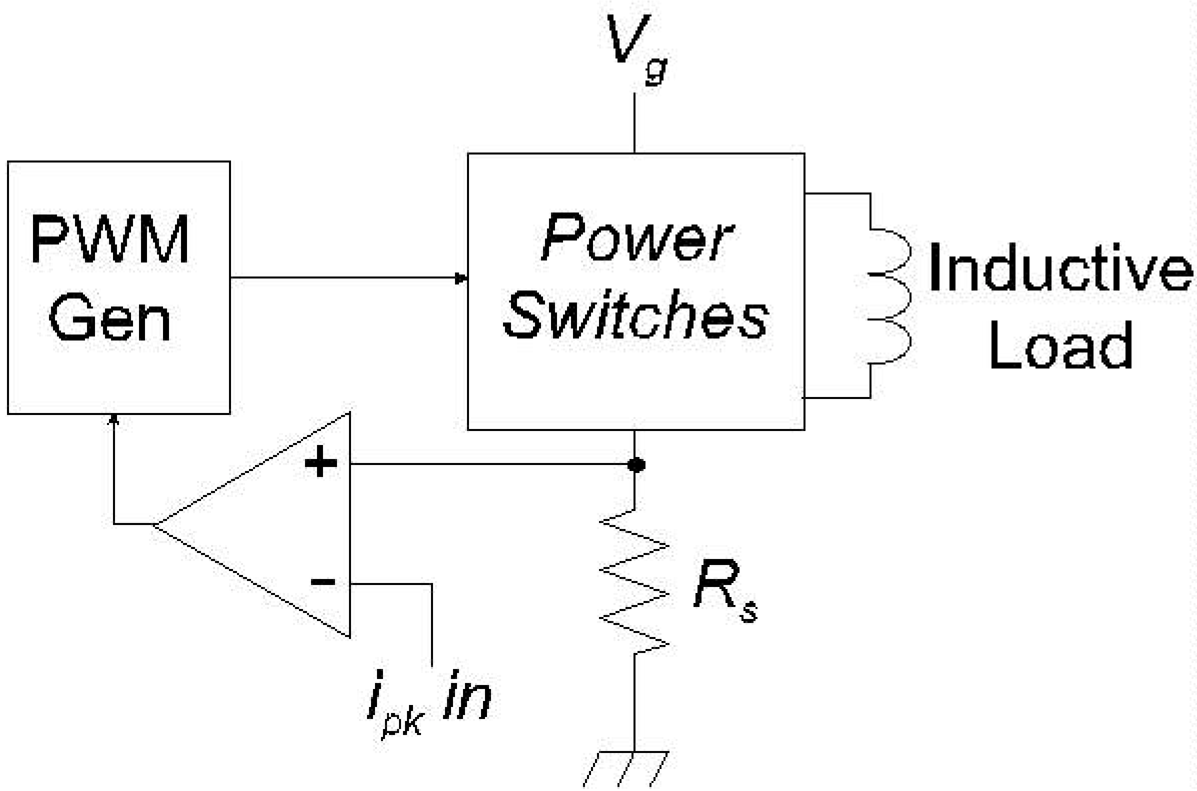
Converter Concepts Apply to Motor Drives

by Dennis L Feucht

Power electronics as a field consists of two main branches, power conversion and motor drives. Good motor-drive design obviously requires extensive use of motor control and driver concepts, and is less obviously benefited by an understanding of power converter concepts. In the literature this subject-matter is often referred to as power conversion, meaning electric-to-electric conversion. (Motor-drive systems are also power converters: electrical- mechanical converters.) This article highlights some power converter concepts that can be applied to motor-drive design.

Current Waveform Stability

Peak-current control loops are common to power converters and are often considered the best approach to converter control. The output current value from the power driver or converter stage is fed back to a comparator. When the output current waveform reaches the commanded peak current value at the end of the on-time, the comparator changes output state, turning the driver power-switch off. The current decreases through the inductive load for the rest of the switching cycle. The scheme is drawn below.



One of the considerations in both converter and motor power-driver design is current waveform stability. Not uncommonly the power driver is part of a current-controlled feedback loop. The goal is to control the motor current in order to control the torque magnitude. A design goal is to keep the average of the per-cycle current waveforms stable, so that the commanded peak current controls this average.

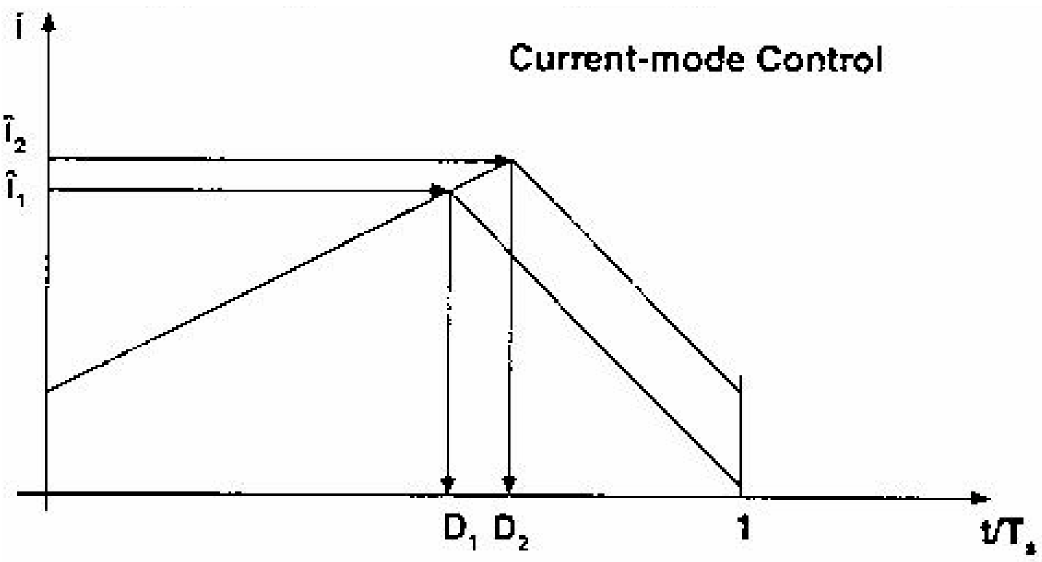
This problem occurs in switching converters, though is milder because there is no motor-induced voltage to destabilize the current waveform. The sequence of successive cycles of current waveforms is stable when the current value at beginning and end of a cycle (the beginning of the next cycle) are the same. That never occurs (without compensation) for a motor except at stall (zero speed). The uncompensated current waveform will always be unstable. A typical solution to current stability is slope compensation, which can keep the waveform stable.

Let's take a look at the basic problem from a motor-drive standpoint, presented below (excerpted from my "PMS Motor and Motor Drive Design" short-course http://www.innovatia.com), with bullet items and illustrations. The load on the switching circuit is inductive, being the motor.

T_s is the switching period of the current waveform, D is the duty-ratio, and $\hat{i}$ indicates a peak (not incremental) current. ω_{me} is the mechanical (motor shaft) speed in s^{-1} and ω_0 is the motor no-load speed. The winding-induced motor voltage is v_ω (the "speed voltage"), V_g is the motor supply voltage, L is the motor inductance, λ_{me} is the motor flux constant (torque or speed constant; $T = \lambda_{me} \cdot i_s$ and $v_\omega = \lambda_{me} \cdot \omega_{me}$), and i_s is the stator (winding) current.

H-bridge power-driver switches can be sequenced in various ways. A 2Q (2 quadrant) sequence switches either an upper or lower switch for the drive polarity (sign) and PWMs the diagonally opposing switch for magnitude control. A 4Q drive switches diagonally opposed pairs for the on- and off-times of the switching cycle, and corresponds to 2's complement (instead of sign-magnitude) control. 4Q drive actively causes the load current to decrease during the off-time, while in a 2Q drive it circulates through H-bridge switches, presenting essentially 0 V to the inductive load. The current thus remains essentially constant during off-time. Slope compensation affects the transfer function of the motor-drive.

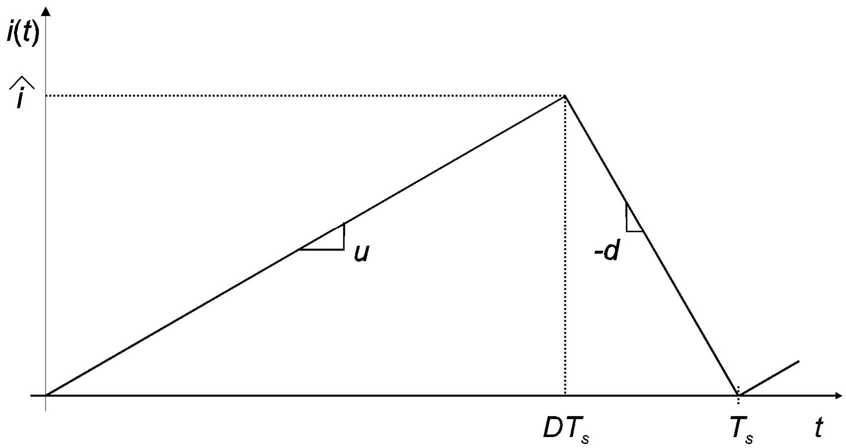
- Driver appears as a current source to motor when current (peak, average) over T_s is independent (controlled) variable.



- D is controlled by sampling peak is during T_s.

- Motor current waveform is inherently unstable in time, for fixed $f_s = 1/T_s$ PWM control

$$\hat{i} = u \cdot D = d \cdot (1 - D)$$



For stable $i(t)$, $u \geq d$
(ratio test for series convergence)
Then

$$\frac{u}{d} = \frac{1-D}{D} \Rightarrow D \leq \frac{1}{2}$$

Consider 4Q drive:

$$u = \frac{V_g - v_\omega}{L} \quad , \quad d = \frac{V_g + v_\omega}{L} \qquad \Rightarrow \qquad u \geq d \text{ when } \omega \leq 0$$

In other words motor current is only inherently current-stable at stall (no speed) or when generating, not motoring. The successive cycles of current constitute a series that mathematically can be represented by the current values at the beginning of each cycle. For a stable average current, the Δi for on- and off-times must be equal, and the beginning values of current for each cycle be the same. The condition for series convergence to a stable state can be determined by the ratio test from calculus. (Equivalently, the z-transform condition of stability can be applied instead to the difference equation for the current in z.) A common analog method of stabilizing motor current is to add an additional sawtooth waveform (usually generated by the PWM oscillator) to the sensed current waveform, thereby increasing its slope and causing the on-time to be decreased.

Slope compensation: add additional ramp to waveform during t_{on}, with slope m. Then solve for value of m for stability:

u + m ≥ d

$$m \geq \frac{2 \cdot v_\omega}{L} = \frac{2 \cdot (\lambda_{me} \cdot \omega_{me})}{L} = 2 \cdot \left(\frac{\lambda_{me}}{L}\right) \cdot \omega_{me} = 2 \cdot \hat{i}_s \cdot \omega_{me} = \bar{i}_s \cdot \omega_{me}$$

where, i_s is the stator (motor) current and λ_{me} is based on peak v_ω and peak i_s.

For 2Q drive:

$$d = \frac{v_\omega}{L}$$

$\Rightarrow u \geq d$ (stable current) when $\omega_{me} \leq \omega 0 \div 2$ and stable when $\omega_{me} > \omega_0 \div 2$ for:

$$m \geq \frac{2 \cdot v_\omega - V_g}{L} = 2 \cdot (\omega_{me} - \omega_0) \cdot \hat{i}_s = (\omega_{me} - \omega_0) \cdot \bar{i}_s$$

where, ω_0 is the motor no-load (zero-torque, maximum speed).

Current-Control Loop Modeling

When current controlled, a converter stage behaves as a current source driving the LC output filter. A current source in series with an inductor removes the effect of the inductor from the dynamic response, so that the equivalent circuit is a current source driving the output filter capacitor. This circuit has no output-LC resonance and no additional pole in the transfer function due to the inductor. This is in contrast to a voltage-driven LC filter.

As peak-current control became widespread, it began to be analyzed, notably by Ray Ridley http://www.ridleyengineering.com, who recognized that the peak-current control comparator was in the nature of a sampling device. He introduced a sample-and-hold (S/H) transfer function, H_e, into the current control loop to account for this sampling behavior, and produced the first rigorous model for peak-current control loops. The exact sampler transfer function is:

$$H_{eexact}(s) := \frac{s \cdot T_s}{e^{s \cdot T_s} - 1}$$

$$H_e(s) := \frac{s^2}{\left(\frac{\omega_s}{2}\right)^2} - \frac{\frac{\pi}{2}}{\frac{\omega_s}{2}} \cdot s + 1$$

and can be approximated by the quadratic "π/2 fit" which fits the curve to the exact value at the origin and at $f_s \div 2$.

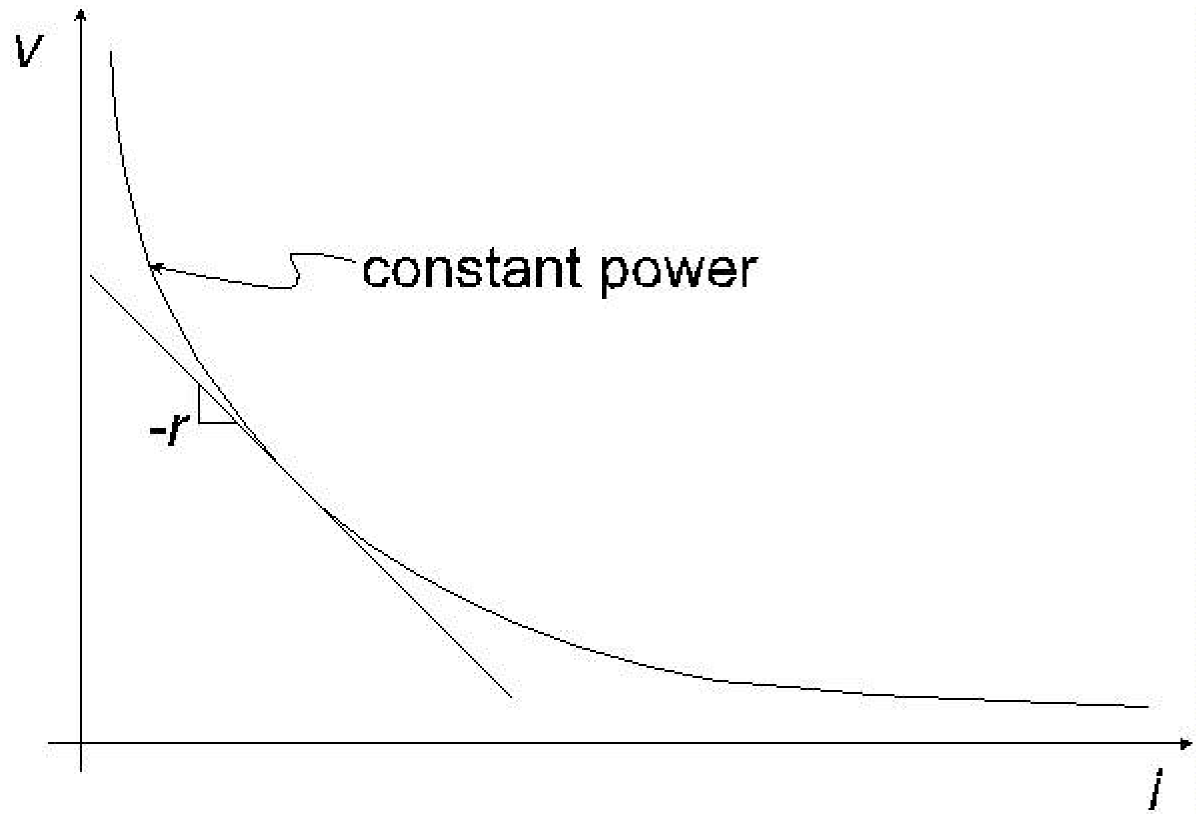
The theoretical development of S/H transfer functions is usually found in control theory textbooks under "sampled-data systems," and also in DSP and instrumentation theory. (My CD on Analog Circuit Design includes some of it http://www.innovatia.com.) What is sampled at the instant of comparator output switching is the change in off-time current, which remains constant for the rest of the cycle. This is seen by the fact that any shift in the off-time current waveform from the previous cycle remains constant during the off-time, and the extent of the shift is determined by the comparator switching time. The circuit is not anything like a typical S/H, but the behavior within the current loop is, and can be modeled by applying the S/H transfer function.

Motor-drive current-magnitude control not uncommonly uses a peak-current control scheme to control torque. For these schemes, converter peak-current-control modeling applies and can explain heretofore puzzling behavioral nuances (such as resonances) that are sometimes masked by sampled-data feedback loops.

Instability from Negative Resistance

One of the subtler problems with power converters is caused by the need to add an input filter to reduce conducted EMI on the input power line. These filters can introduce the side-effect of forming a resonance with the input impedance of the converter stage, resulting in oscillation. The LC of the filter oscillates with the negative incremental (small-signal) input resistance of the converter.

At a given output power and efficiency, a converter is a constant-power input device. When input voltage increases, constant power results in a decrease in input current. This negative input resistance can form an



oscillator circuit with an input filter when its output impedance is too high -- too far from being an ideal voltage source.

Negative resistance can similarly occur in motor drives when constant power is output from the power-driver to the motor. As for the converter the PWM waveform is varied by the control circuitry to achieve, in effect, a given output power for a non-varying load torque at a controlled speed. If the unregulated motor supply voltage increases, the motor-drive PWM duty-ratio, *D*, will be decreased to maintain the same torque-speed (and power) operating point. Drive-supply average current remains constant as average per-cycle voltage applied to the motor decreases with *D*, returning the motor to the previous operating point. The average motor current remains constant but the supply current consists of only the on-time motor current, and none during off-time for a 2Q drive. Therefore, the supply current has decreased. For power calculation the constant supply voltage times the average supply current is the average supply power. The per-cycle average supply current varies by *D*. Therefore, in a somewhat less direct way, the same negative input-resistance effect occurs for a power driver supplying constant power to a motor. If the drive supply is filtered by an LC circuit, instability similar to that of the converter can occur.

Keep in mind that the negative resistance exhibited by these circuits is incremental and dynamic, not static. A static negative resistance would be a power source! A positive voltage source applied to a –*R* would sink, not source, current from it, thereby sinking, not sourcing, power. For instance, a battery connected to a negative static resistance would charge, not discharge. By biasing a –*R* with either a voltage or current, power can be extracted from it. For more on this intriguing (and different) subject, I refer you to the work of Gabriel Kron, a major contributor to the development of motor theory at GE and discoverer of a method claimed to achieve negative static resistance. And he is not alone. There is a history of development of this kind culminating in the work at present of Tom Bearden http://www.cheniere.org and others.

Closure

The design of switched-current control in motor-drives can benefit from the basic theory and insights that have occurred in the context of converter theory development. To apply converter theory to motor power-drivers, the *s*-domain transfer functions and linearizations at operating points of *D*, which require considerable algebraic manipulation to derive, are available in *Fundamentals of Power Electronics*, by Erickson and Macksimović, Kluwer Academic Publishers http://www.wkap.nl.

The overlapping aspects of converter and motor-drive theory suggest that to be a good motor-drive designer, one needs to be conversant with converter control and circuit theory. Motor drives are essentially inverters instead of converters, but it matters not as to the relevance of converter theory. It is all switched-circuit control.