Basic modules

This chapter presents an analysis and description of the basic operations (blocks) required in order to implement a sensorless control scheme for a permanent magnet motor in simulink.

Figure 2.1 represents the layout of a sensorless control technique for AC motor drive [1]. This layout is shown here to get familiar with the basic operations (or modules), which any open loop control scheme for permanent magnet motor could involve. A brief description of the individual modules involved in figure 2.1 is presented in the following lines.

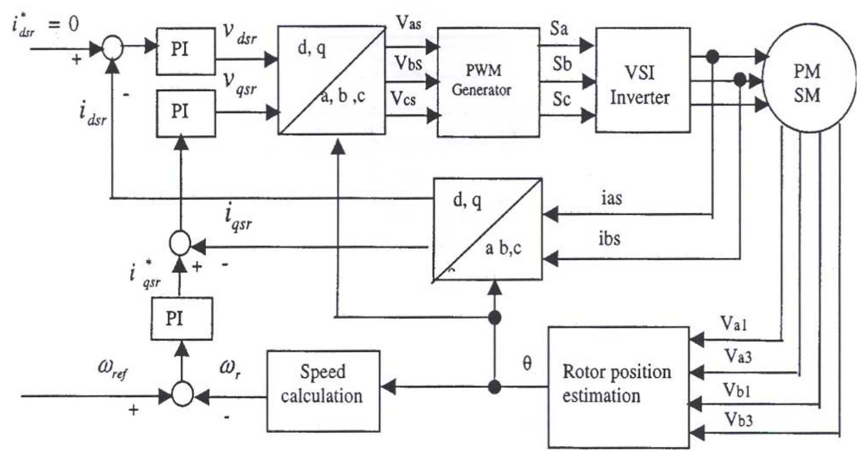


Figure2.1: *Rotor flux oriented sensorless control of PM machine.*

2.1 PM machine model

The machine model can be described as the physical phenomenon happening in the machine by mean of mathematical equations. This is derived by changing the machine reference frame, from the real reference frame (commonly referred to as abc reference frame) to a fictive (assumed) reference frame (e.g. dq reference frame). The idea is to simplify the modeling approach in order to obtain an approximately linear machine model, since a linear machine model allows an easier controller design.

A surface mounted permanent magnet synchronous motor model in the dq reference frame is presented below [2, p. 102], assuming neglected the hysteresis and eddy current losses.

2.1.1 PMSM model in the dq reference frame

Voltage equations:

$$
\begin{aligned}
V_{sd} &= R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_m \lambda_{sq} \\
V_{sq} &= R_s i_{sq} + \frac{d\lambda_{sq}}{dt} + \omega_m \lambda_{sd}
\end{aligned}
\tag{1}
$$

With $\omega_m = \frac{p}{2}\omega_{mech} = \omega_{syn}$ synchronous rotational speed.

Stator flux linkage equations:

$$
\begin{aligned}
\lambda_{sd} &= L_s i_{sd} + \lambda_m \\
\lambda_{sq} &= L_s i_{sq}
\end{aligned}
\tag{2}
$$

With L_s the stator phase inductance of the machine.

Electromagnetic torque:

$$T_{em} = \frac{p}{2}(\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd}) \tag{3}$$

Substituting equation (2) in equation (3) will result in the following torque expression (for a non salient pole machine).

$$T_{em} = \frac{p}{2}\lambda_m i_{sq} \tag{4}$$

With p the number of poles of the machine.

Electrodynamics:

$$\frac{d\omega_{mech}}{dt} = \frac{T_{em} - T_{load}}{J} \tag{5}$$

Where J is the inertia moment of the machine and the load.

The obtained set of equations (1 to 5) represents the motor model in the dq reference frame. These equations will be used to implement the machine model in Simulink.

2.2 PWM module

This module in figure 2.1 represents a non ideal inverter controller. The basic principle of an inverter control is to generate appropriated pulse width modulated (PWM) signals at the input of the gate driver used to drive the power switches (power transistors) of the inverter. This operation is used to open and close the switches in a controlled sequence, thereby providing the required (modulated) voltage and frequency to run the motor.
There are basically two types of PWM techniques used to control an inverter:
The sine wave modulation scheme (traditional way), and the space vector modulation (SVM) scheme.
The sine wave modulation approach is achieved by comparing three phase sinusoidal waveforms with a triangular carrier. The limitations of this approach involve high current harmonics and low modulation index.
The SVM scheme does not suffer from these drawbacks and could allow the use of the entire available DC-Link voltage, therefore this scheme will be the type applied in this project.

2.2.1 SVM technique

Consider the diagram in figure 2.2, representing the schematic of a three phase full bridge, six switches inverter.

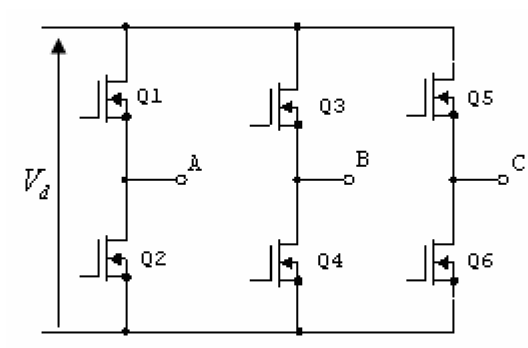


Figure 2.2: *Schematic of the three phase full bridge inverter.*

Eight possible operating states are available to control such an inverter topology. For instance if the upper switch in leg A of the inverter is closed and the other two legs have their lower switches closed as well, the obtained pole voltages will be (V_d , 0, 0). In the following this state is referred to as (1, 0, 0) and may be depicted as a space vector V_1 described as follow [3, p.142]:

$$\overline{V_1} = V_{\alpha_1} + jV_{\beta_1} = \frac{2}{3}(V_{A_1}.e^{j0} + V_{B_1}.e^{j\frac{2\pi}{3}} + V_{C_1}.e^{j\frac{-2\pi}{3}})$$
$$= \frac{2}{3}(V_d.e^{j0} + 0.e^{j\frac{2\pi}{3}} + 0.e^{j\frac{-2\pi}{3}}) = \frac{2}{3}V_d.e^{j0} \qquad (6)$$

The eight states of the inverter contain six non null states and two null states, (0, 0, 0) and (V_d, V_d, V_d) where the phase voltage difference is zero.

Figure 2.3 shows the eight states in the stationary reference frame [3, p. 142].

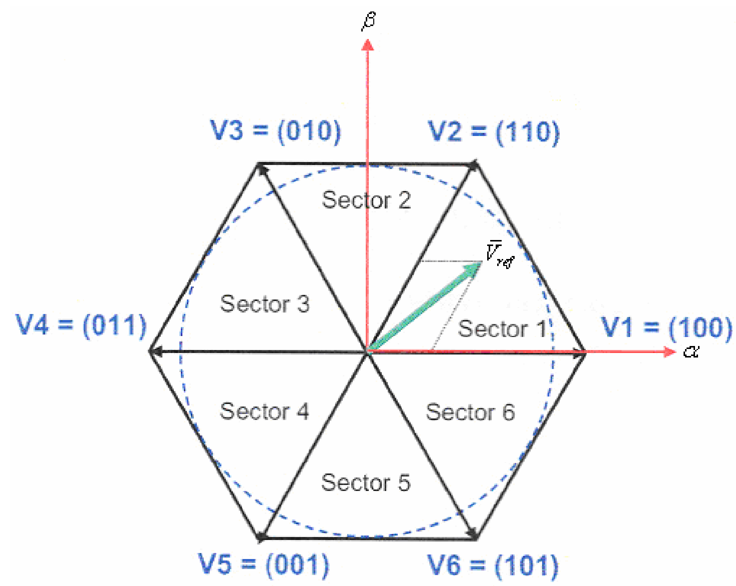


Figure 2.3: *The eight inverter states represented in the stationary reference frame.*

The SVM principle is based on the assumption that every vector $\overline{V}$ inside the hexagon in figure 2.3 has a weighted average combination of the adjacent active state vectors and the two null states vectors. The inverter expresses the vector $\overline{V}$ by switching between the four states. The adjacent active states change as the vector $\overline{V}$ turns in the stationary reference frame. In order to have the minimum switching frequency for each power switch of the inverter, the switching sequence is arranged so that the transition from one state to the next one is performed by switching only one inverter leg.

2.3 Position estimation module

This block is needed to obtain rotor position information. It is built on the basis of mathematic equations leading to the expression of the estimated rotor position. The steps applied to derive these equations will be described with details in the chapter regarding the implementation of the selected sensorless schemes.

2.4 Transformation blocks

These modules are used to implement the transformation tools (Park and Clark transformations), needed to transform the machine variables from one reference frame to another reference frame where necessary.

Clark transformation is required to transform machine variables from three-phase rotating domain to two-phase rotating domain, meanwhile Park transformation helps to transform machine variables from two phase-rotating domain to stationary domain. This is illustrated in figure 2.4, in a block diagram form.

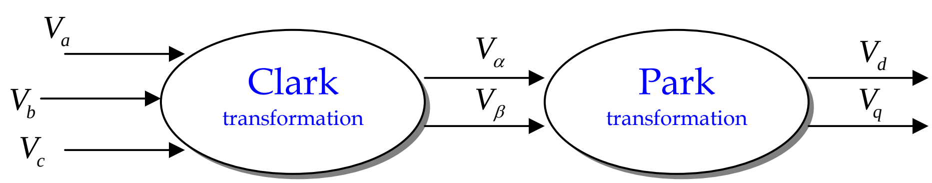


Figure 2.4: *Block diagram explaining the principle of Clark and Park transformations.*

It appears from the block diagram in figure 2.4 that, combining the Clark and Park transformations allows moving from the three-phase rotating domain to the stationary domain (for simplification purpose of the design). As an illustrating example, consider a case where it is needed to transform motor voltages from abc reference frame to dq reference frame. This can simply be seen as the Clark transformation plus a rotation:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \left[f_c \right] . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \left[p(\theta_s) \right] . \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{7}$$

Where f_c and $p(\theta_s)$ can be obtained from literature resources discussing the reference frame transformation issue, (which will not be described in this chapter).

Figure 2.5 shows the relationship between the real (abc) and the assumed (dq) reference frames of the machine. This can be used to understand the Clark and Park transformation principle.

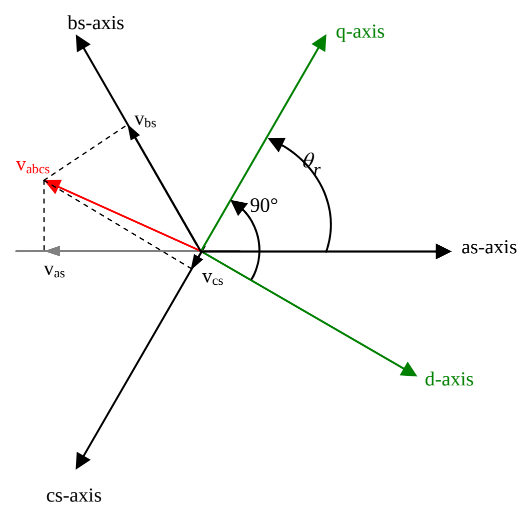


Figure 2.5: *Magnetic axis of the three phases PM machine.*

2.5 Controller description

Generally, several types of control strategies are available for AC machines. The simplest type, known as Voltage/Frequency (V/f) control technique is suitable for low-performance drives operating at constant speed. Field Oriented Control (FOC) and the Direct Torque Control (DTC) are advanced control techniques suitable for AC machines.

The V/f control approach suffers from poor dynamics performance at low speed, due to large proportion of losses encountered at this speed range. Therefore, this scheme will not be applied in this project.

The DTC could be difficult to implement and will not be applied in this project as well.

Then the FOC scheme will be the selected scheme for this project, especially for the reason that the machine to be control in this project is a

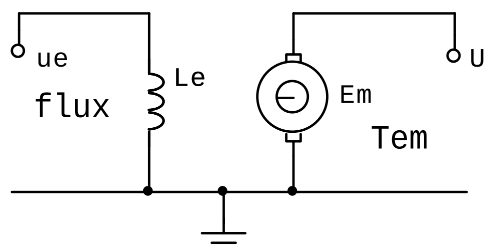
PM motor. Field Oriented Control of PM motors is much simpler than that of IM, since there is no slip in the frequency [4].

2.5.1 Field Oriented Control principle

The FOC (also called vector control) can be applied on both asynchronous and synchronous machines. Advantages of the FOC involve better dynamic response and low torque ripples.

In order to understand the principle of the FOC technique, consider the diagram shown in figure 2.6, representing a separately excited DC motor.

Figure 2.6: *Block diagram showing a separately excited DC motor topology.*



In this type of motor, the excitation for the stator and the rotor is independently controlled. Then the produced torque and the flux can be independently tuned. By construction, the flux and the current are naturally in quadrature in this machine. The key point is to keep the flux produced by the rotor windings orthogonal to the stator field.

On the synchronous machine (PM machine), the rotor excitation is given by the permanent magnet mounted on the shaft. Obviously, as opposed to the DC motor, the flux and the torque depend on each other.

The goal of the field oriented control on AC machines is to be able to separately control the producing torque and the magnetizing flux components, thereby imitating the DC motor operation. When this goal is achieved, additional features due to the decoupling control of torque and flux are acquired, such as fast transient response and good performance at low speed.

A field oriented control scheme is presented in the figure below, in a block diagram form [5, p.45].

As shown on figure 2.7, the excitation flux is kept at the direct axis of the rotor. Then its position can be obtained directly from the rotor shaft by monitoring the rotor angle θ or the rotor speed. In order to produce the largest torque for a given stator current, the stator current space vector contains only the i_q component. The i_d component is present only in flux weakening regime of operation (which is not discussed here). An optimal producing torque could be obtained if the i_d current component is well oriented on the d-axis.

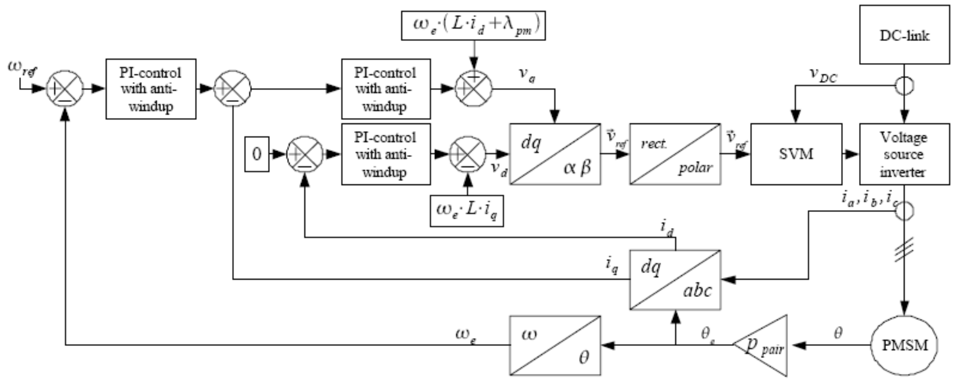


Figure 2.7: *Block diagram showing the field oriented control scheme.*

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