Observer based Speed Estimation method for Sensorless Vector Control of a Permanent Magnet Synchronous Machine

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Abstract- This research work is performing a study robustness of the law control by flow orientation and sensorless vector control by using a Lumberger observer. After mathematical modelling of PMSM, The synchronous machine is fed by a voltage inverter controlled by PWM technology (Pulse Width Modulation). Furthermore, only the motor speed is sensed. The control law aim is to minimize the effects of these variations while keeping the performance inside industrial specifications. As a result, a Lumberger observer is programmed jointly with a controller to estimate the speed rotation. The results are more than satisfactory and prove without any suspicion that presents a very small estimation error for the speed rotation. The simulation results show the effectiveness of the Luenberger observer and presents a good insensitivity to the parametric variations of the motor and the load application.

Key Words: vector control, sensorless PMSM, state observer, dynamic model.

I. INTRODUCTION

The appearance of permanent magnet synchronous machines (PMSM) in the world of electric actuators. The use of these machines have opened new opportunities through their operations in trajectory tracking for especially the machine tool and robotic due to the simplicity of the position and speed control. However, many researches have been concentrated on the elimination of the mechanical sensors at the motor shaft (encoder, resolver, Hall-effect sensor, etc.) without deteriorating the dynamic performances of the drive. Many advantages of sensorless AC drives such as reduced hardware complexity, low cost, reduced size, cable elimination, increased noise immunity, increased reliability and decreased maintenance. Speed sensorless motor drives are also preferred in hostile environments, and high-speed applications [1]. In recent years, the sensorless control systems have been researched to solve the above disadvantages. It can eliminate the need for speed sensors, so the structure of control system is more simple, the costs is reduced, meanwhile, the stability and control precision are improved. With the rapid development of control theory, digital signal processing and computer technology, the sensorless vector control technology is researched more widely. The speed sensorless control of PMSM drive can overcome above difficulties [2].

The studies have shown different methods of sensorless vector control. They are all based on the use of certain electrical variables, currents and voltages, to estimate the rotational speed of the rotor, according to a representative model of the machine. We can distinguish three different categories:

1. Methods based on the local saturation of the magnetic circuit.
2. Methods based on the estimation of the e.m.f.
3. Methods using a state observer [3].

A state observer utilizes measurements of the system inputs and outputs and a model of the system based on differential or difference equations. Observers are algorithms that combine sensed signals with other knowledge of the control system to produce observed signals [4].

The goal of this paper is to propose a speed sensorless methodology based on the Luenberger observer applied in permanent magnet synchronous machines (PMSM). The paper is organised as follows: The permanent magnet synchronous machines model systems is described in section 2. A brief introduction on field-oriented control methodology is presented in section 3. On finds in section 4, the sensorless control by Luenberger observe is illustrated. At the end the simulation results and theirs discuss are presented. A conclusion is given, at the end of this paper.

TABLE I
Operational parameters of the PMSM

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>V</td>
<td>100V</td>
</tr>
<tr>
<td>Resistance Phase</td>
<td>R</td>
<td>0.8Ω</td>
</tr>
<tr>
<td>Cyclic inductance on the direct axis</td>
<td>$L_d$= $L_q$</td>
<td>0.0011H</td>
</tr>
<tr>
<td>Cyclic inductance on the transverse axis</td>
<td>$L_s$= $L_r$</td>
<td>0.0011H</td>
</tr>
<tr>
<td>Amplitude of the flux of the permanent magnets</td>
<td>$\Psi$</td>
<td>0.2Wb</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>$J$</td>
<td>0.00011kg.m²</td>
</tr>
<tr>
<td>Coefficient of viscous friction</td>
<td>$f$</td>
<td>0.0000019N.m/rad</td>
</tr>
</tbody>
</table>

II. MODELING THE MACHINE

The permanent magnet motors are similar to the salient pole motors, except that there is no field winding and the field is provided instead by mounting permanent magnets in the rotor. The excitation voltage can’t be varied. The elimination of field coil, dc supply and slip rings reduces the motor loss and complexity. These motors, also known as “Brushless motors” are finding increasing applications in robots and machine tools [4].

The PMSM model can be derived by taken the following assumptions into consideration [1]:

- The induced EMF is sinusoidal;

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</tbody>
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Eddy currents and hysteresis losses are negligible.

There is no cage on the rotor.

The stator and rotor flux equation of PMSM can be written in the reference frame of Park in the following form [5].

\[
\begin{align*}
\Psi_d &= L_d i_d + \Psi_f \\
\Psi_q &= L_q i_q
\end{align*}
\] (1)

While the equations of the stator voltages are written in this same reference frame in the following form:

\[
\begin{bmatrix}
\Psi_d \\
\Psi_q
\end{bmatrix} =
\begin{bmatrix}
R_d + L_d s & -P \Omega L_q \\
P \Omega L_d & R_q + L_q s
\end{bmatrix}
\begin{bmatrix}
i_d \\
i_q
\end{bmatrix} +
\begin{bmatrix}
0 \\
P \Omega \Psi_f
\end{bmatrix}
\] (2)

Finally, the developed electromagnetic torque can be expressed as:

\[
C_e = \frac{3}{2} p \Psi_f i_d
\] (3)

The conversion of electrical energy into mechanical energy in synchronous machines is governed by the following equation:

\[
J \frac{d}{dt} \Omega = C_e - C_L - C_f
\] (4)

With:

- \( L_d \): Inductance in the longitudinal axis or directly;
- \( L_q \): Inductance quadrature axis or transverse;
- \( P \): Number of pairs of poles;
- \( p \Psi_f i_d \): That the torque will be obtained with a machine with smooth poles;
- \( \Psi_f \): Which corresponds to the flux coupling between the rotor and the stator;
- \( C_L \): Is the load torque or load torque imposed on the machine shaft;
- \( J \): Moment of inertia of the rotating parts of the machine set – load;
- \( C_f \): Electromagnetic torque;
- \( C_f = f \Omega \): The friction torque. \( f \) is the friction coefficient \( \Omega \): The mechanical rotation speed (\( \omega = \Omega \));

III. FIELD-ORIENTED CONTROL

In control a major problem, the model of PMSM is a multivariable and highly coupled system, faced with this complexity vector control produced a decoupling between the control variables of the PMSM and therefore makes it possible to obtain a linear dynamic model similar to that of a DC motor. The current control and speed commands in the repository Park naturally by digital controllers.

A. Principle

In this case, the machine is without saliency and without absorber, the magnets being arranged on the surface of the rotor. This technical consists to maintaining the reaction armature flux in quadrature with the rotor flux produced by the system of excitation like in case of the machine of DC. For an optimal working with a maximum torque, the simplest solution for a synchronous machine is to maintain the direct current equal to zero \( i_d = 0 \), and to control the speed by the quadrature current \( i_q \) with the voltage \( Uq \)[6]. To obtain a reduced and decoupled model of the machine, the expression of the electromagnetic torque becomes:

\[
C_e = \frac{3}{2} p \Psi_f i_d
\] (6)

As the flow is constant, the torque is directly proportional to \( i_q \):

\[ C_e = K_i i_q \]

With:

- \( K \): coefficient depends on the machine

![Fig. 1. Principle of field-oriented control of PMSM](image)

The \( d \) axis stator current component plays the role of the excitement and adjusts the value of the flux in the machine. The \( q \) axis component acts as the induced current and can control the torque.

The Vector Control then controls to the two components \( (i_d) \) and \( (i_q) \) of the stator current by imposing voltages \( (v_d) \) and \( (v_q) \) that fit. To impose voltages \( (v_d) \) and \( (v_q) \), simply impose the reference voltages \( (V_{qref}) \) and \( (V_{dref}) \) at the input of the inverter. Using the controller we get the reference currents \( (i_{qref}) \) and \( (i_{dref}) \) [9]. The global pattern of the principle of PMSM vector control is shown in the figure:

![Fig. 2. Global scheme of vector control with conventional PI control](image)

B. Regulation

The control of current vector control is reduced to two internal loops are made for the direct control of the flux and torque.

B.1. Flow Corrector

The flow is controlled by proportional and integral corrector (PI) whose transfer function is:

\[
\text{Reg}.d(s) = \frac{K_{id}}{s} \left(1 + \frac{K_{id}}{R_{id} s}\right)
\] (7)

The loop flow corrector is shown in figure:
To determine the $K_p$ and $K_i$ parameters of the corrector, simply compensate the dynamics of the system by the zero introduced by the latter. The way forward consist on beginning the compensation time constant of the system, putting:

$$\frac{K_{pd}}{K_{iq}} = \tau_d$$

**B.2. Torque Corrector**

Reg $q$ has the same form of Reg $d$ with the transfer functions form is:

$$R_{eq}(s) = \frac{K_{iq}}{\tau_d} \left(1 + \frac{K_{pd}}{K_{iq}} s\right)$$

(8)

The loop torque corrector is shown in figure:

![Fig. 4. Torque loop controlled by a PI](image)

With:

$$F_q(s) = \frac{\frac{1}{\tau_q}}{1 + \tau_q s} = \frac{i_q}{v_{iq}}, \quad T_q = \frac{L_q}{R_q}$$

By posing:

$$\frac{K_{pq}}{K_{iq}} = \tau_q$$

The current loops therefore correspond to a first order, simply set the system dynamics through an appropriate choice of $\tau_d$ and $\tau_q$. These are chosen such that the time constant of the controlled closed loop system to be less than the time constant in an open loop [10].

**B.3. Speed Corrector**

When the current loop correction is enabled, it is possible to put in place and in cascade a desired speed loop. The speed corrector allows the determination of the reference torque to maintain the speed constant. [9][10].

The block diagram of the speed control is given by:

![Fig. 5. Speed Control](image)

Is added to the loop filter to remove the excess due to the existence of a (zero) in the FTBF system (Machine + PI Corrector). An integral action is necessary to cancel the error in steady state.

**IV. THE SENSORLESS CONTROL BY LUENBERGER OBSERVE**

The Luenberger reduced observer reconstructs the state variables based on the knowledge of inputs and outputs of the system. The outputs of the observer are induced voltages of the motor [7].

The structure of an observer of state is illustrated by the figure (6), it is based on a model of the system, called the estimator or predictor, functioning in open loop. The complete structure of the observer includes a loop of corrective matrix gain, allowing correcting the error between the output of the system and that of the estimator [6].

![Fig. 6. Block diagram of an observer of reduced-order Luenberger](image)

The observer dynamics:

$$\begin{cases}
\dot{\hat{x}} = A\hat{x} + B\cdot u + L(y - \hat{y}) \\
\hat{y} = C \cdot \hat{x}
\end{cases}$$

(9)

The general state space model is given in (9), where $A$ is the system matrix, $B$ is the input matrix, $y$ is the output vector and $C$ is the output matrix. The output vector $y$ is compared with the equivalent vector $\hat{y}$ given by the observer to operate in a closed loop.

$$\begin{cases}
\hat{x} = A\hat{x} + B\cdot u + L(x - \hat{x}) \\
\hat{y} = C \cdot \hat{x}
\end{cases}$$

(10)

Introducing the estimation error:

$$e(t) = x(t) - \hat{x}(t)$$

(11)

The dimensioning of corrective matrix gain $L$ carried out to assure the convergence as soon as possible between the model of the estimator and the real system, Thus, by a wise
choice of the matrix gain (L), we can modify the dynamics of the observer and consequently evolve the speed convergence of the error to zero, while preserving the condition on the matrix \((A-\text{LC})\) which must be a Hurwitz matrix [6].

\[ \hat{x}(t) \text{ is a good estimate of } x(t) \text{ where } e(t) \xrightarrow{t \to \infty} 0. \]

Is obtained:

\[ \dot{e}(t) = (A - LC)e(t) \quad (12) \]

Part \((A,C)\) is observable, so we can choose the matrix with \(L\) gain of the observer so that \(A - LC\) takes all its own values with negative real parts, which ensures the convergence to zero of \(e(t)\) when \(t \to \infty\).

The main objective of the Luenberger observer is to observe the speed and the load torque from the set of stator current of the PMSM [8].

Therefore, in this study we choose the model of a Luenberger observer, and we will apply the system (Permanent Magnet Synchronous Machine + Vector Control).

Choosing the currents \(i_d\) and \(i_q\) as parameters to be estimated by the observer, and we take speed from the machine response.

\[
\begin{align*}
\frac{d\hat{i}_d}{dt} &= -\frac{R_s}{L} \hat{i}_d + P\Omega i_q + \frac{1}{L} v_d + K_d(i_d - \hat{i}_d) \\
\frac{di_q}{dt} &= -\frac{R_s}{L} i_q + P\Omega i_d - \frac{\Psi_p}{L} \omega + \frac{1}{L} v_q + K_q(i_q - \hat{i}_q)
\end{align*}
\]

\(K_d\) and \(K_q\): gain error correction currents \(i_d\), \(i_q\) respectively.

The errors equations are obtained by the difference between the model equations of the machine and the equations of the observer as:

\[
A = \begin{bmatrix} -\frac{R_s}{L} & P\omega \\ -P\omega & -\frac{R_s}{L} \end{bmatrix}; \quad \hat{A} = \begin{bmatrix} -\frac{R_s}{L} & P\omega \\ -P\omega & -\frac{R_s}{L} \end{bmatrix}
\]

\[
A - \hat{A} = \frac{1}{L} \begin{bmatrix} R_s - \hat{R}_s & 0 \\ 0 & R_s - \hat{R}_s \end{bmatrix} = \begin{bmatrix} \frac{-\Delta R_s}{L} & 0 \\ 0 & \frac{-\Delta R_s}{L} \end{bmatrix}
\]

After calculations, we obtain:

\[ \dot{e}(t) = (A - KC)e + \begin{bmatrix} \frac{-\Delta R_s}{L} & 0 \\ 0 & \frac{-\Delta R_s}{L} \end{bmatrix} \hat{e} \quad (14) \]

V. SIMULATING RESULTS

For the validation of the theoretical study, we made simulations using Simulink / Matlab. The curves on Fig.7 show the responses model of the Permanent Magnet Synchronous Machine (PMSM).

For currents \(i_d\) and \(i_q\) (Fig.7.a,b) during start-up, we observe current peaks that are quite significant. In fact, and after a very short time, the current stabilized at their nominal values. Regarding the instantaneous torque (Fig.7.c), we can report the presence of oscillations in the power for a very short time when starting. A strong current surge appears and which is necessary to develop a couple for the machine to produce a rotational movement. However, after the disappearance of the transitional arrangements, the couple tends to zero as we train engine without load. The velocity curve (Fig.7.d) shows strong oscillations during the transient regime, this regime lasts 0.02 s drunk, and thereafter the rate converges to its rated speed of 157 rad/sec. Steady state at time \(t = 0.2s\), we apply a load which causes a change in speed for a short time (oscillations) and then stabilizes in synchronism and resumed the steady state.

![Fig. 7. PMSM Responses in the dq reference frame with the application load](image)
VI. CONCLUSION

In this article, we discussed the simulation of a PMSM model powered by an inverter. The simulation results shown above govern the behaviour of the machine with load without introducing the control appearance. The strong coupling and non-linearity between the variables of the PMSM make the development of an efficient control law to bring the PMSM to operate in very difficult or impossible nominal conditions. The simulation results show that the decoupling is maintained, the dynamic tracking point is satisfactory and disturbance rejection is effective. The application of the sensorless vector control based on the Luenberger observer brought remarkable improvements in the dynamics of the machine and the static regime. Test robustness of this control has been proven, and the simulation results shown in Figures justify and confirm this deduction. To this end, we can say that the assumptions imposed in the specification have been successfully validated.

VII. REFERENCES


