4 Vector Control Of PMSM

4.1. Introduction

Torque is developed in the AC motors by the interaction between the rotor flux and the stator MMF. The torque developed by the motor can be mathematically expressed as

$M_d = \underline{I}_s \; X \; \underline{\psi}_r$

where

$\underline{I}_s$ is the stator MMF vector
and
$\underline{\psi}_r$ is the rotor flux vector

In the case of PMSM, the flux is provided by the rotor magnet. It is not possible to develop additional flux by having a component of stator MMF along the direction of rotor flux since the magnet behaves just like an airgap to any external MMF. Hence to obtain the maximum torque for a given current or to obtain a given torque with a minimum stator current, it is necessary that the stator MMF should be perpendicular to the rotor flux *i.e.*, the stator MMF should be in quadrature with the field.

This is achieved by sensing the instantaneous position of the rotor by means of a position sensor, like a resolver or a position encoder and controlling the position of the stator MMF to be at right angles to the rotor flux. As the rotor flux rotates in space, the stator MMF vector also has to be rotated in synchronism so that the relative position in space is maintained, not only in steady state but also during transients to obtain the best dynamic response. This is done in Vector Control.

CONTROL SCHEMES

The vector control may be done in either Stator Frame of Reference or Rotor Frame of reference.

The control in stator frame involves less computation than that in rotor frame. But the drawback with this scheme is the steady state reference and feedback signals are sinusoidal. The controller may introduce phase lag to the signals and additional signal processing to compensate for this phase lag is required.

The control in rotor frame has constant(DC) reference and feedback signals in steady state. Further with the advent of Analog Devices' AC Vector Processor, which can do the computations involved in this control strategy like transforming from rotor frame to stator frame this scheme, the control in rotor frame, has become viable.

4.2. Control In Rotor Frame

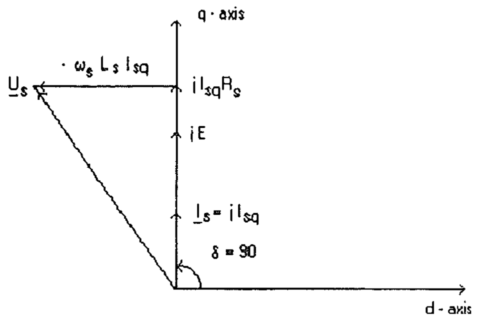
From the space-phasor model of the PMSM it is clear that in order to control the torque and flux of the motor in a decoupled manner, the components i_{ds} and i_{qs} of the stator current $\underline{i}_s$ have to be controlled. The magnitude of i_{qs} should be controlled to adjust the torque and the magnitude of i_{ds} should be controlled to get the field weakening effect.

4.3. Mode Of Operation

Servo drives operate in the constant torque mode from zero to base speed, and in the constant power mode above base speed.

CONSTANT TORQUE OPERATION

In order to produce the largest torque for a given stator current, an optimally efficient operation is achieved by stator current control which ensures that the stator current space phasor contains only a quadrature axis component when expressed in the reference frame fixed to the rotor. The airgap flux remains constant and the maximum steady state torque is dependent on the continuous stator current rating. The phasor diagram for the constant torque operation is shown in *figure* 4.1.



Phasor diagram of PMSM in constant torque mode

Figure 4.1

It can be inferred from the *figure* 4.1 that the stator voltage $\underline{U}_s$ increases with speed, with constant torque on the machine, thus demanding more voltage from the inverter. The maximum speed that can be achieved at rated torque is therefore limited by the maximum permissible inverter voltage. The corresponding speed is defined as the base speed ω_{rb}.

CONSTANT POWER OPERATION

The optimal mode of operation is suitable below the rotor base speed, where sufficient voltage is available from the inverter which supplies the stator windings of the machine. However, at high speeds, at speeds above the base speed - constant power range - the induced EMF increases directly with the rotor speed(the excitation flux remains constant due to permanent magnets), and if a given speed is to be reached the terminal voltage must also be increased to match the stator EMF. The increased stator terminal voltage would require an increase in the voltage rating of the inverter used.

However, with a given inverter, there is a ceiling voltage which can not be exceeded. Thus to limit the terminal voltage of the machine to the ceiling voltage of the inverter, field weakening has to be introduced.

Direct field weakening is not possible as the excitation is derived from permanent magnets. However, a similar effect can be achieved by introducing a negative d-axis current as shown by equation 3.6-5. The magnitude of the stator current, which is the vector sum of the d and q axis current components, will therefore increase if the machine is to develop the same torque as at base speed. In order to limit the stator current to the fixed continuous rating, the torque component I_{qs}, of the stator current has to be reduced such that,

$$I_{ds}^2 + I_{qs}^2 \leq I_{max}^2$$

where I_{max} - RMS continuous rating of the stator.

Hence the maximum output torque of the machine gets limited in the voltage limited constant power mode of operation. The phasor diagram for the constant power mode is shown in *figure* 4.2.

For constant power operation

$\omega_r T_e = \omega_{rb} T_b$

where

ω_r - the angular speed above the base speed ω_{rb}

T_b - the rated (base) torque at base speed ω_{rb}.

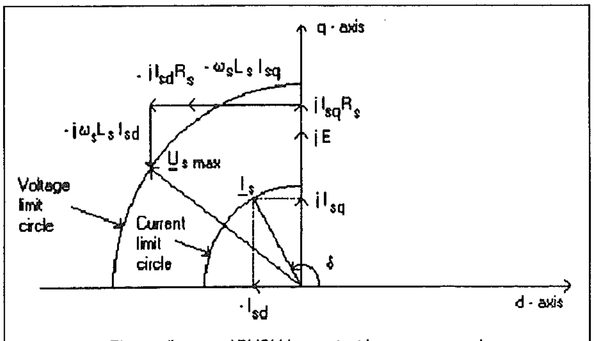
As the torque is directly proportional to i_{qs}, the above equation may be rewritten as

$I_{qs} = (\omega_{rb} / \omega_r) I_{qs\ rated}$

where I_{qs} - q-axis component of stator current at speed ω_r

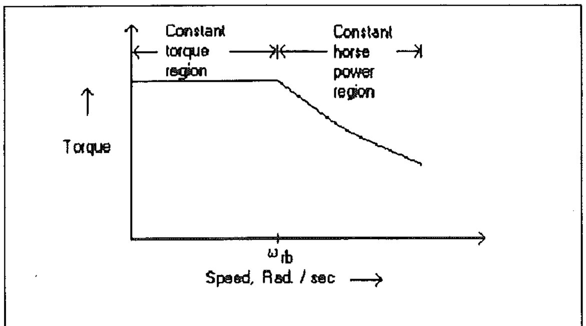
$I_{qs\ rated}$ - stator current at rated torque and at base speed.

The torque-speed characteristics of the motor are shown in *figure* 4.3.



Phasor diagram of PMSM in constant horse power mode

Figure 4.2



Drive characteristics

Figure 4.3

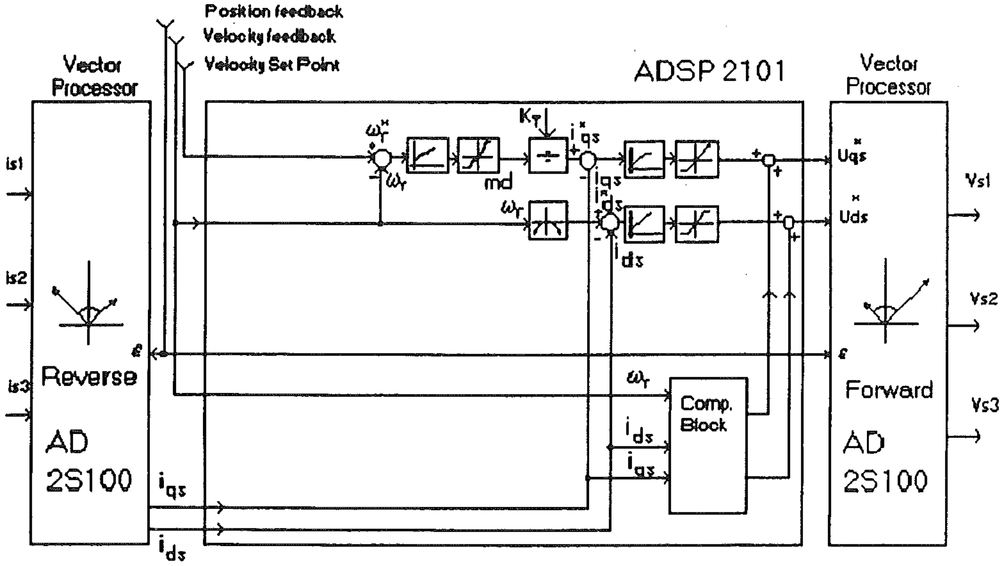
4.4. Structure Of Control Loops

The overall scheme of the controller is shown in *figure* 4.4

The drive is required to operate in the constant torque mode up to base speed ω_{rb} and in the constant horse power (field weakening) mode above base speed. Based on the steady state operation of the machine, explained in previous chapter, the structure of the drive control loops including the constant torque and constant horse power operation is developed as follows.

In order to achieve maximum torque for a given stator current, in the constant torque mode, the stator current space-phasor is to be controlled to lie along the q-axis. The direct axis current is held at zero. The speed controller gives the reference value for the torque demanded from the machine. The reference for the q-axis current is computed by dividing the reference torque by the torque constant K_T of the machine. The machine can take several times the rated current for a short while. Therefore the machine can be allowed to develop a torque equal to the peak torque capability by allowing the required value of the stator current. This may be necessary to reduce the acceleration time. However, in practice the maximum stator current is limited by the maximum current handling capacity of the inverter. Hence the torque reference is limited to the corresponding maximum current handling capacity of the inverter. The reference q-axis current is given by

$i_{qs}^*(t) = T_e^* / K_T$



Field Oriented Control of a PMS Motor

Figure 4.4

The reference for the d-axis current in the constant torque mode is

$$i_{ds}^* = 0$$

In the constant power mode, the stator current must have a component along the negative d-axis.

For a given speed ω_r above the base speed ω_{rb}, the value of the reference for the d-axis component of the stator current is calculated as

$$i_{ds}^* = [\ 1 / (P/2)\, L_s\ ] / [\ (\ \omega_{rb} / \omega_r\ ) - 1\ ]$$

In order to achieve the constant power characteristics the q-axis component of the stator current is limited to the constant horse power boundary. This becomes the first limit for the q-axis component of the stator current. The limit for the q-axis component of current is given by

$$i_{qs\ limit1} = (\ \omega_{rb} / \omega_r\ )\ i_{qs\ rated}$$

The magnitude of the stator current should not exceed the continuous current rating or the maximum current handling capability of the inverter whichever is less. This becomes the second limit for the q axis component of the stator current. The limit for the q-axis component of the stator current due to this constraint is given by

$$i_{qs\ limit2} = \sqrt{(i_{max}^2 - i_{ds}^{*2})}$$

The speed controller design is based on the above considerations. A proportional plus integral controller is used for the speed control loop. The flux controller just checks if the speed is above base speed and depending on the speed d-axis current reference is computed.

The inner most control loop in the control structure is the current controller. The current loop forces the AC line current to follow the current reference.

The control may be done either in stator or rotor frame. The design of the current controller is based on the machine voltage equations. The stator voltage equations, in rotor co-ordinates, are given by equations 4.4-1 and 4.4-2. The equations are as follows.

$$u_{ds}(t) = R_s\, i_{ds}(t) + L_s\, d/dt\, [\, i_{ds}(t)\,] - \omega_s\, L_s\, i_{qs}(t) \qquad ...4.4\text{-}1$$

$$u_{qs}(t) = R_s\, i_{qs}(t) + L_s\, d/dt\, [\, i_{qs}(t)\,] + \omega_s\, L_s\, i_{ds}(t) + K_E\, \omega_r(t) \qquad ...4.4\text{-}2$$

The desired response of the current loops is a first order lag of time T. This behavior is mathematically expressed as follows.

$$di_{ds}(t)/dt = (1/T)\, [\, i_{ds}^*(t) - i_{ds}(t)\,]$$

$$di_{qs}(t)/dt = (1/T)\, [\, i_{qs}^*(t) - i_{qs}(t)\,]$$

The voltage reference outputs are transformed from 2-phase rotor frame reference to 3-phase stator frame reference signals and fed to the voltage controlled inverter after pulse width modulation.

4.5. Summary

There are four cascaded controllers in the control scheme. The velocity controller generates torque reference which is used to compute the q-axis component of current. The flux controller calculates the d-axis component of current depending on the mode of operation. The current controllers generate voltage reference as output and necessary transforms are done before feeding to the voltage controlled inverter.

NOTES