# DESIGN TECHNIQUES IN POWER INTEGRATED CIRCUITS FOR AUTOMOTIVE BLDC MOTOR CONTROL


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## ABSTRACT

**Existing and new techniques in the design of integrated circuits for 3-phase brushless motor control are reviewed, with particular emphasis on the requirements for automotive applications. Several motor drive schemes are presented with suitable circuit topologies addressing the key elements of power dissipation, packaging and circuit implementation efficiency.**


## I. INTRODUCTION

Brushless DC (BLDC) motors are increasingly replacing brush DC motors in many automotive applications. The main advantage of the BLDC motor in these applications is its inherently better reliability when compared to brush DC motors. The main obstacle to their widespread use has been the increased complexity and cost of the drive electronics. However, with improvements in silicon technology, design techniques and packaging the overall cost effectiveness of the BLDC motor solution is matching or exceeding brush DC motor solutions.

## II. APPLICATIONS

The first applications of BLDC motors were assisted steering systems and main engine cooling fans. As motor costs have reduced and the electronics have been integrated close to, or even into, the motor, the use of BLDC motors expanded into electrohydraulic systems and recently in mechanical positioning functions such as electronic braking, clutch actuators and semi-automatic gear shift systems. Other functions, such as starter alternator systems, which were previously not cost effective or technically feasible, are being made possible by the use of a single BLDC used as a motor or a generator with essentially the same electronic control. Further integration of the electronics into the motor and the ability to operate at higher temperatures, in conjunction with improvements in motor design are enabling cost effective implementation of new safety and comfort systems.

## III. CONSTRUCTION TRENDS

The increased reliability of the BLDC motor is achieved mainly, as the name suggests, by removing the brushes. In a brush DC motor these would provide the winding current commutation which now has to be controlled electronically. The BLDC motor also has the advantage that the field windings are static allowing heat to be removed more efficiently.

One of the major limitations in using electronically commutated motors in automotive applications has been the ability of the power circuits and associated control circuits to withstand the extreme environmental conditions found in the engine compartment of modern automobiles. In earlier systems the motor control and power switching components were mounted away from the motor in order to reduce the maximum operating temperature. However this means that the large voltage spikes associated with current switching in pwm motor control and electronic commutation cause problems when trying to reduce the EM RF emissions. This applies not only to the larger motors used for power steering and cooling but even to small stepper motors used, for example, in headlight leveling.

To combat this EMC issue and reduce the wiring required there has been a substantial increase in the number of projects where the electronics is either integrated into the motor or mounted very close to the motor.

Whether the electronics are mounted directly in the motor casing, on the outside of the motor casing, close to the motor on a bulkhead or even mounted directly on the engine block the benefits and the requirements are similar. All configurations have a smaller size with reduced wiring, which in turn reduces the EM RF emissions. The disadvantage is that the electronic packaging required is more advanced. From the printed circuit to the silicon encapsulation, all must be able to consistently operate at ambient temperatures up to 150C and in some cases well beyond this. Often chip-scale packages or even chip-on-board techniques are used.

With a maximum ambient temperature close to the maximum operating temperature of the silicon, precautions must be taken during the design. The heat dissipated by the driver circuit must be as low as possible and any heat generated must be removed as efficiently as possible.

## IV. 3-PHASE DRIVE OPTIONS

For BLDC motors used in under hood applications the currents required are usually in excess of 3A and the preferred arrangement is to use discrete MOSFETs with separate gate drive circuits. Below 2A it is possible to use an integrated controller/FET IC for automotive applications but great care has to be taken with thermal management. The motor current and therefore the torque is usually controlled by pulse width modulating (pwm) the motor supply using a bridge arrangement of low on-resistance MOSFETs. Due to the currents involved the relative timing of the FET switching points and therefore the management of the gate voltage by the gate drive circuit is critical. Before looking at the specific requirements of the gate drive circuits, consider the motor drive schemes.

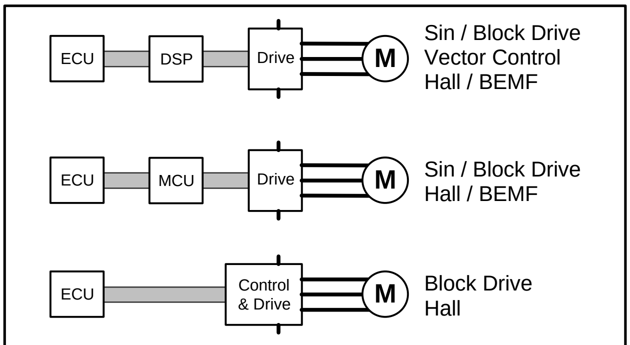


Fig.1: 3-Phase BLDC Control Options

For slow moving motors used for positioning the preferred motor drive is sinusoidal. This provides a lower torque ripple than block commutated drive but at the expense of a slightly lower average torque and a more complex drive scheme. In sinusoidal drive all three phases of the motor are constantly driven. This means that the power switches driving each of the three phases must be independently managed and the control circuit will have to produce at least three pwm signals.

For constantly rotating motors, such as pumps and fans, where the torque ripple is less noticeable, block commutation, also known as trapezoidal drive, can be used. In this scheme only two phases are active and it is simpler to control the current with a single pwm input.

The commutation scheme can also add to the drive complexity. The point at which the phase changes, or the ratio of the phase currents in the case of sinusoidal drive, is determined from the motor position. This can be provided by optical encoders, magnetic encoders, back-emf sensing or Hall effect sensors.

The simplest schemes use hall sensors and block commutation. This can be provided by a completely integrated controller/FET driver. If back-emf sensing is required then additional processing, provided by a small microcontroller, will be necessary. For a full sinusoidal control scheme the relative phase currents are determined by the pwm duty cycle on each of the phases. This requires further processing and at least three pwm outputs from the control circuit demanding a more complex microcontroller or possibly a DSP controller.

The most complex schemes use vector control and sinusoidal drive to provide precision positioning for applications such as electronic power steering. These systems all require a digital signal processor to provide the necessary power to perform all the vector transformations and estimation of the relative phase currents.

## V. AUTOMOTIVE REQUIREMENTS

To be suitable for automotive use, electronic components must meet several criteria, specific to the automotive environment. The power supply is nominally 12V to 14V but under starting conditions this can drop below 5V. Usually, power electronics used to drive motors will have to operate down to 7V; sometimes lower. Other conditions such as double battery starting can cause the supply to reach 24V, and in extreme circumstances, when an alternator load dump occurs, the supply can exceed 40V for short periods. So the electronics driving the motor must be able to operate continuously from 7V to 24V and must survive operation up to at least 40V.

The ambient temperature can also vary widely. From a low of -40C during starting in extreme winter conditions, to a high of 150C in confined spaces in the engine compartment. To operate at these high temperatures power dissipation is reduced by using low on-resistance power switches, usually n-channel MOSFETs, and by implementing power reduction features in the FET gate drive circuits.

Since MOSFET threshold voltage drops with increasing temperature it is usually preferable to use higher threshold FETs rather than lower threshold ‘Logic’ FETs. This requires the gate driver to maintain 10V on the gate for optimum conduction under all conditions and limits the gate voltage to less than the gate-source breakdown voltage, typically 20V.

Safety requirements dictate a number of diagnostic features. These include monitoring of the power switches to detect short circuits and excessive currents, monitoring the power supplies in case of over- or under- voltage, and detecting when the driver is exceeding a safe operating temperature.

To keep cost and size as low as possible the number of external passive components should be kept to a minimum. In simple drive systems all that should be required are a few capacitors to provide charge pumps, supply decoupling and timing information, plus a few resistors. It is also useful for the driver IC to generate all the supplies internally and sometimes to provide regulated low-voltage supplies for supporting circuits and sensors.

## VI. 3 HALF BRIDGE DRIVE

There are several options when driving three-phase motors. For high power systems, using high power FETs, it may be necessary to use individual half bridge drivers in order to provide the high gate charge currents required.

To determine the size of the gate driver there are two values of the current from the driver to the gate of the FET, which need to be considered. The first is the short-term charge and discharge current required to turn the FET on and off. The second is the average of this charge current over the pwm period.

The gate charge current can be a few amps and is usually provided by a storage capacitor. For example in a starter motor which may require a current of 400A the power FETs may have an equivalent gate capacitance of 50nF which has to be discharged in say 200ns. A rough calculation shows that this will require a transient current of about 2.5A. If the pwm switching frequency is say 20kHz then each half bridge will require an average current from the supply of about 10mA to keep the storage capacitors charged. Both the charge current and the average current will cause the driver to dissipate power and generate heat so for large drive systems it is often preferable to separate the phases in order to spread the heat dissipation.

With three individual half bridges all drive schemes (Fig.1) can be supported since all phases can be independently controlled allowing full sinusoidal control or simple block commutation. This option can also simplify the circuit layout since the driver can be located close to the pair of power FETs.

To describe some of the features required in a gate driver, the Allegro A3946 is used here as an example of a single half-bridge gate driver (Fig.2). The A3946 provides one high-side drive and one low side-drive plus the associated power supply management and diagnostic circuits. The high-side drive uses a bootstrap capacitor to provide the above supply voltage required to keep the high-side FET active.

The internal regulators provide 5V for the logic and 12V for the drive circuits from a regulating charge pump converter. The 12V regulator maintains a minimum gate drive voltage during low supply voltage conditions and limits the gate drive voltage at high supply voltage.

The diagnostics provide indication of supply problems, faults on the external FETs and overheating.

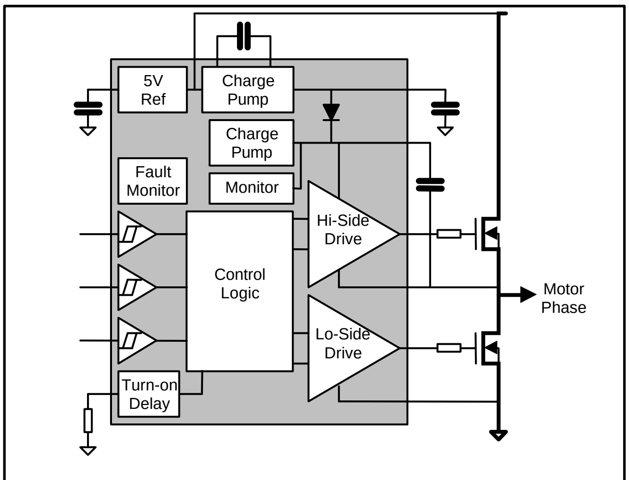


Fig.2: Half Bridge Gate Driver – A3946

Two of the main features of the A3946, which are common to many gate drive products, are the bootstrapped high-side drive and a charge pump converter.

## VII. BOOTSTRAP HIGH-SIDE DRIVE

Normally an n-channel MOSFET is used as the power switching element in switched-mode drivers. This provides the most cost-effective method of delivering large currents without dissipating excessive heat. To make an n-channel MOSFET turn on the voltage between the gate and the source is taken above the threshold voltage of the FET.

FETs that are used to sink the load current to ground (low-side switches) are relatively easily managed since the source voltage is usually close to ground. The regulated supply, $V_{REG}$ in this case, is sufficient to power the low-side gate drive.

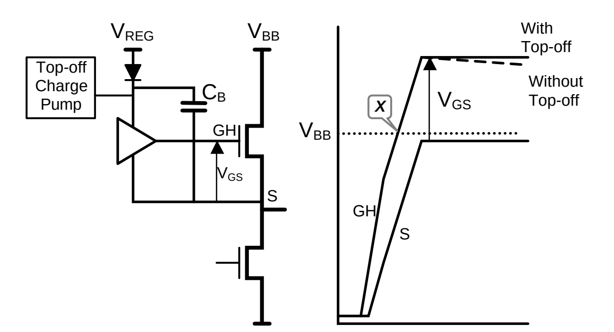


Fig.3: High-Side Bootstrapped Drive

FETs that are used to source current from the supply (high-side switches) are more difficult to control since the source of the FET is not held near ground. Referring to Fig.3, starting with the high-side FET switched off; the voltage at the source will normally be at, or near to, ground. To turn the FET on, the gate voltage $V_{GH}$ is driven positive with respect to the source, $V_S$. As the FET starts to turn on, $V_S$ will rise. At some point $V_S$ will reach a value such that $V_{GH}$ must exceed the supply voltage in order to keep the FET turned on (point ***X*** in Fig.3). At this point the high-side drive requires a floating supply referenced to $V_S$. This is provided by a bootstrap capacitor (**$C_B$**) connected between $V_S$ and the positive supply to the high-side drive. This capacitor will be charged from $V_{REG}$ when $V_S$ is near ground. As $V_S$ rises the voltage across the capacitor will remain high and provide the supply for the high-side drive when $V_{GH}$ must exceed $V_{BB}$. In this way the high-side FET is maintained in its full conducting state.

If the high-set FET is to remain on for a long time the bootstrap capacitor voltage will decay. To keep the high-side switch fully on, an additional internal (top-off) charge pump provides about 100µA to keep the bootstrap capacitor charged to at least 10V above the main supply voltage. Recent enhancements now include bootstrap voltage management that monitors the bootstrap voltage and automatically takes action to recharge if necessary.

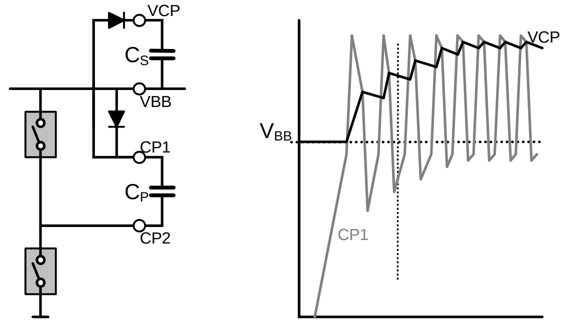

Fig.4: Charge Pump

## VIII. CHARGE PUMP

To allow full gate drive at low supply voltage, a boot regulator is rerquired. Where the current from this regulated supply is low, typically less than 15mA, the most cost-effective solution for a boost supply is a switched-capacitor charge pump. Although capacitors are not as flexible, and therefore not as efficient as inductors, the circuit construction is often simpler requiring only a control circuit and two capacitors.

In the circuit shown in Fig.4, the pump capacitor ($C_P$), connected between CP1 and CP2, transfers charge taken from VBB to the storage capacitor connected between VCP and VBB. Initially the storage capacitor is discharged. The pump capacitor is charged through a diode by closing the lower switch. The lower switch opens and the upper switch closes causing $V_{CP2}$, the voltage at CP2, to rise to the supply voltage $V_{BB}$. At this point $V_{CP1}$ rises above $V_{BB}$ and starts to charge the storage capacitor. After a time the upper switch is opened and the lower switch closed and the cycle starts again. In this way VCP can be pumped up to, and maintained at a level approximately twice the value of the main supply $V_{BB}$. Replacing the diodes with synchronous rectifying switches usually enhances the efficiency of the charge pump.

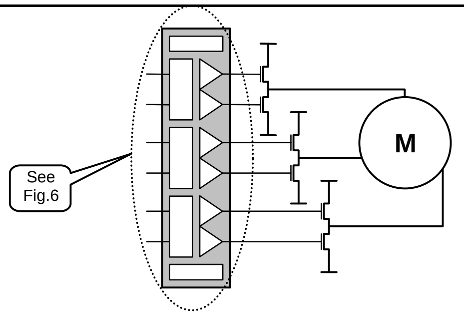

Fig.5: Combined 3-Phase Drive

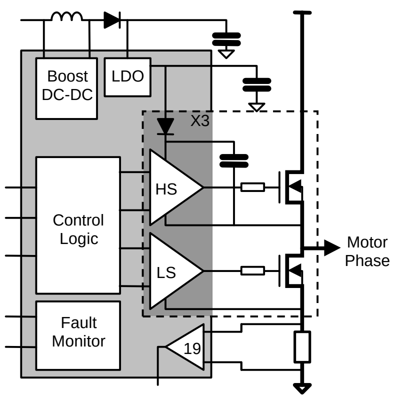

Fig.6: 3-Phase Gate Driver – A3935

## IX. 3-PHASE DRIVE

For medium power systems it is often preferable to reduce the size of the 3-phase driver by integrating the three half bridge drivers in a single IC (Fig.5). This allows the functions common to all three half bridges to be shared and integrated diagnostics to be implemented. However power dissipation may limit the drive capability.

Since the three half bridges have independent control inputs, all drive schemes can be supported since all phases can be independently controlled allowing full sinusoidal control or simple block commutation.

The A3935 (Fig.6) is an example of an integrated 3-phase FET driver. The A3935 incorporates three bootstrapped high-side FET drivers and three low-side FET drivers plus power supply management and diagnostics. In addition, a differential amplifier is provided to amplify the voltage across a low ohmic sense resistor.

Due to the current required to provide the charge currents for all three phase drives the converter used must be high efficiency to minimise dissipation and allow operation at high ambient temperatures. The A3935 therefore uses an external inductor in a boost configuration.

The three phases are independently controlled allowing high-side or low-side pwm with any decay mode combination in trapezoidal or sinusoidal drives. The A3935 is used in a number of sinusoidal drive systems such as cooling fans and power steering systems often controlled by a microcontroller or DSP.

## X. CONTROLLER/DRIVER

The next step in integration incorporates the commutation logic to allow inputs from the Hall sensors in the motor to determine the commutation points. This removes the need for a high powered processor and is suitable for small to medium power motors where only simple block commutation is required. Power management features common to all three phase drives can be shared and pwm current control can be provided since all necessary control is now integrated. (Fig.7)

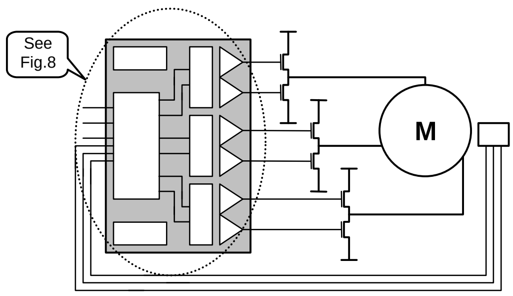

Fig.7: 3-Phase Controller/Driver

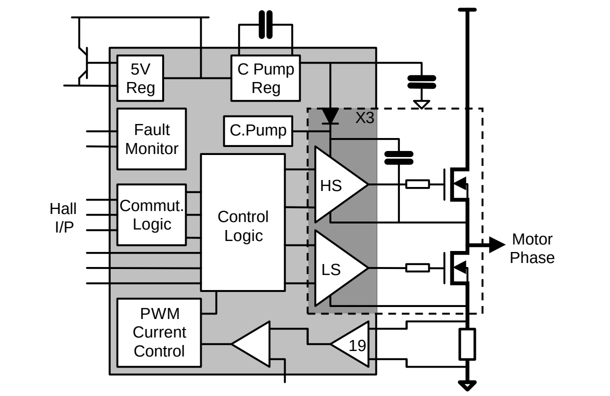

Fig.8: 3-Phase Controller/Driver – A3930

The A3930 (Fig.8) is an example of a highly integrated 3-phase motor controller and FET gate driver suitable for automotive use. Like the A3935, the A3930 incorporates three bootstrapped high-side FET drivers and three low-side FET drivers plus power supply management, diagnostics and sense amplifier. Integrated pwm current control and hall commutation logic makes the A3930 able to fully control a block commutation mode (Trapezoidal) driven 3-phase motor.

The A3930 also provides a top-off charge pump and sophisticated bootstrap management to provide a wide pwm duty cycle operating range.

## XI. PACKAGING

To further extend the temperature range small, near-chip-scale power packaging has been developed. The mainstay of highly integrated power ICs has been the PLCC and SOIC packages. Often these packages have internally fused ground pins to reduce the thermal resistance.

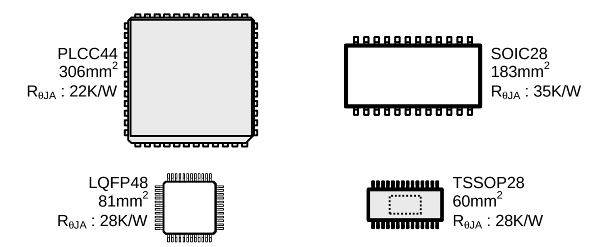

Fig.9: Advances in Packaging

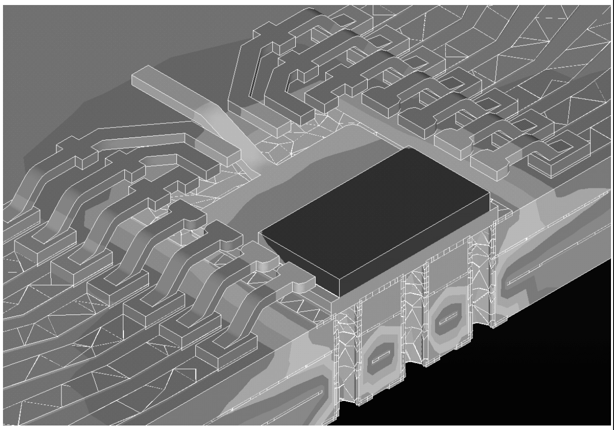
Fig.10: Enhanced Thermal Performance

To allow power ICs and power control ICs to operate effectively in higher ambient temperature applications where increased integration is required, such as fully integrated motor assemblies, new packages have been developed. Examples of this packaging are the LQFP and TSSOP packages with exposed pads (Fig.9). These packages give significant area savings compared to their predecessors while maintaining or improving the thermal resistance. They also provide similar benefits of power slug packages at costs, which are similar to standard non-power package options. The thermal resistance is improved by exposing the die attach pad on the underside of the package. For standard board mounted applications this exposed pad can reduce the junction to ambient thermal resistance to 28K/W.

Another feature of the exposed thermal pad is to provide the user with the ability to greatly improve the thermal performance. If the temperature of the pad is controlled it is possible to make use of the extremely low (0.5K/W) thermal resistance from junction to exposed pad.

## XII. THERMAL MANAGEMENT

The thermal model in Fig.10 shows the structure of an exposed pad TSSOP package when mounted on a 4-layer PCB. Vias are added under the exposed pad connection to optimise the thermal performance.

Simulated and measured results show that the thermal resistance from junction to exposed pad can be as low as 0.5K/W and the junction to ambient thermal resistance maintained even with only 25% solder coverage between the exposed pad and the PCB.

## XIII. CONCLUSION

Using advanced circuit techniques and packaging the current family of Allegro FET gate drives provides a cost-effective solution to motor drives. The implementation can be simplified if using the internal features but is also flexible enough to be used in complex 3-phase systems where DSPs are employed for precision control.

Highly integrated design, advanced BCD technology, inherent low power design, power saving techniques and advanced power packaging ensure that the product range is suitable for automotive use.

In addition to the products, Allegro has many years of experience in supplying to the automotive industry and has implemented all the required quality systems to ensure high performance and high reliability.

## REFERENCES

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