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Research Article

Impact of PLL Parameters Variation on the Pulsating Voltage Injection Technique Based PMSM Position Estimation at Low Speeds

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Abstract: This study highlights the impact of an universal Phase Locked Loop (PLL) parameters variation on PMSM position estimation at low speeds. Indeed, the PLL parameters variation impact on the PMSM rotor position estimation performance and robustness cannot be neglected anymore. For this purpose, the study presents the theory and simulation results of a demodulation scheme applied to Sensorless PMSM control based on the Pulsating Voltage Injection (PVI) technique. Comprehensive simulations, carried out under MATLAB/SIMULINK®, are discussed according to the variation of the PLL proportional and integral parameters.

Keywords: Demodulation scheme, low speeds, Permanent Magnet Synchronous Motor (PMSM), Phase Locked Loop (PLL), Pulsating Voltage Injection (PVI) technique, rotor position estimation

INTRODUCTION

Sensorless techniques used for Permanent Magnet Synchronous Motor (PMSM) control are primarily based on two main categories; fundamental model-based techniques such as Back-EMF Observer, Flux modulation and Kalman Filter (Paramasivam and Arumugam, 2004; Boucetta, 2008; George, 2008; Asseu *et al*., 2011) and anisotropies-based techniques (Aihara *et al*., 1999; El Murr *et al*., 2008; Kechiche *et al*., 2011).

The first sensorless techniques category fails at low speed due to their sensitivity to the machine parameters estimation errors. High performance position control at low speeds is only possible using the second sensorless techniques category.

Some of the techniques based on anisotropies are those based on High Frequency Signal Injection (HFSI) techniques. An interesting field of research is related to the Pulsating Voltage Injection (PVI) technique in order to estimate the PMSM rotor position, (Aihara *et al*., 1999; El Murr *et al*., 2008; Kechiche *et al*., 2011).

In PVI scheme, PMSM position extraction requires the use of a Phase Locked Loop (PLL) structure, (El Murr *et al*., 2008; BelHadj Brahim *et al*., 2011; Kechiche *et al*., 2011). This technique is independent from PMSM parameters but the position estimation precision depends on PI parameters of the used PLL. In fact, to maintain stability and perform accurate position estimation, some restrictions are required for the PLL: the error between the estimated and actual rotor position should be small and the input carrier frequency should be synchronized with the demodulator carrier frequency. In another hand, the position error precision differs from an application to another.

Usually, it is very difficult to set the PI controller parameters of the PLL estimator since there is not a standard method to perform the controller parameters. Besides, it is very complicated to determine the transfer function of the system.

In this study, a universal PLL is considered to study the PI controller parameters variation impact on the rotor position estimation performance.

MATERIALS AND METHODS

High frequency PMSM model: The salient pole PMSM model used in this study is considered in the (d, q) rotor reference frame, where the d-axis is oriented along the permanent magnet flux and the q-axis is perpendicular to it.

This model is available in the following conditions (Boucetta, 2008; Feraga *et al*., 2009; Kechiche *et al*., 2011; Asseu *et al*., 2011):

- The induced EMF is supposed sinusoidal.
- The magnetic circuit motor is not saturated and the rotor amortization effect is neglected.
- The air-gap irregularities due to stator notches are ignored.
- The Eddy currents and hysteresis losses are neglected.
- The stator resistances temperature effect is ignored.

In the (d, q) reference frame, the stator voltage components are given by Eq. (1):

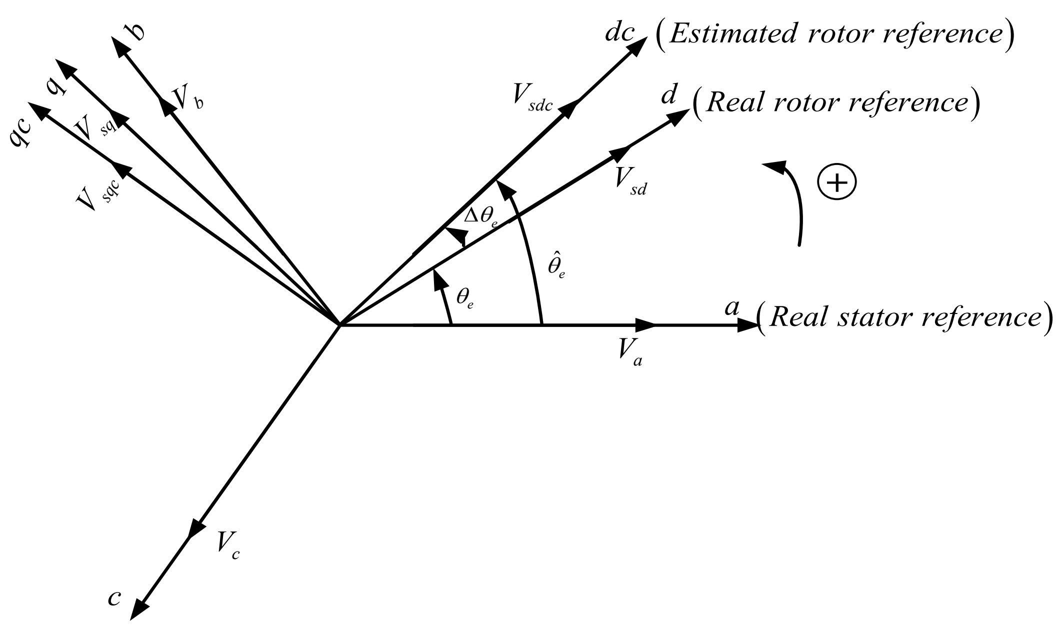

Fig. 1: Relation between the (d, q) and estimated (dc, qc) rotor reference frames

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} (R_s + sL_{sd}) & -L_{sq}\omega_e \\ L_{sd}\omega_e & (R_s + sL_{sq}) \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \psi_f \omega_e \end{bmatrix} \quad (1)$$

where,

$$\psi_{sd} = L_{sd} i_{sd} + \psi_f \quad (2)$$

and,

$$\psi_{sq} = L_{sq} i_{sq} \quad (3)$$

The electromagnetic torque is given by Eq. (4):

$$C_{em} = \frac{3}{2}\left((L_{sd} - L_{sq}) i_{sd} i_{sq} + \psi_f i_{sq}\right) \quad (4)$$

As the PVI technique consists in injecting a high frequency voltage on the d-axis rotor voltage, it causes the magnetic saliency excitation (Aihara *et al*., 1999; Sakamoto *et al*., 2001; BelHadj Brahim *et al*., 2012).

Then, the PVI results in high frequency voltage and current components and in an error rotor position $\Delta\theta_e$ defined by Eq. (5):

$$\Delta\theta_e = \hat{\theta}_e - \theta_e \quad (5)$$

where,

θ_e = The actual rotor position

$\hat{\theta}_e$ = The estimated rotor position

In this case, these high frequency components can be considered in a (dc, qc) rotor reference frame which makes $\Delta\theta_e$ with the (d, q) reference (Fig. 1).

As the HF injected voltage is expressed by:

$$v_c = V_{cmax} \sin(\omega_c t) \quad (6)$$

where,

ω_c = The HF injected voltage pulsation

V_{cmax} = The maximum voltage of the HF injected voltage

Then, the stator voltage equations at high frequency, considered in the (dc, qc) rotor reference frame are given by Eq. (7):

$$\begin{bmatrix} V_{sdc} \\ V_{sqc} \end{bmatrix} = R_s \begin{bmatrix} i_{sdc} \\ i_{sqc} \end{bmatrix} + j\omega_c \left[L_{dqc1}\right] \begin{bmatrix} i_{sdc} \\ i_{sqc} \end{bmatrix} + \hat{\omega}_e \left[L_{dqc2}\right] \begin{bmatrix} i_{sdc} \\ i_{sqc} \end{bmatrix} + \omega_e \psi_f \begin{bmatrix} \sin\Delta\theta_e \\ \cos\Delta\theta_e \end{bmatrix} \quad (7)$$

where,

$$\left[L_{dqc1}\right] = \begin{bmatrix} L_{dc} & -L_{dqc} \\ -L_{dqc} & L_{qc} \end{bmatrix} \quad (8)$$

and,

$$\left[L_{dqc2}\right] = \begin{bmatrix} L_{dqc} & -L_{qc} \\ L_{dc} & L_{dqc} \end{bmatrix} \quad (9)$$

V_{sdc}, V_{sqc} = The voltage components resulting from the PVI

i_{sdc}, i_{sqc} = The current components resulting from the PVI
L_{dc}, L_{qc}, L_{dqc} = Defined by (10), (11) and (12):

$$L_{dc} = \frac{L_{sd} + L_{sq}}{2} + \frac{L_{sd} - L_{sq}}{2}\cos 2\Delta\theta_e = L_0 + L_1 \cos 2\Delta\theta_e \quad (10)$$

$$L_{qc} = \frac{L_{sd} + L_{sq}}{2} - \frac{L_{sd} - L_{sq}}{2}\cos 2\Delta\theta_e = L_0 - L_1 \cos 2\Delta\theta_e \quad (11)$$

$$L_{dqc} = \frac{L_{sd} - L_{sq}}{2}\sin 2\Delta\theta_e = L_1 \sin 2\Delta\theta_e \quad (12)$$

where,

$$L_0 = \frac{L_{sd} + L_{sq}}{2} \quad (13)$$

and,

$$L_1 = \frac{L_{sd} - L_{sq}}{2} \quad (14)$$

The stator voltage equations can be simplified by considering the following assumptions (Aihara *et al*., 1999; BelHadj Brahim *et al*., 2012):

- The stator resistance R_s can be neglected compared to the high frequency reactance.
- HF injected voltage pulsation ω_c is very higher compared to ω_e, so ω_e is assumed to be neglected.
- The production of the back-EMF is negligible because the vibration of the rotor is very small.

Thus, stator voltage equations given by (7) can be approximated as follows:

$$\begin{bmatrix} V_{sdc} \\ V_{sqc} \end{bmatrix} = j\omega_c \begin{bmatrix} L_{dc} & -L_{dqc} \\ -L_{dqc} & L_{qc} \end{bmatrix} \begin{bmatrix} i_{sdc} \\ i_{sqc} \end{bmatrix} \quad (15)$$

Then, the PMSM high frequency stator currents defined in the estimated rotor reference frame (dc, qc) and resulting from (15) are given by Eq. (16):

$$\begin{bmatrix} i_{sdc} \\ i_{sqc} \end{bmatrix} = \begin{bmatrix} i_{cp} - i_{cn}\cos(2\Delta\theta_e) \\ i_{cn}\sin(2\Delta\theta_e) \end{bmatrix} \sin(\omega_c\ t) \quad (16)$$

where,

$$i_{cp} = \frac{L_0 V_{cmax}}{j\omega_c L_{sd} L_{sq}} \quad (17)$$

and,

$$i_{cn} = \frac{L_1 V_{cmax}}{j\omega_c L_{sd} L_{sq}} \quad (18)$$

i_{cp} = The positive component of the *HF* current vector and is proportional to the average value of the (d, q) stator inductances.
i_{cn} = The negative component of the *HF* current vector and is proportional to the (d, q) inductances variation level.

Starting from (14), the relation between the carrier current components (i_{sqc} and i_{sdc}) and the error rotor position $\Delta\theta_e$ is highlighted. Then, it is well shown that saliency effect is necessary to estimate the rotor position using the HFSI technique. Moreover, the Eq. (16) shows that the carrier current component i_{sqc} is directly proportional to the rotor position error $\Delta\theta_e$. Then, it is easier to extract the rotor position from i_{sqc} than from i_{sdc}, (Aihara *et al*., 1999; BelHadj Brahim *et al*., 2012).

In this study, Eq. (19) will be considered to extract the rotor position error:

$$i_{sqc} = i_{cn}\sin(2\Delta\theta_e)\sin(\omega_c\ t) \quad (19)$$

CARRIER CURRENT DEMODULATION SCHEME IN CLOSED LOOP CONDITIONS

Sensorless SVPWM control strategy: Figure 2 shows the classical sensorless SVPWM control scheme used for the PMSM drive. This sensorless control strategy is based on a PI speed controller, a PI direct current controller, a PI quadratic current controller and a rotor

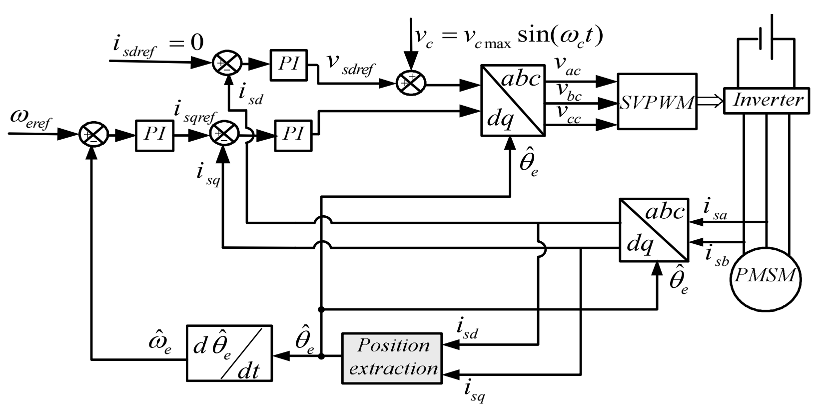

Fig. 2: Sensorless SVPWM control strategy for the PMSM drive

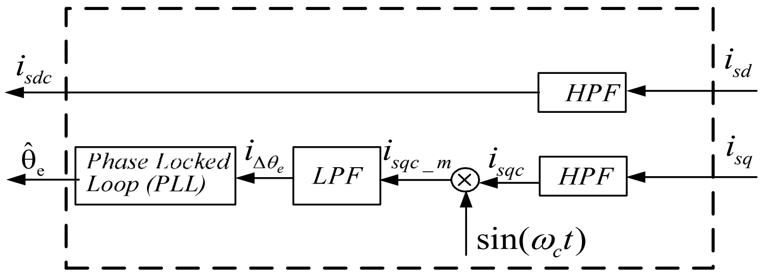

Fig. 3: PMSM rotor position error estimation using PVI technique

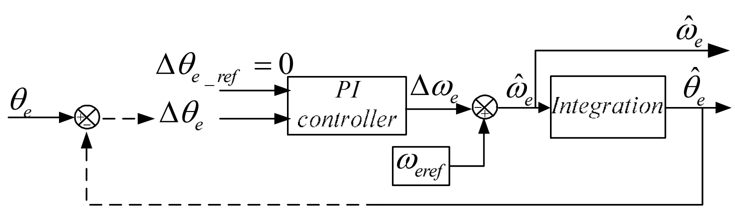

Fig. 4: PLL structure based position controller

position extraction module. In addition, conventional transformations and modules for SVPWM control such as Clark, Park and inverse Park transformations and space vector PWM generation module are considered.

The i_{sd_ref} has been set to zero in order to obtain the maximum torque.

The demodulation strategy to extract the rotor position error principal will be detailed in the next subsection.

Demodulation strategy: In order to extract the rotor position error $\Delta\theta_e$ from (19), i_{sqc} must be demodulated.

The demodulation scheme principle is shown in Fig. 3. In fact, the current signal i_{sqc}, oscillating at the signal injection frequency f_c, is obtained from i_{sq} using a High-Pass Filter (HPF).

The current signal i_{sqc} is then demodulated by multiplying it by a sinusoidal wave at the same frequency as the carrier. The obtained signal, noted i_{sqc_m}, is given by the Eq. (20):

$$i_{sqc\_m} = i_{sqc}\sin(\omega_c t) = \frac{i_{cn}}{2}\sin(2\theta_e) - \frac{i_{cn}}{2}\sin(2\theta_e)\cos(2\omega_c t) \quad (20)$$

The i_{sqc_m} is Low-Pass Filtered (LPF) in order to extract the signal containing the error rotor position noted $i_{\Delta\theta_e}$.

Finally, as $\Delta\theta_e$ aims at a low values, then $i_{\Delta\theta_e}$ can be approximated as follows:

$$i_{\Delta\theta_e} = i_{cn}\Delta\theta_e \quad (21)$$

Therefore, the exact rotor position can be obtained by adjusting $i_{\Delta\theta_e}$ to zero. Then, the electrical position θ_e can be directly extracted from the PMSM rotor position $i_{\Delta\theta_e}$ using a Phase Locked Loop (PLL).

Phase Locked Loop (PLL) strategy: In order to extract the rotor position $\hat{\theta}_e$, a closed loop control scheme based on a PLL strategy has been used. The PLL consists of a PI controller and an integrator. The use of the PI controller allows the estimated speed $\hat{\omega}_e$ processing and therefore, the rotor position error $\Delta\theta_e$ minimization.

The PLL position controller feedback path shows the electric measured position θ_e which is the input of the (a, b, c) to (d, q) transform block (Fig. 2). Then, the (d, q) PMSM supply currents are applied as inputs to the demodulator (Fig. 2) which in turn estimates the PMSM rotor position, that allows closing the loop.

Usually, it is very difficult to set the PI controller parameters of the estimator since there is not a standard method to perform the controller parameters. Besides, it is very complicated to determine the transfer function of the system (Fig. 4).

Then in this study, a universal PLL is considered to study the PLL parameters variation impact on the rotor position estimation performance.

Impact of the PLL parameter variation on the PMSM position estimation: The PLL parameter variation impact on the demodulation scheme performance will be studied. The position estimation results are obtained from simulations carried out using the MATLAB/SIMULINK® environment and discussed according to different values of the PI controller parameters.

Table 1: PMSM mechanical parameters

Rated speed (rpm)	1000
Number of pole pairs	3
Rotating inertia ($Kg.m^2$)	0.00015
Viscous friction (Nm/rad/sec)	4.722e-4
Rated torque (N.m)	1.3

Table 2: PMSM electrical parameters

Rated power (W)	1000
Rated phase voltage (V)	380
Rated current (A)	2.6000
d-axis inductance (H)	0.0149
q-axis inductance (H)	0.0181
Stator resistance (Ω)	1.6450
Rotor permanent magnet flux (Wb)	0.0705

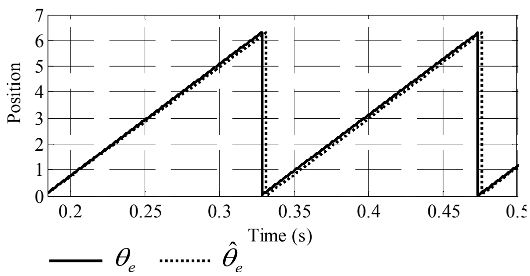

Fig. 5: Actual and estimated electrical positions in closed loop conditions; case of $K_p = 11$ and $K_i = 2$

The mechanical and electrical parameters of the considered PMSM are listed in Table 1 and 2, respectively.

The simulations are carried out under closed loop conditions and no load torque. The reference stator current frequency is of 7 Hz. The amplitude of the high frequency injected voltage is of 57V and the carrier frequency is of 1 kHz.

For this study, the relative error position does not have to exceed 0.3%.

Since there is no standard method to determine the transfer function of the studied system in closed loop conditions and then the PLL PI parameters, several trials have been carried out in order to determine satisfactory values of the proportional and integral parameters which allow ensuring the position error minimization.

In fact, the best relative position error have been obtained for the PLL proportional and integral parameters respectively at the values $K_p = 11$ and $K_i = 2$.

To compare the actual and the estimation position for these parameters values, the position extraction bloc output result is superposed with the actual PMSM position simulated (Fig. 5).

The previous simulation results have shown that the demodulation technique based on the universal PLL allows the PMSM rotor position estimation with a relative error $\Delta\theta_e$ equal to 0.247%.

RESULTS AND DISCUSSION

Impact of the PLL proportional parameter: In order to study the impact of the universal PLL proportional parameter, the integral parameter has been fixed at $K_i = 2$ and the proportional parameter value has been varied in the range (9, 16) under the same simulation conditions mentioned above.

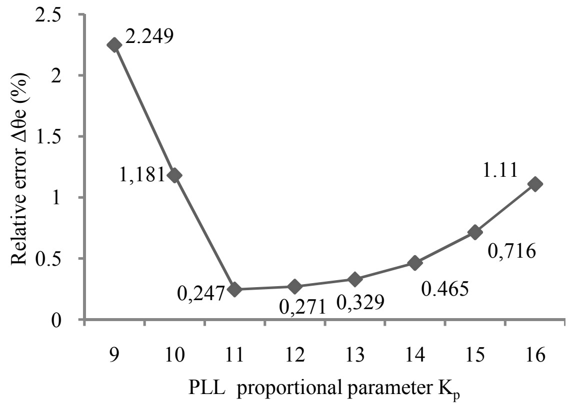

Fig. 6: $\Delta\theta_e$ as a function of K_p

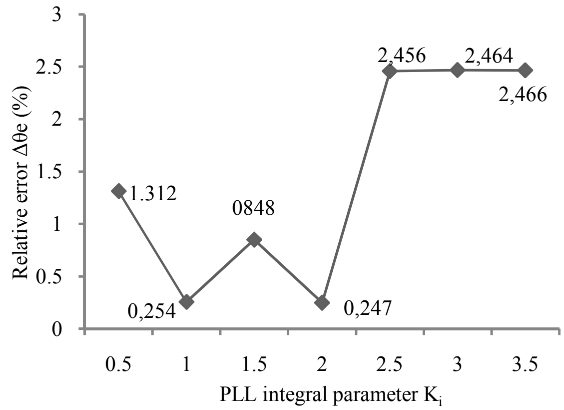

Fig. 7: $\Delta\theta_e$ as a function of K_i

Figure 6 presents the evolution of the relative rotor position error $\Delta\theta_e$ as a function of the PLL proportional parameter K_p.

Figure 6 shows clearly that by decreasing the PLL proportional parameter K_p under the value 11, the relative position error increases considerably. However, by increasing the PLL proportional parameter K_p over the value 11, the relative position error increases at a slower rate.

Impact of the PLL integral parameter: The proportional parameter of the universal PLL has been fixed at $K_p = 11$ and a variation has been applied to the universal PLL integral parameter in the range (0.5, 3.5).

Figure 7 presents the evolution of the relative rotor position error $\Delta\theta_e$ as a function of the PLL integral parameter K_i.

According to these simulations, it can be clearly noted that a small PLL integral parameter variation can cause considerable increasing of the relative position error and engenders bad position estimation performances. Moreover, a desired position error can be obtained for several values of the PLL integral parameter. Then, it is difficult to establish the law governing the rotor position error variation according to K_i.

CONCLUSION

This study has presented PMSM rotor position estimation for sensorless vector control using a Pulsating Voltage Injection Technique at low speed.

In literature, PVI techniques are usually known to be associated to the use of universal PLL and to be parameters independent. Therefore, it has been shown in this study that the PLL parameters have an important influence on the position estimation performances, especially as it is difficult to set the PI controller parameters of the position estimator according to known rules since there is not a particular method by which these parameters may be performed.

Moreover, it can be noted that the difference between the actual and the estimated speed at the beginning of the estimation process may also have an impact on the estimation processing.

The PMSM rotor position estimation using a PLL requires to be performed at closed loop conditions. Then, the technique performances degrade as approaching the standstill region and this may limit the performance of this technique. An experimental benchmark is currently in progress in order to validate the obtained results.

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