

Application Note AN-1090

IRMCF3xx Series Controller Dynamics and Tuning

By Eddy Ho, International Rectifier

Table of Contents

	Page
Introduction	2
Current Controller.....	2
Speed Controller	6
Field-Weakening Controller	10
Critical Over Voltage Protection	12
Interior Permanent Magnet Motor Control	14

This application note describes how to tune the embedded control loops on the IRMCF3xx series of control IC's. This covers the IRMCF312, IRMCF311 and IRMCF343 digital control IC's for air-conditioning systems and the IRMCF341 IC for washing machine applications. The control loops include the ID and IQ current control loops, the velocity control loop, the field weakening loop, IPM control and bus voltage protection. The note describes the equations used to derive the control loop constants and experimental methods to tune control constant

Introduction

This application note describes how to tune the embedded control loops on the IRMCF3xx series of control IC's. This covers the IRMCF312, IRMCF311 and IRMCF343 digital control IC's for air-conditioning systems and the IRMCF341 IC for washing machine applications. The control loops include the ID and IQ current control loops, the velocity control loop, the field weakening loop, IPM control and bus voltage protection. The note describes the equations used to derive the control loop constants and experimental methods to tune control constants.

There are 3 main control loops associated with IRMCK3xx series products. These control loops are current control loop, speed control loop and Field-weakening control loop. The following table summarizes the parameter dependence of each control loop.

Parameters	Current Controller	Speed Controller	Field-Weakening Controller
Motor Inductance	Yes	No	Yes
Motor Resistance	Yes	No	No
Voltage constant (Ke)	No	Yes	Yes
System Inertia	No	Yes	No

Motor parameters are required (Parameter Configurator) for drive setup. These parameters are normally obtained from motor data sheet. IR Sensorless motor controller can tolerate +/-10 % motor parameter error without noticeable performance degradation.

Increased parameter mismatch between motor and controller will result in degradation of torque per Amp capability. The degree of degradation is dependent on the operating conditions (speed, load) and motor characteristics (motor parameters and saturation).

Current Controller

The iMotion current controller utilizes Field-Oriented synchronously rotating reference frame type regulators. Field-Orientation provides significant simplification to the control dynamics of the current loop. There are two current regulators (one for d-channel and one for q-channel) employed for current regulation. The q-channel (torque) control structure is identical to d-channel (flux). The current control dynamics of d-channel is depicted in Figure 1. The motor can be represented by a first order lag with time constant $T = L/R$. This time constant involves motor inductance and equivalent resistance (R: cable + winding). For a surface mounted permanent magnet motor, the d and q channel inductances are almost equal. In the case of Interior permanent magnet motor, the q-channel inductance is normally higher than the d-channel inductance.

In the current control dynamic diagram Figure 1, forward gain A translates digital controller output to voltage (include inverter gain) and feedback gain B translates current feedback (Ampere) to internal digital counts via A/D converter. The calculation of the controller gains (K_{xreg} , $K_{p_{reg_D}}$) is done by using pole-zero cancellation technique as illustrated in Figure 2 where the current controller is rearranged to give transfer function block C(S). Setting $K_{p_{reg_D}}/K_{xreg}$ of C(S) to the time constant of the motor (T), the controller zero will cancel off the motor pole (pole-zero cancellation). Therefore, the controller dynamics can be further simplified as shown in Figure 3. The equivalent transfer function of Figure 3 is a first order lag with time constant T_c . By selecting appropriate current regulator response (typically 0.5 to 1 msec, entry of parameter configurator, Current Reg BW = $1/T_c$) for a particular application, the current regulator gains can be readily obtained. It may be noticed that using pole zero cancellation technique, motor inductance enters into proportional gain calculation and resistance enters into integral gain calculation.

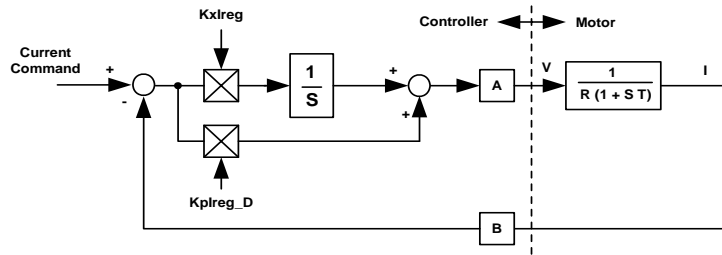


Figure 1. Current Control Dynamics

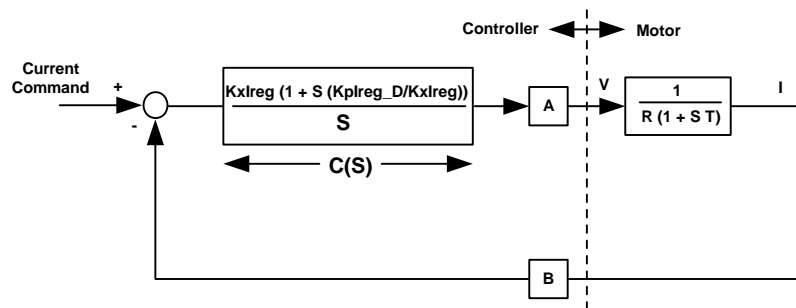


Figure 2. Pole Zero Cancellation

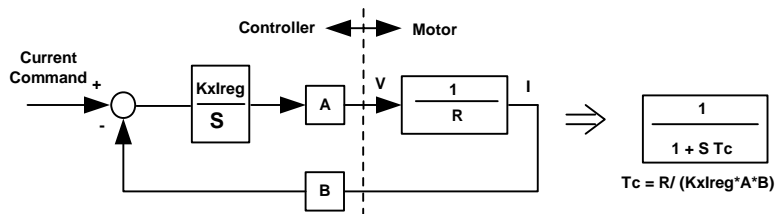


Figure 3. Simplified Current Control Dynamics Due to Pole Zero Cancellation

Based on the pole-zero cancellation technique, the controller gains are evaluated by:

$$K_{plreg} = \frac{L_q \cdot \text{Current Reg BW}}{A \cdot B}$$

$$K_{xlreg} = \frac{R \cdot \text{Current Reg BW} \cdot 2^5 \cdot T}{A \cdot B}$$

Where A and B are the internal digital controller scaling ($A \cdot B = .006016$) and T is the controller sampling time introduced for sampling compensation.

The following gain calculation illustrates a drive application setup with Parameter configurator entries shown below:

8	Inductance Lq	4.00E-02	H
10	Inductance Ld	4.00E-02	H
12	Stator Resistance	6.1	ohms/ph
42	"----- Inverter Switching Frequency -----"		
43	PWM Switching Frequency	10	KHz
61	"----- Current Regulator Tuning -----"		
62	Current Reg Bandwidth	1500	rad/sec

The current regulator gains are calculated as:

$$K_{plreg} = \frac{0.04 \cdot 1500}{0.006016} = 9973$$

$$K_{plreg_D} = \frac{0.04 \cdot 1500}{0.006016} = 9973$$

$$K_{xlreg} = \frac{6.1 \cdot 1500 \cdot 2^5 \cdot 0.0001}{0.006016} = 4867$$

The current controller in the Sensorless FOC block module directly uses these gains.

MCE designer provides current loop diagnostic test function. This test provides the response of the current control loop and also the steady state accuracy.

- ===== Diagnostics =====
- Parking Diagnostic
- Current Reg Diagnostic ←
- Startup Diagnostic
- Open-Loop Diagnostic

Once current regulator diagnostic is executed, step current response can be observed from trace function or current probes on w-phase. It is recommended to use current probe to observe step current response. Figure 4 shows (current probe) the step current response of w-phase when Current Reg diagnostic function is executed. In this figure, 25% step rated motor current is commanded. The step level can be controlled by parameter ParkI (inside Current Reg Diagnostic function). Figure 5 shows the expanded version of Figure 4. The measured current loop response is critically damped at 0.65 msec time constant (0 – 66.3% of final steady value), which is approximately equal to the anticipated current regulator bandwidth response ($1/1500 = 0.667\text{msec}$).

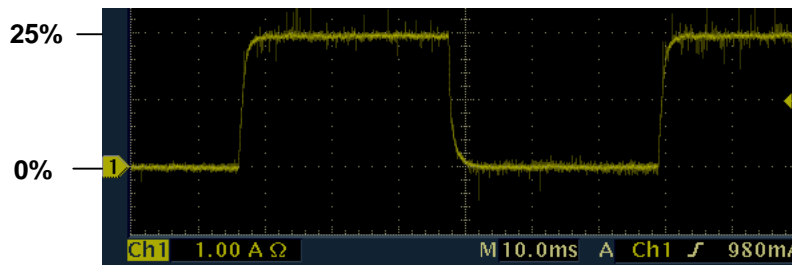


Figure 4. Step Current Response

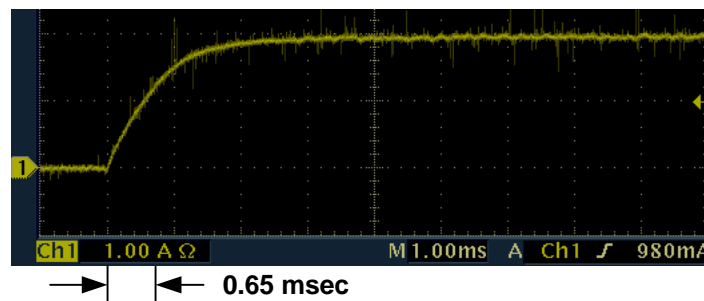


Figure 5. Step Current Response (Expanded Time Scale)

Speed Controller

The speed controller is the most outer-loop controller in a cascaded speed drive system. Figure 6 shows the cascaded control dynamics of the speed control loop. In practice, the inner current loop has much higher control bandwidth than the speed controller, therefore for speed control dynamic purpose, the inner current loop can be ignored as shown in Figure 7. Parameter M (Figure 7) relates command current digital counts to actual current in Amps. The motor mechanical dynamic is a first order function with mechanical time constant equals to J/F (Inertia/Friction). Pole-zero cancellation technique (outlined in current regulator tuning section) can be used to simplify tuning of the speed controller proportional and integral gains (K_{pSreg} , K_{xSreg}). In practice, information on mechanical friction (F) is difficult to obtain. In addition, temperature dependent friction characteristic is present in some applications. Therefore, manual speed tuning may be required to achieve optimal speed response. Some applications cannot tolerate high speed regulator bandwidth due to mechanical resonance present in mechanical arrangement.

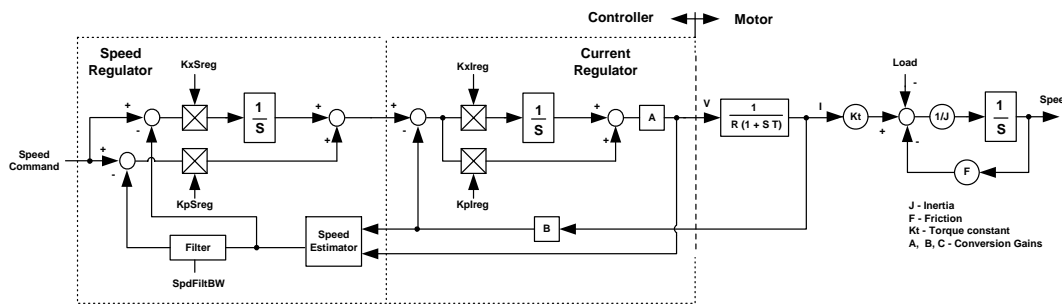


Figure 6. Cascaded Control Dynamics

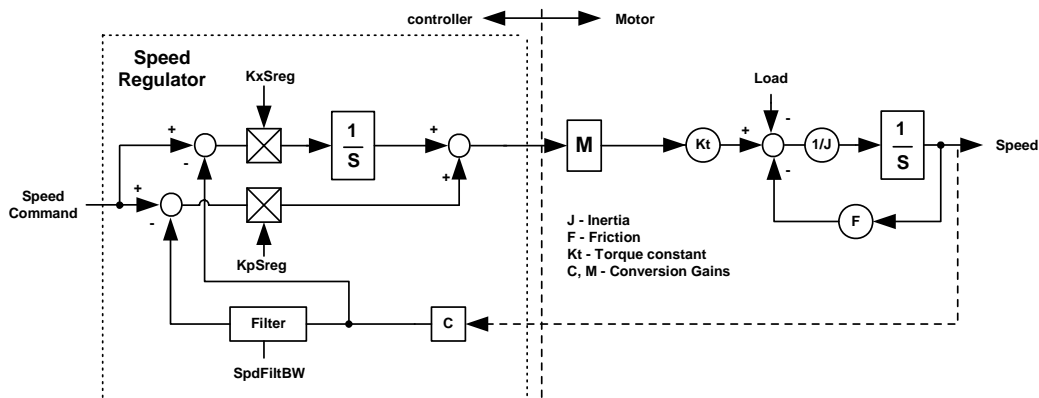


Figure 7. Simplified Speed Control Loop Dynamics

As mentioned earlier, information on mechanical parameters (Friction and Inertia) may be inaccurate and Parameter Configurator will output less optimal gains for the controller. Manual tuning of speed regulator can be used to optimize speed performance. Figure 8 shows speed response (trace buffer speed feedback signal) of a high inertia fan under speed ramping. As can be seen, the speed response shows oscillatory behavior due to non optimized gain values.

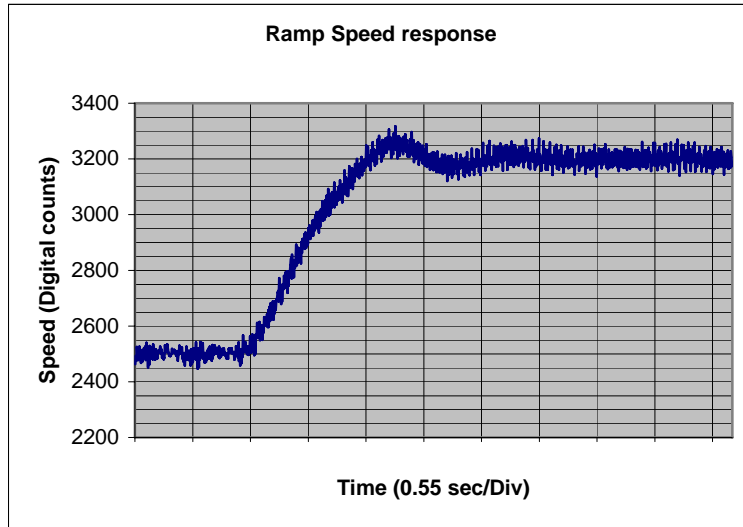


Figure 8. Ramp Speed Response

There are many different approaches of tuning PI regulator for various applications. The following steps provide an example guide line of speed regulator tuning for fan applications.

- 1) **Tuning of KpSreg.** Run drive at a convenient speed say 30% rated rpm. Perform small step (30 to 35% rated rpm) speed response with **KxSreg set to zero**. The step response can be achieved by using a fast speed ramp setting (AccelRate). Under such condition, first order speed response is expected as shown in Figure 9. This figure shows the speed responses using 3 different proportional gains (KpSreg = Kp1, Kp2, Kp3).

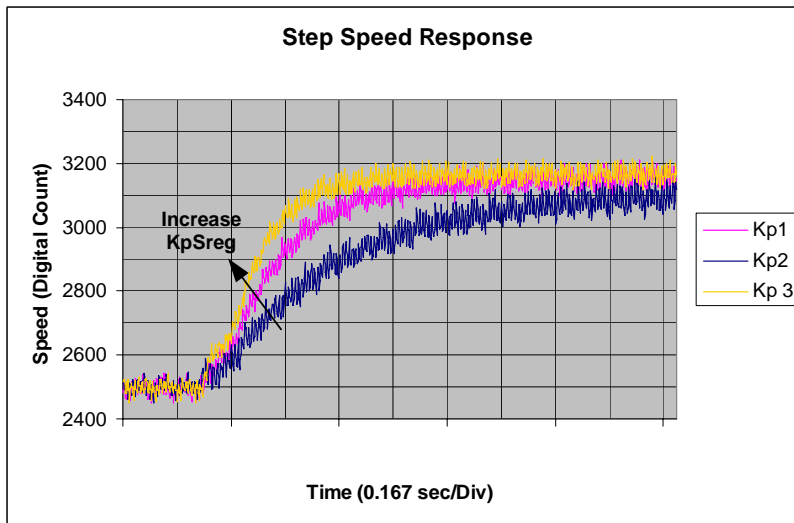


Figure 9. Step Speed Response under Different KpSreg Gains

Adjust KpSreg until the desired transient response (Speed regulator bandwidth) is obtained. For this fan application with high inertia to friction ratio, Kp3 is selected to yield approximately 0.2 sec first order time constant.

- 2) **Tuning of KxSreg.** After the desired proportional gain (KpSreg) is selected (step 1), please resume nominal ramp rate and speed regulator integral gain (KxSreg). Under such circumstance (with KpSreg = Kp3 and KxSreg = Kx1), issue a ramp speed command under the same speed range (30 to 35%) as illustrated in step 1. Figure 10 shows ramp speed responses under 3 different integral gains (Kx1, Kx2 and Kx3). The response with the original (imported from Parameter Configurator) integral gain (Kx1) exhibits oscillatory behavior. The integral gain is being reduced (Kx2 and Kx3) just enough to remove speed oscillation. For this fan application, the response obtained is acceptable with KxSreg = Kx3.

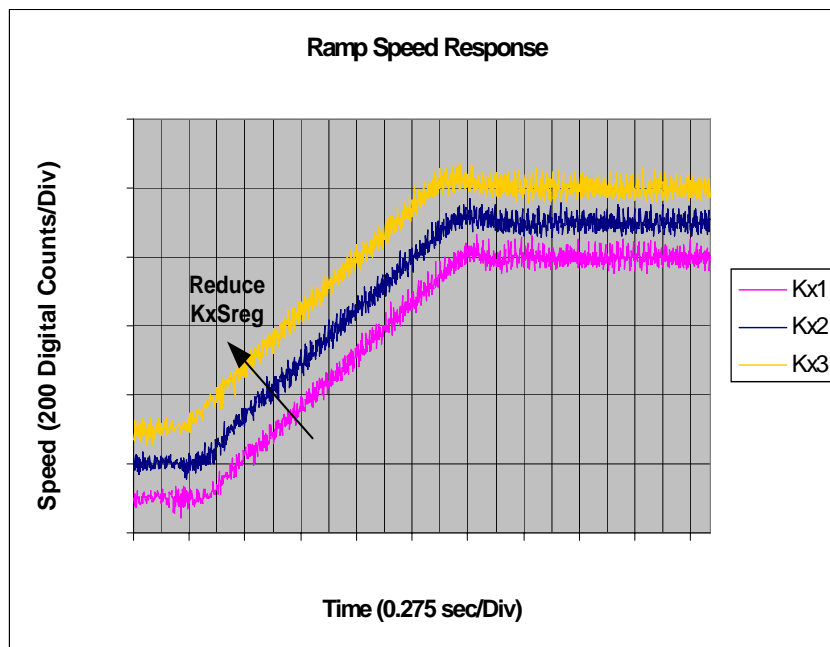


Figure 10. Ramp Speed Response under Different KxSreg Gains

- 3) Figure 11 shows ramp speed response with non-optimized (KpSreg = Kp1, KxSreg = Kx1) and optimized (KpSreg = Kp3, KxSreg = Kx3) speed regulator gains. A tighter control response is exemplified with the gain optimization.

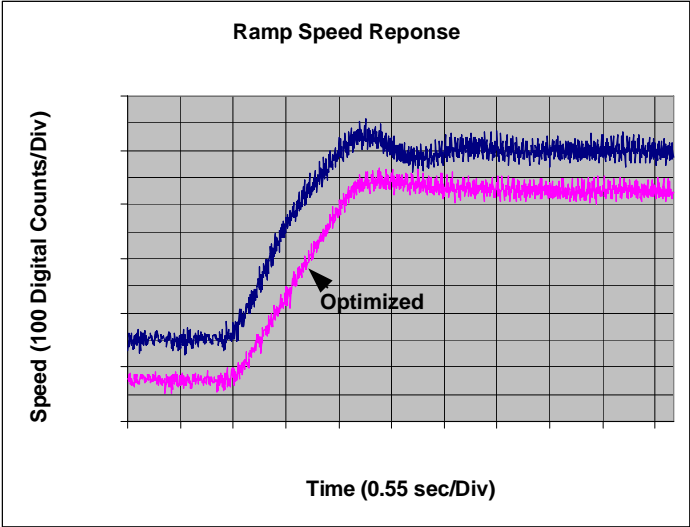


Figure 11. Comparison of Optimized and Non-optimized Speed Response

- 4) It may be noticed that there is still slight overshoot on the optimized Ramp Speed response (Figure 11). Most applications can tolerate a slight overshoot (<10%). Increasing KpSreg or reducing speed ramp rate as shown in Figure 12 can further reduce speed overshoot. It is recommended to keep overshoot to minimal possible for applications (i.e. Washer Spin Mode), which require Field-Weakening range of more than 1.5.

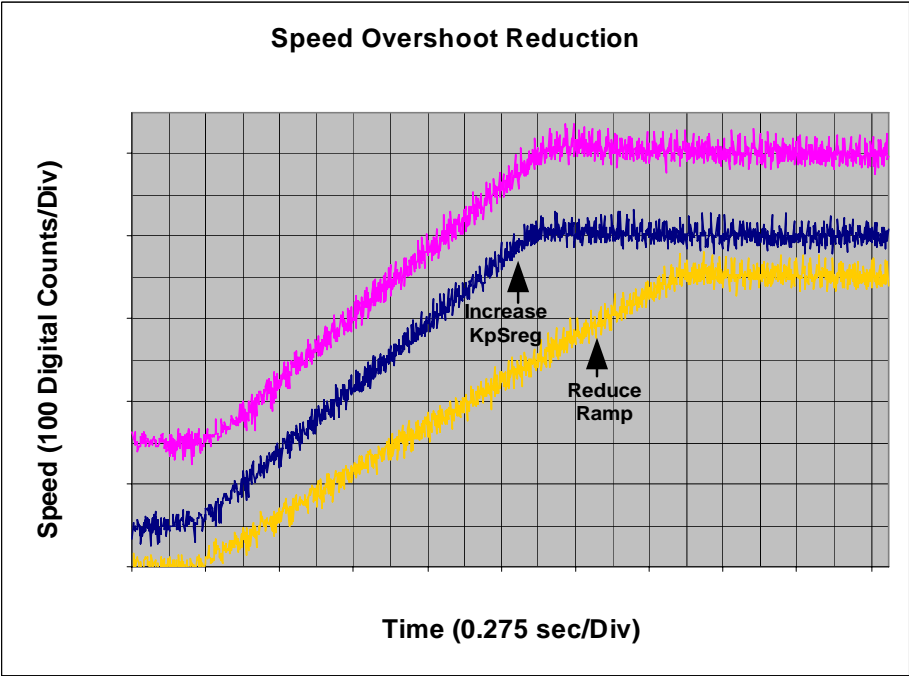


Figure 12. Speed Overshoot Reduction

Field-Weakening Controller

Field weakening is required for wide speed range applications. Back EMF (BEMF) of a motor increases with speed up to the point that inverter output voltage reaches its maximum level. Further increase in motor speed requires flux weakening to maintain the motor terminal voltage at its maximum possible level as shown in Figure 13.

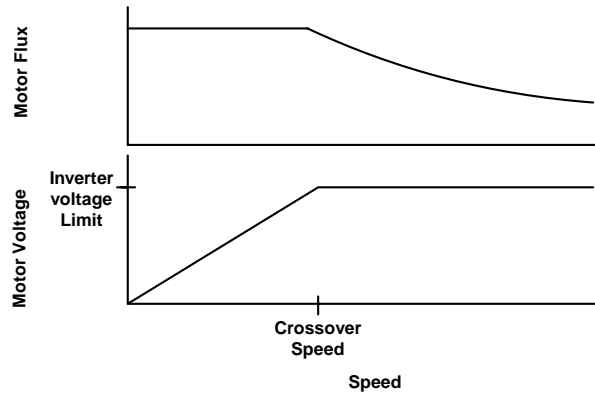


Figure 13. Field-Weakening Characteristics

Figure 14 shows a block representation of the Field-Weakening Controller dynamics. The output of the controller (Fwk_Id) represents a d-axis current component, which opposed the rotor magnet flux (Flux). By injecting a negative d-axis current, the resultant flux can be reduced and hence the motor voltage can be limited to stay within the ceiling voltage of the inverter output. The control loop gain increases with motor frequency as shown in Figure 14. Inside the Field-Weakening controller, gain modulation is used to decouple the variation of loop gain due to motor frequency.

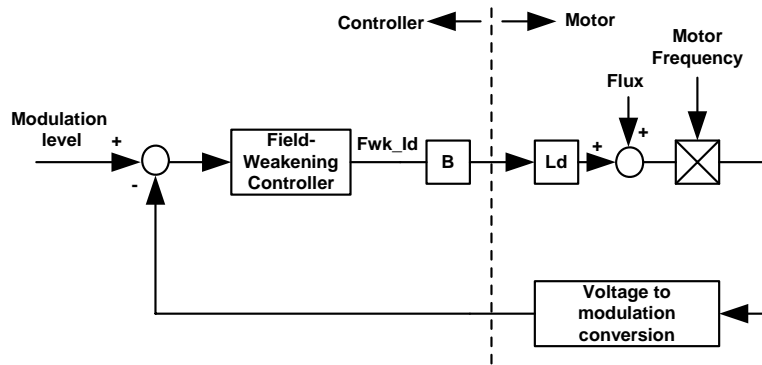


Figure 14. Field-Weakening Control Dynamics

Figure 15 shows the Field-weakening controller. This controller is implemented in the MCE application. As can be seen from this figure, when modulation exceed a prescribed level specified by FwkLvl, a negative d-axis current (Fwk_Id) will start and lowering down the main flux. The Field-Weakening controller acts as a modulation index limiter. The gain modulation block serves to compensate the increase in loop gain due to increase in motor frequency as mentioned earlier.

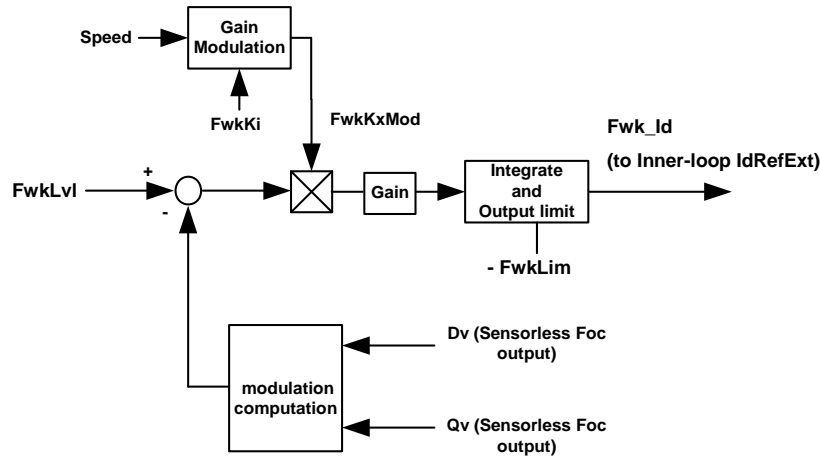


Figure 15. Field-Weakening Controller Block

With gain modulation incorporated, the control loop gain is decoupled from motor frequency. Figure 16 shows a simplified representation of the Field-weakening control dynamic. The equivalent transfer function of Figure 16 is a first order lag system. Parameter M in Figure 16 is a function of motor inductance, nominal dc bus voltage and the motor crossover frequency (function of motor K_e). Parameter configurator sets the field-weakening controller gain (FwkKi) based on parameter M and a prescribed field-weakening loop response (0.25 sec).

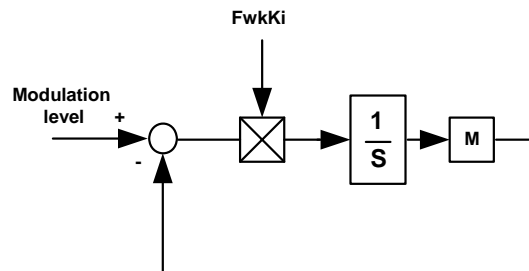


Figure 16. Simplified Field-Weakening Control Dynamics

The response of the Field-weakening loop can be observed from the command d-axis current (using MCEdesigner trace function). Under light Field-weakening condition (-10% rated motor current on field-weakening controller output current), a step change (-2%) in the modulation limit level (FwkLvl) is issued. When modulation limit reduces, the Field-Weakening controller increases d-axis motor current (negative) in order to reduce motor flux and satisfy the modulation limit (voltage limit). Figure 17 shows a step change in FwkLvl and the response of the command d-axis current. First order response is exemplified from Figure 17. The tuning of the Field-Weakening controller is straightforward since it only involves one controller gain. The response of the Field-Weakening controller should be high enough to catch up with speed changes. In practice, most appliance applications do not require high dynamic speed changes in Field-Weakening region. Therefore the response of Field-weakening can be relaxed (typically: 0.1 to 0.4 sec response time. Parameter configurator preset to 0.25sec).

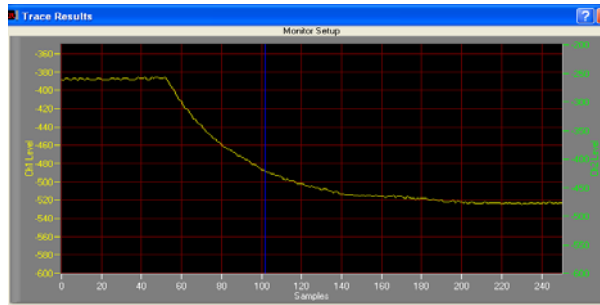


Figure 17. Field-Weakening Control Responses,
Vertical: Id command (digital counts) Horizontal: Time (0.1 sec/ div)

Critical Over Voltage Protection

In order to achieve high-speed operation under limited voltage capability, motor flux is suppressed by injection of a negative d-axis current (Field-weakening) to the motor. In case of an inverter shunt down at high speeds, all inverter devices will be disabled and the negative d-axis field forcing will be lost. Under such circumstance, the motor flux will resume and motor voltage will build up according to motor K_e as shown in Figure 18. This is a critical over voltage condition in which the motor BEMF builds up and charges the dc bus capacitor voltage to an exceedingly large value.

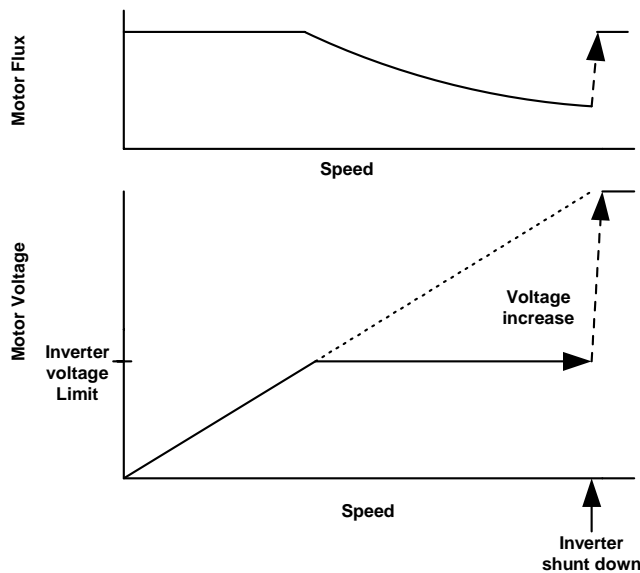


Figure 18. Inverter Shunt Down during Field-Weakening

In iMotion control IC (3xx series), the critical over voltage protection is implemented in MCE application software. Critical over voltage condition is detected by comparing dc bus voltage feedback to a configurable voltage level (configurable by Parameter Configurator: dc bus critical voltage). When critical over voltage is detected, command bit CriticalOv (inputs of MCE module

Space Vector PWM) will be set. This will trigger a zero vector (low side devices turn-on) PWM state independent of any condition (including faults). The use of a zero vector enforces short circuit to the motor terminal and hence prohibits charging of dc bus capacitors. Figure 19 illustrates critical over voltage condition and the engagement of zero vector protection. Upon application of the zero vector, motor current will circulate within the motor windings and the rotational energy of the motor will be dissipated inside the motor (copper and core losses).

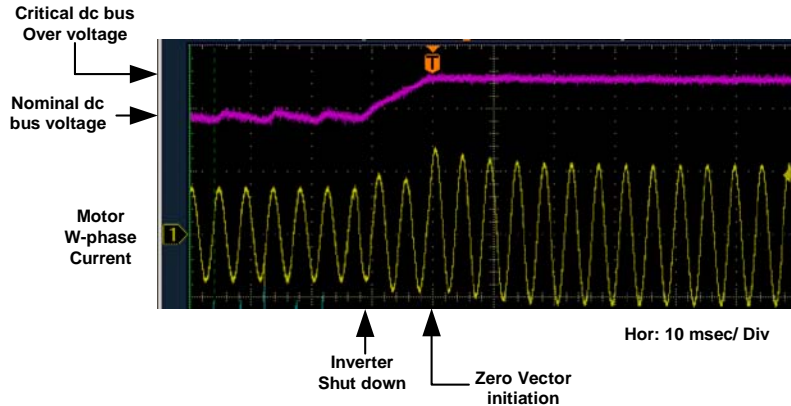


Figure 19. Critical DC Bus Over Voltage
(top: dc bus voltage, bottom: motor current)

The interface between the critical over voltage detection and the Space Vector PWM module is shown in Figure 20.

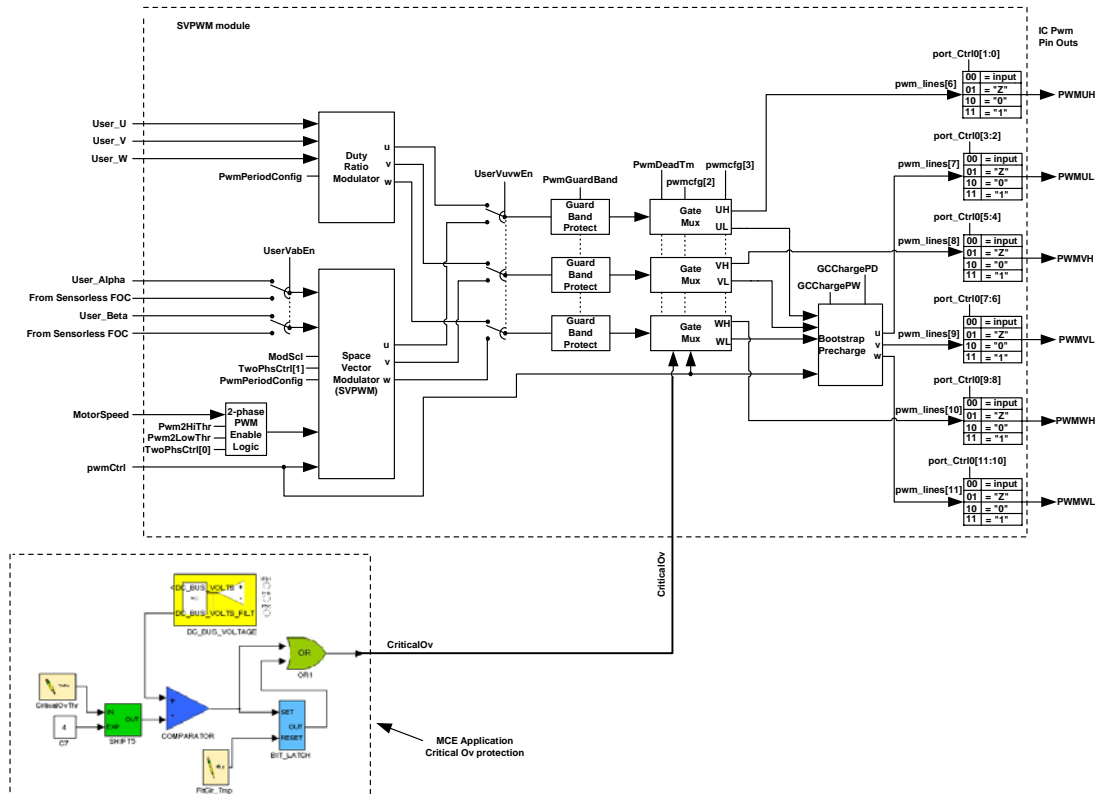


Figure 20. Critical Over Voltage Interface

In addition to the iMotion control IC, gate driver IC (IRS2631) of the iMotion chip set also provides over voltage protection. The gate driver IC can be configured to protect dc bus over voltage in the event of control IC failure using also the zero vector injection method.

Interior Permanent Magnet Motor Control

The motor torque developed by a permanent magnet motor is given by:

$$\text{Torque} = \frac{P}{2} \cdot \left(\underbrace{\text{FluxM} \cdot I_q}_{\text{Cylindrical Torque}} + \underbrace{(L_d - L_q) \cdot I_d \cdot I_q}_{\text{Reluctance Torque}} \right)$$

Where

P	number of rotor poles
L_d, L_q	d and q-axis inductance (d axis aligns to rotor magnet).
I_d, I_q	d and q-axis current components.
FluxM	Flux linkage of permanent magnet

There are two torque components associated with the motor torque equation. The first component (Cylindrical torque) is due to interaction between rotor magnet flux and stator q-axis current. The second component (reluctance torque) is due to motor saliency (difference in d and q inductance). This saliency term is negligible ($L_d = L_q$) in Surface Mounted Permanent magnet (SPM) motors. In the case of an Interior Permanent Magnet Motor (IPM) where L_q not equal to L_d , the torque per ampere rating is boosted by the saliency torque term. In motoring operation, a negative I_d injection will contribute to the increase in reluctance torque.

Figure 21a shows the current vector trajectory for optimal torque per ampere generation of an IPM motor. As current magnitude increases, the current angle advancement also increases which indicates an increase in d-axis current demand in the negative direction. The required current angle for optimal torque per ampere generation is depicted in Figure 21b. In iMotion control IC, this optimal current characteristics is approximated by a linear fit as shown in Figure 21b. Two parameters (AngDel and AngLim) are used to characterize the behavior of optimal current angle for generating maximum torque per ampere. Parameter AngDel fixes the slope of the linear line and parameter AngLim limits the maximum allowable angle advancement. Parameter configurator computes AngDel with 2 points (zero and rated current point). The implementation of this linear interpolation and the calculation of command d-q current are shown in Figure 22.

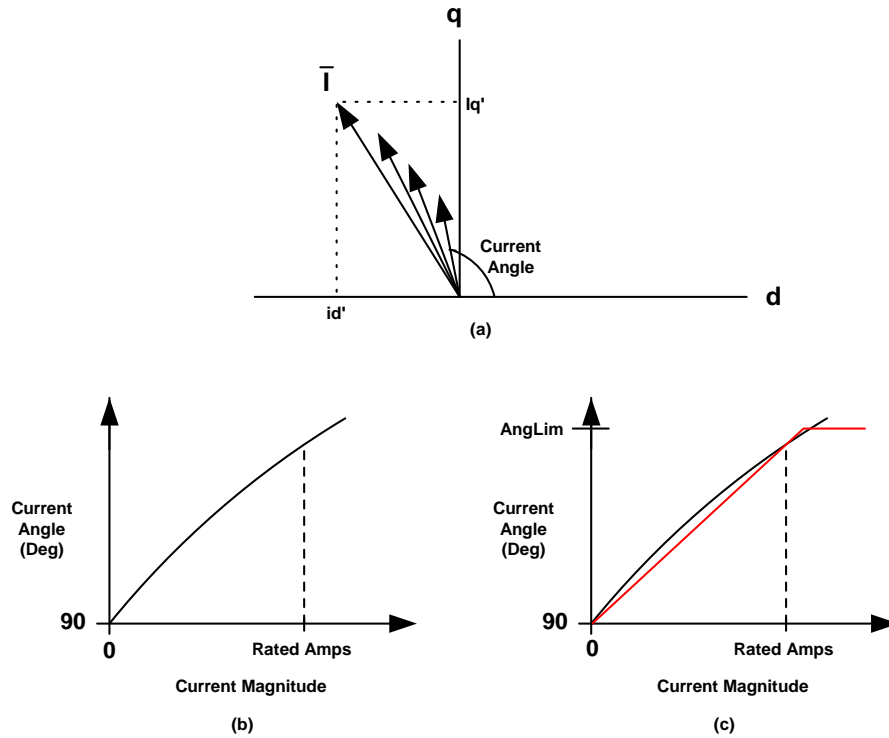


Figure 21. Current Angle at Maximum Torque per Ampere

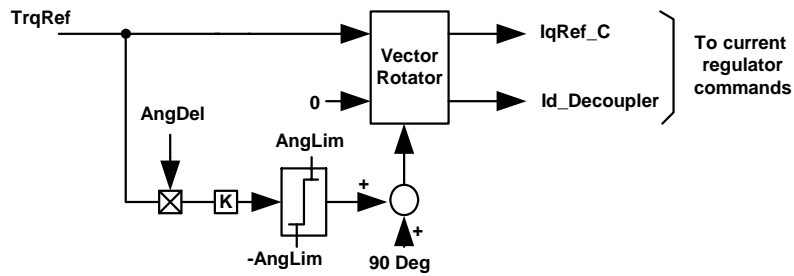


Figure 22. Current Decoupler for Optimal Torque per Ampere Operation