Application Report
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Hardware design considerations for an efficient vacuum cleaner using a BLDC motor

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ABSTRACT

A vacuum cleaner is a device that uses an air pump to create a partial vacuum to suck up dirt and dust particles from a given surface. Vacuum cleaners are used in homes as well as in industries and come with a variety of power levels, small battery-operated hand-held devices, domestic central vacuum cleaners and huge stationary industrial appliances. A universal motor is typically used as suction motor across vacuum cleaners. The universal motor is a series DC-motor that is specially designed to operate on alternating current (AC) as well as on direct current (DC). Universal motors have high starting torque, operate at high speed, and are lightweight. Universal motors are also relatively easy to control. However, because of the wear in commutator brushes this type of motor is not preferred for continuous use. Because of commutation these motors are typically very noisy. The associated disadvantages of DC motors are also applicable to universal motors because this type of motor is closer in concept to DC motors than AC motors. Major OEMs (original equipment manufacturers) are considering alternative motor types to overcome these disadvantages. This application note considers the use of a BLDC motor for vacuum cleaner application with good performance benefits.

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Trademarks

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1 Suction Principle

A motor is attached to a centrifugal fan with angled blades. As the fan blades turn, they force air forward toward the exhaust port. When air particles are driven forward, the density of particles (and therefore the air pressure) increases in front of the fan and decreases behind the fan. The pressure level in the area behind the fan drops below the pressure level outside the vacuum cleaner (the ambient air pressure). This creates suction, which is a partial vacuum, inside the vacuum cleaner. The ambient air pushes into the vacuum cleaner through the intake port because the air pressure inside the vacuum cleaner is lower than the pressure outside. As long as the fan is running and the passageway through the vacuum cleaner remains open, there is a constant stream of air moving through the intake port and out of the exhaust port.

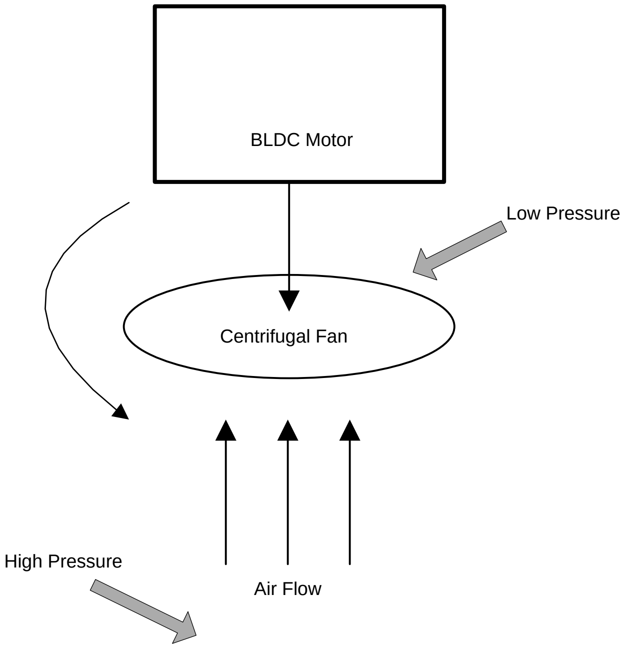

Figure 1. Suction Principle

The suction motor load consideration is interesting. One or more fans are attached to the motor shaft and are rotated at a very high speed. The air entering the fan near the hub is forced to spin with the fan as the air passes through the fan. The load to the motor is the force required to overcome the inertia of the air as it enters the fan and is spun. When the air flow through the motor is reduced by increasing the resistance to the air flow, the load on the motor is actually reduced and the speed tends to fall. Therefore to increase the suction the current drawn from the mains increases, and hence the motor speed increases. The effect of this is to increase the suction created by the motor which helps to counteract the effect of the resistance to the air flow. Restricting the air flow completely creates the maximum possible suction. This maximum suction occurs when a sealed suction gauge is used. In essence, the maximum suction is greater than the suction which is produced in the normal operating range of the motor. Air watts is an effort to rate the output power of the vacuum cleaner instead of the input power drawn from the power source. ASTM International defines the air watt as shown in Equation 1.

$$\text{Air watts} = 0.117354 \times F \times S$$

where

- F is the rate of air flow in ft^3/m
- S is the vacuum in inches of water lift (1)

2 Brushless DC Motors (BLDC)

The brushless direct-current (BLDC) motor is configured like a DC motor turned inside out with the permanent magnets on the rotor and the windings are on the stator. Because of the absence of brushes the disadvantages are eliminated such as sparking, noise, efficiency, and also enable very high speed compared to universal motors. These motors are also known as electronically commutated motors (ECMs or EC motors) and are synchronous motors that are powered by a DC electric source through an integrated inverter, which produces an AC electric signal to drive the motor; additional sensors and electronics control the inverter output. The commutation is electronically controlled. Commutation sequence and commutation time is provided by position sensor feedback or by any sensorless methods like back electromotive force (EMF) sensing.

The BLDC motor is the ideal choice for applications that require high reliability, high efficiency, and high power-to-volume ratio. A BLDC motor is highly reliable because it does not have any brushes that wear out and require replacement. When operated in rated conditions, the life expectancy of a BLDC motor is over 10 000 hours.

2.1 Construction of BLDC Motors

BLDC motors can be constructed in several different physical configurations. In the conventional (also known as inrunner) configuration, the permanent magnets are part of the radially center core. In the outrunner (or external-rotor) configuration, the radial-relationship between the coils and magnets is reversed. The stator coils in the outrunner configuration form the center core of the motor, while the permanent magnets spin within an overhanging rotor which surrounds the core. For this application, the inrunner configuration was selected. Figure 2 shows that the rotor is in the center with the permanent magnets and that the stator contains the windings. The inrunner configuration has lower rotor inertia and more efficient heat dissipation when compared to the outrunner model. The most common BLDC motor topology uses a stator structure consisting of three phases. As a result, a standard six-transistor inverter or six-mosfet inverter is the most commonly used power stage.

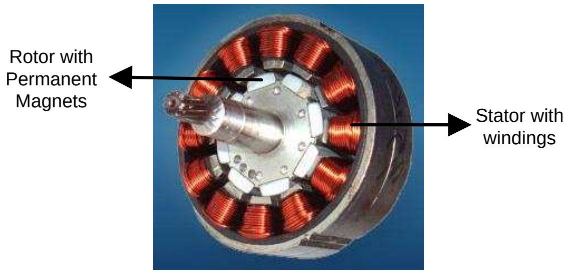

Figure 2. Cross Section of BLDC Motor

2.2 Working of the BLDC Motor

The starting-current setup in the circuit through the stator windings sets up a magnetomotive force (mmf) which is perpendicular to the main mmf set up by the permanent magnet. According to Fleming's left-hand rule, a force is experienced by the armature conductors. As the armature conductors are in the stator, a reactive force develops a torque in the rotor. When this torque is more than the load torque and frictional torque, the motor begins rotating. The process of removing current from one circuit and giving it to another circuit is known as commutation. Figure 3 shows the phase current and developed torque in the BLDC motor. In every case there are two phases that are contributing to positive torque and one phase contributing to zero torque. If the torque of each commutation interval is combined, the total torque is a contribution of two torques from two phases that are perfectly flat.

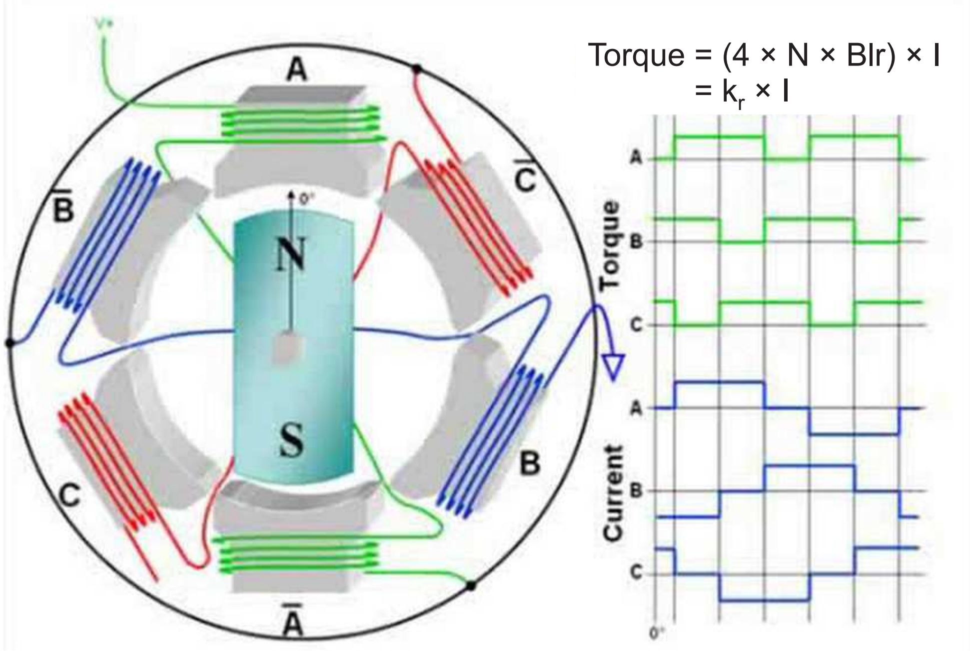

Figure 3. Working of BLDC motor

The commutation process is implemented using a microcontroller. The rotor position must be known for exact commutation. Two methods are used to find the rotor position: sensor control (uses hall effect position sensors) and sensorless control.

2.2.1 Types of Control

2.2.1.1 Sensor Control

Sensor control uses the Hall Effect arrangement at the back-end of the motor to detect the rotor position. Three Hall Effect sensors are placed 120 electrical degrees apart. These are digital Hall Effect sensors. The sensors detect the transition from the north pole to the south pole of the rotor. There are several disadvantages of Hall Effect sensors including:

- The sensors are very expensive.
- Sensing requires a magnetic disk.
- Additional mechanical parts and wiring issues cause reliability problems.
- Hall Effect sensors require an additional power supply.

2.2.1.2 Sensorless Control

The disadvantages of Hall Effect sensors listed in Section 2.2.1.1 are compensated for by using sensorless control. One of the ways of overcoming the disadvantages of Hall Effect sensors is by using back-EMF sensing. This method works because one coil is always de-energized according to the working principle. The rotor position is then detected using the back-EMF signature of that coil. This signature is the Zero crossing of that back-EMF signal.

The BLDC motor is a permanent magnet motor with a trapezoidal back-EMF, as opposed to the sinusoidal back-EMF found in a permanent-magnet synchronous motor. Figure 4 shows the trapezoidal waveforms of a three-phase BLDC. In every commutation step, one phase winding is connected to a positive supply voltage, one phase winding is connected to a negative supply voltage, and one phase is floating. The zero crossings of phase back EMFs are indicated by ZC. The zero crossing occurs directly in the middle of two commutations. At a constant speed, or a slowly varying speed, the time period from one commutation to zero-crossing and the time period from zero-crossing to the next commutation are equal which is used as basis for the implementation of sensorless-commutation control. The floating phase, where the zero crossing must be detected, changes for every commutation step. One ADC channel for each phase winding is needed to detect zero crossings.

The sensorless commutation method has challenges during startup or at very low speeds.A common method is to use excite the winding with a random start up commutation. A table of inter-commutation delays for the first few commutations is stored in flash. This sequence is executed without attention to the back-EMF feedback. The control is then passed over to the sensorless commutation controller.

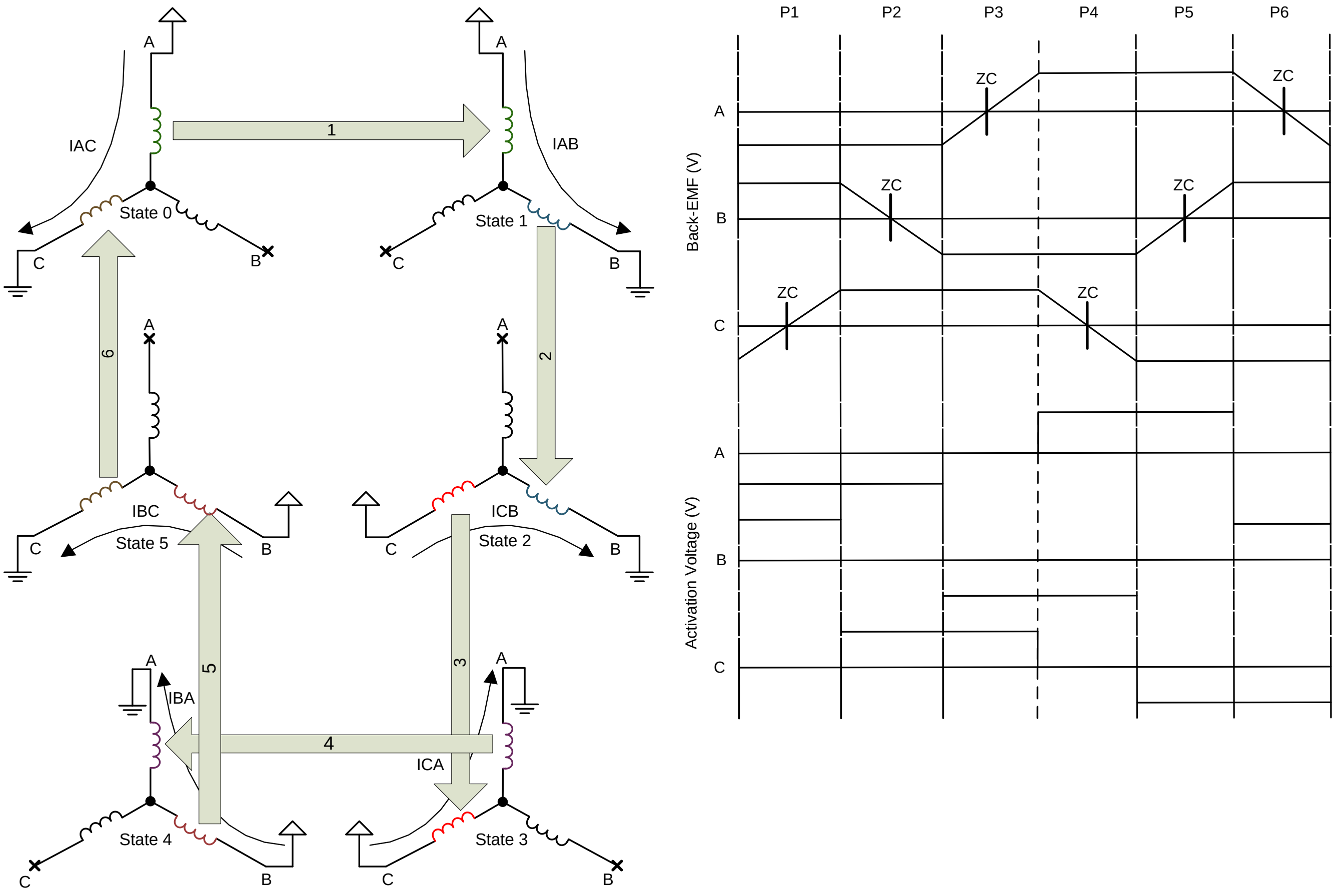

Figure 4. Energizing Sequence and Trapezoidal Waveforms

2.2.1.2.1 Sensorless Control: Using Zero Crossing of the Back EMF Signal

Rotor-position detection occurs by using one of the two previously-mentioned methods. Figure 5 shows the process of commutation. The 3-phase BLDC motor has been split into 12 stator poles as shown in Figure 5. Phase winding energizes such that a positive current creates a south pole at A and A bar has a north pole. Similarly C has a north pole and then C bar has a south pole. Commutation can begin when the rotor position is determined. When the rotor begins to move the south pole of the rotor enters the region of the stator where the north pole exists. The sensor detects this movement, and before the rotor can reach the north pole (region under the phase A), phase A is turned off because the rotor has entered a new commutation zone. Phase B then turns on. The magnetic pattern on the stator is advanced by 30 degrees. The rotor must move further in order to reach the north pole as shown in Figure 5(2). As the rotor travels toward the north pole, it crosses a new commutation zone and the process continues on. There are six stator commutation states and depending on the rotor position, the respective commutation state can be applied.

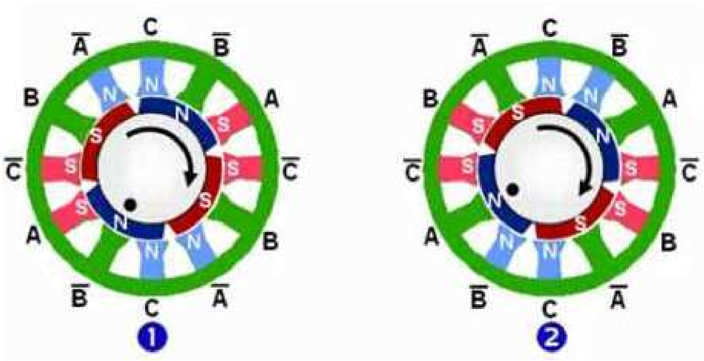

Figure 5. Commutation Process

2.2.1.3 Calculations

Use Equation 2 to calculate the no-load speed.

$$\text{No-load speed} = V / KE \times 1000 \text{ (RPM)}$$

where

- KE = back-EMF constant (V/kRPM) (2)

The KE constant can also be used to determine how fast a motor runs with a certain voltage applied to it. The higher the applied voltage for a motor with a given back EMF constant (KE), the faster the motor runs. Conversely the lower the applied voltage for a motor with a given back EMF constant (KE), the slower the motor runs.

To calculate the voltage required at the motor, use Equation 3.

$$\text{Voltage at motor (V)} = ([\tau_L + \tau_M] / K\tau \times [R_\theta]) + (KE \times w)$$

where

- τ_L = load torque (oz-in)
- τ_M = friction torque of motor (oz-in)
- $K\tau$ = Torque Constant (oz-in/A)
- KE = back EMF constant (V/kRPM)
- R_θ = Thermal resistance (Ω)
- w = desired motor speed (kRPM)
- Torque (τ) = $K\tau \times$ Current (I) (3)

Use Equation 4 to calculate efficiency.

$\eta = P_O / P_I$

where

- P_O is the output power (see Equation 5)
- P_I is the input power (see Equation 6) (4)

$P_O = \omega \times \tau$

where

- ω = angular velocity (rad/s)
- τ = torque (Nm) (5)

P_I = rated voltage × rated current (6)

Table 1 lists the specifications of the selected motor (part number DN4261-24-053).

Table 1. BLDC Motor Specifications

	VALUE
Rated speed	4000 RPM
KE	3.72 V/kRPM
Kτ	5.027 oz-in/A
Rated torque	0.125 Nm = 17.7 oz-in
Weight	0.45 Kg
Body length	61 mm
Number of phases	3
Number of poles	8

To find voltage required at motor for different torques use Equation 7.

Voltage at motor (V) = $([(\tau_L + \tau_M) / K\tau] \times R_\theta) + (KE \times w)$

where

- $R_\theta = 2.6\ \Omega$
- τ_L neglects τ_M (7)

Calculate the voltage to produce a torque of 15 oz-in at 3000 RPM using Equation 8.

$V = ([15 / 5.027] \times 2.6) + (3.72 \times 3) = 18.91\ V$ (8)

Use Equation 9 to find the voltage used to produce a torque of 15 oz-in at 4000 RPM.

$V = ([15 / 5.027] \times 2.6) + (3.72 \times 4) = 22.63\ V$ (9)

These equations can be used to calculate a similar voltage requirement for any given torque and speed.

The curve in Figure 6 is linear which provides better speed controllability.

As shown in Figure 7 the rated current of the motor is 3.54 A. The characteristic is linear.

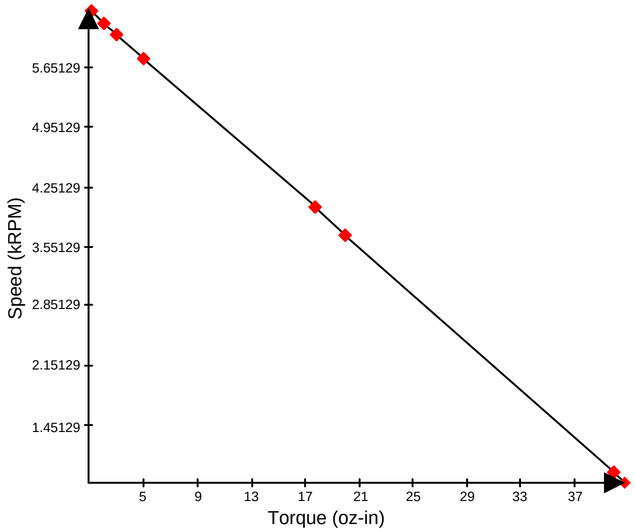

Figure 6. Speed Versus Torque

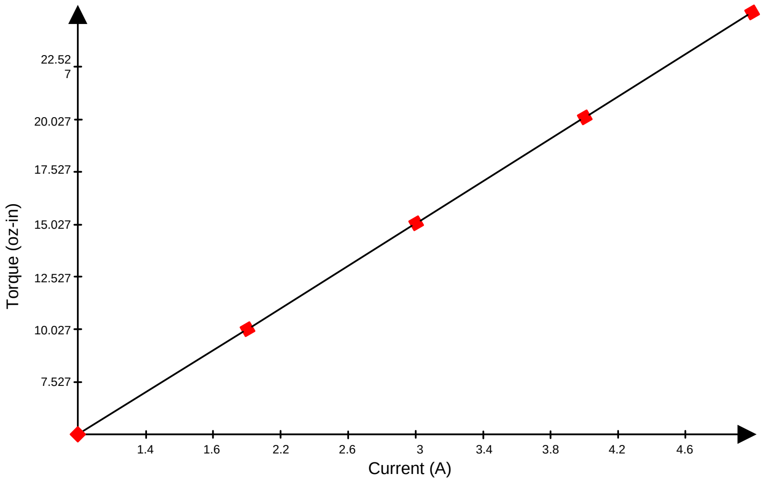

Figure 7. Current Versus Torque

Table 2. BLDC Motor Advantages

BLDC ADVANTAGE	REASON
Linear speed-torque characteristics, better controllability	Internal feedback. Permanent magnet design with feedback gives BLDC motors linear characteristics when compared to open-loop AC-induction motors or brush DC motors. Series DC motors have exponentially decreasing characteristics.
High starting torque	Internal feedback gives higher starting torque. The torque produced at any instant in a BLDC is twice the torque produced in brush DC motor of the same rating, as two phases are on in every commutation step.
Adjustable speed	With the Texas Instruments DRV8323R motor driver, smooth speed control is possible.
Higher efficiency	A permanent magnet in the rotor reduces efficiency loss and increases the efficiency.
Better heat removal	The heat generated in the stator is dissipated easily as it is outside of the rotor unlike the brush DC motor.
Noiseless	Because of the absence of brushes the operation is noiseless.

3 Microcontrollers

TI's C2000™ microcontroller (MCU) family can control BLDC motors using either scalar or vector-control techniques. The rotor position can also be estimated using back EMF voltage information. This mode of feedback control eliminates the need for sensors and additional wires. The position and the speed estimators can also be used to calculate rotor position. Integrated high-speed 12-bit ADC converters, high-resolution pulse-width modulators (PWMs) and a quadrature encoder input (QEI) on the C2000 MCUs make them ideal for implementing BLDC motor control. The ability of the C2000 MCU core to execute complex mathematical functions in a short time makes this family of MCUs ideal for implementing vector-control techniques and controlling multiple motors at the same time. The PWMs in this family have programmable dead band delays to drive high- and low-side gate drivers. The hardware-based fault-detection systems shut down systems faster without intervention from the software. The MSP430™ MCU devices are based on a 16-bit RISC architecture with ultra-low-power operation in active mode and sleep mode.

4 Gate Driver and MOSFETs

Gate Drivers accept a low-power input from a controller IC and produce the appropriate high-current gate drive for a power MOSFET. A gate driver is used when a PWM controller cannot provide the output current required for driving the gate capacitance of the associated MOSFET. The gate driver turns the MOSFET on and off. Motor drivers can be constructed from discrete components, completely integrated inside an IC, or can employ both discrete and integrated components. TI has a wide range of discrete gate drivers such as the UCC27210, UCC27200, UCC27710, TPS28225, and UCD7201 device for this purpose. External MOSFETs such as the CSD88539, CSD88537, CSD18514, CSD18531, and CSD18533 device which are 60-V FETs can be used with pre-drivers such as the DRV8323R device. TI's DRV8312 and DRV8332 devices are pre-driver and FETs in an integrated package.

5 Isolation

Isolators have logic input and output buffers separated by a silicon-dioxide (SiO2) isolation barrier, providing high voltage isolation. These devices block high voltages, isolate grounds, and prevent noise currents from entering the local ground and interfering with or damaging sensitive circuitry. TI’s ISO7420 and ISO7140 series with 4-kV isolation and ISO7520 and ISO7641 series with 6-kV isolation specs are used in this application report.

6 Power Management (6 to 60-V DC Power Supply)

A power-management block involves converting AC to DC and stepping down the DC levels as required by the BLDC motor. TI has a wide range of high-voltage input DC-DC converters such as the TPS54060, TPS54560, and TPS54361 devices that can be used in this application.

7 CAP and QEP interfaces

For motor-control systems based on sensors, integrating CAP and QEP sensor interfaces can both simplify design and reduce cost. The sensor interfaces integrated into C2000 MCUs are built to work across different types of sensors with built in 32-bit hardware for capturing an absolute time or a delta time, in continuous or one-shot modes. This ability allows the interfaces to run independently in the background without requiring constant management from the CPU.

8 Enhanced Controller Area Network (eCAN)

A controller area network (CAN) is used for serial communications between controllers in electrically noisy environments. The eCAN interface on the C2000 MCUs provides efficient distributed real-time control with data rates up to 1 Mbps, 32 fully-configurable mailboxes, 32-bit time-stamping, and programmable wake-up for low-power operation.

9 High-Resolution and Synchronized ADCs

The precision of sensorless systems is directly dependent upon accurate current measurements. Accurate current measurements require not only an accurate reading (for example, resolution) but that the reading must occur at a specific time. Advanced control techniques often have a short window that a feedback sample must be acquired. As a result, precise timing has two parts: the ADC must be closely synchronized to PWM events and samples must be acquired quickly.

10 DRV8323R

TI's DRV8323R device is a three-phase driver with triple current-shunt amplifiers and a buck regulator. The DRV8323R device includes three current-shunt amplifiers for accurate current measurement. The operating supply voltage of the device is 6 to 60 V and can support up to a 200k-Hz switching frequency.

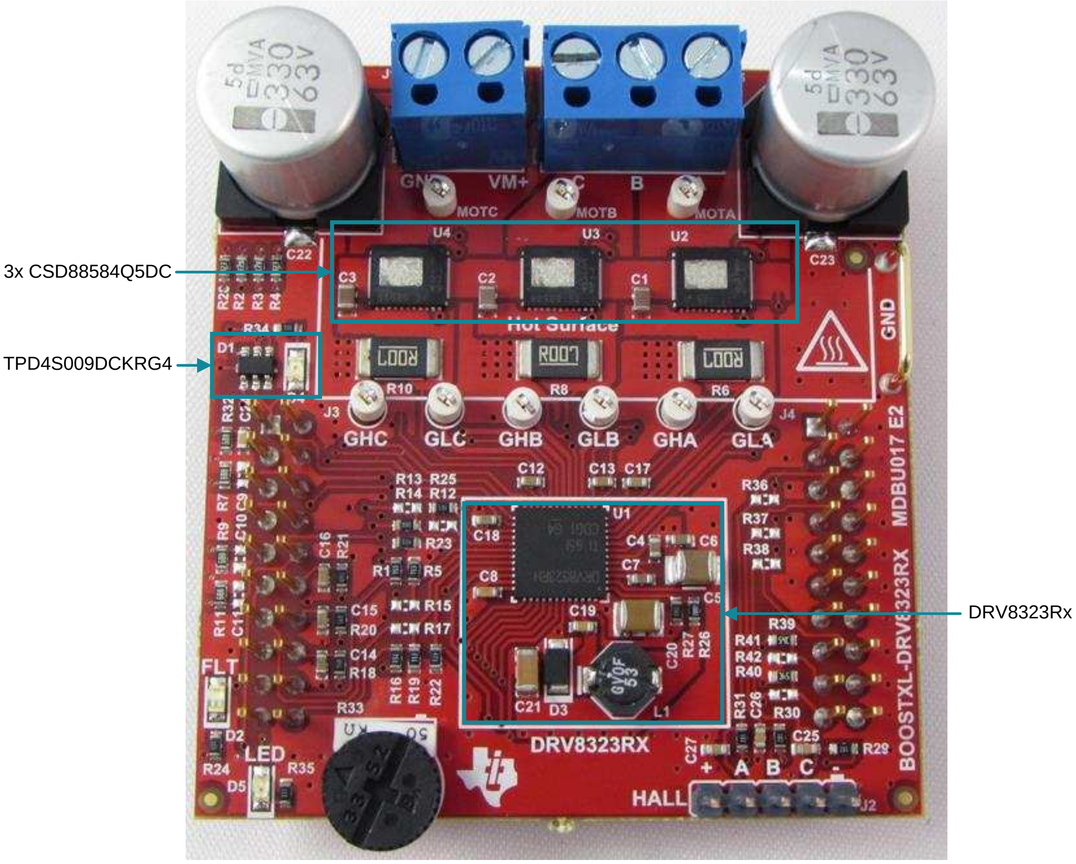

Figure 8. TI BLDC Driver Circuit

11 Feedback Stage

Figure 9 shows the functional block diagram of the motor control. The following sections list the three feedback loops involved.

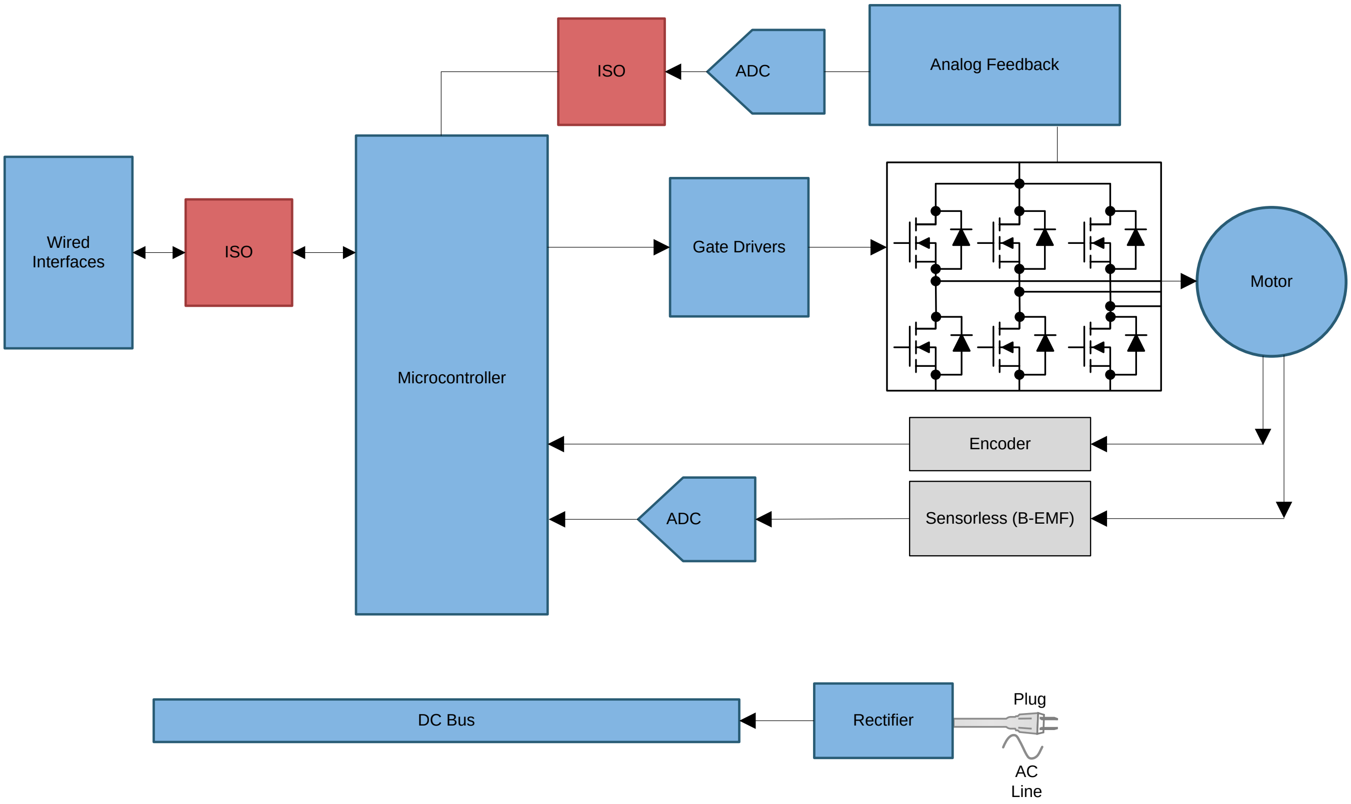

Figure 9. Block Diagram of BLDC Motor Control

11.1 Torque or Commutation Loop

The torque loop is used for sensorless applications to control the current through the motor. The torque is related to the current and therefore this feedback measures the current. A sense resistor measures the voltage and current sense amplifier senses the current and sends the signal to the ADC which digitizes the current and sends it to the controller. Measuring the motor current is often used as a safety feature. In case the motor is in a stalled position, the current increases dramatically. Because of this exceptional increase in current, the ADC values reach a current-limit level that causes the system to shut down.

11.2 Speed Loop

This feedback involves optical encoder. An optical encoder is a device that converts motion into a sequence of digital pulses. The output of the optical encoder is digital and there is no need for ADC.

11.3 Position Loops

A resolver or optical encoder can be used. If a resolver is used then an ADC must be used. An optical encoder provides a digital output which eliminates the need for an ADC. The position loop is the back-EMF signal feedback loop, which is required for commutation.

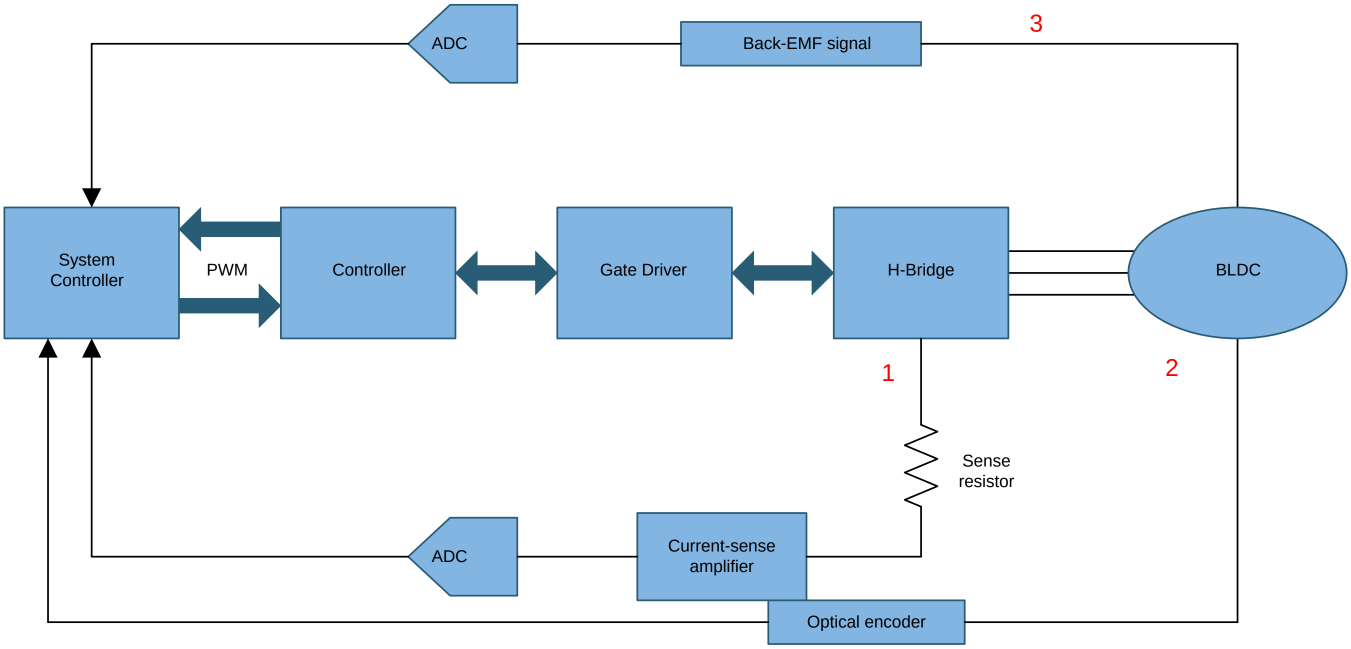

Figure 10. Feedback Loops for Sensorless Control

12 Conclusion

Table 3 lists the performance comparison between a universal AC motor and a BLDC motor. The comparison in Table 3 shows that the BLDC motor provides twice the efficiency gain with better control, no noise, and lighter weight.

Table 3. Performance Comparison Between BLDC and Universal Motor

	AC MOTOR	BLDC MOTOR
Power Efficiency Noise	150 W 35% hum	50 W 90% complete silence
Size and Weight	The AC motor is bigger in size and 33% to 50% heavier than BLDC mortors	
Rotation speed	Limited to AC frequency (50 to 60 Hz) and is non-adjustable	Stepless control and auto adjustment by working temperate
Temperature Rise	95°C	40°C to 45°C because of higher efficiency
Application Range	Single purpose	Muli-purpose
Life Span	Short	Long

13 About the Author

The author would like to thank the former electrical engineering students of M.S. Ramaiah Institute of Technology (MSRIT) including Varun Nandakumar, Rajath Raghavendra, and Chandana P for fabricating the BLDC motor to be mounted on the vacuum cleaner and testing the application as part of their final-year bachelor's of engineering (BE) project.

14 References

1. Texas Instruments Motor Drive and Control website, www.ti.com/motor
2. *Permanent Magnet Synchronous and Brushless DC motors* (Ramu, 2009)
3. *Speed Regulation of a Small BLDC Motor using Genetic-Based Proportional Control* (Poonsawat and Kulworawanichpong, 2008)
4. *Simplified Sensorless Control for BLDC Motor, Using DSP Technology* (Dixon, Rodriguez, and Huerta)

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from A Revision (#IMPLIED) to B Revision — Page

- Changed equation 1 3
- Changed wording of section 2. 4
- Changed caption for Figure 2. 4
- Deleted content from section 2.2. 5
- Deleted content from section 2.2.1.2. 6
- Changed caption for Figure 5. 9
- Changed device. 11
- Changed caption for Figure 9. 12
- Changed caption for Figure 10. 13

Changes from Original (June 2014) to A Revision — Page

- Changed the placement fo the Hall Effector sensors from 1200 degrees to 120 degrees in the *Sensor Control* section .. 5

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