

Electronic Design of Compact BLDC Motor Control

Clark Kinnaird
Texas Instruments

ABSTRACT

As many automotive functions evolve from purely mechanical to electrically-driven, the use of efficient brushless DC motors is becoming prevalent. This paper discusses the design of a BLDC motor controller, including the technical tradeoffs, hardware implementation, and testing results.

This design example examines the specific requirements for a compact solution for driving a water pump, but the design methodology and tradeoffs also apply to other motor control applications where efficient control of motor speed is needed. Practical details such as component parameters are discussed to guide designers in identifying the link between critical performance requirements and component selection.

The paper includes discussion of circuits which mitigate EMC issues inherent in switching supplies and power stages. Attention is also paid to ancillary design topics such as reverse battery protection, overvoltage due to load dump, thermal issues, and other fault-tolerant considerations. Compared to previous papers, the intent is to discuss the application with a holistic view, considering the practical interrelations between the various circuits and functions.

The final design hardware is discussed, with test results showing comparison to expected performance. Lessons learned provide guidance for similar designs, with variations for increased power applications, or alternate loads, such as direct-drive or gear-driven positioning systems.

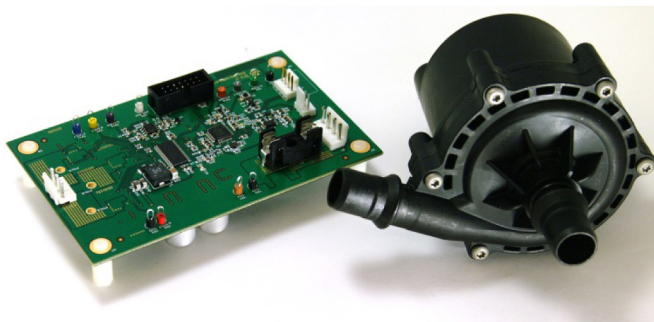


Figure 1. Controller board and BLDC-driven pump

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INTRODUCTION

Many automotive subsystems are transitioning from mechanical to electrical in implementation. This trend is driven by several motivations, including higher power efficiency for reduced emissions, longer product lifetimes, and the desire for more comprehensive diagnostic features. Subsystems that previously were driven by gears,

chains, or belts are being powered from an ever-increasing electrical power bus, directed by a communications network linking all parts of the car.

For subsystems such as pumps, blowers and other rotary-driven equipment, using an electric motor can provide all the above advantages, and also has the benefit of flexibility in terms of location, orientation, and mounting. Eliminating the mechanical means of

driving a shaft, with all the associated linkages, friction losses, and alignment challenges, means freedom in putting the pump or blower where it best functions, rather than where belts or chains can reach.

While the electric motor will be located at the shaft being driven, the drive and control electronics can be located locally, or can be connected via cable from a central control unit. Partitioning the electronics gives designers flexibility in terms of space constraints, thermal management, communications, cabling etc.

Brushless DC motors are well suited to automotive applications due to their proven reliability and high efficiency. In applications such as oil pumps, water pumps, and turbo blowers where the motor lifetime and power dissipation are key parameters, these motors solve many design challenges.

Designing the BLDC motor drive electronics requires making several decisions about circuit architecture, component selection, and performance parameters. The technical tradeoffs require designers to understand the application requirements and the limitations of available technology.

APPLICATION OVERVIEW

While there are many possible applications for BLDC motors in the automotive environment, this discussion will focus on a subset most applicable for our design. Our control board is designed for a 3-phase brushless DC motor using 12V supply. The motor current is limited to less than 10A, for motor power ratings of about 100W.

To save both size and cost and to enhance reliability, our design does not require Hall effect or other position feedback signals from the motor, but instead used field-oriented control (FOC) to determine the motor phase and correct commutation [1]. While this adds some complexity to the microcontroller [2] and sensor signals, the reduction in system size and complexity is significant. The overall block diagram of the system is shown in Figure 2.

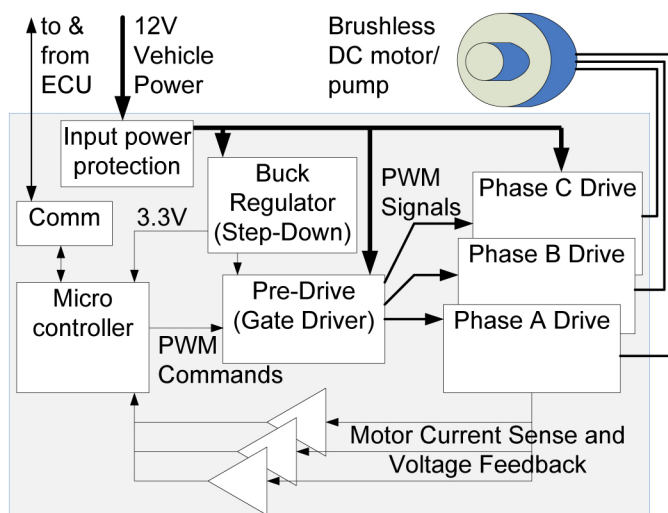


Figure 2. Block diagram overview of the BLDC pump motor control board

Rotary Direct-Drive Water Pump

Our design implements a controller for a rotary brushless DC motor which directly drives a water pump. This is a common application, and is similar to others such as rotary blowers or oil pumps. Characteristics of the application are:

- motor motion is continuous, with no mechanical limits
- flow rate is a non-linear function of motor speed as well as the fluid properties
- motor torque is a non-linear function of speed

Other applications which are extensions of the present discussion would include rotary pumps with indirect drive (e.g. geared shafts) and linear motors, for which position information is needed to control motion near the limits of travel. While these applications would require additional control features, the basic design tradeoffs discussed below would still hold.

BLDC Motor Features

Rotary brushless DC motors are reliable because there are no brushes to wear out. The stator can be mounted to facilitate dissipation of the winding power through an effective heatsink. As discussed in the section on controllers, there are several methods to commutate the windings and provide motion feedback without the need for separate feedback elements such as encoders or tachometers.

Three-phase BLDC motors can provide reliable rotary motion with high power efficiency, which is crucial where increased fuel mileage and reduced emissions are needed. Beyond reliability, the elimination of brushes also eliminates the wide-spectrum spark noise associated with current across the brushes to the rotor, which is a benefit in terms of electromagnetic compatibility (EMC).

With regards to electrical design, the motor characteristics of most concern are the motor voltage, current and power ratings, the maximum speed expected, and characteristics of the windings, especially the inductance and resistance. Given the 12V nominal automotive battery voltage, the motor current is directly related to the power rating. Our controller board design encompasses motor power ranges up to about 100 Watts, thus the drive current will be up to about 8 Amps.

Pump Features

Rotary pumps typically use internal impeller vanes designed specifically for the fluid and flow rate needed by each application. In general flow in only one direction is expected, and speed control rather than position control is desired. For automotive applications, the pump flow rate should be stable over a wide range of fluid viscosity, operating temperature, and electrical supply voltage.

The characteristic curves of flow rate versus motor speed are key to the pump performance. This includes also the minimum and maximum speed ratings, as well as the torque as a function of speed. All of these depend on the fluid being pumped, as well as environmental conditions such as temperature and pressure.

Controller Board Features

The pump controller board receives commands from the master controller, typically an engine control unit (ECU). It then drives the motor for the commanded speed, with power supplied from the 12V battery system. The controller also monitors the status of the motor and of its own circuits, and reports the status to the ECU. In the case of faults such as short-circuit of the motor or over temperature of the board components, the controller will take preventative measures to avoid damage.

ELECTRONIC DESIGN TRADEOFFS

The following sections discuss the design process and engineering tradeoffs needed for each of the major sections of the controller board.

Microcontroller

To fully take advantages of the benefits of an electric/electronic subsystem, the microcontroller should be selected to match the requirements of the application [3]. For this specific water-pump application, the requirements are summarized in [Table 1](#).

Table 1. Controller requirements for pump application

Electrical motor type	3-phase brushless DC rotary motor
Phase voltage level	Battery (12V) voltage
Commutation	Electrically commutated, sensorless using field oriented control (FOC)
Phase voltage waveform	Pulse-width modulation PWM frequency $> 1/\tau_{elec}$
Motion control method	Closed-loop speed control One direction only Up to 3500 RPM
Motion feedback element	Sensorless feedback from motor windings
Communications	CAN, LIN, or coded PWM
Analog-to-digital converters	At least 4 (3 voltage sense + 1 current sense)

For our compact design we use the TMS320F28027 “Piccolo” microcontroller which has integrated functions that support all of the operations needed by our application. Key among these features are:

- Analog-to-digital converters to sample the motor voltage and currents
- PWM channels to command the pre-drive and drive stage
- Existing FOC algorithm for motor phase commutation
- Serial communications (I2C, SPI, SCI) control

The Piccolo microcontroller has field-oriented control (FOC) algorithms implemented in ROM libraries, already optimized for sensorless commutation and speed control of brushless DC motors. The specific Piccolo selected (TMS320F28027F) implements a sensorless observer algorithm based not just on the back-EMF, but also flux, angle, speed and torque. Using flux for commutation also enables stable operation at lower speeds. Unlike the back-EMF signal, the flux amplitude does not diminish at low speeds, so control remains accurate, which enables smoother operation at low speeds, and provides more reliable motor starting, even under heavy loads, such as viscous oil at low temperature.

The pulse-width modulation frequency for our design is 40 kHz. This gives sufficient granularity of response to accurately control the control loops for our motor. That is, with a standard 20 MHz clock for our microcontroller, each PWM period is 500 clock cycles, so we have sufficient resolution to provide commands to better than 1% precision. Also BLDC motors in the 50W range will typically have an electrical time constant (L/R) of a few milliseconds; thus, our PWM period of 25 microseconds is sufficiently faster than the motor's electrical response time, so that the coils' current will mimic that of a continuously-driven circuit.

To measure and control the motor speed, the microcontroller must have accurate measurements of the motor phase voltages and currents. Several analog-to-digital converters are needed, and these should have sufficient resolution and sampling speed to provide the feedback for closed-loop control. The Piccolo microcontroller includes up to 13 ADCs, each with resolution of 12-bits. With sampling rate of 4.6 Msps and conversion time less than 1 usec, this is sufficient for both the 3 phase voltage measurements and current measurements. Note that current measurements for each motor phase will be made when the low-side FET is on, which may be an interval as brief as 100 ns when the drive duty cycle is low during slow speed operation.

Table 2. Microcontroller specifications

Microcontroller feature	Application requirement	TMS320F28027F
Clock rate	20 MHz or more	Up to 60 MHz
PWM channels	6 channels	8 channels
ADC channels	5 or more	7 or 13 (depends on package)
ADC resolution	10 bits or more	12 bits
ADC sampling rate	> 5 times PWM rate	4.6 MSPS
Serial communications	At least one bi-directional channel	I ² C, SPI, and SCI available

To facilitate a compact design, we take advantage of the integration of several functions into the microcontroller. The on-chip voltage regulator takes 3.3V input and generates all the required internal voltage rails (3.3V I/O & 1.8V core). The integrated POR/BOR maintains system integrity during power-on-reset or brown-out conditions, such as during vehicle cold-crank events. The POR/BOR independently manages both voltage rails to avoid any failure ambiguity. The on-chip comparators eliminate the need for external fault detection circuitries. The comparators are coupled with an internal 10-bit DAC for flexible management. The comparator outputs can generate trips, ADC conversions, generic interrupts, etc. as needed for detecting fault conditions. These include current spikes, overvoltage due to load dump or overheating due to motor stall.

Drive Stages

The design of the drive stage requires attention to high current levels, and rapidly switching the relatively high voltages which are applied to the motor windings. Critical components are the drive FETs and current sense resistors.

Ideal switches would have no voltage drop across them; the on-state drain-to-source resistance $R_{DS(ON)}$ is a measure of how close to ideality FETs are. Thus the $R_{DS(ON)}$ directly affects the efficiency that can be achieved. Knowing that a “fixed” voltage is available to drive the motor, the percentage loss due to $R_{DS(ON)}$ can be calculated. For example, assuming 12V battery voltage and 1A_{RMS} drive current, the loss across each FET is

$$loss = \frac{I \cdot R_{DS(ON)}}{V_{BATT}} \cdot 100\% = \frac{1 \cdot R_{DS(ON)}}{12} \cdot 100\% = R_{DS(ON)} \cdot 8.33\%$$

Thus for a 1A motor drive, each Ohm of $R_{DS(ON)}$ in a transistor reduces the efficiency by 8 percent. To increase the efficiency of the motor drive stage, the lowest $R_{DS(ON)}$ possible is desired. For our design, with drive current up to 10A, the FET on resistance should be on the order of 10 milliOhms or less, to keep the losses reasonable. However, as the channel size of the FET increases (leading to lower $R_{DS(ON)}$), the gate capacitance also typically increases. This leads to a tradeoff between losses due to $R_{DS(ON)}$ and losses due to switching delays. As the FET gate capacitance increases, more charge is needed to turn on the FET completely; at a fixed gate drive current, this means longer switching time. For high-efficiency, the gate charge/discharge time should be a small fraction of the PWM period. So a high gate-drive current is required, as discussed in the section below on pre-drive.

Figure 3 illustrates the tradeoff in FET selection; devices with low $R_{DS(ON)}$ have high values of gate charge, and vice versa.

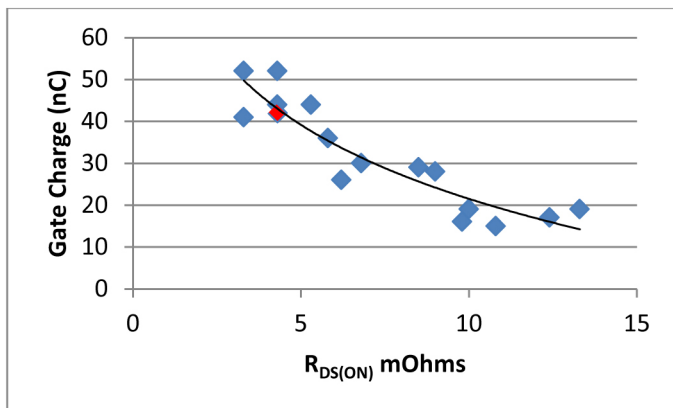


Figure 3. Relation between gate charge and channel resistance of a sampling of FETs. An ideal FET would lie at the origin, with zero gate charge and zero channel resistance.

The drive FETs chosen for this design (CSD18501 - highlighted in red in Figure 3) were selected based on several features. First, their drain-to-source voltage range is rated up to 40V, which means they

are not damaged by transients expected on the vehicle 12V power line. Their $R_{DS(ON)}$ of around 4 milliOhms gives 40 mV of loss with a 10A current, about 0.3% of the 12V supply. The gate charge of 42 nC dictates the required gate drive current required from the pre-drive, as discussed below.

The phase voltage is filtered and sampled to provide feedback to the microcontroller about the rotor position based on the back EMF for each phase. In Figure 4 the filter elements are R22, R25 and C18, with D3 providing a limit to prevent the signal from overdriving the ADC inputs. The low-pass filter transfer function is

$$\frac{V_{out}}{V_{in}} = \left[\frac{R_{25}}{sC_{18}R_{22}R_{25} + R_{22} + R_{25}} \right]$$

which for our values has a DC gain of 0.125 and a single pole at

$$s = \frac{1}{C_{18}(R_{22}||R_{25})} = 2291 \text{ rad/sec} = 365 \text{ Hz}$$

The DC gain will scale the 12V nominal supply to 1.5V, with sufficient headroom to allow for higher voltage on the vehicle power line, even up to 24V. The low-pass filter eliminates the pulse-by-pulse variation of the PWM and passes signals up to the expected maximum product of motor speed times the number of rotor poles. That is, for a typical BLDC motor with 4 magnetic pole pairs on the rotor, there are 4 magnetic cycles in each rotation of the motor axis. Our low-pass filter will thus have little effect on the measured phase voltage (back EMF voltage) for rotation at rates up to:

$$365 \frac{\text{cycles}}{\text{sec}} \cdot \frac{\text{rotation}}{4 \text{ cycles}} \cdot \frac{60 \text{ sec}}{\text{minute}} = 5475 \text{ rpm}$$

While sufficient for relatively slow rotating systems such as water pumps, for applications such as blowers it may be desirable increase the low-pass filter frequency.

Current sense resistors are the simplest method for measuring the drive current to provide feedback to the controller. The resistance value of the sense resistors represents another design tradeoff. For best current measurement fidelity, the resistance should be selected such that at maximum current, the voltage is full-scale on the controller's analog-to-digital converter. However, since that voltage is also an efficiency loss, the smallest practical value is desired. In our design, we expect maximum motor current in the range of 10 Amps. For a 3.3V ADC range, this would dictate sense resistors about 300 mOhms; however, this would also mean 33 Watts dissipated in the sense resistors, an unacceptable loss. So we reduce the sense resistor value to 10 mOhms and add a gain stage to amplify the signal. Here again is another tradeoff; the gain stage must have sufficient gain-bandwidth product to amplify the signal which has a fundamental frequency at the switching frequency of the PWM drive.