha}^2 + \psi_{s\beta}^2} \tag{11}$$

$\psi_s$ is the stator flux vector, and $\psi_{s0}$ is its initial value.

For simplicity, it is assumed that the stator voltage drop $R_s.is$ is small and neglected, the stator flux variation can be expressed as: $\Delta\psi_s \approx V_s.\Delta t$.

The change of torque can be controlled by keeping the amplitude of the stator flux linkage constant and by controlling the rotating speed of the stator flux linkage as fast as possible. It's shown in this section that both the amplitude and rotating speed of the stator flux linkage can be controlled by selecting a proper stator voltage vectors as shown in figure 1. The primary voltage vector $V_s$, is defined by the equation (8)

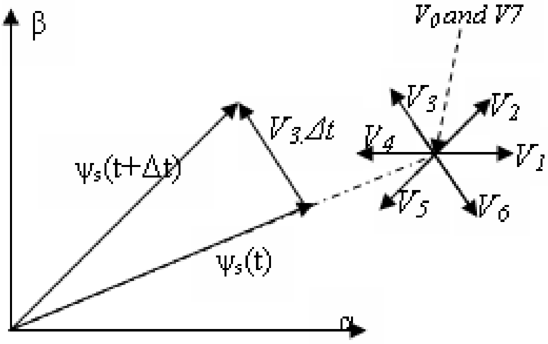

Figure.1. Stator flux variation in stationary (α, β) frame

In DTC technique, the inverter switches are controlled using the flux and torque errors, and the position of the stator flux within the six-region control of the motor. The flux and torque errors are evaluated as follows:

$$\Delta\psi = \psi_{sref} - \psi_s \tag{12}$$

$$\Delta T = T_{ref} - T_{em} \tag{13}$$

$$\theta = tg^{-1}\left(\frac{\psi_\beta}{\psi_\alpha}\right) \tag{14}$$

Where $\theta$ is the angle between stator flux vector and $\alpha$ axis, $\psi_{s\alpha}$, $\psi_{s\beta}$ are the stator flux components in $(\alpha, \beta)$ reference frame.

**Switching table**:

In order to determine the inverter switching pattern using flux and torque errors, for the flux and torque control two hysteresis controllers are employed. The inverter is switched based on these errors and position of the stator flux within the six-region control as can be seen from Table 1, in such a way that the inverter output voltage vector minimizes the flux and torque errors and determines the out-put flux rotation direction of these controllers.

Table.1. DTC switching table

| n | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Flux | Couple | | | | | | |
| $K_\psi$=1 | $K_{Cem}$=1 | $V_2$ | $V_3$ | $V_4$ | $V_5$ | $V_6$ | $V_1$ |
| | $K_{Cem}$=0 | $V_7$ | $V_0$ | $V_7$ | $V_0$ | $V_7$ | $V_0$ |
| | $K_{Cem}$=-1 | $V_6$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $V_5$ |
| $K_\psi$=0 | $K_{Cem}$=1 | $V_3$ | $V_4$ | $V_5$ | $V_6$ | $V_1$ | $V_2$ |
| | $K_{Cem}$=0 | $V_0$ | $V_7$ | $V_0$ | $V_7$ | $V_0$ | $V_7$ |
| | $K_{Cem}$=-1 | $V_5$ | $V_6$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ |

## 4. CONTROL STRUCTURE

Figure (2) illustrates the BLAC drive scheme considered in this investigation. The drive consists of a Luenberger observer for speed estimation, flux and torque controllers, space flux position, and brushless AC machine. The rotor speed $w_r$ is compared with the reference speed $w_{ref}$. The resulting error is processed in the PI speed controller for each sampling interval. The output of this is considered to be the reference torque $T_{ref}$.

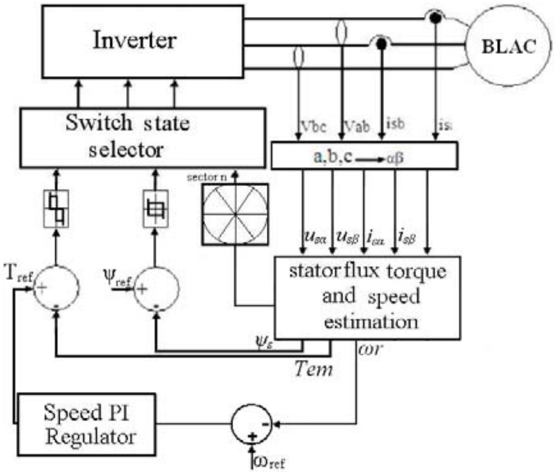

Figure.2. A direct torque control scheme

## 5. SPEED ESTIMATION USING CONVENTIONAL APPROACH

Since a stator flux-linkage is required in order to implement direct torque control, the estimation of rotor speed from a stator flux-linkage is common. After calculating equation (1), the angular position of the stator flux-linkage vector can be obtained as in [6] and [9]:

$$\theta = arctan\left(\frac{\psi_{s\beta}}{\psi_{s\alpha}}\right) \tag{15}$$

Therefore, the rotational speed of the stator flux linkage is given as:

$$\omega = \frac{d\theta}{dt} \approx \frac{\theta(k) - \theta(k-1)}{T_s} \tag{16}$$

Where $\theta(k)$ and $\theta(k-1)$ represent the position of the stator flux-linkage vector at sample time $t_k$ and $t_{k-1}$ respectively and $Ts = (t_k - t_{k-1})$.

## 6. SPEED ESTIMATION USING LUENBERGER OBSERVER

The objective here is to use a speed observer in order to delete all mechanical sensors. We estimate the rotation speed and load torque using the measured currents and voltage, and the speed estimated by classical method.

In the stator flux reference frame, the developed torque is: [10]-[11]

$$T_{em} = \sqrt{\frac{3}{2}}.p.\psi_m.i_{s\beta} \tag{17}$$

Where $i_{s\beta}$ is the quadrate component of the stator current vector, $\psi_s$ is the stator flux magnitude, and $p$ is the number of pole pairs.

From (5) and (17)

$$\begin{aligned} \frac{d\omega}{dt} &= \frac{1}{J}\left(\sqrt{\frac{3}{2}}.p.(\psi_m i_{s\beta}) - T_L - B_m.\omega\right) \\ \frac{dT_L}{dt} &= 0 \end{aligned} \tag{18}$$

The second order Luenberger observer (shown in Figure3) is given by: [12]

$$\begin{cases} \dot{\hat{X}} = A.\hat{X} + B.U + L(Y - \hat{Y}) \\ \hat{Y} = C.\hat{X} \end{cases} \tag{19}$$

With:

$$\hat{X} = \begin{bmatrix} \hat{\omega} \\ \hat{T}_L \end{bmatrix}; \quad L = \begin{bmatrix} l1 \\ l2 \end{bmatrix} \tag{20}$$

We have finally:

$$\begin{bmatrix} \frac{d}{dt}\hat{\omega} \\ \frac{d}{dt}\hat{T}_L \end{bmatrix} = \begin{bmatrix} \frac{-f}{J} - l_1 & \frac{-1}{J} \\ -l_2 & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega} \\ \hat{T}_L \end{bmatrix} + \begin{bmatrix} \sqrt{\frac{3}{2}}\frac{p\psi_m}{J} \\ 0 \end{bmatrix} (i_{s\beta}) + \begin{bmatrix} l_1 \\ l_2 \end{bmatrix} .\omega_{classi} \tag{21}$$

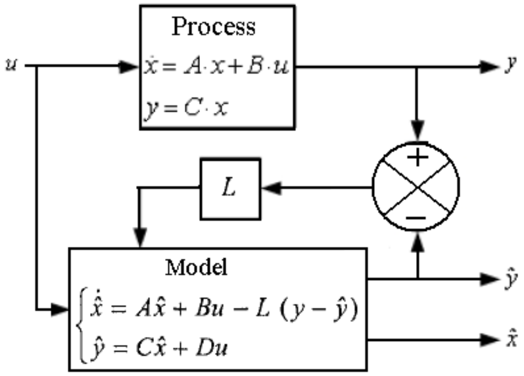

Figure.3. Principle Observer diagrams

The matrix L determines how fast the simulation error approaches zero and should be chosen carefully to achieve good stability and a nice response of the observer.

## 7. SIMULATION RESULTS

To verify the technique proposed, digital simulations based on MATLAB/SIMULINK have been implemented.

The PMSM used for the simulations has the following parameters (presented in table 2) [8]:

Uc = 350[V], f = 50[Hz], Rs = 0.3[Ω], Ld = 3.366[mH], Lq = 3.366[mH], J = 10.8e-5[Kg/m$^2$], Bm = 0[Nm/rad/s], $\psi_m$ = 0.0776[V/rad/s], p = 5.

Conventional PI regulator coefficient:

ki = 0.0553; kp =1.441.

For proposed method and conventional DTC the dynamic responses of speed, flux, and torque for the starting process without load *Tl*=0, we applied a load torque equal to *Tl*=7Nm at 0.6s, at t=1.7s we remove the load torque.

We Inverse the speed at t=1s.

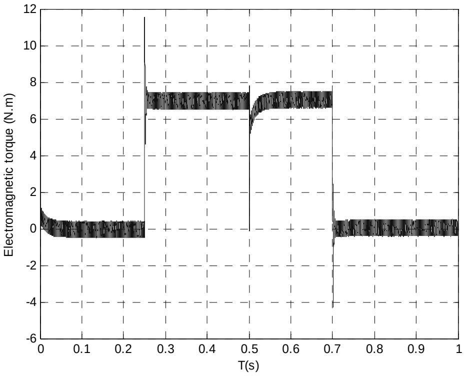

Figure.4. Electromagnetic torque response.

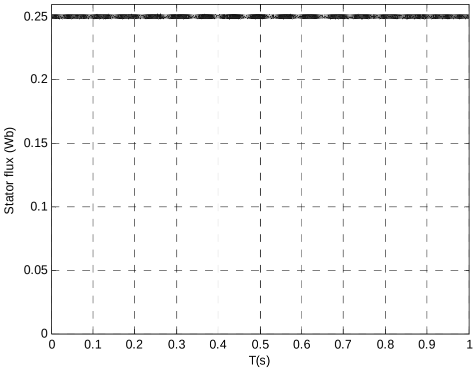

Figure.5. Stator flux response.

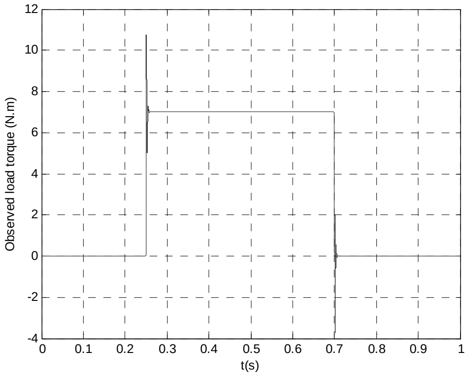

Figure.6. Observed load torque using Luenberger observer.

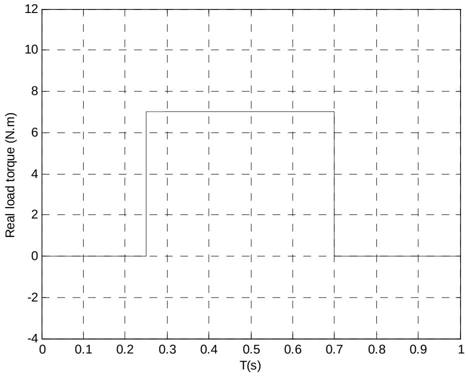

Figure.7. Real load torque.

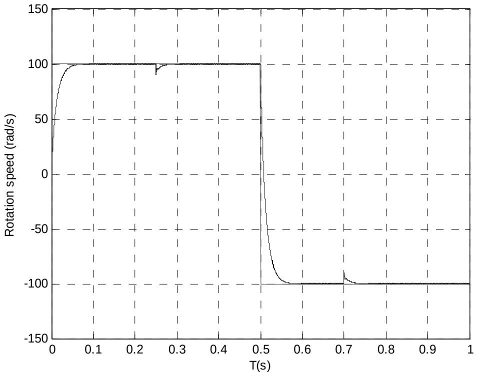

Figure.8. Rotation speed observed using Luenberger observer.

Figure 8 represents the robustness and dynamic response of the speed observed using Luenberger observer with the step change of reference.

The comparison between classical estimated speed and the speed observed is shown in figure 9.

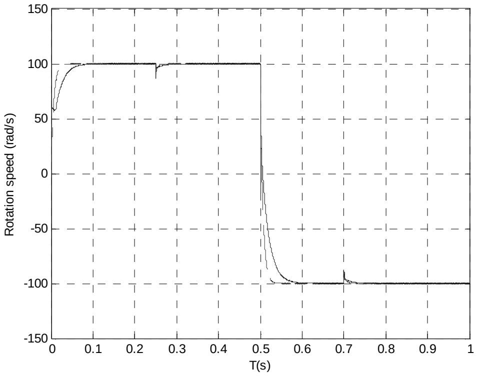

Figure.9. Comparison between classical estimated speed and observed Speed using Luenberger observer (dashed line).

For Luenberger observer method good dynamic response in speed without overshooting in starting and inversion, we observe an influence of load disturbances and at the inversion in torque response as shown in figure 4. No influences observed in flux response when load disturbance application and at the inversion as seen in figure 5. The observed load toque shown in figure 6 is similar to the real load torque applied figure 7 with a small overshooting in transient response.

Figure 9 shows that Luenberger observer method gives very fast response and good dynamic comparing with classical method.

## 8. CONCLUSION

In this paper, Sensorless direct torque control scheme using two types of speed estimator, one is based on the angle of the stator flux linkage; the other is based on Luenberger observer for speed and load torque estimation are presented. The simulation results show that both methods can well estimate the speed of the brushless AC machine; the first method makes the selected voltage vector incorrect, the motor unsteady. The speed estimator that is based on Luenberger observer can make the motor start steadily and have good dynamic. Compared to the sensorless based on the angle of stator flux linkage, the second method decrease considerably the ripples of both torque and flux. The scheme of speed estimator based on Luenberger observer is proved by the simulation that it is simple and easy to implement in sensorless DTC system of super high-speed of BLAC machine.

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## STATES OF THE ARTS

In this table we present the state of the art of sensor less control, and no paper studied sensorless DTC of BLAC machine using Luenberger observer which confirm the originality of this idea

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|---|---|
| [1] R. Ghosn (2001). Contrôle vectoriel de la machine asynchrone à rotor bobiné à double alimentation. Thesis for a doctoral degree, LEEI-INSEEIHT, Toulouse. | In this thesis, speed sensorless control of indirect field oriented for doubly fed induction machine drives is studied. Several kinds of speed estimator are presented; one is based on the angle of the rotor flux linkage. In the second method the stator flux based MRAS (SF-MRAS) is used for estimating the rotor speed. 2$^{nd}$ order Leunberger observer is the third method studied, in where the reference speed is estimated by SF-MRAS method. |
| [2] L. Yong, Z. Zi-Qiang, H. David. Simplified EKF Based Sensorless Direct Torque Control of Permanent Magnet Brushless AC Drives. International Journal of Automation and Computing Volume 1, Number 1/ October 2004. | A simplified extended Kalman filter (EKF) based sensorless direct torque control technique for brushless AC machine is presented. Its performance is compared with that obtained with other sensorless methods for estimating the rotor speed and position from a stator flux-linkage. |
| [3] A.R. Haron, N.R.N. Idris,. "Simulation of MRAS-based speed sensorless estimation of induction motor drives using MATLAB/SIMULINK". Power and Energy Conference, 2006 PECon '06 IEEE International 28-29 Nov. 2006 Page(s):411 – 415. | In this work, the performance of the rotor flux based MRAS (RF-MRAS) and back e.m.f based MRAS (BEMF-MRAS) for estimating the rotor speed was studied. |
| [4] B. Chunyuan R, Shuangyan M, Liangyu. Sensorless DTC of Super High-speed PMSM. Automation and Logistics, 2007 IEEE International Conference on, Publication Date 18-21 Aug. 2007, page(s): 3060-3064. | The object studied in this investigation is the super high-speed permanent magnet synchronous micro-turbine generators. Two kinds of speed estimator are presented, one is based on the angle of the stator flux linkage; the other is based on the angle of the rotor flux linkage. |