Don't Burn Your Bridges!

COURTESY: ON SEMICONDUCTOR

Since the advent of the electric starter, the number of motors in automotive applications continues to grow. Motors move mirrors, seats, HVAC blender doors, throttle plates, cooling fans, fuel pumps, door locks, window lifts, and many other loads. Motor types can be brushed, brushless, stepper or linear. Some require motion in only one direction while others move in two directions. Bridge drivers are used when bi-directional control is needed.

Bridge (or H-Bridge) drivers provide an effective means of changing the direction of motor supply current, thus changing the direction of motion. Along with this primary function, the drivers must provide diagnostic capabilities and protections for themselves and the motor. But even with protections, there are opportunities for disaster. A brief review of basic motor theory and bridge operation will be useful to understand how these opportunities can arise.

DC Motor Basics

We'll use the Permanent Magnet DC (PMDC) brush motor as an example, a diagram of which is shown in Figure 1. When supply voltage V_S is applied to the motor, armature current I_A is developed causing magnetic field B_A to be developed by armature winding inductance L_A. The developed field reacts against the PM field producing armature force F_A, and thereby developing torque T_L. This torque is what begins to turn the motor's armature and provide useful mechanical energy to the load.

The initial current when V_S is applied is high, limited only by the source and armature resistances RS and R_A. The initial current therefore produces high

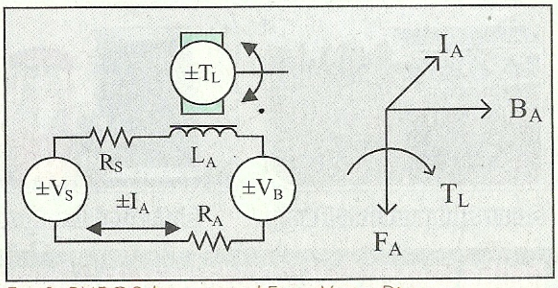

Fig. 1. PMDC Schematic and Force Vector Diagram

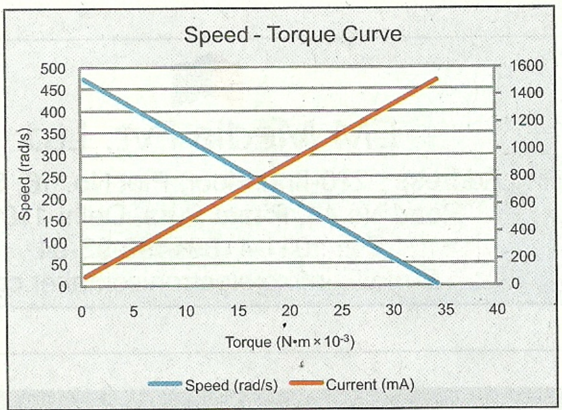

Fig. 2. Idealized Canon FN30 M 12V Motor Speed-Torque Curve

starting torque. These conditions are referred to as stall current (I_S) and stall torque (T_S). As the armature begins to build rotational velocity, the windings turn through the PM field and begin to generate back-EMF V_B. The polarity of V_B is such to oppose V_S. As a result, when the load has been accelerated to its final velocity, armature current is reduced to some lower value. The idealized relationship between current, torque, and speed (speed-torque curve) is plotted in Figure 2.

Several equations useful for understanding the electro-mechanical aspects of the foregoing description are considered. For the electrical behavior, we have:

$$I_A = \frac{V_S - V_B}{R_S + R_A} = \frac{V_S - K_B\omega}{R_S + R_A} \quad \text{Equation 1}$$

where K_B is the motor's back-EMF constant and ω is its rotational velocity. Setting $\omega = 0$, Equation 1 tells us what the stall current will be. The motor's

electrical time constant is:

$$t_E = \frac{L_T}{R_T}$$ *Equation 2*

where L_T is the total inductance (armature, parasitic and wiring) and R_T is the total resistance. For the mechanical behavior, we have:

$$T_L = K_T I_A - F\omega = K_T I_A - \frac{K_T K_B \omega}{R_S + R_A}$$ *Equation 3*

where K_T is the motor's torque constant and Fω is the motor's viscous friction loss. Setting $\omega = 0$, Equation 3 tells us what the stall torque will be. The motor's mechanical time constant is:

$$t_M = \frac{J_T}{F} = \frac{R_T J_T}{K_B K_T}$$ *Equation 4*

where J_T is the lumped (motor, reflected geartrain and load) inertia and RT is the total resistance.
The electrical and mechanical energy stored in the system at any point in time can also be described. For the electrical:

$$W_E = \frac{1}{2} L_T I_A^2 + K_B \omega I_A$$ *Equation 5*

and for the mechanical:

$$W_M = \frac{1}{2} J_T \omega^2$$ *Equation 6*

Combining Equation 5 and Equation 6 gives us the total energy stored, W_T:

$$W_T = W_E + W_M = \frac{1}{2} L_T I_A^2 + K_B \omega \; I_A + \frac{1}{2} J_T \omega^2$$ *Equation 7*

In practice, when the stored energy can be returned to the source, half is lost during the transfer due to electrical resistance and mechanical friction losses such that the recovered energy W_R is:

$$W_R = \frac{1}{4} L_T I_A^2 + K_B \omega^2 I_A + \frac{1}{4} J_T \omega^2$$ *Equation 8*

Table 1 lists the specifications of the Canon motors used to gather some test case data presented later

FN30 M 12V 7-slot PMDC Motor – Typical Parameters @25 °C			
Parameter	Value	Units	Symbol
Rated Input Voltage	12	V	VS
Rated Output Power	3.3	W	PM
Rated Current	440	mA	IR
Rated Torque	9.81×10-3	N•m	TR
Rated Speed	335	rad/s	ωR
No-load Speed	471	rad/s	ωN
No-load Current	60	mA	IN
Starting Torque	34.3×10-3	N•m	TST
Rotor Inertia Moment	220×10-6	kg•m2	JA
Torque Constant	23.5×10-3	N•m/A	KT
Back EMF Constant	23.5×10-3	V•s/rad	KB
Mechanical Time Constant	32×10-3	s	τM
Winding Resistance	8.0	Ω	RA
Winding Inductance	4.1×10-3	H	LA
Thermal Resistance	24	°C/W	RθM

Table 1. Test Motor Typical Specifications

in this article. For fun, you could plug the motor specifications into the previous equations!

H-Bridge Basics

The H-Bridge, so called because the configuration resembles the letter "H", is built up from two half-bridges using MOSFET power switches as shown in Figure 3. The operational modes along with the load current paths are described in Table 2.
The labels "FWD" and "REV" are arbitrary. The freewheel and brake modes are both dynamic, the difference being reduced driver power dissipation with two MOSFETs conducting in the brake mode. In these modes, the load current is contained within the high or low side loop. Another dynamic brake mode called "plugging" (mode 13&14) is obtained by switching the current direction "FWD→ REV". This mode provides high braking torque, and

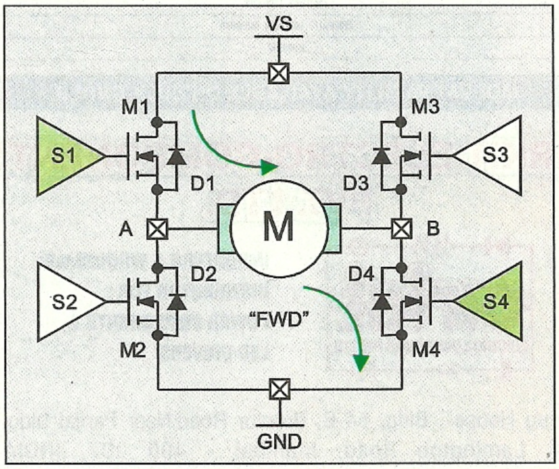

Fig. 3. H-Bridge Configuration in "FWD" Mode

Mode	Description	Symbol	S1	S2	S3	S4	Current Path
0	High-Z	Z	OFF	OFF	OFF	OFF	None
1	Forward	FWD	ON	OFF	OFF	ON	VS-M1-A-B-M4-GND
2	FWD-Freewheel High	FFH	ON	OFF	OFF	OFF	B-D3-M1-A
3	FWD-Brake High	FBH	ON	OFF	ON	OFF	B-M3-M1-A
4	FWD-Freewheel Low	FFL	OFF	OFF	OFF	ON	B-M4-D2-A
5	FWD-Brake Low	FBL	OFF	ON	OFF	ON	B-M4-M2-A
6	FWD-Z	F-Z	OFF	OFF	OFF	OFF	GND-D2-A-B-D3-VS
7	Reverse	REV	OFF	ON	ON	OFF	VS-M3-B-A-M2-GND
8	REV-Freewheel High	RFH	OFF	OFF	ON	OFF	A-D1-M3-B
9	REV-Brake High	RBH	ON	OFF	ON	OFF	A-D1-M3-B
10	REV-Freewheel Low	RFL	OFF	ON	OFF	OFF	A-M2-D4-B
11	REV-Brake Low	RBL	OFF	ON	OFF	ON	A-M2-M4-B
12	REV-Z	R-Z	OFF	OFF	OFF	OFF	GND-D4-B-A-D1-VS
13	FWD-REV	F-R	OFF	ON	ON	OFF	GND-M2-A-B-M3-VS
14	REV-FWD	R-F	ON	OFF	OFF	ON	GND-M4-B-A-M1-VS

Table 2. H-Bridge Operational Modes

depending on load conditions, can develop almost twice the motor stall current as the back-EMF V_B is now placed in series with V_S. This can develop four times the power dissipation in the driver. In the case of locked rotor, $\omega = 0$ and only the motor inductance and resistance present the bridge load since no back-EMF is developed. This can lead to trouble in modes 6, 12, 13 & 14 where the stall current can be steered inversely back to V_S.

Protections

Driver protections must include current limit, temperature limit, and overcurrent shutdown. Protections may also include power supply over and/or under voltage shutdown. ON Semiconductor offers several H-Bridge driver products, three of which are the NCV7703, NCV7708, and NCV7729. The drivers have all of the described protections, and target applications for these products are mirror positioning, HVAC blender door, and electronic throttle respectively. Additionally, the NCV7708 has six independent high side and six independent low side drivers with

Product	RDS(ON) - Ω	Continuous Current - A	Package	
NCV7703	0.8	0.5	SOIC-14	
NCV7708	0.8	0.5	SOIC-28	
NCV7729	0.15	5	PSOP-20	

Table 3. ON Semiconductor Bridge Driver Product Highlights

flyback clamps for more flexible configuration, and the NCV7729 has selectable current limitation. While the products are all fully protected, care must be taken in their applications to avoid or manage high impulse stresses. After all, even an air bag is useless if you're struck by a train!

Time for a Brake?

Electrical devices can and will fail by too much voltage (dielectric breakdown), too much power (thermal breakdown), or a combination of the two. For example, an overvoltage event could trigger a snap-back ESD protection and lead to a thermal breakdown, melting the driver.

Figure 4 shows a locked rotor case where a reverse-battery protection diode D_R is present in the application, and the bridge mode is F_Z(recall there are the other modes for inverse current as well). D_R blocks the inverse current from being returned to the battery. In the absence of other loads to absorb the inverse energy from L_A, the V_S voltage can exceed the driver's maximum voltage rating, or trigger an ESD protection. A bulk electrolytic capacitor (C_B) must be placed close to the driver's V_S terminal to absorb the inductive energy.

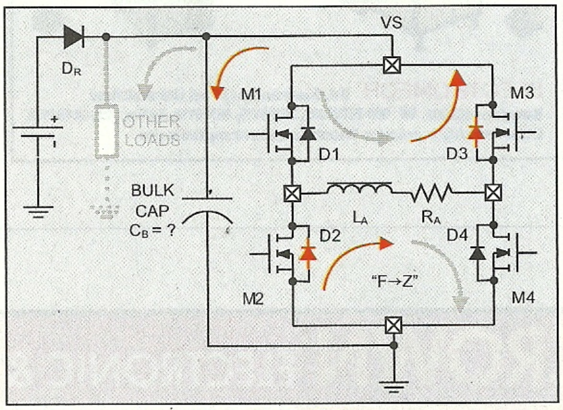

Fig. 4. Inverse Current from Locked Rotor

Looking back to Equation 8 gives us a way to determine how to dimension C_B. With the rotor locked we have $\omega = 0$ and we're left with just the inductive energy. Considering the initial energy stored in C_B and the inductive energy returned, we have:

$$\frac{1}{2}C_B V_F^2 = C_B \frac{1}{2} V_i^2 + \frac{1}{4} L_T I_A^2 \qquad \textit{Equation 9}$$

Reducing and re-arranging Equation 9 gives us:

$$C_B = \frac{1}{2} \frac{L_T I_A 2}{2V_f^2 - V_i^2} \qquad \textit{Equation 10}$$

or alternatively:

$$V_f = \sqrt{V_i^2 + \frac{1}{2}\frac{L_T I_A^2}{C_B}} \qquad \textit{Equation 11}$$

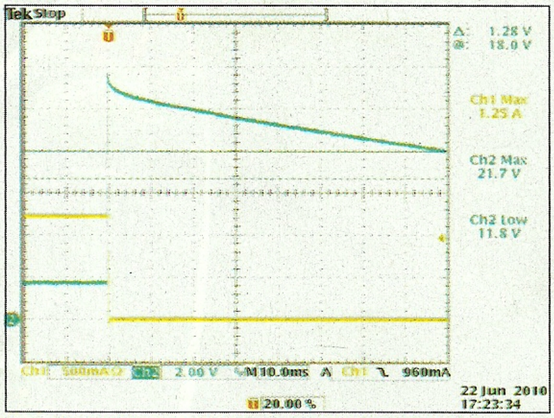

Fig 5. NCV7708 & FN30 M Locked Rotor→Z via EN Input: CB = 10 uF

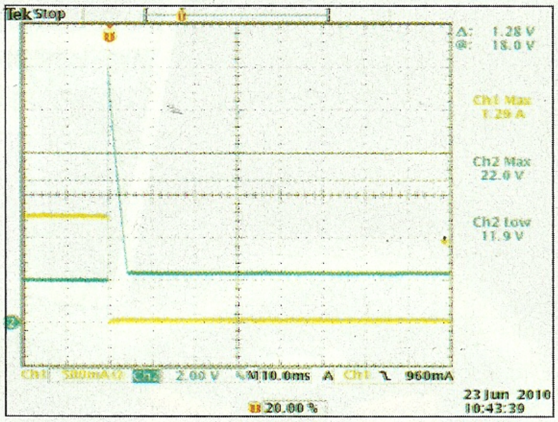

Fig. 6. NCV7708 & FN30 M Locked Rotor→Z via SPI Input: CB = 10 uF

where Vi and Vf are the initial and final capacitor voltages.

Figure 5 shows the result when an NCV7708 is driving the FN30 motor in locked rotor and the Z mode is entered by disabling the driver. The blue trace is the V_S voltage (with 10 V offset), and the yellow is the stall current. This case approximates the "no-other-loads" situation. Figure 6 shows the case where Z mode is entered by turning the active switches off with about 19 mA of "other load" current. In both cases a 10 **μF** C_B capacitor was used to illustrate the high peak voltage attained.

The test cases are for only one motor in a locked rotor or stall condition. It would be best to avoid having several motors in a stall condition, both to manage the drivers' total power dissipation and to avoid a large value of C_B. In some cases however, a global protection function such as a common enable input or power-on reset could send all drivers into Z. When choosing C_B, be sure to account for all motors that could be in locked rotor if a global protection is activated.

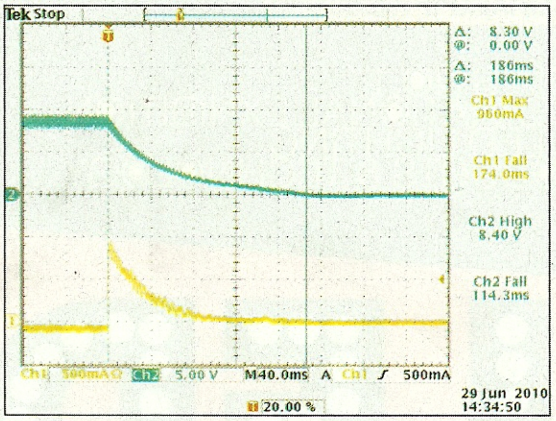

Fig. 7. NCV7708 & FN30 M Brake High

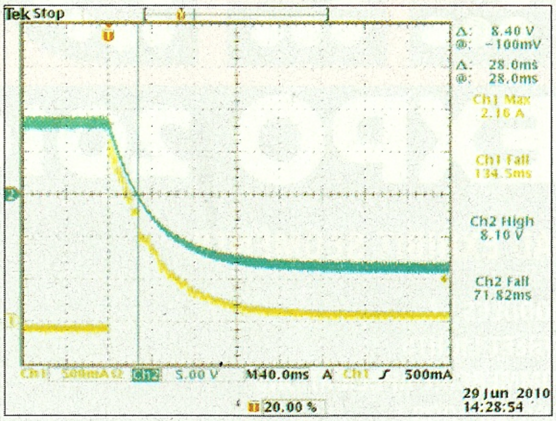

Fig. 8. NCV7708 & FN30 M Plug Brake

Finally, we'll examine the power profile of the driver for the dynamic brake high and plug brake modes. For the test set-up the shafts of two FN30 motors are directly coupled together, the second being used to provide a matched inertial load to the first, and also used as a tachometer. This effectively doubles τM, which is much greater than the electrical time constant T_E. The armature current is very quickly reversed and the deceleration is governed by T_M. In the figures below, the tachometer voltage is the blue trace and the motor current the yellow trace.

In Figure 7, the motor is running lower than its no-load speed so the peak current at brake is lower than the stall current. The motor reaches $\omega = 0$ in 186 ms, and the instantaneous power in the NCV7708 is $I_2 \times 2RDS_{(ON)} = 0.96^2 \times 1.6 = 1.47$ W. In Figure 8, the initial conditions are the same as in Figure 7, but here the motor reaches $\omega = 0$ in 28 ms and begins to turn in the opposite direction. Normally, the plug brake employs zero speed detection so that the motor doesn't reverse. The instantaneous power in the NCV7708 is $2.16^2 \times 1.6 = 7.46$ W!.