Optimizing Power MOSFET Performance In Motor Drive Designs

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The metal-oxide-semiconductor field-effect transistor, or MOSFET, is the most commonly used transistor in present-day electronic circuit design. The MOSFET has countless properties that make it useful in various functions. These properties include scalability, low turn-on current, high switching speeds, and high off-state impedance. MOSFETs are used in integrated circuit (IC) designs for both analog and digital, switching power applications, motor drive, load switches and numerous other applications.

Unlike its companion, the bipolar junction transistor, the MOSFET is a voltage enhancement-mode device that makes system-level control much simpler. Despite this, there still remain several key parameters that must be managed in order to ensure optimal system performance. This is especially true in motor drive applications utilizing high-drive currents and hard-switching of the power MOSFETs when the motor is in operation. This article provides a look into several MOSFET properties and how they affect the performance of a motor drive design.

For those familiar with MOSFET operation and three-phase motor drives, this article will be mostly a review of fundamentals. Parameters that influence MOSFET selection are explained, equations are given for calculating conduction and switching losses in the motor drive applications, and factors such as switching frequency and edge rates, which influence both switching losses and EMI, are discussed. Tradeoffs in the different performance factors and in performance versus device cost are noted.

The article also points to application notes offering further discussion on calculation of MOSFET losses and the use of slew rate limiting to reduce switch-node ringing. Finally, this article notes a gate drive IC with adjustable drive current architecture, which makes it easier for designers to assess the impact of higher MOSFET switching speeds and their parasitic effects in three-phase motor drive designs.

Power MOSFETs In Motor Drives

In typical three-phase motor drive applications, power MOSFETs are configured in a triple inverter configuration (Fig. 1). The MOSFETs act as switches to connect the power or ground rails from the system to the motor terminals. This configuration allows for each of the three windings to be energized with either a positive or negative drive current.

Ideally, the MOSFETs act as perfect switches without power loss, but in reality this is not the case. MOSFETs suffer from both conduction and switching power losses that ultimately reduce the overall efficiency of the motor drive system. While these power losses can never be completely removed, they can be minimized with proper understanding of the MOSFET's key parameters and operation.
Before moving further, let us review several fundamental components of the power MOSFET (Fig. 1 again) that are integral to its performance.

- **R_{DS(ON)}**: The resistance seen between the drain and source terminals of the power MOSFET when it is enhanced. A key component of the MOSFET conduction losses. Dependent on the gate-to-source voltage.

- Terminal equivalent capacitances (C_{GS}, C_{GD}, C_{DS}): Capacitances seen between the three terminals of the power MOSFET. A key component of the MOSFET switching loses. Often normalized to charge values (Q_{GD}, Q_{GS}) in MOSFET data sheets.

- Body diode: Parasitic diode created by the construction of the power MOSFET. Often used as the freewheeling diode in motor drive designs. A smaller component in both conduction and switching losses.

- Terminal equivalent inductances (L_G, L_S, L_D): Inductances created by the package pins and bond wires of the power MOSFET. While not a direct contributor to power losses, these do play a part in the device’s switching performance.

**R_{DS(on)} Is King?**

The first commonly encountered question in selecting proper power MOSFETs is, *what are the key specifications?* These specifications are those most closely tied to the MOSFET performance and thermal capability. Many system designers often point to the MOSFET’s on resistance or R_{DS(ON)} as it has long been held as the predominant specification in selecting a power MOSFET due to its contribution to conduction losses.

The case study in Table 1 shows that while R_{DS(ON)} remains an important factor, it is not the only key parameter to consider. Let us calculate the two main power losses (MOSFET conduction and switching losses) for the
system shown in Fig. 2. This example uses a half-bridge inverter driving a constant current source to simplify the calculations.

Table 1. Case study design parameters for example motor drive design.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{SUPPLY}} )</td>
<td>Supply voltage</td>
<td>48</td>
<td>V</td>
</tr>
<tr>
<td>( I_M )</td>
<td>Drive current</td>
<td>25</td>
<td>A</td>
</tr>
<tr>
<td>( R_{\text{DS(ON)}} )</td>
<td>MOSFET on-resistance</td>
<td>5</td>
<td>mΩ</td>
</tr>
<tr>
<td>( f_{\text{SW}} )</td>
<td>Switching frequency</td>
<td>25</td>
<td>kHz</td>
</tr>
<tr>
<td>( t_{\text{RISE}} )</td>
<td>Switching rise time</td>
<td>100</td>
<td>Ns</td>
</tr>
<tr>
<td>( t_{\text{FALL}} )</td>
<td>Switching fall time</td>
<td>100</td>
<td>Ns</td>
</tr>
<tr>
<td>( D )</td>
<td>Switching duty cycle</td>
<td>50</td>
<td>%</td>
</tr>
</tbody>
</table>

![Diagram of MOSFET half-bridge inverter test configuration for case study.](image)

**High-Side MOSFET**

Conduction losses are calculated with a simple \( P = I^2R \) equation. This equation is multiplied by the percent of the period that the MOSFET is conducting.

\[
P_{\text{CON,LOSS}} = I_{\text{DS}}^2 \times R_{\text{DS(ON)}} \times D \tag{1}
\]

\[
P_{\text{CON,LOSS}} = 25^2 \times 0.005 \times 0.50 = 1.5625 \text{ W} \tag{2}
\]

Switching losses are calculated with a slightly more complicated version of \( P = IV \). In this case, the area is calculated for the current and voltage overlap using the rise and fall times. This is then combined with the MOSFET switching frequency.

\[
P_{\text{SW,LOSS}} = \frac{1}{2} \times V_{\text{DS}} \times I_{\text{DS}} \times t_{\text{RISE}} \times f_{\text{SW}} + \frac{1}{2} \times V_{\text{DS}} \times I_{\text{DS}} \times t_{\text{FALL}} \times f_{\text{SW}} \tag{3}
\]
\[ P_{\text{SW \_LOSS}} = 48 \times 25 \times 100E-9 \times 25E3 = 3 \text{ W} \]  \hspace{1cm} (4)

Low-Side MOSFET

\[ P_{\text{CON \_LOSS}} = I_{DS}^2 \times R_{\text{DS(ON)}} \times (1 - D) \]  \hspace{1cm} (5)

\[ P_{\text{CON \_LOSS}} = 25^2 \times 0.005 \times (1 - 0.50) = 1.5625 \text{ W} \]  \hspace{1cm} (6)

\( P_{\text{SW \_LOSS}} \) is ignored in this scenario since the low-side MOSFET switches with \( V_{\text{DS}} = 0 \text{ V} \) (soft-switching).

Table 2. Summary of MOSFET power losses in case study.

<table>
<thead>
<tr>
<th>MOSFET</th>
<th>Conduction</th>
<th>Switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-side</td>
<td>1.5625 W</td>
<td>3 W</td>
</tr>
<tr>
<td>Low-side</td>
<td>1.5625 W</td>
<td>0 W</td>
</tr>
<tr>
<td>Total</td>
<td>3.125 W</td>
<td>3 W</td>
</tr>
</tbody>
</table>

In this example, you can clearly see that conduction losses due to \( R_{\text{DS(ON)}} \) are not the only dominant losses. This highlights the importance of selecting a MOSFET that has both proper conduction and switching performance. You can learn more about how to calculate MOSFET power dissipation in Texas Instruments’ SLPA009 application report[1].

**Tackling MOSFET Switching Losses**

The primary methods to reduce switching losses are to either decrease the pulse-width modulation (PWM) switching frequency or reduce the rise and fall times of the MOSFET. Further reductions to the PWM switching frequency are often not feasible due to current ripple requirements of the motor or the need to stay above the audible frequency range (>20 kHz).

Reducing rise and fall times requires a deeper understanding of how the slew rate is determined. Fundamentally, the MOSFET slew rate is tied to two parameters shown in equation 7.

\[ t_{\text{SLEW}} = \frac{Q_{\text{GATE \_SW}}}{I_{\text{GATE}}} \]  \hspace{1cm} (7)

where \( Q_{\text{GATE \_SW}} \) is the gate charge required for the MOSFET to enter its full conduction state and \( I_{\text{GATE}} \) is the rate that charge is delivered (current) to the MOSFET gate, typically through an external gate driver.

To better understand the first parameter \( Q_{\text{GATE \_SW}} \), let us examine the typical turn-on behavior for a power MOSFET (Fig. 3). As the driver delivers charge to the MOSFET, the gate-to-source voltage (\( V_{\text{GS}} \)) begins to rise. The gate crosses the threshold voltage (\( V_{\text{th}} \)) and the drain-to-source channel begins carrying current (\( I_{\text{DS}} \)). The MOSFET then enters the area that primarily determines its switching performance. This region is known as the Miller region and occurs when the \( Q_{\text{GD}} \) charge is delivered causing the drain-to-source voltage (\( V_{\text{DS}} \)) to slew. After this the MOSFET gate charges to its final value. These steps lead to the common three-stage \( V_{\text{GS}} \) turn-on waveform (green line).
To minimize $V_{DS}$ rise and fall time, select a MOSFET with as minimal of $Q_{GD}$ as possible since this is the primary component of $Q_{GATE\_SW}$ shown in equation 7.

The second parameter, $I_{GATE}$, is the current magnitude that can be delivered to the MOSFET gate during the Miller region. The higher the drive current, the more rapidly charge can be delivered; thus, reducing the switching time. Typical gate drivers can have capabilities from 100 mA up to 10 A.

**How Fast Is Too Fast?**

The previous sections highlight the need for both minimal $R_{DS(ON)}$ and $Q_{GD}$. Unfortunately, both of these parameters directly contribute to the cost of the power MOSFET (Fig. 4).

Realizing this, the last parameter to adjust is the drive current to the MOSFET gate. Equation 7 shows that this current should be increased to further reduce the rise and fall times. The higher the drive current, the faster the
MOSFET will switch. But as with all engineering parameters, it cannot be increased indefinitely without consequences to the system.

At high edge rates, effects from the MOSFET parasitic capacitances and inductances become more and more apparent. These parasitic effects typically manifest as two common issues visualized in Fig. 5.

![Fig. 5. Oscilloscope capture of MOSFET parasitic voltage overshoot and ringing.](image)

Fig. 5 shows the turn-off waveform for a half-bridge inverter driving a constant current load. The first parasitic effect is voltage overshoot on the switching node. In the turn-off scenario the switch-node voltage drops below ground. In the turn-on scenario the switch-node voltage rises above supply. These voltage excursions can cause stress to the driver circuitry or the MOSFET itself.

The second effect is ringing on the switching node due to the resonant (LC) circuit that is formed. This ringing is often greater than 1 MHz and can contribute heavily to the electromagnetic radiation of the system. This can cause issues for applications trying to pass stringent electromagnetic compliance requirements as in automotive systems. While there are methods to combat both of these effects, often the most effective solution is to limit the slew rate of the power MOSFETs. You can learn more about the source and prevention of these effects in Texas Instruments’ SLPA010 application report.[2]

**Dialing It In**

Getting your motor drive system to its optimal performance point will require balancing the performance, cost and parasitic tradeoffs we investigated in this article. New motor MOSFET gate drivers are designed to make this process simpler for system designers.

For example, the DRV8305,[3] a gate driver IC for three-phase motor drive applications, incorporates an adjustable drive current architecture to easily analyze the results of higher MOSFET switching speeds and their parasitic effects. This can reduce the extra cost, time and printed circuit board (PCB) area required to accomplish the same with external tuning components. You can read more about this architecture in Texas Instruments’ SLVA714 application report.[4]

While these are not the only MOSFET questions a motor drive system designer will face, they are some of the most critical. The MOSFET is an integral component of modern circuit design, and understanding it properly will help maximize performance in your system.
References


3. The DRV8305 data sheet.

4. “Understanding IDrive and TDrive in TI Motor Gate Drivers” by Nicholas Oborny, TI Application Report (SLVA714A), May 2016.

5. Motor Drive & Control TI blog series. Nick has been an ongoing contributor to this blog.

About The Author

Nicholas Oborny is a systems engineer with the Analog Motor Drivers group at Texas Instruments. Nick supports next-generation motor driver development for three-phase brushless, stepper and brushed dc motor systems, as well as motor system design support and application debugging. Nick graduated magna cum laude from Texas A&M University with a Bachelor of Science in computer engineering, College Station, Texas. When not working with motors, Nick enjoys playing competitive indoor volleyball, hiking, camping, and reading science fiction novels. If you have questions about this article or motor drivers in general, you can post them to the TI E2E Community Motor Drivers forum.

For further reading on power conversion for motion control, see the How2Power Design Guide, select the Advanced Search option and select "Motion Control" in the Application category. Also select "Motor drives" in the "Power Supply Function" category.