Input Capacitor and Over Voltage Protection Circuit Design

Application Note

Prepared by ***Leo Zhang and Hongqiang Qin***

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ABSTRACT

In a motor control system, the mechanical energy may be recycled back into the DC input rail during periods when the motor speed decreases. In real applications, it is necessary to add enough input capacitance to absorb this energy. A DC over-voltage protection (OVP) circuit may also be required. This application note describes how to choose the input capacitor value and how to design the OVP circuit.

WHY MECHANICAL ENERGY IS RECYCLED TO THE INPUT RAIL

When the motor speed is decreasing, the controller may generate a negative torque to slow the speed of the motor. The motor now works as a generator, which converts mechanical energy into electrical energy. This energy is recycled back into the DC input rail.

Figure 1 shows the control system model.

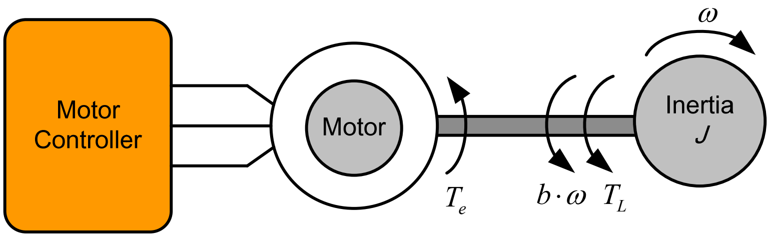

Figure 1: Motor Control System Model

From the model above, we can get the electrical torque using Equation (1):

$$T_e - T_L - b \cdot \omega = J\frac{d\omega}{dt} \quad (1)$$

Where T_e is the electrical torque generated by the motor, ω is the angular speed of the motor, J is the inertia of the rotor and load, b is the friction ratio, and T_L is the load torque. In most cases, b is a very small value and can be disregarded. The electrical torque can be expressed with Equation (2):

$$T_e = J\frac{d\omega}{dt} + T_L \quad (2)$$

From the sign of T_e, we can determine whether or not mechanical energy has been converted to electrical energy. If $T_e < 0$, mechanical energy is recycled back to the DC input rail. If $T_e > 0$, no mechanical energy is recycled.

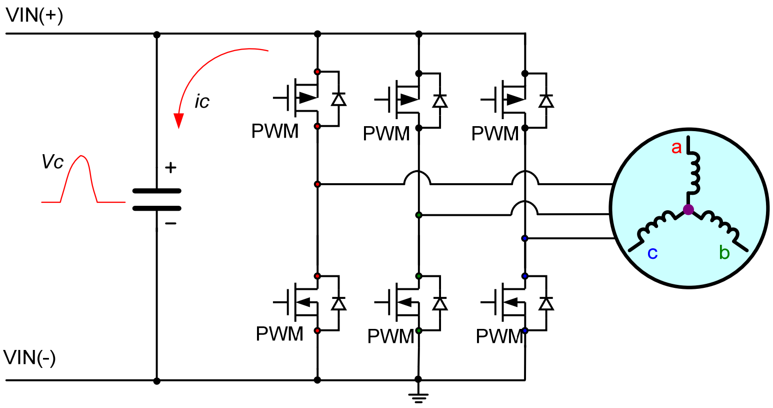

Figure 2: Energy Recycling during Motor Speed Decrease

As Figure 2 shows, the recycled electrical energy charges the input capacitor. If there is insufficient capacitance on the DC input rail, a high-voltage spike occurs and may damage the power stage. If it is not practical to fit enough capacitance on the input rail, an OVP circuit can also be used to discharge the energy and limit the input rail voltage.

DESIGN PROCEDURE

The energy recycled back into the DC input rail is related to many factors, such as the rate of speed deceleration, the mechanical load, and the motor characteristic parameters. To simplify the calculation, assume that the motor deceleration speed is constant (see Figure 3).

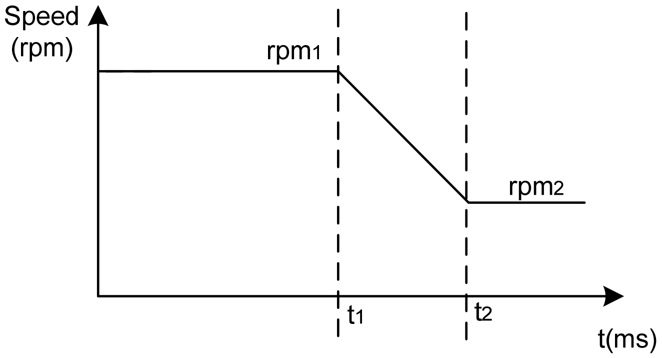

Figure 3: Motor Speed Curve

During the deceleration period, the motor speed starts to decrease from rpm_1 at time t_1 and becomes rpm_2 at time t_2.

The angular speed at t_1 can be calculated with Equation (3):

$$\omega_1 = \frac{rpm_1}{60} \times 2\pi \, rad/s \tag{3}$$

The angular speed at t_2 can be calculated with Equation (4):

$$\omega_2 = \frac{rpm_2}{60} \times 2\pi \, rad/s \tag{4}$$

The angular acceleration can be calculated with Equation (5):

$$\alpha = \frac{d\omega}{dt} = \frac{\omega_2 - \omega_1}{t_2 - t_1} \tag{5}$$

Input Capacitance Calculation

From Equation (2), the electrical torque can be expressed as Equation (6):

$$T_e = J\frac{d\omega}{dt} + T_L = J \cdot \alpha + T_L \tag{6}$$

The power consumption from the input bus can be expressed with Equation (7):

$$\begin{gathered} P_{in} = P_e + P_R \\ P_e = T_e \cdot \omega = (J \cdot \alpha + T_L) \cdot \omega \\ P_R = 3 \cdot I_{rms}{}^2 \cdot R_s \end{gathered} \tag{7}$$

Where P_{in} is the input power from the DC rail, P_R is the power of the motor winding resistor, and I_{rms} is the RMS value of the winding phase current.

During speed deceleration, P_e becomes negative and the motor works as a generator. The energy is charged back to the input rail as shown in Equation (8):

$$\Delta E = \int_{t_1}^{t_2} P_{in} dt = \int_{t_1}^{t_2} (J \cdot |\alpha| \cdot \omega - T_L \cdot \omega - 3 \cdot I_{rms}{}^2 \cdot R_s) dt = \int_{t_1}^{t_2} (P_M - P_L - P_R) dt \tag{8}$$

Where P_M is the mechanical power change during speed deceleration, P_L is power consumed by the mechanical load, and P_R is the power consumed by the winding resistors.

Supposing at t_x, when P_M - P_L - P_R = 0, the energy charged back reaches the maximum value. The input DC bus maximum voltage (V_{max}) at t_x can be calculated with Equation (9):

$$\Delta E_{\max} = \int_{t_1}^{t_x} P_{in} dt = \frac{1}{2} \cdot C_{in} \cdot (V_{\max}{}^2 - V_{nom}{}^2) \tag{9}$$

Where V_{max} is the maximum voltage value of the input bus, and V_{nom} is the nominal voltage value of the input bus.

For easy calculation, it is suggested to use an MPS spreadsheet tool to calculate how much input capacitance is needed with a given maximum allowed voltage. Please contact an MPS FAE for this spreadsheet. The detailed derivation is shown in Appendix 1.

Over-Voltage Protection (OVP) Circuit Design

If the input capacitor value cannot be as large as the value calculated above due to space or other limitations, it is necessary to add an OVP circuit at the DC rail input.

You can use a comparator to detect when the DC bus voltage increases. When the DC input voltage is above the required clamping voltage value (V_{clamp}), a comparator outputs high logic, which can be used to turn on a MOSFET to clamp the input voltage (see Figure 4).

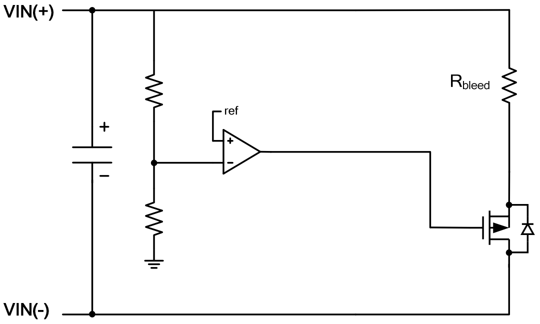

Figure 4: Protection Circuit Using a Comparator

When the voltage is larger than V_{clamp}, the MOSFET turns on, and current flows through the resistor to discharge excess energy. The bleeding resistor design guidelines are shown below.

- Resistor value limitation: A resistance value too large causes the peak DC voltage to exceed the allowed clamping voltage. For most cases, a resistor with several ohms to tens of ohms is sufficient.
- Thermal limitation: A power-rating resistor too small makes the resistor too hot when absorbing energy. For most cases, a resistor with few watts power rating is enough to handle the energy.

Please see Appendix 2 for the calculation details of how to design this circuit.

DESIGN SUMMARY

The energy recycled back into the DC rail causes a voltage spike. It is necessary to add enough input capacitance to absorb this energy. If it is impossible to add enough capacitance, add a voltage clamping circuit at the DC input rail.

Following the design procedures described in this application note should help you understand the principles of how to choose the input capacitor value and how to design the protection circuit correctly. You can also use an MPS spreadsheet tool to calculate the required values quickly. Please contact an MPS FAE for this spreadsheet.

APPENDIX 1: DETAILED DERIVATION OF INPUT CAPACITANCE CALCULATION

The power recycled from the mechanical side can be calculated with Equation (10):

$$\Delta E = \int_{t_1}^{t_2} (P_e - P_R)dt = \int_{t_1}^{t_2} (T_e \cdot \omega - P_R)dt = \int_{t_1}^{t_2} (J \cdot |\alpha| \cdot \omega - T_L \cdot \omega - 3 \cdot I_{rms}{}^2 \cdot R_s)dt \tag{10}$$

The motor electrical torque (T_e) provided by the motor can be calculated with Equation (11) and Equation (12):

$$T_e = C_T \cdot I_{peak} = C_T \cdot \sqrt{2} \cdot I_{rms} \tag{11}$$

$$T_e = J \cdot |\alpha| - T_L \tag{12}$$

Where C_T (N*m/A) is the torque constant of motor.

The energy back to DC input rail can be expressed with Equation (13):

$$E(t) = \int_{t_1}^{t_2} (P_e - P_R)dt = \int_{t_1}^{t_2} \left[J \cdot |\alpha| \cdot \omega - T_L \cdot \omega - 3 \cdot \left(\frac{J \cdot |\alpha|}{\sqrt{2} \cdot C_T}\right)^2 \cdot R_s \right] dt \tag{13}$$

If $P_e > P_R$, energy is recycled back and stored in the input capacitor.

Figure 4 shows an $E(t)$ vs. t plot.

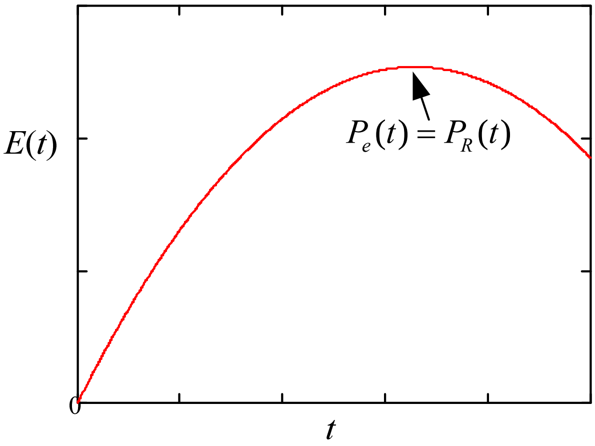

Figure 5: Energy Recycled Back against Lasting Time

$E(t)$ reaches the maximum value at t_x when $P_e(t)$ = $P_R(t)$, t_x and ω_x are shown in Equation (14) and Equation (15):

$$t_x = \frac{\omega_1}{|\alpha|} - \frac{1.5 \cdot R_s}{C_T{}^2} \frac{J}{1 - T_L / (J \cdot |\alpha|)} \tag{14}$$

$$\omega_x = \omega_1 - |\alpha| \cdot t_x \tag{15}$$

The maximum energy generated by the inertia load can be calculated with Equation (16):

$$\Delta E_M = \frac{1}{2} \cdot J \cdot (\omega_1{}^2 - \omega_x{}^2) \tag{16}$$

The energy consumed by the load torque can be calculated with Equation (17):

$$\Delta E_L = T_L \cdot \frac{(\omega_1 + \omega_x)}{2} \cdot t_x \tag{17}$$

The energy consumed on the winding resistance can be calculated with Equation (18):

$$\Delta E_L = 3 \cdot (\frac{I_{peak}}{\sqrt{2}})^2 \cdot R_s \cdot t_x = 1.5 \cdot R_s \cdot (\frac{J \cdot |\alpha| - T_L}{C_T})^2 \cdot t_x \tag{18}$$

Given the maximum allowed input voltage (V_{max}), the input capacitance can be calculated with Equation (19):

$$C_{in} = \frac{2 \cdot (\Delta E_M - \Delta E_L - \Delta E_R)}{{V_{\max}}^2 - {V_{nom}}^2} \tag{19}$$

APPENDIX 2: OVER-VOLTAGE PROTECTION CIRCUIT DESIGN DETAILS

If the input capacitor value cannot be as large as the calculated value due to space or other limitations, a smaller capacitor value should be used. However, this means that when energy is recycled into the DC input rail, the peak voltage may exceed the allowed maximum voltage. Therefore, an OVP circuit must be added at the DC rail input. A comparator over-voltage detection circuit can be used to implement a protection circuit with a bleed resistor (see Figure 6).

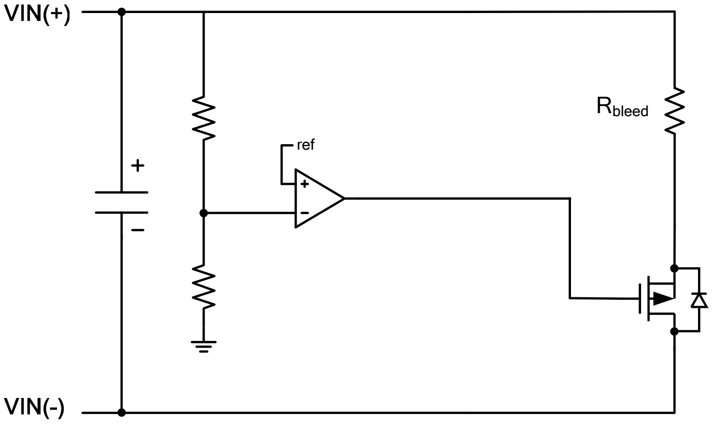

Figure 6: Protection Circuit Using a Comparator

When the voltage is larger than V_{clamp}, the MOSFET turns on, and current flows through the resistor to discharge excess energy. The voltage on the capacitor is latched at V_{clamp}.

The energy stored on the capacitor at V_{clamp} can be calculated with Equation (20):

$$E_C = \frac{1}{2} \cdot C_{bus} \cdot (V_{clamp}^2 - V_{nom}^2) \tag{20}$$

Where C_{bus} is the input capacitor value.

When the OVP circuit is active, set the angle speed and time (ω_{bleed}, t_{bleed}) with Equation (21):

$$\omega_{bleed} = \omega_1 - \alpha \cdot |t_1 - t_{bleed}| \tag{21}$$

The mechanical energy change can be calculated with Equation (22):

$$E_M = \frac{1}{2} J \cdot \left(\omega_1^2 - \omega_{bleed}^2\right) \tag{22}$$

The energy consumed by the load torque can be calculated with Equation (23):

$$E_L = T_L \frac{(\omega_1 + \omega_{bleed})}{2} \cdot |t_1 - t_{bleed}| \tag{23}$$

The energy consumed on the winding resistor can be calculated with Equation (24):

$$E_R = 3 \cdot R_s \cdot I_{rms}^2 \cdot |t_1 - t_{bleed}| \tag{24}$$

The protection circuit starts to work when Equation (25) is satisfied:

$$E_{bleed} = E_M - E_L - E_R - E_C = 0 \tag{25}$$

ω_{bleed} and t_{bleed} can be calculated from Equations 20-25.

The power that the resistor must dissipate can be calculated with Equation (26):

$$P_{bleed} = P_e - P_R = \left|T_e\right| \cdot \omega - 3R_s \cdot I_{rms}^2 \tag{26}$$

Where P_{bleed} is at its maximum when $\omega = \omega_{bleed}$ and can be calculated with Equation (27):

$$P_{bleed\_\max} = \left|T_e\right| \cdot \omega_{bleed} - 3R_s \cdot I_{rms}^2 \tag{27}$$

Bleed Resistor Selection

The maximum power dissipated is P_{bleed_max}. The maximum bleed resistor value can be calculated with Equation (28):

$$R_{\max} = \frac{P_{bleed\_\max}}{V_{clamp}^2} \tag{28}$$

Select the bleed resistor $R < R_{\max}$.

The total energy to be discharge can be calculated with Equation (29):

$$E_{total} = \Delta E_{C\_\max} - E_C \tag{29}$$

The average power can be calculated with Equation (30):

$$P_{avg} = \frac{E_{total}}{t_2 - t_{bleed}} \tag{30}$$

Ensure that the resistor can handle the pulsed power.

Bleed MOSFET Selection

The peak current can be calculated with Equation (31):

$$I = \frac{V_{clamp}}{R} \tag{31}$$

The peak voltage of the MOSFET should be larger than V_{clamp}.