UNITRODE
APPLICATION NOTE

UC3620

BRUSHLESS DC MOTORS GET A CONTROLLER IC THAT REPLACES COMPLEX CIRCUITS

A COMMUTATOR AND DRIVER CHIP, COMPLETE WITH THERMAL AND UNDER-VOLTAGE PROTECTION AND TRANSIENT SUPPRESSION, RADICALLY SIMPLIFIES THE CONTROL OF BRUSHLESS DC MOTORS

INTRODUCTION

The popularity of the three-phase, brushless DC motor is on the rise for a number of good reasons: There are no brushes to wear out or to arc over, heat dissipation is better because the windings are on the stator, and good torque control is both possible and relatively easy to achieve with the availability of electronic circuits. The motor's main drawback has been the need to design and assemble a complex circuit consisting of six output power transistors with transient suppression diodes, a switching current control circuit, and a Hall logic decoder plus loop control and protection circuitry.

The advent of the UC3620 controller chip greatly simplifies the designer's problem, for it integrates all these elements. This chip easily and safely controls motors requiring up to 2A of continuous current, and has a peak rating of 3A. The device has a maximum V_{CC} rating of 40V and is available in a 15-pin package rated at 25W. Only a half dozen external components are needed to get a motor running.

A three-phase brushless DC motor has two, four, or more permanent magnet poles mounted on its rotor. The required rotating field is produced by the stators stationary windings, whose three phases must be commutated in the proper sequence. This sequence is governed by the rotor's angular position, and consequently, some means must be provided both to sense this position and to use that information to control the commutation sequence.

The sensing is accomplished by three Hall-effect devices mounted on the stator close to the rotor magnets, at the correct rotational angles. An electronic circuit decodes the Hall device signals and controls the direction of the currents applied to the three motor phases. This power switching is done by power transistors.

Another function must be added to the driving electronics namely, that of controlling the motor current and maintaining it at the correct value. At high speed, the electric motor's back emf limits the phase currents. But at low speeds the back emf is low (it is zero at stall), and therefore if the current is to be kept constant, the applied voltage must be reduced. This is done by sensing the motor current and using its value to regulate the duty cycle of the applied voltage, thereby controlling the average motor voltage. In this way, a constant-current source of motor power is obtained.

HOW IT WORKS

In the controller chip, each of the three output stages is a totem-pole pair (Figure 1) capable of sourcing and sinking the motor's full rated current. Inductive transients from the load are clamped to V_{CC} by Schottky diodes and to ground by the intrinsic substrate diodes thus obviating the need for external clamping devices.

The power output stages have two functions. The first is to commutate the three motor phases in the proper sequence, producing unidirectional torque in the rotor. The second is to switch the applied motor voltage in the manner selected and programmed by the user, maintaining the output current at the desired level. This switching control of current is accomplished in a fixed-off-time, two-quadrant mode, providing the automatic peak current limiting and low ripple current essential to high electrical efficiency at the motor windings.

The emitters of the three bottom transistors of the totem-pole output stages are connected to Pin 1 , through which all the motor current flows. If a low-value resistor is placed between this pin and ground, a usable voltage proportional to motor current is derived without appreciable I^2R losses.

This current-sensing voltage serves as a feedback signal for the switching current control loop. It is applied to the I_{SENSE} input through an RC filter, which prevents false triggering due to noise spikes in the current waveform.

An internal voltage comparator determines whether the voltage $V_{I\,SENSE}$ is equal to V_{REF}, a positive variable reference voltage dependent on the output of the chip's error amplifier. If Q of the monostable multivibrator (that follows the comparator) is high, the chip's output stages are enabled, the output current increases and $V_{I\,SENSE}$ also increases until it becomes positive with respect to V_{REF}.

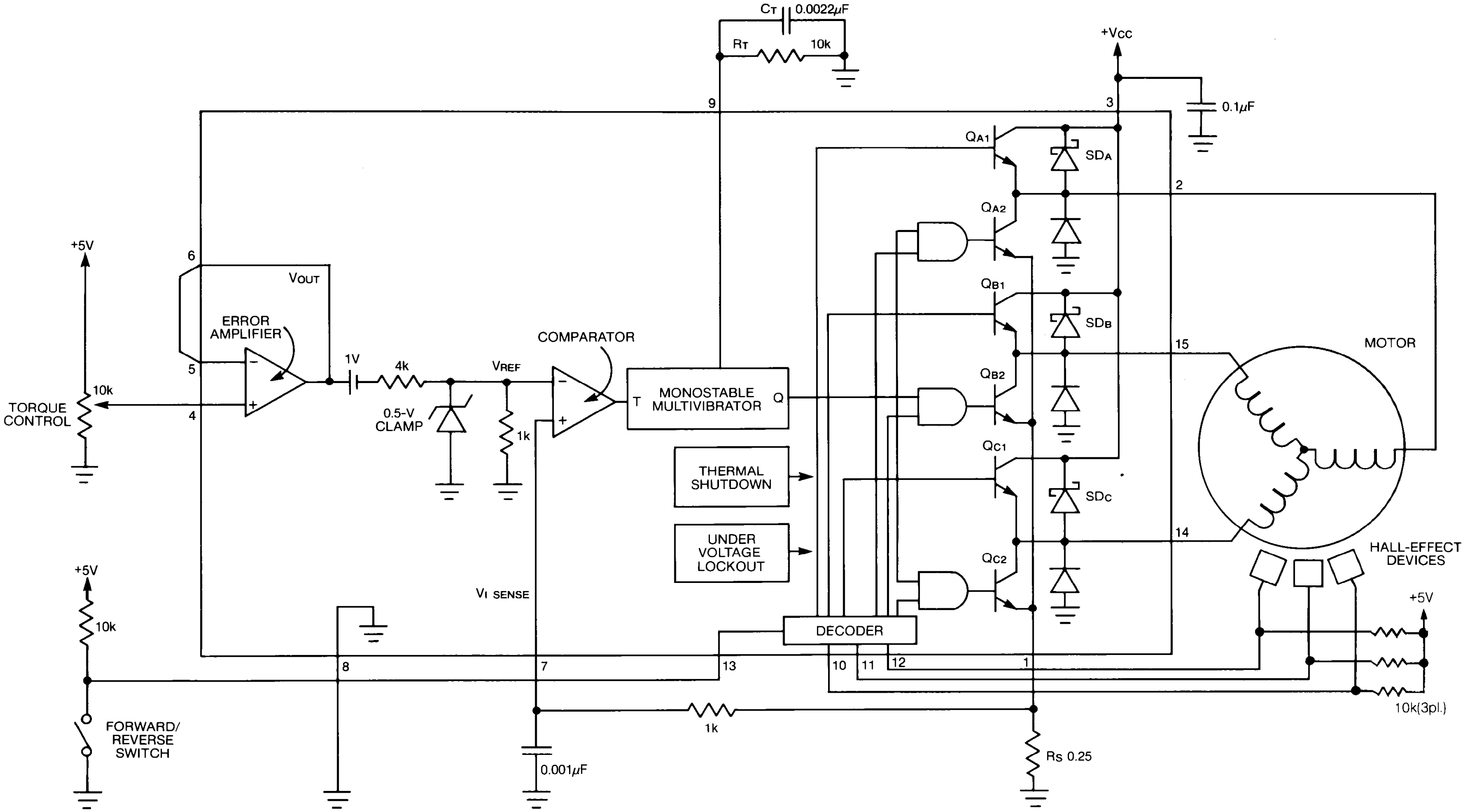

FIGURE 1. THE UC3620 CHIP PROVIDES FULL CONTROL OF MOTOR CURRENTS UP TO 2A, WITH ROTATION IN BOTH DIRECTIONS. HALL-EFFECT DEVICES INTERNAL TO THE MOTOR PROVIDE POSITION INFORMATION THROUGH A DECODER TO THREE TOTEM-POLE DRIVERS. COMPARING THE CHANGING VOLTAGE ACROSS R_S WITH THE ERROR AMPLIFIER OUTPUT HELPS KEEP THE CURRENT CONSTANT.

At this point the comparator resets the monostable, forcing Q low and disabling the output stages. The motor current now circulates through one of the Schottky diodes and the conducting upper transistor because of the stored inductive energy, until the monostable off -time has elapsed (Figure 2). Q then returns to the high state and the cycle is repeated.

The switching off-time is fixed, since it is determined by the user's choice of timing components R_T and C_T. At the start of the off-time, capacitor C_T is charged to +5V, and the monostable outputs are held in the off state until this voltage decays exponentially to a level of 2V. Since resistor R_T supplies the only path for the discharging current, it is possible to calculate the time required, t_{OFF}, in seconds:

$$\exp\left(\frac{-t_{OFF}}{R_T C_T}\right) = \frac{2}{5}$$

or:

$$\frac{-t_{OFF}}{R_T C_T} = \ln(2/5) = -0.916$$

$$t_{OFF} = 0.916 R_T C_T$$

When the 2 volt level is reached, the monostable is set again and the cycle repeats.

The reference voltage, V_{REF}, then is the controlling voltage of what is in effect a transconductance amplifier of which the controlled output is the motor current through resistor R_s. To repeat, the circuit controls the peak value of the current. If the switching frequency is high (low current ripple), the assumption may be made that the average value of motor current, I_M, is approximately equal to the peak, and so:

$$V_{REF} = I_M R_S$$

$$G_T = \frac{I_M}{V_{REF}} = \frac{1}{R_S} \text{ Siemens}$$

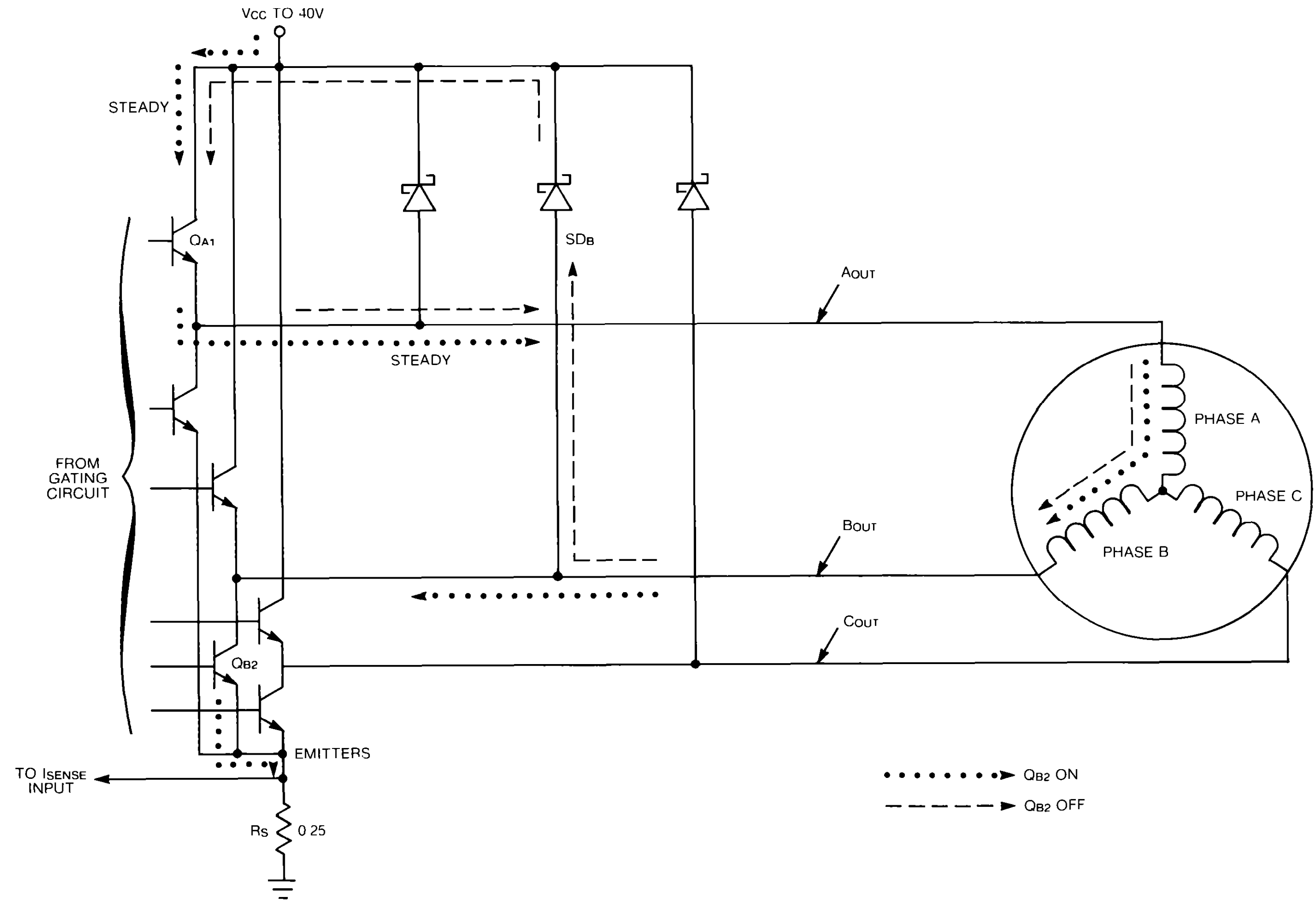

FIGURE 2. WHEN Q_{B2} IS ON, CURRENT FLOWS THROUGH Q_{A1} AND TWO MOTOR WINDINGS TO GROUND (DOTTED ARROWS). DURING THE TIME THAT Q_{B2} IS OFF, THE STORED ENERGY IN THE WINDING INDUCTANCE FLOWS THROUGH SCHOTTKY DIODE SD_B, TRANSISTOR Q_{A1}, AND BACK THROUGH THE WINDINGS (DASHED ARROWS).

The maximum value of V_{REF} is limited to 0.5V by a zener diode (Figure 1 again). This value sets a limit to the maximum motor current as well, since:

$$I_{MAX} = \frac{0.5}{R_S} \text{ amperes}$$

Consequently, the proper selection of R_S protects both the motor and the chip from excess current.

The motor is connected to the chip's three outputs A_{OUT}, B_{OUT}, and C_{OUT}. The motor windings are Y-connected, and the driver energizes two phases at a time, the third one being off. Thus each driver output will be in one of three states: high (V_{CC}), off (high impedance), or low (0V), generating six possible combinations (Table 1).

Table 1. Terminal Conditions for Different Driver Output States

OUTPUT STATE	TERMINAL A	TERMINAL B	TERMINAL C
$A\bar{B}Z$	High	Low	High Z
$AZ\bar{C}$	High	High Z	Low
$ZB\bar{C}$	High Z	High	Low
$\bar{A}BZ$	Low	High	High Z
$\bar{A}ZC$	Low	High Z	High
$Z\bar{B}C$	High Z	Low	High

SIX STATES

In each of the six possible states, one of the upper transistors is on, together with one of the bottom transistors. In any of the states, it is the bottom transistor that controls switching, while the upper device remains conducting. For example, in state $A\bar{B}Z$, current flows continually through upper transistor Q_{A1}, but switches between lower transistor Q_{B2} and Schottky diode SD_B (Figure 2 again). This switching action results in low current ripple through the motor and is known as two-quadrant operation, in which the power supply current flows only in one direction namely, into the driver (Figure 3). One advantage of this unidirectionality is that a shunt regulator is not necessary to prevent an overvoltage at the V_{CC} bus during motor deceleration.

A more significant advantage is that it results in the least current ripple for a given switching rate. More precisely, the current waveform's form factor (the ratio of its rms to its average value) is closer to unity. Since the amount of I^2R heating depends on the rms value of I, whereas torque depends on the average value, a form factor approaching unity results in greater motor efficiency.

The current reference voltage V_{REF} at the inverting input of the chip's comparator depends on the output voltage, V_{OUT}, of the error amplifier. The relationship between the two is:

$$V_{REF} = \frac{V_{OUT} - 1}{5}$$

The offset of 1V between V_{OUT} and the 5:1 voltage divider ensures that the error amplifier can always achieve zero current at the motor. The amplifier itself has a high gain of 80dB minimum, an f_t of 0.8MHz; and is internally compensated for stable operation.

In a feedback speed control application even with a reduction in gain of 14dB due to the 5:1 resistive attenuator between the amplifier and the comparator there is still a minimum DC gain of 66dB, which is more than adequate for most requirements. The same consideration applies to the 1 V offset, which is overshadowed by the high-gain loop as well.

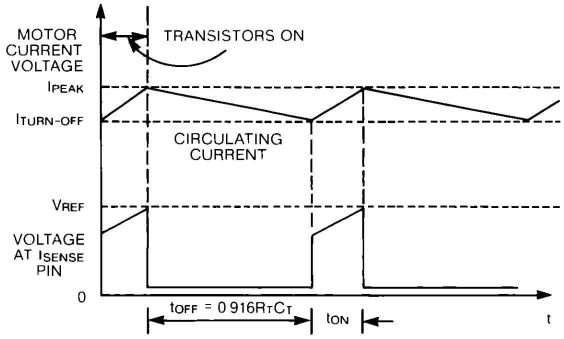

FIGURE 3. THE CHIP'S SWITCHING CIRCUIT CONTROLS MOTOR CURRENT ON A PULSE-BY-PULSE BASIS. WHEN THE BOTTOM TRANSISTOR OF AN OUTPUT STAGE IS ON, THE CURRENT AT FIRST RISES RAPIDLY AND THEN DECAYS SLOWLY AS IT CIRCULATES THROUGH THE TRANSISTOR'S ASSOCIATED DIODE THE FORM FACTOR OF THE WAVEFORM IS THEREFORE CLOSE TO UNITY. SO THAT HEATING OF THE COILS IS REDUCED.

The chip also includes two protection circuits to help make it more reliable. The under-voltage lockout prevents the output stages from being energized unless the supply voltage can provide sufficient base current to the drive transistors. The maximum V_{CC} start-up threshold is set at 8V and has a built-in hysteresis of 0.5V.

A thermal shutdown circuit affords protection against excessive junction temperatures. This circuit disables the drive transistors when the chip's temperature is between 150°C and 180°C. When the temperature returns to a safe value, normal operation is automatically restored.

When the power source for a motor is DC, a commutator is needed to, in a sense, alternate the power applied to the windings. A brushless DC motor uses an external power commutator. As a rule, however the motor has an electronic device internal to it that generates information relative to angular position for use in controlling the commutator.

CONTROLLING BRUSHLESS MOTORS TO 2A

The control chip was designed to drive any three-phase brushless DC motor of up to 2A and is particularly suited for motors with integral Hall-effect devices. H_A, H_B, and H_c (Figure 1 again) are TTL-compatible inputs that, together with the Forward-Reverse input (FWD / REV), determine the output states (Table 2).

The commutation logic built into the UC3620 is intended for use with motors with 120 electrical degree Hall codes. Motors that use the alternative 60 electrical degree code can be easily accomodated with the addition of an inverter to reverse polarity of one of the Hall signals.

When used as described, the device operates in a current feedback mode and acts as a current controller or rather as a transconductance amplifier. This closed-loop circuit can be made part of another feedback loop to control the motor speed. Controlled speed loops are of interest in many applications some of which require a very high degree of control accuracy. For example, a crystal-referenced phase-locked loop is needed to control the spindle speed of magnetic disk drives.

Table 2. Hall Device Logic Coding

HALL DEVICE INPUTS			FORWARD / REVERSE LINE	DRIVER OUTPUT
H_A	H_B	H_C		
1	0	1	1	$A\bar{B}Z$
1	0	0	1	$AZ\bar{C}$
1	1	0	1	$ZB\bar{C}$
0	1	0	1	$\bar{A}BZ$
0	1	1	1	$\bar{A}ZC$
0	0	1	1	$Z\bar{B}C$

Note: A change of state in the Forward Reverse line inverts the output states, thus reversing the direction.