Chapter 6
Flux Weakening and Speed Limiting

Introduction

Typically, the upper speed limit of a permanent magnet motor is reached when the back emf rises to the maximum available voltage from the inverter. This speed limit is referred to as the base speed.

Operation above the base speed can be achieved by forcing the *d*-axis current to a negative value. This causes a voltage drop across the motor winding inductance, which opposes the rotor induced back emf voltage, reducing the voltage needed from the inverter to drive the motor at a given speed.

The maximum speed that can be obtained using this method has several limits. One obvious limit is that too much negative current will cause motor over-heating, but usually there are one or two other effects that come in before this occurs.

One speed limiting effect that occurs for high inductance motors, such as stepper motors, is due to the need to induce enough reverse voltage across the inductance to not only oppose the back emf but to also to create some voltage headroom to allow enough *q*-axis current to flow to generate the required torque. The motor is not stable when the reverse voltage across the inductance exceeds the back emf, putting a limit on the maximum speed for a given torque. Because of this effect, stepper motors have a maximum torque output that reduces as speed is increased above the base speed.

Another speed limiting effect occurs for motors that have a very low inductance compared with their resistance, such as the low-inductance, high-speed motors used for driving the propellers in quad-copters and other aerial vehicles. Often, at base speed, the voltage drop across the motor resistance due to the motor current is comparable to or greater than the reverse voltage drop across the inductance when a negative applied *d*-axis current. In this situation, even a small negative *d*-axis current can cause unstable operation.

Flux weakening with traditional field-oriented control designs has several additional problems. Because some voltage headroom is required on the output of the inverter to allow the feedback current controllers to operate, the maximum output voltage and thus the base speed is reduced. Also, to maintain the voltage headroom at the wanted value, a further (slow) feedback loop must be added around the current *d*-axis feedback loop to control the *d*-axis reference current to regulate the output voltage. This slows down the dynamic response time during flux weakening.

The use of feed-forward current control in this controller makes flux weakening easier to implement and removes the limitations of traditional field-oriented control. The output voltage is easily controlled by direct control of the *d*-axis applied current i_d' in Figure 1.1. Also, because of the feed-forward control, output current responds immediately to changes in i_d', resulting in very fast dynamic response to speed and load changes. Further, with no voltage headroom requirement, operation with over-modulation, where voltage clipping is used to drive the fundamental component of the output voltage above the maximum available from the inverter is possible. This can result in up to 10% higher fundamental output voltage.

Flux Weakening

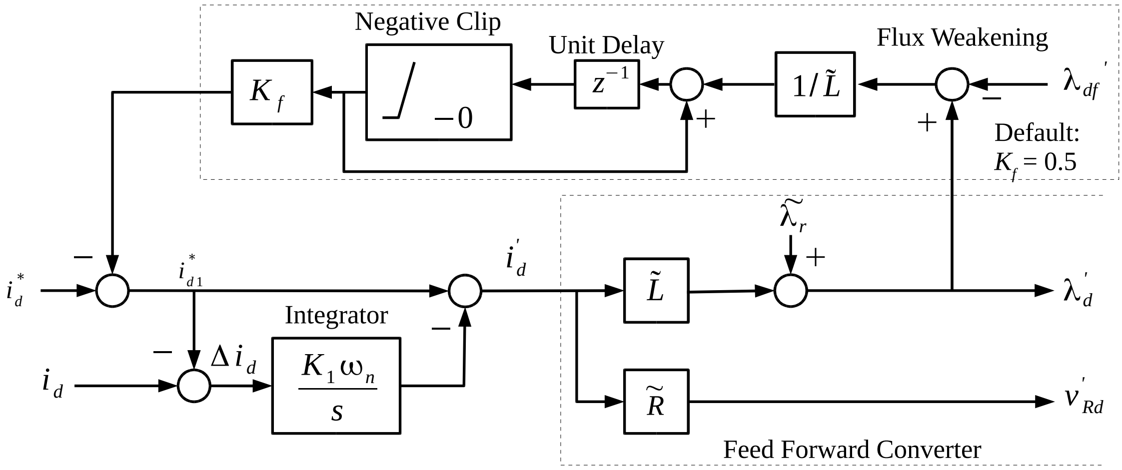

Figure 6.1. Flux weakening implementation.

Operation above base speed can be achieved by adding a negative *d*-axis current to suppress the rotor flux induced voltage down to the available supply voltage or less.

One way of operating above base speed in this controller is to disable the *d*-axis current feedback correction shown in Figure 1.1 and control the *d*-axis applied current i'_d directly to set the maximum motor output voltage at or below the maximum available voltage. The output voltage can be set exactly because of the feed forward nature of the controller. The problem with this method is that the turning on and off of the *d*-axis current feedback could cause a torque disturbance making the optimum time at which to turn on and off the feedback is difficult to determine. Usually, hysteresis would have to be added to the feedback on/off process to prevent oscillation between states.

To avoid this problem, a local feedback method is used to control the *d*-axis current reference so that it adds the correct amount of *d*-axis current for flux weakening. The block diagram of the added feedback is shown in Figure 6.1. The local feedback is made to operate much faster than the *d*-axis current correction feedback effectively over-riding it, fixing the applied flux λ_d' to the calculated reference flux λ_{df}' , and thus fixing the output voltage when in flux weakening mode.

The feedback compensator for the local feedback loop is a *z*-domain integrator with the output limited to positive values only. This ensures flux weakening comes in and out of operation smoothly. The gain K_f is set to 0.5 for the fastest stable response time. The reference value λ_{df}' is the calculated value of the *d*-axis flux required to keep the output motor voltage at a chosen fixed value at or slightly above (if over-modulation is wanted) the available voltage. Its value is calculated as follows:

From Figure 3.2 and Equation 3.4 and ignoring transient components (terms Lpi_d and Lpi_q in Equation 3.4), the applied output *d* and *q* axis voltages are given by:

$$v_d' = -\omega' \lambda_q' + v_{Rd}' \tag{6.1}$$

$$v'_q = \omega' \lambda'_d + v'_{Rq} \tag{6.2}$$

The d flux reference λ'_{df} must be chosen so that when in flux weakening mode:

$$\sqrt{v'^2_q + v'^2_d} = V_M \tag{6.3}$$

where V_M is the maximum fundamental output voltage during flux weakening.

In Equation 6.2, flux linkage λ'_d is dependent on v'_q, which, when operating at maximum voltage V_M, is, from Equation 6.3:

$$v'_q = \text{sign}(\omega')\sqrt{V_M^2 - v'^2_d} \tag{6.4}$$

Using Equation 6.2, the flux linkage reference is given by:

$$\begin{aligned}\lambda^*_{df} &= \frac{1}{\omega'}(v'_q - v'_{Rq}) \\ &= \frac{1}{\omega'}[\text{sign}(\omega')V_M\sqrt{1-(\frac{v'_d}{V_M})^2} - v'_{Rq}] \\ &= \frac{1}{|\omega'|}[V_M\sqrt{1-(\frac{v'_d}{V_M})^2} - \text{sign}(\omega')v'_{Rq}]\end{aligned} \tag{6.5}$$

An inspection of Equation 6.5 shows that v'_d/V_M must be kept less than one. The applied d-axis voltage v'_d depends on the applied torque, so it can be limited in magnitude by controlling the q-axis torque current limits as follows:

The q axis applied flux linkage and current are related by the equation:

$$\lambda'_q = i'_q \tilde{L} \tag{6.6}$$

where $\tilde{L}$ is the estimated motor inductance.

Using this relation in Equation 6.1 to find i'_q:

$$i'_q = -\frac{1}{\tilde{L}\omega'}(v'_d - v'_{Rd}) \tag{6.7}$$

The absolute maximum value of v'_d is limited to V_{DM},which must be less than V_M to ensure v'_d/V_M is less than 1. In an actual implementation, V_{DM} would typically be set to 80% of V_M. This leaves enough voltage margin for flux weakening to operate. To maximise available torque, values as high as 90% have been successfully tried.

From Equation 6.1 for positive speed and positive torque, voltage v'_d is negative. It must be limited to $-V_{DM}$. This sets the maximum limit of i'_q to:

$$i'_{qmax}=\frac{1}{\tilde{L}\omega'}(V_{DM}+v'_{Rd}) \quad \text{for} \quad \omega'>0 \qquad (6.8)$$

For positive speed and negative torque v'_d is positive. This voltage must be limited to V_{DM}, restricting the negative limit of i'_q to:

$$i'_{qmin}=-\frac{1}{\tilde{L}\omega'}(V_{DM}-v'_{Rd}) \quad \text{for} \quad \omega'>0 \qquad (6.9)$$

For negative speed and negative torque, v'_d is negative. It must be limited to $-V_{DM}$, restricting the negative limit of i'_q to:

$$i'_{qmin}=\frac{1}{\tilde{L}\omega'}(V_{DM}+v'_{Rd}) \quad \text{for} \quad \omega'<0 \qquad (6.10)$$

Finally, for negative speed and positive torque v'_d is positive. It must be limited to V_{DM}, restricting the positive limit of i'_q to:

$$i'_{qmax}=-\frac{1}{\tilde{L}\omega'}(V_{DM}-v'_{Rd}) \quad \text{for} \quad \omega'<0 \qquad (6.11)$$

From the above, it can be seen that the equations for i'_{qmax} and i'_{qmin} are swapped depending on the motor rotational direction.

For practical implementation, the above four equations can be combined to create the following continuous torque limits:

$$i'_{qmax}=\frac{1}{|\omega'|\tilde{L}}\left(V_{DM}+\text{sign}(\omega')v'_{Rd}\right) \qquad (6.12)$$

$$i'_{qmin}=\frac{1}{|\omega'|\tilde{L}}\left(-V_{DM}+\text{sign}(\omega')V'_{Rd}\right) \qquad (6.13)$$

These limits can then be applied to the input command i^*_q on top of the normal torque current limits. They should be disabled at zero speed to avoid division by zero.

Speed Limiting

Associated with flux weakening, there is a need to limit the maximum speed to limit the flux weakening current for some types of motors, especially low inductance motors such as quad-copter motors.

For high inductance motors using heavy flux weakening, such as stepper motors, the back emf is much higher than the applied inverter voltage when operating at high speed. This results in the *d*-axis current being naturally limited to K_{emf}/L where K_{emf} is the emf constant in Volts/radians per sec. www.ghunter.net/tests.mp4 This current limit is usually less than the maximum rated current of the motor so there is no limit to the maximum speed except when the available torque drops below the load torque.

For low inductance motors, in the flux weakening region, the negative *d*-axis current will keep rising as speed is increased, reaching values well above the rated current. For low inductance and high resistance motors such as quad-copter motors, the negative *d*-axis current may need restricting to values much lower than even the rated current to prevent unstable operation.

Where the *d*-axis current needs to be limited, this is achieved by limiting the speed. For this controller, the speed is limited to control the maximum *d*-axis current using the method shown in the block diagram of Figure 6.2.

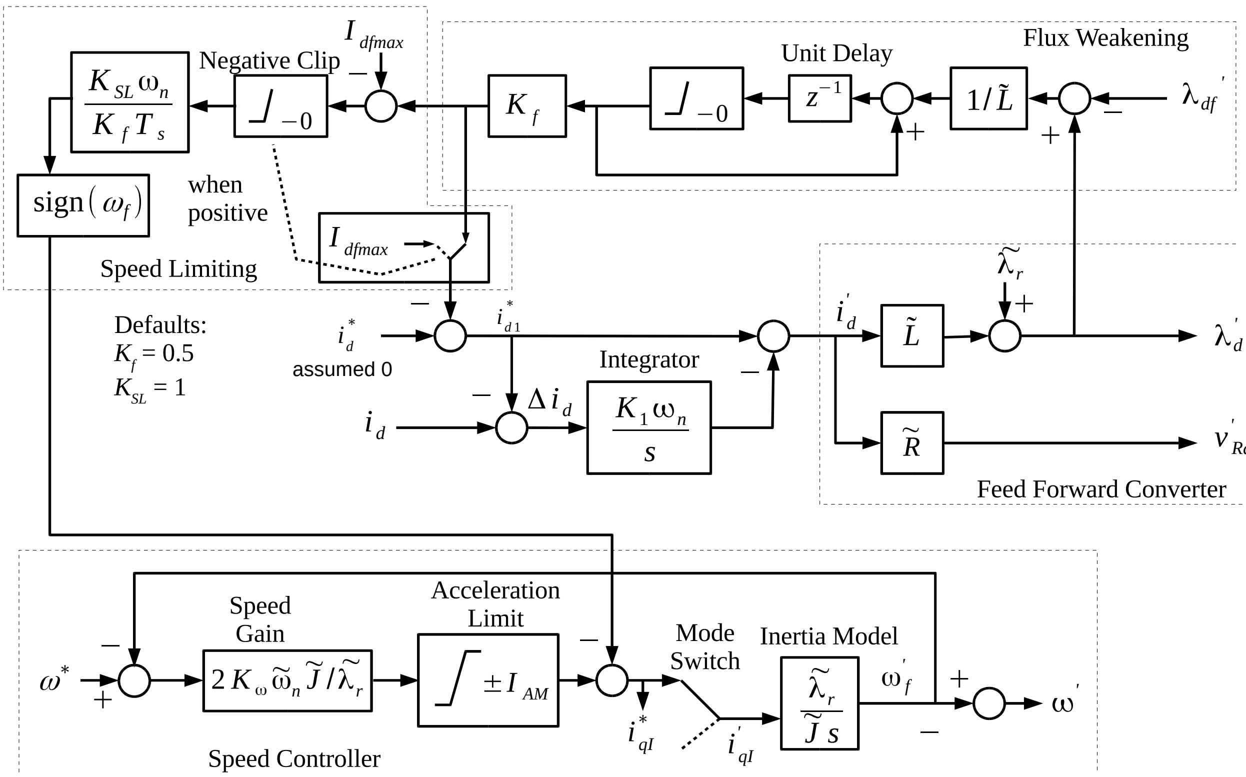

Figure 6.2. Speed limiting.

The speed limiting works as follows: When the negative *d*-axis current is less than a maximum allowed value I_{dfmax}, the flux weakening works as normal. When the flux weakening feedback loop increases the negative *d*-axis current to greater than I_{dfmax}, the control of flux weakening by varying the *d*-axis current is stopped and instead flux weakening is controlled by varying the speed via control of the inertial *q* axis current i_{qI}' (and also i_{qI}^*) instead. Note that in order to control i_{qI}' and thus the speed, the speed limiting output will increase sufficiently to force the Acceleration Limit to operate, effectively disabling the speed controller. Also note that for negative speeds, the sign of the speed limiting output must be inverted as indicated in the block diagram.

With the speed-limiting feedback loop gain scaled to the values shown in the block diagram, the frequency response of this loop is $K_{SL}\omega_n$ radians/sec. The response time with K_{SL} = 1 has been found to be fast enough for any practical application.