ML4435

Sensorless BLDC Motor Controller

Features
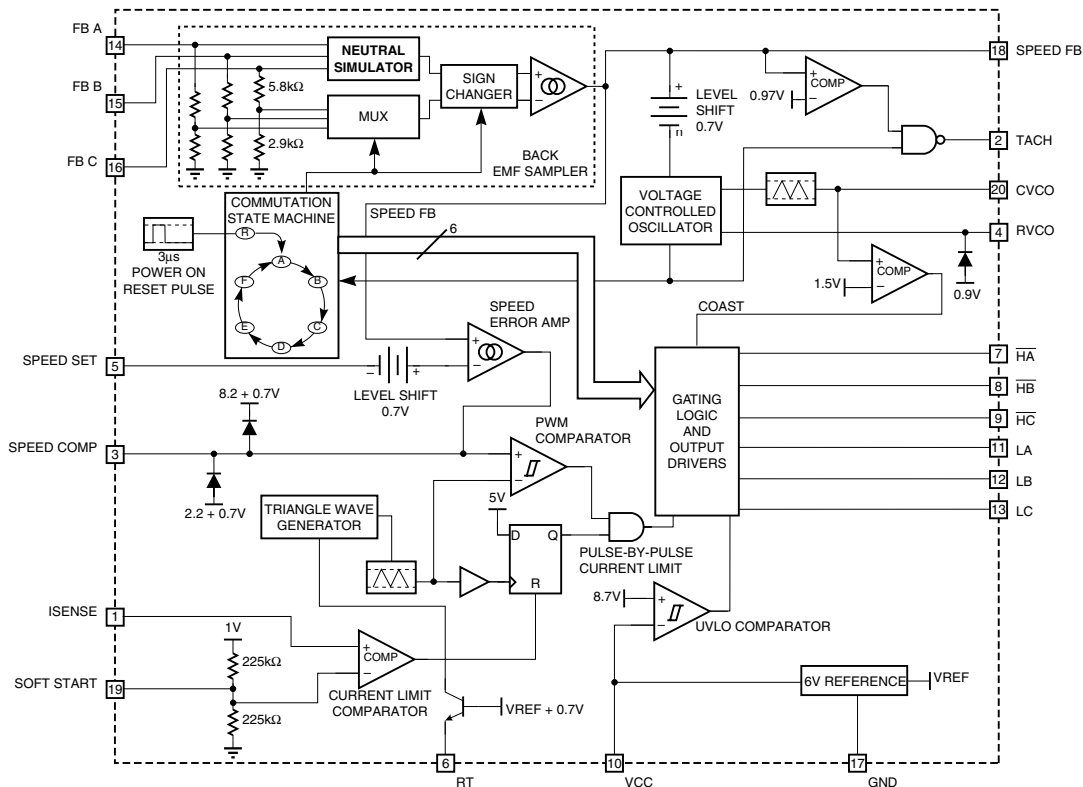
- Proprietary back-EMF sensing commutation technique for motor communication without hall effect sensors
- PWM pulse-by-pulse current limiting to protect motor and FET drivers
- Stand-alone operation; motor starts and stops with power applied to the IC*
- Soft-start function limits start-up current
- PWM speed control for efficiency and minimum FET sizing
- Onboard under voltage lock out and power fail detect
- Tach output senses commutation of the motor

Description

The ML4435 provides all the circuitry for sensorless speed control of 3 phase Brushless DC Motors. Controller functions include start-up circuitry, Back EMF commutation control, Pulse Width Modulation (PWM) speed control, pulse-by-pulse current limiting, motor coasting, and under-voltage protection.
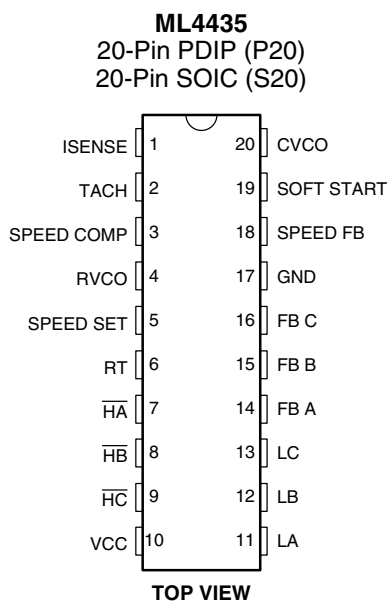
Motor starting is accomplished by commutating the motor at a low frequency to produce low speed motion. The low speed motion is used to generate a Back EMF signal. A back EMF sampling circuit locks on to the motors position and controls commutation timing by forming a phase locked loop (PLL). The commutation control circuitry also outputs a speed feedback signal used in the speed control loop. The speed control loop consists of an error amplifier and PWM comparator that produces a PWM duty cycle for speed regulation. Motor current is limited by a pulse-by-pulse PWM shutdown comparator that is tripped by the voltage across an external current sense resistor. Commutation control, PWM speed control, and current limiting are combined to produce the output driver signals. Six output drivers are used to provide gating signals to an external 3 phase bridge power stage sized for the Brush-less DC (BLDC) motor voltage and current requirements. Additional functions include a motor coast function and an under voltage lock out circuit to shut down the output drivers in the event of a low voltage condition on the VCC to the ML4435.

Block Diagram

*Some External Components Required

Pin Assignments

ML4435
20-Pin PDIP (P20)
20-Pin SOIC (S20)

ISENSE	1	20	CVCO
TACH	2	19	SOFT START
SPEED COMP	3	18	SPEED FB
RVCO	4	17	GND
SPEED SET	5	16	FB C
RT	6	15	FB B
$\overline{HA}$	7	14	FB A
$\overline{HB}$	8	13	LC
$\overline{HC}$	9	12	LB
VCC	10	11	LA

TOP VIEW

Pin Description

NAME	PIN	FUNCTION
ISENSE	1	Motor current sense input which triggers pulse by pulse current limit when ISENSE exceeds 0.55V
TACH	2	A clock output of 6 pulses per commutation cycle when SPEED FB is greater than 0.97V otherwise the TACH output is at 5V
SPEED COMP	3	Connection node for speed loop compensation components
RVCO	4	Connection node for external resistor to set VCO frequency
SPEED SET	5	DC input for setting motor speed
RT	6	External resistor from this pin to ground controls the IC's PWM timing (frequency)
$\overline{HA}$	7	High-side output driver for motor phase A
$\overline{HB}$	8	High-side output driver for motor phase B
$\overline{HC}$	9	High-side output driver for motor phase C
VCC	10	Power Supply input
LA	11	Low-side output driver signal for motor phase A
LB	12	Low-side output driver signal for motor phase B
LC	13	Low-side output driver signal for motor phase C
FB A	14	Back EMF signal input for motor phase A
FB B	15	Back EMF signal input for motor phase B
FB C	16	Back EMF signal input for motor phase C
GND	17	Signal and power ground
SPEED FB	18	Connection node for back-EMF sensing compensation components
SOFT START	19	Connection node for external soft start capacitor which reduces start up current
CVCO	20	Connection node for external capacitor to set VCO frequency. Forcing this input below 1.5V causes the commutation to stop and the motor to coast

Electrical Tables

Unless otherwise specified, Ta= Operating Temperature Range, VCC = 12V ±10%, RT = 50k

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
REFERENCE						
RT			5.8	6	6.2	V
VCO						
RVCO	Lower Range[2]			0.2		V
	Upper Range[2]			6		V
CVCO	Lower Threshold[2]			2		V
	Upper Threshold[2]			3.75		V
	Coast Enable Threshold[2]			1.5		V
	Back EMF Blanking Threshold[2]			2.875		V
SPEED FEEDBACK						
	Output Range[2]		0		6.7	V
	V Minimum Frequency[2]	V Speed Feedback		0.9		V
	TACH Out Disabled Threshold[2]	TACH Out = Hi		0.97		V
	I Back EMF Sampler[2]	V Speed Feedback = 3.3V		±80		µA
BACK EMF SENSING						
	Feed Back Input Range[2]	FB A, FB B, and FB C	0		VCC	V
TACH						
	TACH Out Low	ISINK = 100µA		0.2	0.4	V
	TACH Out High	ISOURCE = 100µA	4.3	4.8		V
SPEED ERROR MP						
	SPEED SET Range[2]		0		6	V
	I SPEED COMP	V SPEED COMP = 5.1V		±45		µA
	SPEED COMP Output Lower Clamp[2]	I = ±45µA		2.15		V
	SPEED COMP Output Upper Clamp[2]	I = ±45µA		8.2		V
OSCILLATOR						
	PWM Frequency	N1, N2, N3	17	25	33	kHz
	Duty Cycle[2]	N1, N2, N3	0		100	%
CURRENT SENSE						
	V SOFT START		0.48	0.58	0.68	V
ISENSE	Threshold[2]			0.58		V
OUTPUTS (N1, N2, N3, P1, P2, AND P3)						
	Output Low	ISINK = 20mA	0	0.5	1	V
	Output High (VCC-VOUT)	ISOURCE = 20mA	0	0.5	1	V
UNDER VOLTAGE LOCKOUT						
	Start Threshold		8.7	9.2	9.7	V
	Under Voltage Threshold		8.2	8.7	9.2	V
SUPPLY						
ICC	Supply Current			15		mA

Note 1: Limits are guaranteed by 100% testing, sampling, or correlation with worst case test conditions.
Note 2: Guaranteed by design, not tested.

Functional Description

Component Selection

Selecting external components for the ML4435 requires calculations based on the motor's electrical and mechanical parameters. The following is a list of the motor parameters needed to for these calculations:

The maximum DC motor supply voltage V MOTOR (V)

The maximum operating current I MAX (A)

The winding resistance measured line to line Rl-l Ω

The number of magnetic poles N (Unitless)

The Back EMF constant Ke (V s/RAD)

The torque constant Kτ (N m/A) of the motor (Kτ = Ke in SI units)

The maximum speed of operation RPMMAX (RPM)

The moment of inertia J (Kg m^2) of the motor and its load

The viscous damping factor ζ (Unitless) of the motor and its load

If one or more of the above values is not known, it is still possible to pick components for the ML4435, but some experimentation may be necessary to determine the optimal values. All quantities are in SI units unless otherwise specified. The following formulas and component selection graphs should be considered as a starting point from which to optimize the application. All calculations for capacitors and resistors should be used as the first approximation for selecting the closest standard value.

Supply Voltage and On Chip Voltage Reference

VCC

The supply voltage at VCC (pin 10) is nominally 12V ± 10%. A bypass capacitor of 0.1µF to ground as close as possible to VCC (pin 10) is recommended.

RT

An internal 6V reference is generated inside the ML4435. The reference appears on RT (pin 6). A resistor to ground on RT sets the PWM frequency. This resistor can be replaced with a potentiometer for use in setting the speed command. This topic is discussed under the PWM SPEED CONTROL section. Note: Buffer this pin with an op amp with at least a 1MΩ input impedance if external circuits are necessary.

Output Drivers

The output drivers LA, LB, LC, $\overline{HA}$, $\overline{HB}$, and $\overline{HC}$ provide totem pole output drive signals for a 3 phase bridge power stage. All control functions in the ML4435 translate to outputs at these pins. LA, LB, LC provide the low side drive signals for phases A, B, and C of the 3 phase power stage and are 12V active high signals. $\overline{HA}$, $\overline{HB}$, and $\overline{HC}$ provide the high side signals for phases A, B, and C of the 3 phase power stage and are 12V active low signals.

Current Limiting in the 3 Phase Bridge Power Stage

A current sense resistor RSENSE shown in Figure 1 is installed in the 3 phase power stage to regulate the maximum current in the power stage and the BLDC motor. Current regulation is accomplished by shutting off the output drivers LA, LB, and LC for the remainder of the PWM period if the voltage across RSENSE exceeds the current limit threshold set by the SOFT START (pin 19). The maximum power dissipated in RSENSE is shown in Figure 2.

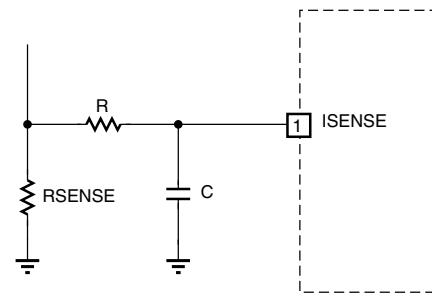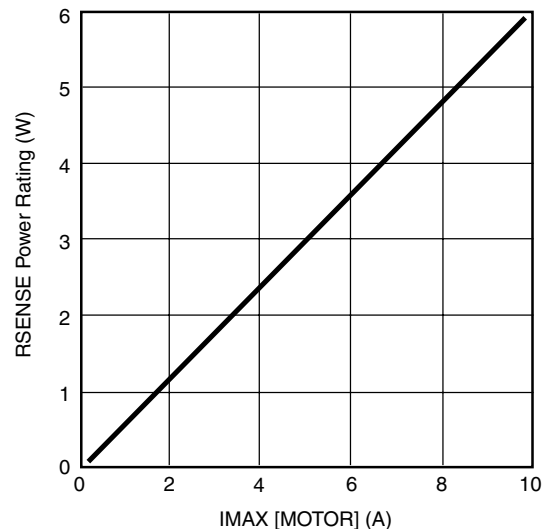**Figure 1. Current Limit with RSENSE**

Figure 2. RSENSE Power vs. Motor Current

Soft Start

The voltage at SOFT START (pin 19) sets the current limit threshold. The ML4435 has an internal voltage divider with a 1.1V supply voltage. This circuit is shown in Figure 3. The divider consists of two 225kΩ resistors setting the current limit threshold to approximately 0.55V. An external voltage divider off of VCC or an external reference can be used to override the default setting of SOFT START by using a divider with 10 times the current draw of the internal divider.
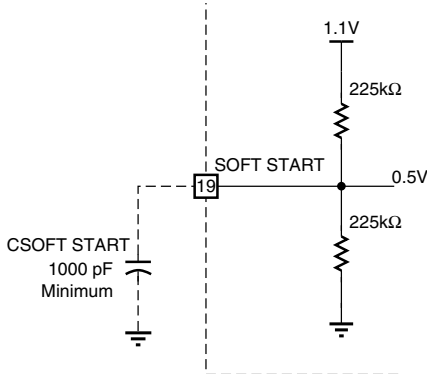
Figure 3. SOFT START Function

A capacitor to ground on the SOFT START pin can be used to provide a soft ramping of the current limit on power up. The ramp time can be selected using Figure 4.
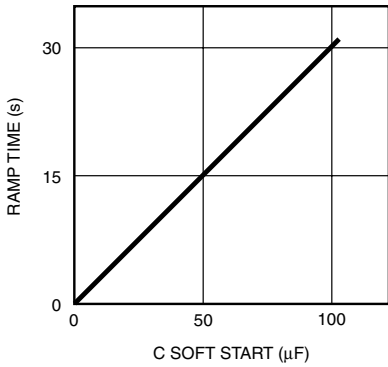

Figure 4. SOFT START Ramp Time vs. CSOFTSTART

RSENSE

The function of RSENSE is to provide a voltage proportional to the motor current, for current limiting. The default trip voltage across RSENSE is 0.6V as set by the SOFT START (pin 19). The current sense resistor should be a low inductance resistor such as a carbon composition. For resistors in the milli ohms range wire wound resistors tend to have low values of inductance. RSENSE can be selected using Figure 4. The power rating of RSENSE should be sized to handle the power dissipation (I MAX squared times RSENSE) seen at maximum current.

ISENSE Filter

An RC lowpass filter is required at the ISENSE input pin to remove the voltage spike on the leading edge of the current sense signal caused by the diode reverse recovery shoot through current. Absent the filter, false triggering of the current limit could occur.

The recommended starting values for this circuit are R = 1KΩ and C = 1000pF a configuration that will filter out spikes less than 1μs long. It is recommended that the capacitor value not be increased beyond 3300pF.

Pulse-By-Pulse Current Limiting

When current limit is activated by the voltage on ISENSE exceeding the voltage on SOFT START the current limit is tripped, turning off LA, LB, and LC for the remainder of the PWM period.
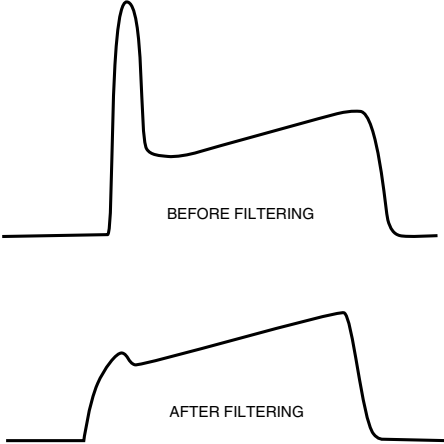

Figure 5. ISENSE Filter Wave Forms

Commutation Control

A 3 phase Brushless DC motor requires electronic commutation to achieve rotational motion. Electronic commutation requires the switching on and off of the power switches of a 3 phase half bridge. For torque production to be achieved in one direction the commutation is dictated by the rotor's position. Electronic commutation in the ML4435 is achieved by turning on and off, in the proper sequence, one L output from one phase and one $\overline{H}$ output from another phase. There are six combinations of L and $\overline{H}$ outputs (six switching states) that constitute a full commutation cycle as illustrated in Table 1 labeled state A through F. This switching sequence is programmed into the commutation state machine as illustrated in Figure 6. Clocking of the commutation state machine is provided by the output of a VCO.

OUTPUT DRIVERS

STATE	LA	LB	LC	$\overline{HA}$	$\overline{HB}$	$\overline{HC}$
A	LOW	LOW	HIGH	LOW	HIGH	HIGH
B	LOW	LOW	HIGH	HIGH	LOW	HIGH
C	HIGH	LOW	LOW	HIGH	LOW	HIGH
D	HIGH	LOW	LOW	HIGH	HIGH	LOW
E	LOW	HIGH	LOW	HIGH	HIGH	LOW
F	LOW	HIGH	LOW	LOW	HIGH	HIGH

☐ = DRIVER ON

Table 1. Communication Control States

Voltage Controlled Oscillator

The VCO outputs a TTL compatible clock on the TACH (pin 2) proportional to the input voltage to the voltage controlled oscillator SPEED FB (pin 18). The proportion of frequency to voltage or VCO constant Kv is set by a resistor to ground on RVCO (pin 4) and capacitor to ground on CVCO (pin 20) as shown in Figure 7. RVCO sets up a current proportional to the VCO input voltage SPEED FB minus 0.7V. This current is used to charge and discharge CVCO between the threshold voltages of 2V and 3.75V as shown in Figure 7. RVCO has a lower voltage limit of 0.2V. The resulting triangle wave of CVCO corresponds to the clock on the TACH pin, this is also illustrated in Figure 7. Kv should be set so that the VCO output frequency corresponds to the maximum commutation frequency FMAX and thus the maximum motor speed when the VCO input is equal to or slightly less than 6V. CVCO and RVCO can be selected by first calculating FMAX and then using the selection graph in Figure 8. FMAX is calculated as follows:

$$FMAX = 0.05 \text{ x } RPMMAX \text{ x } N$$

Where: RPMMAX = The maximum speed of operation (RPM). N = The number of magnetic poles (Unitless).
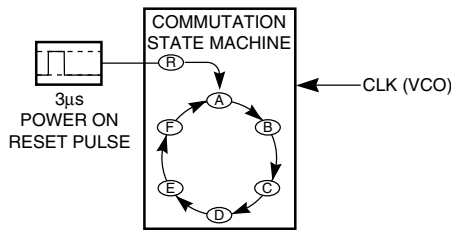
Figure 6. Commutation State Machine
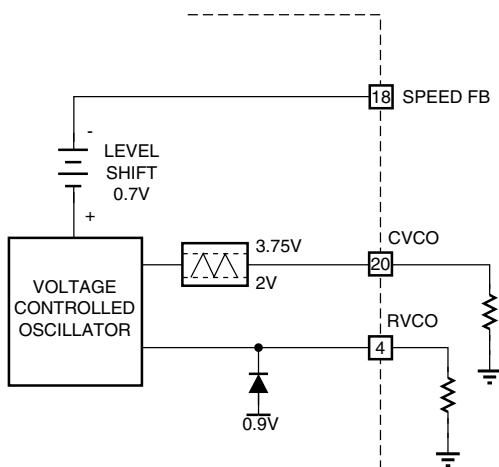
Figure 7. VCO Control

Tach

The TACH (pin 2) outputs the VCO frequency. This is 6 times the commutation frequency. The TACH out also indicates a low motor speed by staying TTL high when the motor is at its minimum speed (SPEED FB below 0.97V).

Back EMF Sampler

The input to the VCO (pin 18) SPEED FB is controlled by the Back EMF Sampler. The back EMF sense pins FB A, FB B, and FB C inputs to the back EMF sampler require a signal from the motor phase leads that is below the VCC of the ML4435. The phase sense input impedance is 8.7kΩ. If the motor voltage is greater than the VCC of the ML4435 then this requires a series resistor RFB from the motor phase lead shown in Figure 8. RFB can be selected by using the graph in Figure 9 or using the following equation:

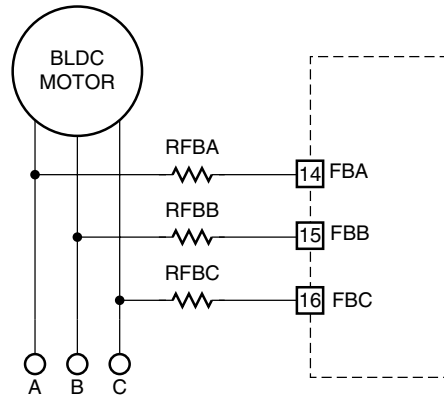$$RFB \ = \ 8.7k\Omega\left(\frac{VMOTOR}{12} - 1\right)$$

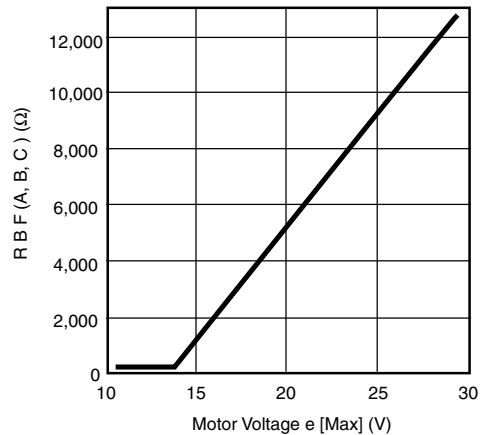**Figure 8. Back EMF Sampler Configuration**

Figure 9. RFB vs. VMOTOR [MAX]

The back EMF sampler takes the motor phase voltages divided down to signals that are less than VCC (12V nominal) and calculates the neutral point of the motor by the following equation:

$$VNEUTRAL = (FB \ A + FB \ B + FB \ C)/3$$

This allows the ML4435 to compare the back EMF signal to the motors neutral point without the need for bringing out an extra wire on a WYE wound motor. For DELTA wound motors there isn't a physical neutral to bring out so this reference point must be calculated anyway.

The back EMF sampler takes the motor phase that is not driven (i.e. if LA and $\overline{HB}$ are on then phase A is driven low and phase B is driven high then phase C is sampled). The sampled phase provides a back EMF signal that is compared against the neutral of the motor. The sampler is controlled by the commutation state machine. The sampled back EMF is compared to the neutral through an error amplifier. The output of the error amplifier outputs a charging or discharging current to SPEED FB (pin 18) which provides the voltage to the VCO.

Back EMF Sensing Phase Locked Loop Commutation Control

The three blocks: The commutation state machine, the VCO, and the back EMF sampler form a phase locked loop that locks the commutation clock onto the back EMF signal. The complete phase locked loop is illustrated in Figure 10. The phased locked loop requires a lead lag filter that is set by external components on SPEED FB (pin 18). The filter components in Figure 10 work for most applications. If performance is unstable C1 and C2 can go up or down a decade in
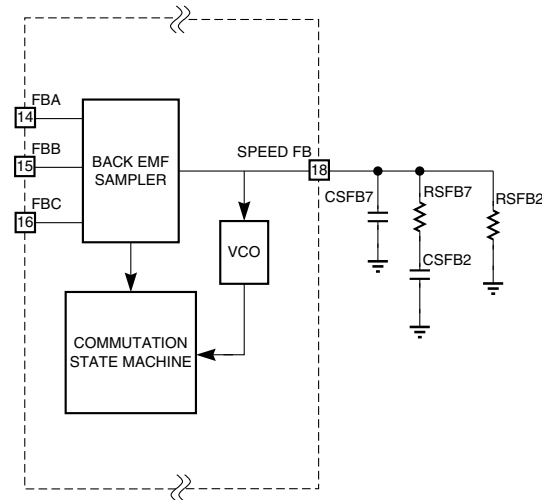
value as low as the C2 stays equal to C1 x 10.

Figure 10. Phase Locked Loop

Motor Start-Up

When power is first applied to the ML4435, the motor is at rest and thus, the back EMF is equal to zero. The motor needs to be rotating for the Back EMF sampler to lock onto the rotor position and commutate the motor. The ML4435 uses a minimum VCO frequency to begin commutating the motor. This low frequency commutation is set by the 0.2V clamp on RVCO, this provides a commutation frequency at 1/30th of the maximum frequency.

Run Mode

After the Back EMF sensing PLL has locked on to the motor's position, the motor is running in closed loop control. At this point, the speed control loop should force the motor speed to the speed that corresponds to the SPEED SET voltage.

PWM Speed Control

Speed control is accomplished by setting a speed command

at SPEED SET (pin 5) with an input voltage from 0.2 to 6V. The accuracy of the speed command is determined by the external components RVCO and CVCO. There are a number of methods to control the speed command on the ML4435. One method is to use a potentiometer from RT to ground with the wiper going to SPEED SET. If SPEED SET is
controlled from a microcontroller, a DAC that uses RT as its input reference can be used. The RT voltage must be buffered connecting it to external circuits. The speed command is compared with the sensed speed from SPEED FB minus 0.7V (pin 18) through a transconductance error amplifier. The output of the speed error amplifier is SPEED COMP (pin 3). SPEED COMP is clamped between 8.2V and
2.2V. A signal of 8.2V corresponds to full PWM duty
cycle and 2.2V corresponds to 0% duty cycle. Speed loop compensation components are placed on this pin as shown in Figure 11.

The speed loop compensation components are calculated as follows:

$$C_{SC}2 = \frac{1.44 \times NxKexVMOTOR \times R_{VCO} \times C_{VCO}}{2 \times \pi \times J \times RI \times freq^2}$$

$$Rsc = \frac{10}{2 \times \pi \times freq \times Csc2}$$

$$Csc1 = 10 \times Csc2$$

Where freq is the speed loop bandwidth in Hz.

The voltage on SPEED COMP (pin 3) is compared with a triangle wave oscillator to create a PWM duty cycle. The PWM oscillator creates a triangle wave function from 3V to 7V as shown in Figure 11. The frequency of the triangle wave oscillator is set by a resistor to ground on RT (pin 6). RT can be selected from the graph in Figure 12.

The PWM duty cycle from the speed control loop is gated the pulse-by-pulse current limit that controls the LA, LB, and LC output drivers.
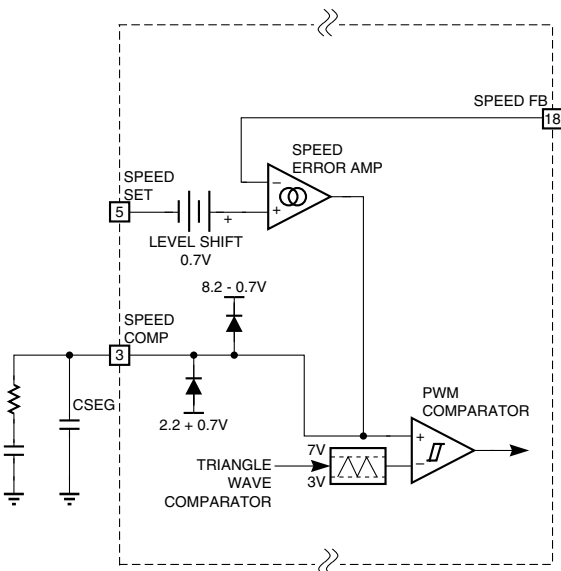

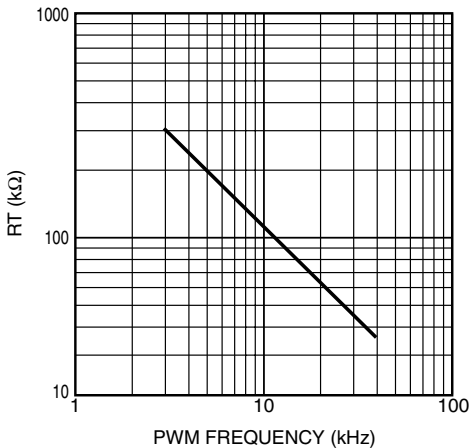**Figure 11. PWM Oscillator Circuit**

Figure 12. RT vs PWM Frequency

Coast

When CVCO (pin 20) is pulled below 1.5V the output drivers LA, LB, LC and $\overline{HA}$, $\overline{HB}$, and $\overline{HC}$ are turned off. The COAST function shuts all power off from the motor allowing it to coast to a stop. The COAST function in (pin 20) is configured as shown in Figure 13 and can be driven by a switch to ground or open collector to ground also shown in Figure 13.
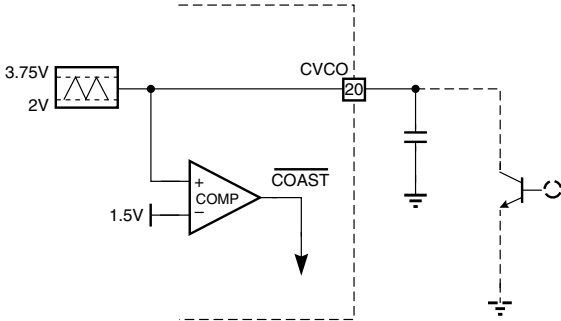

Figure 13. Coast Control

Under Voltage Protection

Undervoltage protection is used to protect the 3 phase bridge power stage from a low VCC condition. Undervoltage is triggered at VCC of 9.2V or under. Undervoltage also turns off all output drivers LA, LB, LC, $\overline{HA}$, $\overline{HB}$, and $\overline{HC}$. The comparator that triggers undervoltage protection has 500mV of hystersis.

Interfacing the Output Drivers to the 3 Phase Bridge Power Stage

The most flexible configuration is to use high side drivers
to control N-Channel MOSFETs (or IGBTs) allowing applications from less than 12V up to 170V. Figure 14a shows the ML4435 and all the support circuitry in a typical application. Figure 14b shows a power stage using the IR2118 high side drivers from International Rectifier and high voltage MOSFETs.
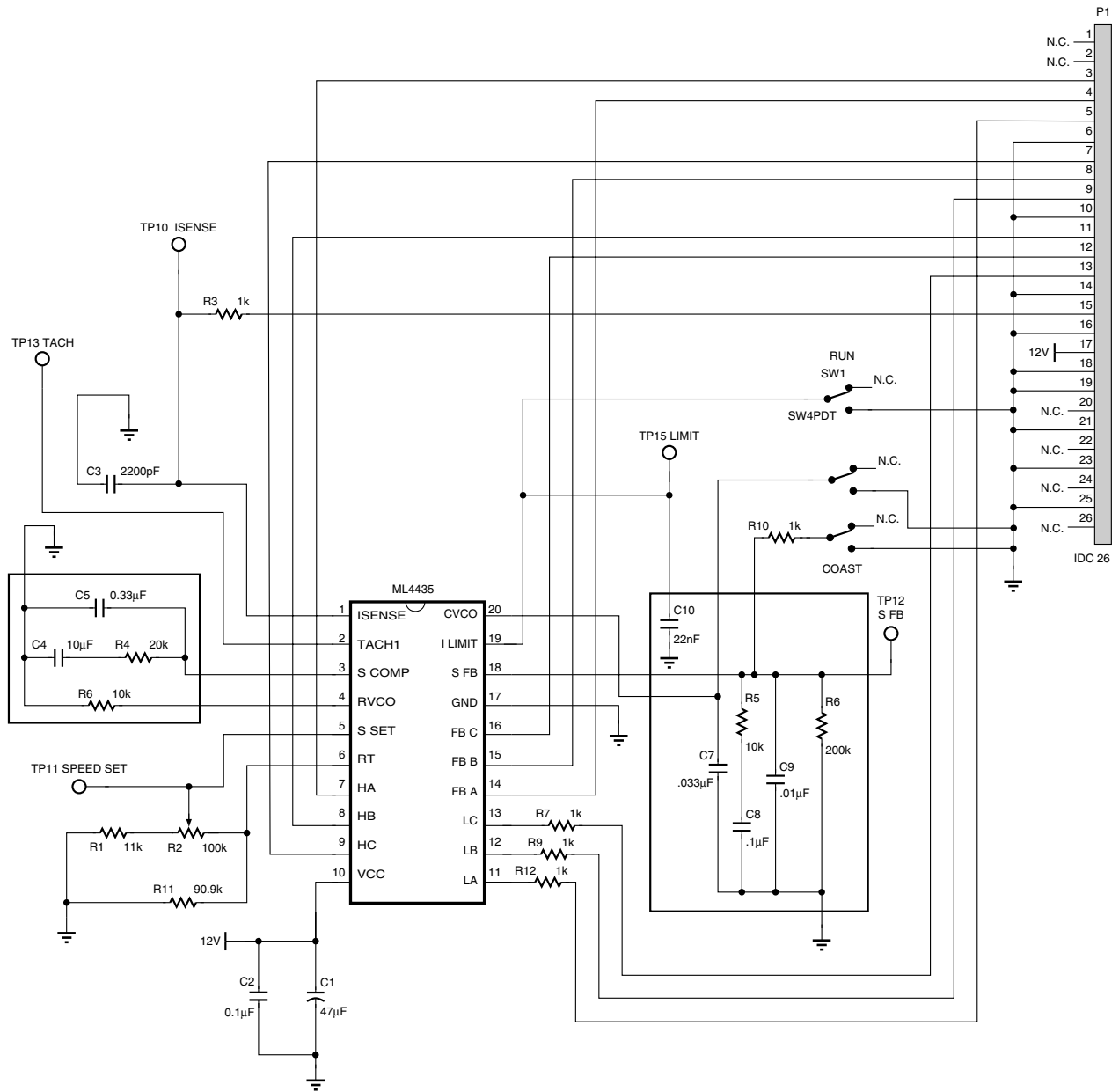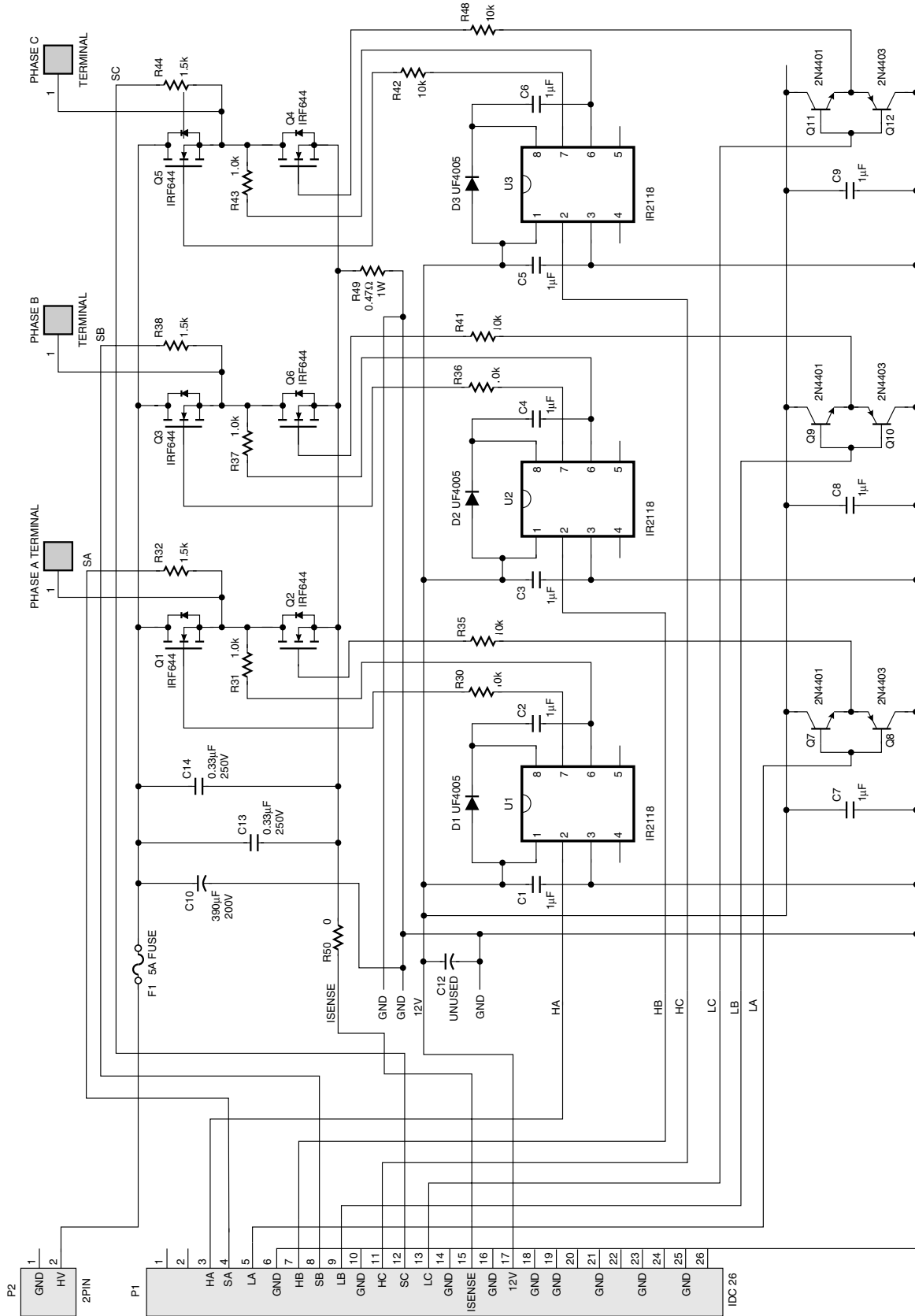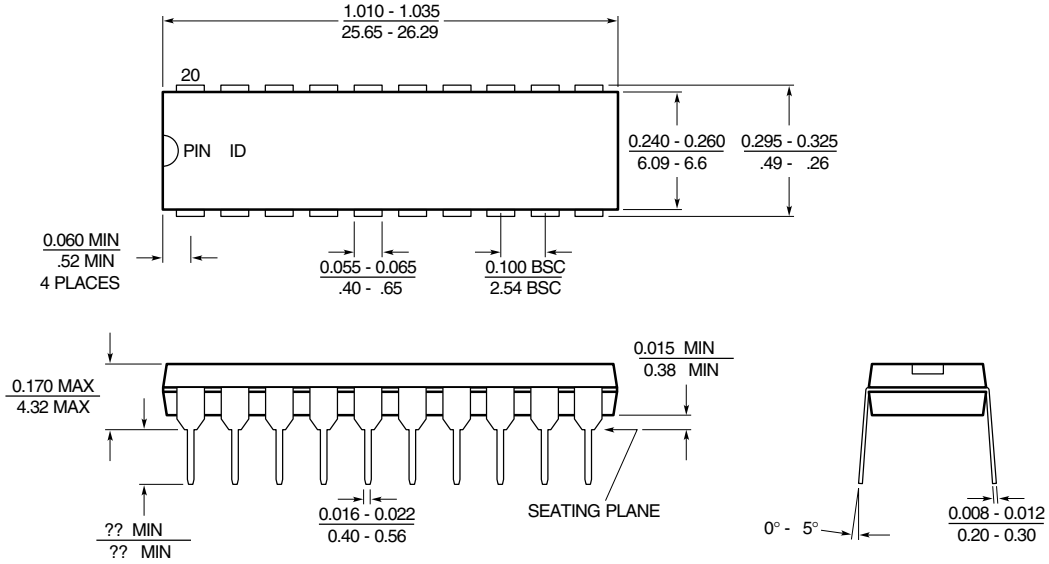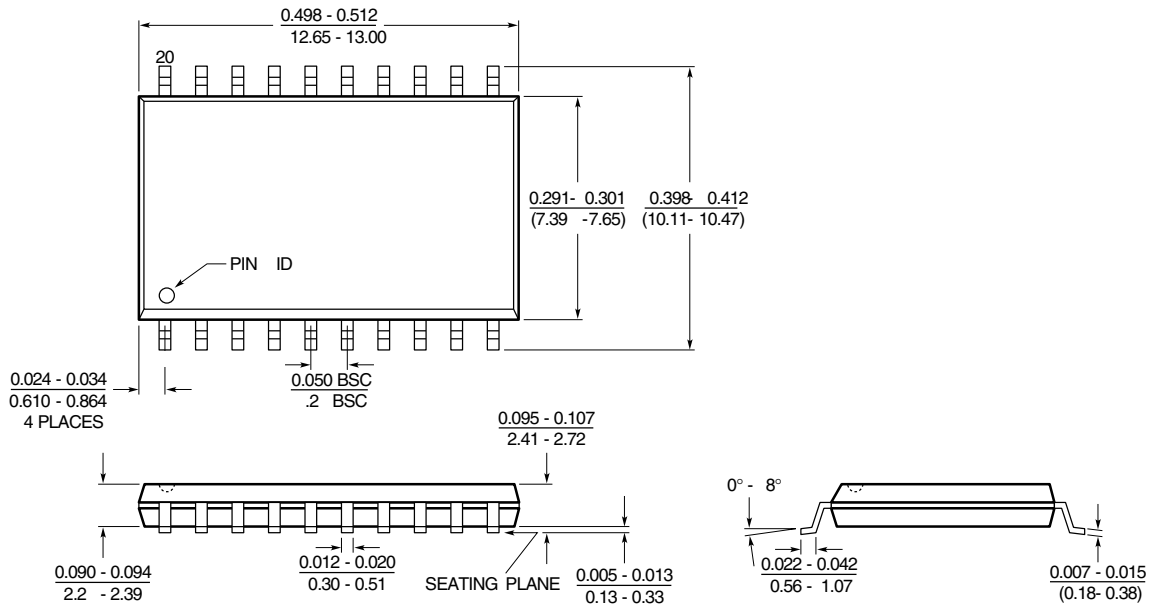
Figure 14a. ML4435 Typical Application

Figure 14b. Power Stage

Mechanical Dimensions

Package P20
20 Pin PDIP

1.010 - 1.035
25.65 - 26.29

20

PIN ID

0.240 - 0.260
6.09 - 6.6

0.295 - 0.325
.49 - .26

0.060 MIN
.52 MIN
4 PLACES

0.055 - 0.065
.40 - .65

0.100 BSC
2.54 BSC

0.015 MIN
0.38 MIN

0.170 MAX
4.32 MAX

?? MIN
?? MIN

0.016 - 0.022
0.40 - 0.56

SEATING PLANE

0° - 5°

0.008 - 0.012
0.20 - 0.30

Package S20
20 Pin SOIC

0.498 - 0.512
12.65 - 13.00

20

0.291 - 0.301
(7.39 - 7.65)

0.398 - 0.412
(10.11 - 10.47)

PIN ID

0.024 - 0.034
0.610 - 0.864
4 PLACES

0.050 BSC
.2 BSC

0.095 - 0.107
2.41 - 2.72

0° - 8°

0.090 - 0.094
2.2 - 2.39

0.012 - 0.020
0.30 - 0.51

SEATING PLANE

0.005 - 0.013
0.13 - 0.33

0.022 - 0.042
0.56 - 1.07

0.007 - 0.015
(0.18 - 0.38)

Ordering Information

PART NUMBER	TEMPERATURE RANGE	PACKAGE
ML4435CP	0°C to 70°C	20 Pin PDIP (P20)
ML4435CS	0°C to 70°C	20 Pin SOIC (S20)
ML4435IP	-40°C to 85°C	20 Pin PDIP (P20)
ML4435IS	-40°C to 85°C	20 Pin SOIC (S20)