AN1102
Key MOSFET parameters for Motor Control applications

Siva Uppuluri, Applications Engineer, Diodes Inc.

Automotive manufacturers are increasingly turning to the use of Brushless Direct Current (BLDC) motors instead of brushed or stepper motors as they enable precise control over a wide dynamic range enabling more efficient, cooler running of higher power motor control solutions that are more reliable. Much of the growth in BLDC motor control is coming from previously mechanically driven applications such as power steering, fuel pumps, water pumps and transmission actuation.

The BLDC motor as the name suggests, does not use brushes for energising the motor phases; thereby eliminating all the mechanical wear and tear due to friction and power losses, and to arcing that are associated with its conventional brushed counterparts. A typical BLDC motor control scheme comprises a microcontroller, gate driver and MOSFETs. Figure 1 shows a 3 phase BLDC configuration with sensors. The microcontroller handles the interface with other ECUs usually via the CAN/LIN bus as well as providing the switching signals to the pre-driver circuit that in turn will provide the high-current outputs to drive the MOSFETS.

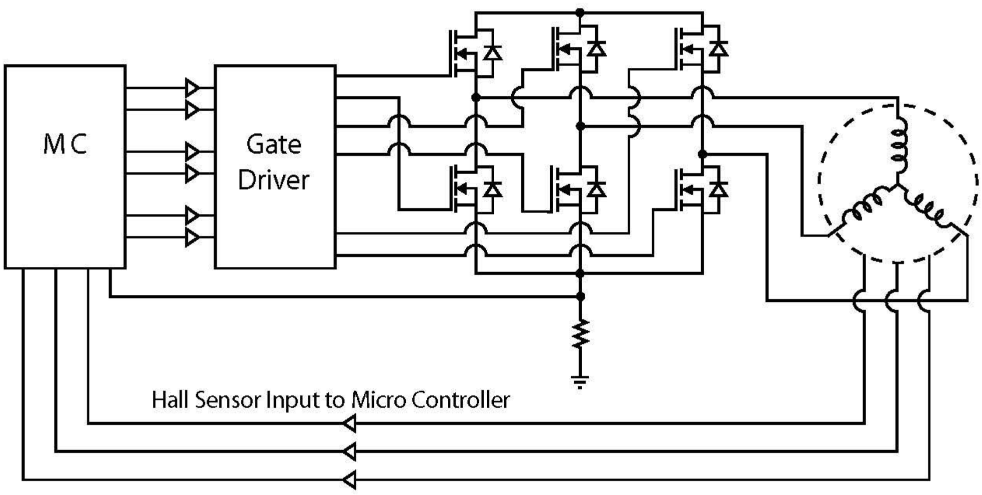

Figure 1. The topology of a sensor-controlled brushless DC motor

In a BLDC motor, a permanent magnet rotor is used and a rotating electro-magnetic field is applied to it with the stator. The two challenges involved in an efficient BLDC motor design are: 1) detecting the position of the rotor accurately and 2) energising the stator coils in the correct order at the precise time. The rotor's position is continuously monitored with the help of Hall effect sensors (or in the case of sensor less topologies, through the use of control algorithms) and the stator coils are energised by turning on and turning off the MOSFETs in a bridge configuration. For the same die size, an N-channel MOSFET will have approximately half the on-resistance, RDS(on), compared to a P-channel device. And as die size is a dominant factor of a MOSFET's cost, N-channel MOSFETs are, in most cases, the preferred solution.

These MOSFETs can be subject to wide variation in voltage, avalanche events, high peak current and high ambient operating environments. Therefore, the selection of the correct MOSFET for a given BLDC motor control design will determine the drive circuit efficiency and long-term reliability of the BLDC solution. This application note considers, in turn, the MOSFET parameters and characteristics that will determine the reliability, efficiency and design of a BLDC motor control application.

These parameters can be classified into 3 major categories based on their effects on the overall performance:

1) Reliability related parameters.
2) Efficiency related parameters.
3) Design related parameter.

Reliability related parameters:

When choosing a MOSFET for a motor drive application, it is important to consider the extreme and fault condition stresses on the device and choose a MOSFET with sufficient headroom. This will ensure the long-term reliability of the system.

Breakdown voltage (BV_{DSS}):

When choosing a MOSFET for a BLDC design it is recommended that a device is selected with sufficient breakdown voltage *(BV_{DSS})*) to protect against any transient voltage that may appear due to trade-offs made in circuit design and/or during fault conditions. Furthermore, it is not a good practice to operate the MOSFETs close to their rated breakdown voltages, hence sufficient headroom over the normal operating voltages is required. It is normally recommended to ensure that the MOSFET will never see a voltage in excess of 2/3 the rated breakdown voltage. It is for this reason that for half-bridges used in motor applications, it is common practice to choose 40V MOSFETs for 12V line voltages and 60V MOSFETs for 24V line voltages.

Pulse drain to source current (Ids) rating or surge current ratings:

In motor applications, the start-up and stall currents could be up to 2 to 3 times greater than the DC full load current. Although it is a common practice to provide the DC full load operating currents for motors, it is important to keep the surge current rating in mind while selecting MOSFETs for these applications.

Efficiency related parameters

In an automotive applications, BLDC's are exposed to high ambient operating temperatures. It is therefore essential that the junction temperature rise of the MOSFET is kept to a minimum to aid long term reliability. All the efficiency parameters are collectively responsible for the power dissipation in the MOSFTs and the associated elevation in the operating junction temperature. The power losses in the MOSFETs, package, PCB layout and thermal management will ultimately determine the junction temperature rise. Thermal management itself an important topic, but it is beyond the scope of this application note -Refer to AN1100 on the Diodes website for a detailed description of thermal data and usage.

On State Resistance

Every MOSFET has a resistive element, described as on state resistance or $R_{DS(ON)}$, that dissipates power as current is conducted through the device. These conduction losses are inversely proportional to the size of the MOSFET; the lower the $R_{DS(ON)}$, and hence conduction losses, the greater the MOSFET size. The conduction losses can be determined by:

$PD = I^2R$ Where;

I = current and R = MOSFET $R_{DS(ON}$ at a given temperature.

Rds(on) decreases with increasing Vgs, however typically once the Vgs is increased beyond 10V Rds(on) tends to flatten off as the MOSFET is completely enhanced after 10V of Vgs resulting in the least possible Rds(on) for most MOSFETs. Datasheets often clearly state the required Vgs value for complete enhancement of the MOSFET, see figure 2. Graphs for Diode's DMTH6004SPSQ are used for figure 2 and figure 3.

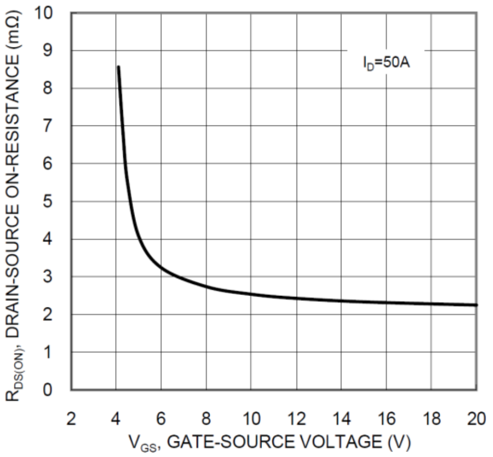

Figure 2: V_{GS} versus $R_{DS(ON)}$

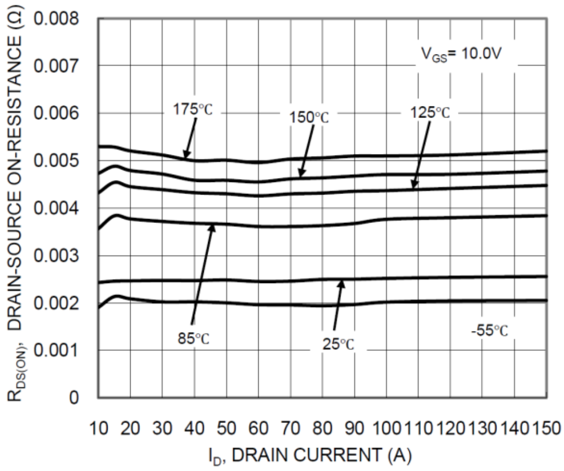

Figure 3: Drain current versus $R_{DS(ON)}$

$R_{DS(ON)}$ increases as drain current and operating temperature increase. This information is provided in product datasheet graphs. Although a few MOSFETs exhibit low $R_{DS(ON)}$ at low currents and temperatures, $R_{DS(ON)}$ can significantly increase with current and temperature. Fig 3 shows the drain current versus $R_{DS(ON)}$ for the DMTH6004SPSQ at various temperatures. Hence when choosing the MOSFET it is recommended that different MOSFETs are compared at the relevant operating conditions using graphs similar to figure 2 and figure 3.

Gate Charge and Crss parameter:

Gate charge (Qg):

The other major source of power loss is through switching losses. As the MOSFET switches on and off, its intrinsic parasitic input capacitance needs to be charged and discharged during each switching transition. The amount of 'gate charge' that is required to raise the gate voltage (V_{GSS}) to a required level (usually 10 or 12V) is inversely proportional to the $R_{DS(ON)}$ of the MOSFET. So, as $R_{DS(ON)}$ decreases gate charge (Qg) increases. Although this is not a problem in non-switching applications, it has a significant impact on the efficiency of the switching applications and its effect increases as switching frequency increases, making it an important parameter for motor applications.

BLDC motor circuits often operate at frequencies in excess of 20kHz and Qg has an impact on the overall efficiency figures. A benchmarking exercise on different MOSFETs in a 24V BLDC motor application, to follow, will demonstrate the effect of Qg in combination with other parameters on the overall efficiency. Also Low Qg MOSFETs decrease the driving stresses on the gate drivers, which result in a lower operating temperature for the gate drivers.

Reverse Transfer Capacitance (Crss)

C_{rss} is the dynamic capacitance between the gate and the Drain of a MOSFET; it is also referred to as Miller capacitance or transfer capacitance. This parameter has a direct impact on the dv/dt related failures/false turn-on events, so is a very significant parameter when selecting MOSFET for half bridge configurations.

For the circuit shown in figure 4, when the high-side MOSFET is turning on, the voltage at the switch node shoots up to V_D in a short period of time. This dv/dt event at the switch node (S) is also coupled to the gate of the low-side MOSFET through the C_{rss}. This coupling current in combination with the gate resistance results in a rise in the gate voltage with respect to its source. This could potentially turn on the low-side device resulting in a shoot-through event. The effect of C_{rss} increases with increasing frequency making Crss an important parameter to consider when designing in a MOSFET for half bridge configurations.

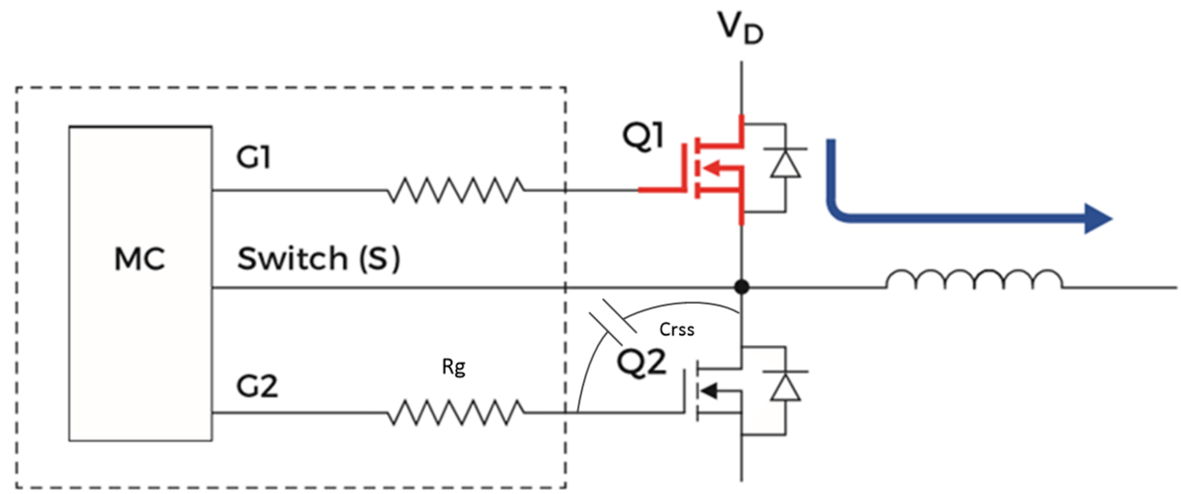

Figure 4: Typical bridge circuit for driving a phase of BLDC motor

Idg' → transient drain to gate current

Idg' = Crss of Q2 * dv/dt at the switch node

Vgs' → transient Vgs

Vgs' = Idg' * Rg

If Vgs' > threshold of the low-side MOSFET, it results in a shoot-through event.

Switching times:

Switching times comprise two times; the delay time and rise/fall time. Delay times limit the overall operating frequency, whereas rise/fall times have a directly proportional effect on the switching losses. Typical switching information can be found in most datasheets. The two parameters that affect the switching times are C_{iss} and C_{oss} , these can also be found in the datasheet. In the BLDC motor applications, the speed of the motor is controlled by controlling the speed of rotation of the electromagnetic field and the torque is controlled by controlling the current with a PWM signal, hence the switching performance of the MOSFET is an important parameter to consider.

Reverse recovery current of the body diode:

Just like a normal PN diode, the body diode of the MOSFET will store charge during conduction. In half-bridge topologies there is always a finite time during which the body diode conducts due to the dead-time incorporated into the microcontrollers driving the half bridge MOSFETs. *Other than the recovery losses, it has other effects depending on the operating frequency and parasitic elements involved in the applications.*

A commonly used full bridge circuit for motor drive applications is shown in figure 5a and 5b. A combination of Q1, Q4 or Q3, Q2 can be used to control the direction of rotation. The speed of the motor is set by the speed of the rotating magnetic field. To control the torque, average current through the stator coil is controlled. To achieve this, one of the MOSFETs is subjected to PWM control. Irrespective of whether the low-side or high-side MOSFET is used for PWM control, the reverse recovery problem still exists as is explained in the following paragraphs.

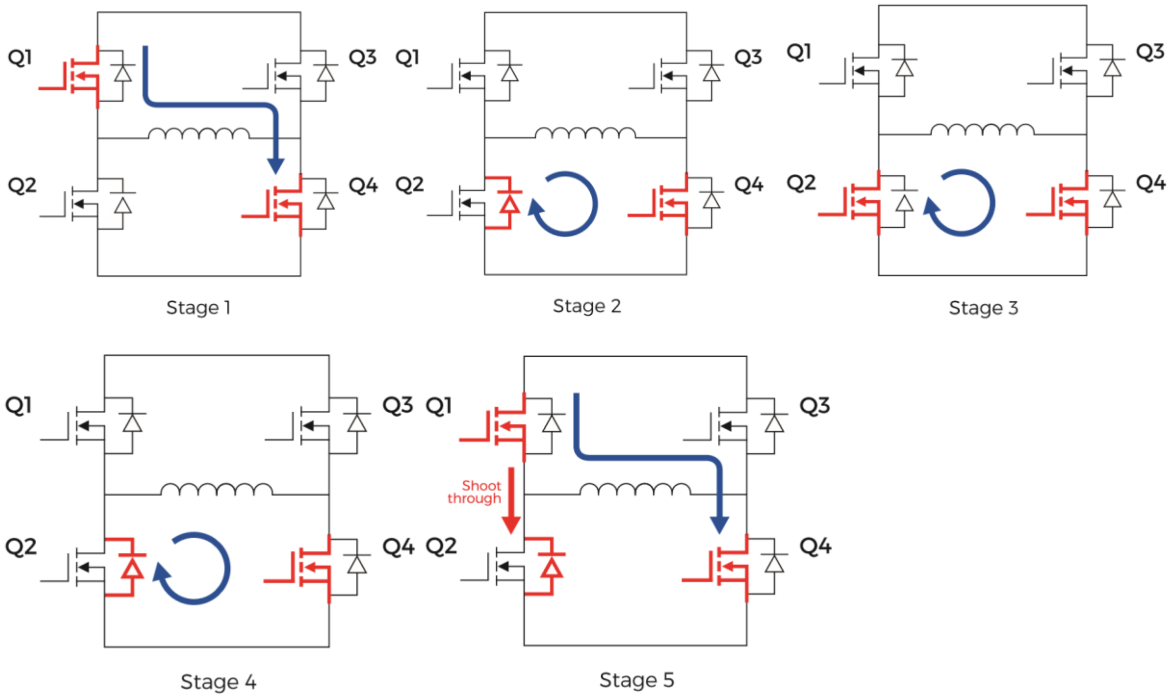

Figure 5a: Case 1 full bridge circuit

Low Side PWM Control : Q1 PWM, Q4 ON

STAGE 1: Q1 ON, Q4 ON → current builds ups in the motor winding.

STAGE 2: Q1 OFF, Q4 ON → current in the inductor continues to flow in the same direction through the Q4 and the body diode of Q2

STAGE 3: Q1 OFF, Q4 ON, Q2 ON → current now flows through the channel of Q4 and the channel of Q2

STAGE 4: Q1 OFF, Q4ON, Q2 OFF → before turning on the Q1, Q2 is turned off based on the dead time settings. During this period current switches back to the body diode of Q2

STAGE 5: Q1 ON, Q4 ON → during this period the voltage at the switch pin (S1) shoots up to Vd (drain pin of the high side MOSFETs), line voltage powering the bridge. And the dV/dt depends on how quickly the Q1 is turned on.

During stage 5, the body diode of Q2 is reverse biased while it is still conducting current. This results in a recovery current that flows through Q1 and the body diode of Q2, which represents a shoot-through scenario until the body diode of Q2 is completely recovered. After the recovery instant, the parasitic inductance in the current path results a voltage swing in an attempt to maintain the current in the path. This voltage excursion coupled with the parasitic capacitances in the path result in further high frequency noise at the switch node leading to EMI.

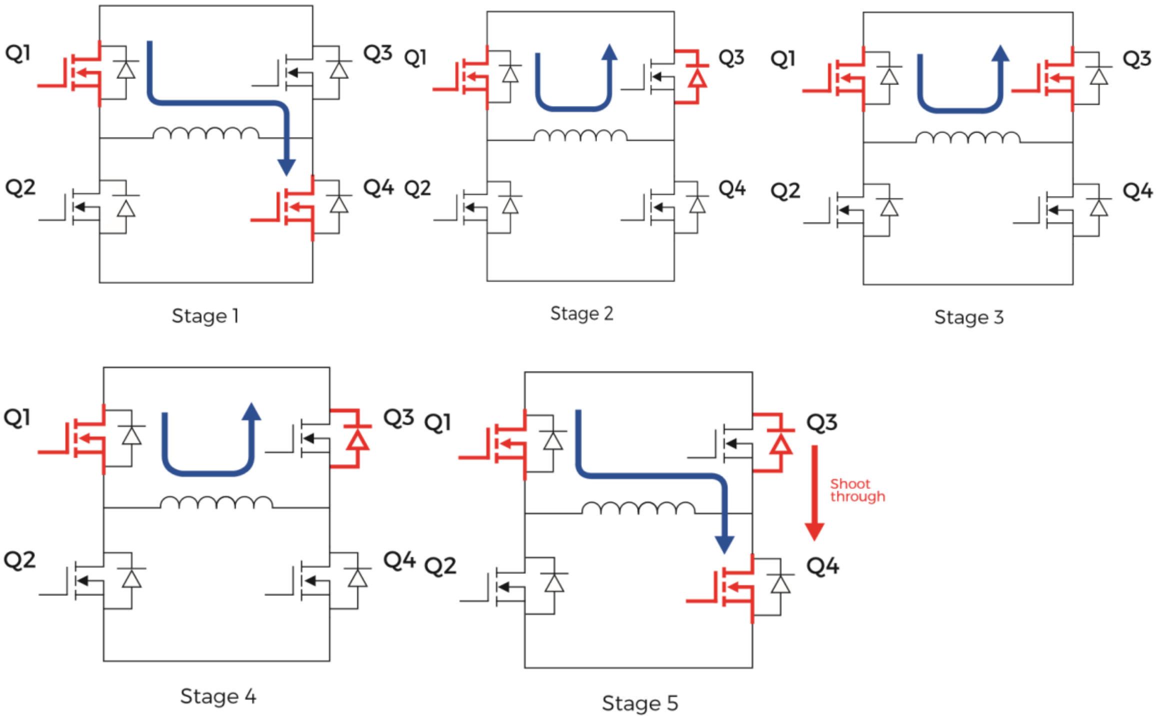

Figure 5b: Case 2 full bridge circuit

High Side PWM control : Q1 ON, Q4 PWM

STAGE 1: Q1 ON, Q4 ON → current builds ups in the motor winding.

STAGE 2: Q1 ON, Q4 OFF → current in the inductor continues to flow in the same direction through Q1 and the body diode of Q3

STAGE 3: Q1 ON, Q4 OFF, Q3 ON → current now flows through the channel of Q1 and the channel of Q3

STAGE 4: Q1 ON, Q4 OFF, Q3 OFF → before turning on the Q4, Q3 is turned off based on the dead time settings. During this period current switches back to the body diode of Q3

STAGE 5: Q1 ON, Q4 ON → during this period the voltage at the switch pin (S2) shoots down to 0V approximately. And the dV/dt depends on how quickly the Q4 is turned on.

During stage 5, the body diode of Q3 is reverse biased while it is still conducting current. This results in a recovery current to flow through the Q4 and Body diode of Q3, which represents a shoot-through scenario until the body diode of Q3 is completely recovered. After the recovery instant, the parasitic inductance in the current path results a voltage swing in an attempt to maintain the current in the path. This voltage excursion coupled with the parasitic capacitances in the path result in further high frequency noise at the switch node leading to EMI.

Although, new drive techniques are reducing the dead time to a very low value to nullify the recovery related issues, often the effects of reverse recovery can be minimised by choosing a MOSFET with a body diode that has a low reverse recovery charge (Q_{RR}) and fast reverse recovery time (t_{RR}) or by using an external Schottky diode with low Q_{RR}.

Design related parameters:

Zero temperature coefficient (ZTC) point:

The transfer characteristics graph in the datasheet at a point marked ZTC, shown in figure 6, show two regions of possible operation: 1) For operation below ZTC, drain current (I_D) is characterised with a positive temperature coefficient; 2) for operation above ZTC, I_D is characterised with a negative temperature coefficient.

For most of the applications a negative temperature coefficient for the current is desired as it provides an inherent safety feature that protects the MOSFETs from temperature runaway related failures. But from figure 6A, if the MOSFET is being operated with a gate-to-source voltage below the ZTC point, the positive temp coefficient of current can exacerbate hot spots and current crowding. Operation below the ZTC point is not a recommended practice either under DC conditions or during a switching transient. However, it is more likely for DC operation to cause a failure.

As mentioned in the Qg section of this application note, to decrease the Rds(on) of the MOSFETs one of the pursued design methods is to increase the size of the MOSFETs but this results in a high gate charge requirement making the MOSFET slow and not suitable for high frequency applications. The other method pursued to decrease the Rds(on) is to increase the trench density of the MOSFET chip which in turn increases the number of vertical current flow paths. This is a particularly popular practice in <100V rated MOSFETs. Often these high current density MOSFETs have a ZTC point at a much higher current, making it more susceptible for a ZTC related failure. Figure 6B shows the transfer characteristics of a high density trench MOSFET with a higher ZTC point.

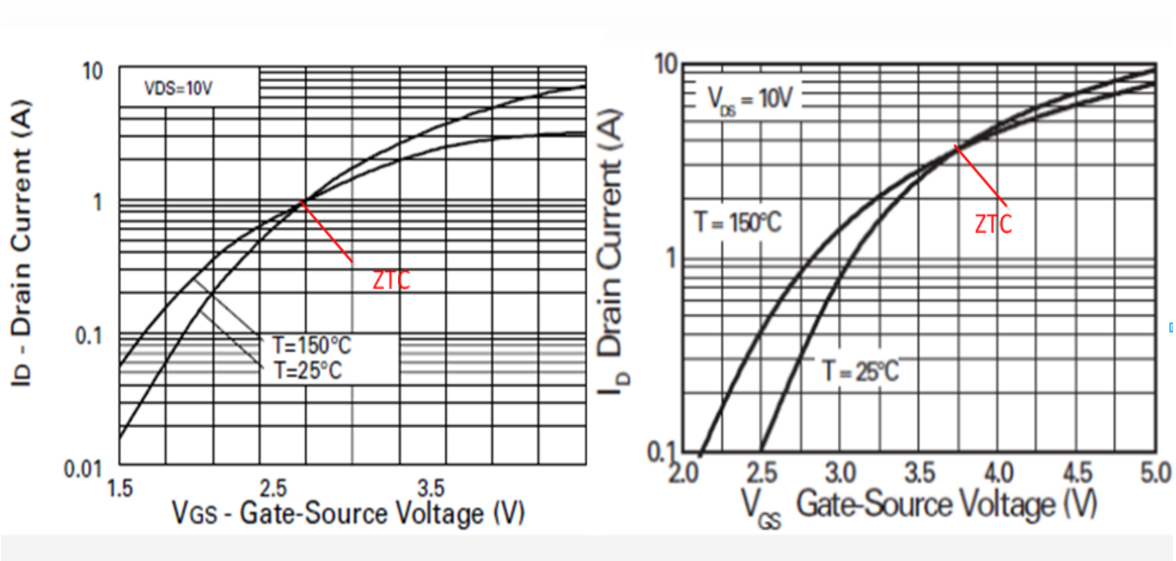

Figure 6A: Low density planar MOSFET (ZXM61N03F)

Figure 6B: High density trench MOSFET(ZXMN3A01E6)

Although it is a usual practice to drive the MOSFETs with a sufficient drive (~12V), in BLDC motor applications it is worth keeping in mind the ZTC point. However, for applications that work with a lower gate drive voltage, for example current limiting applications, the ZTC point is a key parameter to consider.

MOSFET evaluation in a 24V BLDC motor circuit

A DRV8301 evaluation board driving a Teknic BLDC motor was used as the platform to evaluate the performance of the MOSFETs shown in table 1. Each MOSFET was evaluated in turn with the motor running at 1000 through to 4000 rpm, under fixed torque conditions. The efficiency of the drive board, case temperature of the MOSFETs and the gate drivers was measured.

Parameter	Competitor 1	Diodes DMTH6004SK3Q	Competitor 2
Rds(on)	5.2mΩ @ Vgs = 10V & Id = 30A	3mΩ @ Vgs = 10V & Id = 30A	3.8mΩ @ Vgs = 10V & Id = 90A
Qg	80nC	95.4nC or 70nC	98nC
Crss	365pF	105pF	58pF
Coss, Ciss	770pF/4300pF	1383pF/4556pF	1700pF, 8000pF
IFs	300A	150A	360A
Tr/Tf	20/15 ns	11.7/12 ns	70/5 ns
BV	60V	60V	60V
Trr/Irr/Qrr	75ns/2.5A/95nC	50.5ns/NA/80.8nC	125ns/NA/110nC
Package	D2PAK	DPAK	DPAK

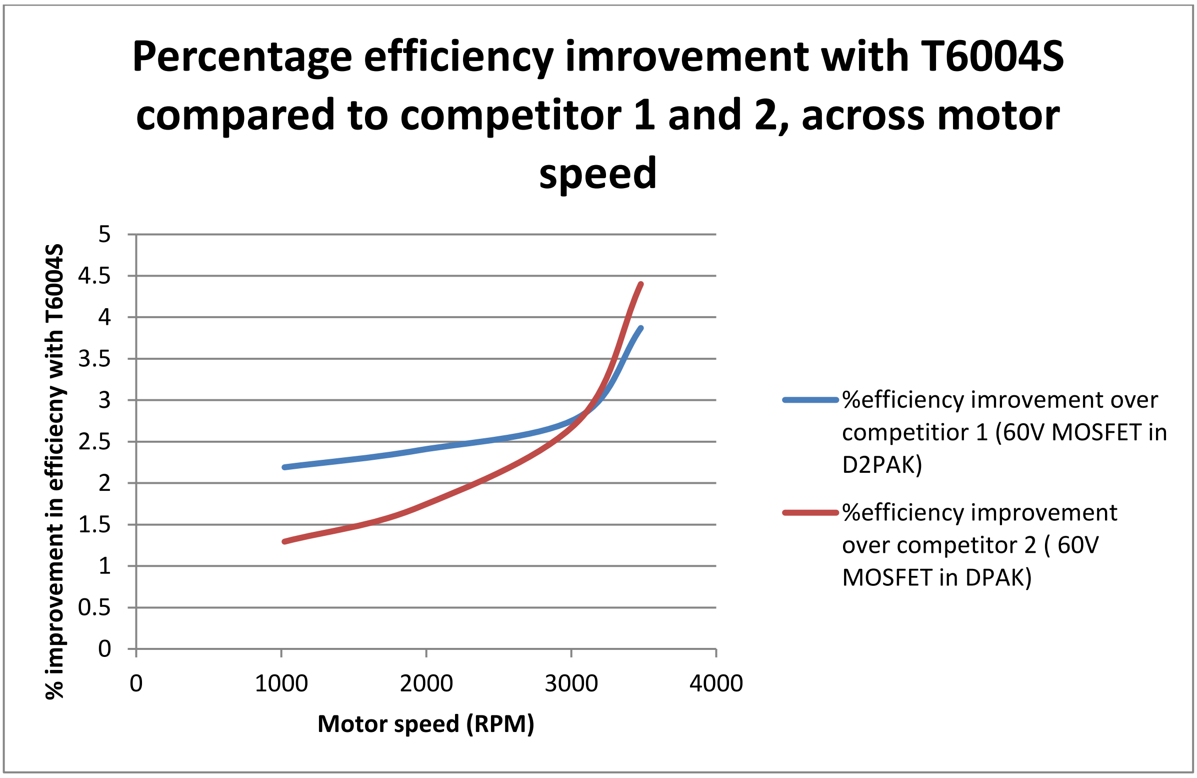

Figure 7a: Speed vs efficiency

The efficiency improvement shown in the figure 7a can be attributed to the decreased power losses in the bridge MOSFETs and decreased gate drive losses in the gate driver IC due to lower gate charge requirements. The efficiency improvement due to the MOSFETs in the full bridge will be translated into the operating temperature of the MOSFETs and the gate driver IC. Figure 7b shows how the higher gate charge requirements resulted in an increased operating case temperature of the gate driver IC.

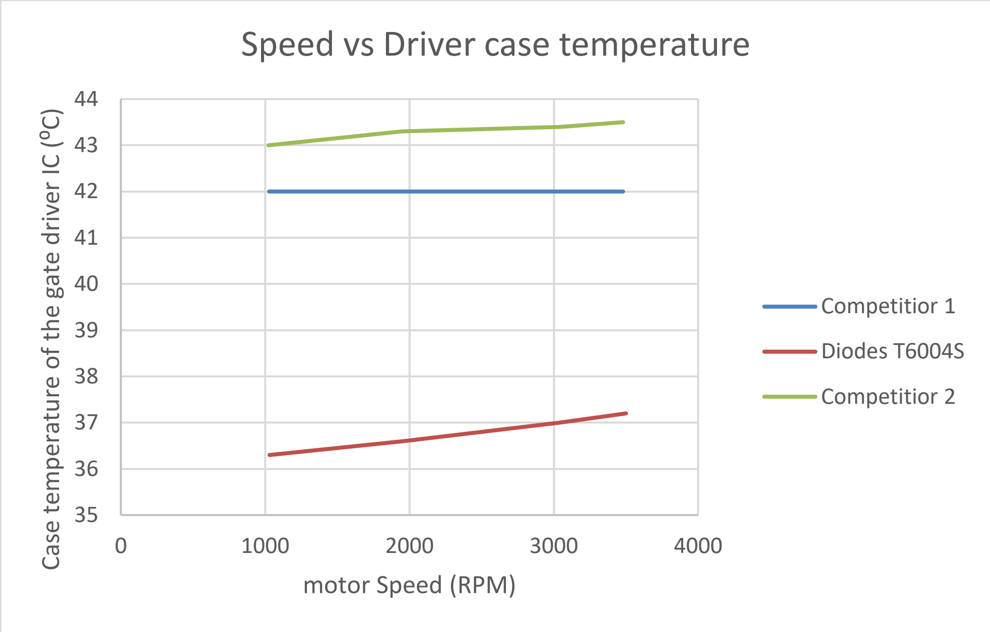

Figure 7b: Speed vs driver case temperature

Figure 7c and 7d shows the operating case temperatures of low side and high side MOSFETs respectively. Results show that the thermal performance of the competitor 1's MOSFET, in a D2PAK, can be achieved with T6004S in smaller DPAK.

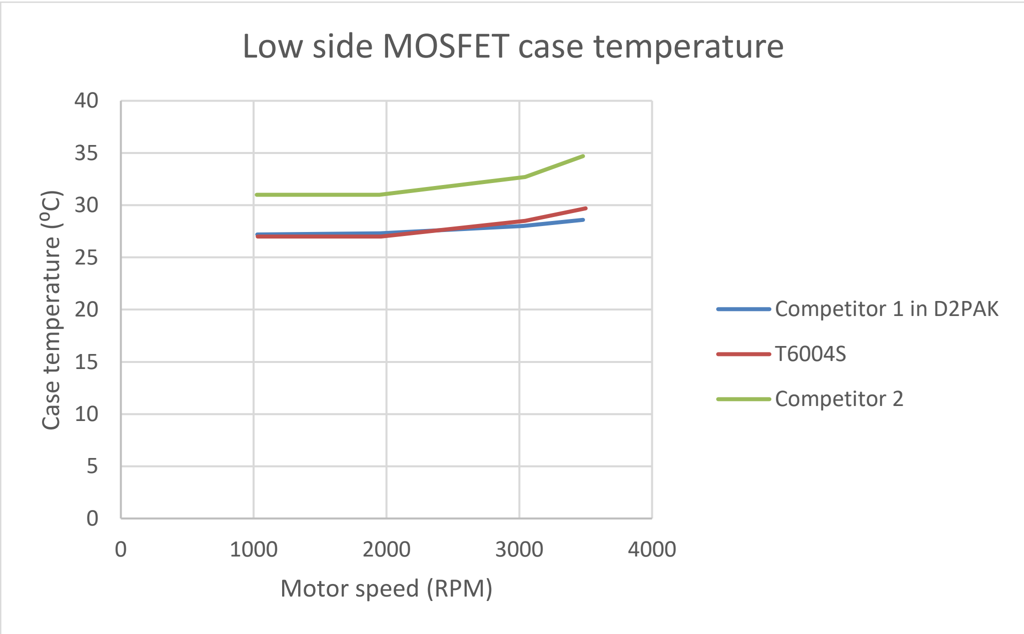

Figure 7c: Low side MOSFET's operating case temperature

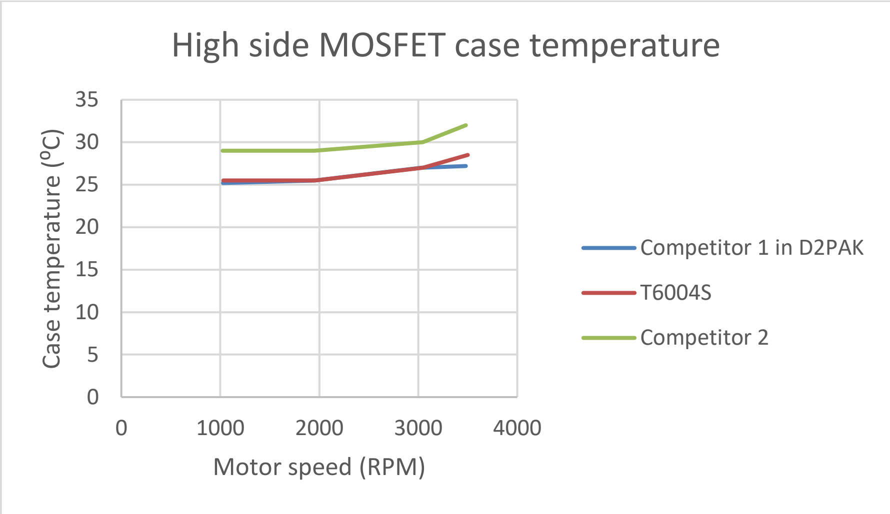

Figure 7d: High side MOSFET's operating case temperature

Conclusion: Brushless DC motors offer many advantages over motors that use brushes, and while both have been replacing mechanically driven systems in automotive applications for some time, it is the BLDC that looks likely to dominate. The unique operational environment of the automotive sector imposes significant demands on performance, as well as safety, reliability and quality. Meeting these while still delivering energy savings requires careful component selection, but will ultimately result in a solution that will meet manufacturers' expectations. The key MOSFET parameters for motor drive application are discussed. It is demonstrated with results, collected on a 24V BLDC motor drive board, how even a subtle difference in these parameters can result in considerable difference in the overall efficiency of the motor drive circuit, which in turn helps cooler operation of the gate driver IC and cooler operation of the MOSFETs in a significantly smaller package resulting in a reliable and cost effective solution.