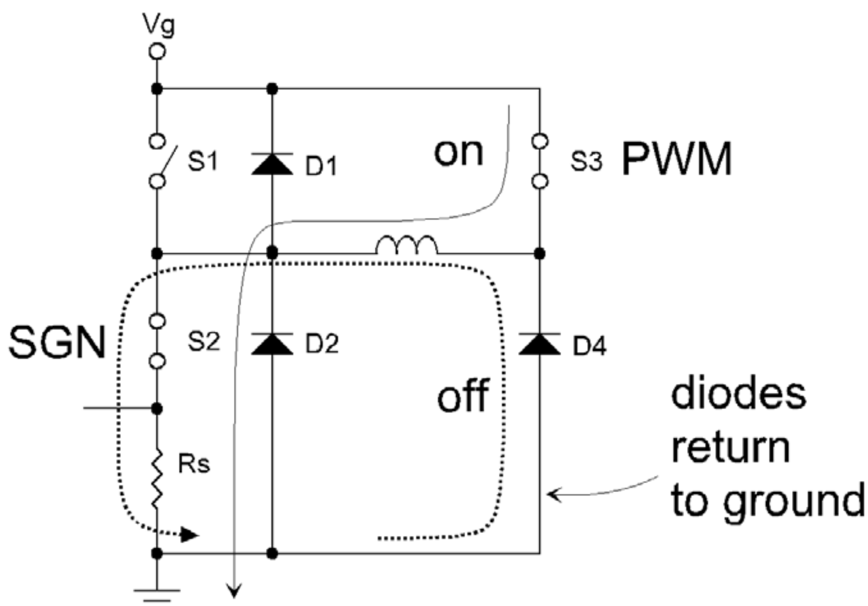
Motor Drives and Audio Amplifiers

by Dennis L Feucht

Motor drives and audio amplifiers are not usually juxtapositioned. They belong in quite different industries selling to different market sectors for quite different applications. Audiophiles and motion control buffs do not tend to congregate, appear at the same conferences, or read the same journals. Nevertheless, some underlying technologies of each are growing towards each other and on the leading edge are now overlapping. How can this be?

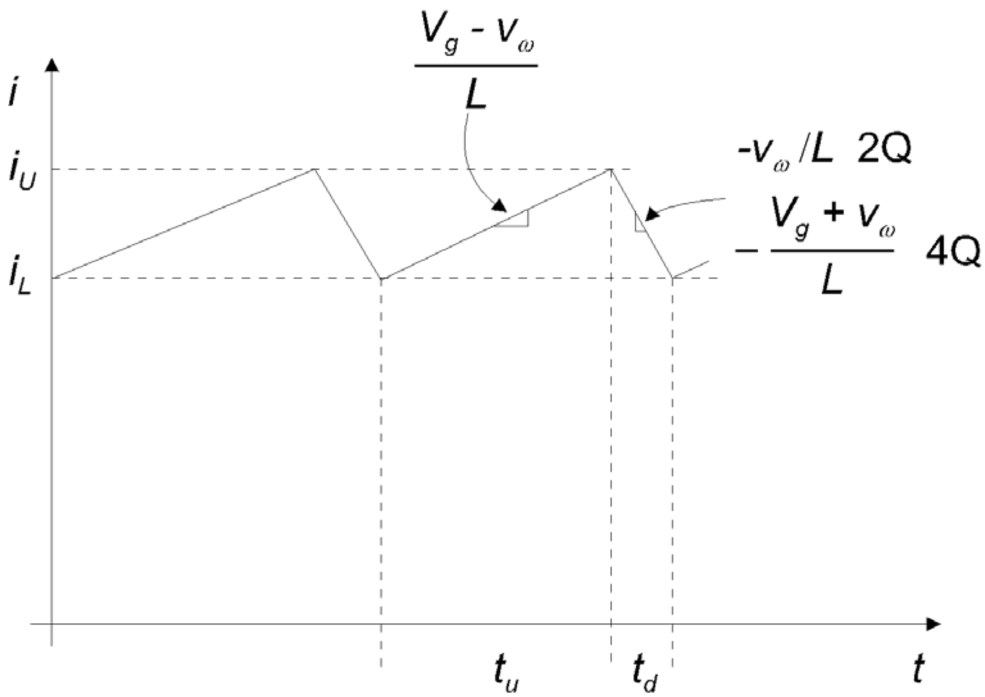
The Motor Driver

Motor drives consist of two dominant subsystems: the controller and the power driver. I call it a *power driver* because it is hardly worthy of being called an amplifier, though it does control power applied to the motor. Motor drivers have evolved from simple ground-based switches of open-loop step-motors to the familiar H-bridge drivers of today. An H-bridge, as shown below, outputs bipolar waveforms using a single power supply and four power switches, S1 - S4. The inductor of value *L*, representing a motor winding, is the load across the output, driven differentially by two half-bridges, S1 - S2 and S3 - S4.



The behavior shown here is that of a half-cycle of drive in which current is flowing from right to left through the load and is being pulse-width-modulated (PWMed) by turning S3 on and off at a switching frequency, f_s, where the fraction of on-time is the duty-ratio, *D*. The upper switch is PWMed so that when off, load current diverts to diode D4 (shunting switch 4, off and not shown), and flows through the sense resistor, R_s, during both on- and off-times for complete sensing of the load current waveform. By turning on S2 and PWMing S3, the polarity (or sign) of the output is chosen. The opposite sign is chosen by turning on S4 instead and PWMing S1.

By PWMing, limited continuous control can be achieved and the PWMed H-bridge can be considered a primitive power amplifier. The nonlinear switching behavior introduces switching noise as can be seen of the output current waveform, shown below. The dynamic (ac) component of the current is the sawtooth-shaped *current ripple* and is undesirable.



Current ripple causes loss of efficiency by increasing both winding loss from skin and proximity effects and magnetic loss in the stator laminations which are often made of low-frequency electrical steel, not high-frequency ferrites. If f_s is an audible frequency, then the motor inevitably behaves as a parasitic audio speaker. Laminations or windings vibrate, emitting annoying sound that is only useful to the motor-drive technician as a rough indicator of drive behavior.

Additionally, this ripple component causes a voltage drop across the motor winding series impedance, modeled as a series RL. It is in addition to the drop caused by the desired output, the motor drive current of a much lower frequency. This switching-frequency noise adds to the motor induced voltage, v_ω. It is an appreciable voltage because at f_s the inductive reactance of the series impedance is so much higher than the motor electrical frequency. For winding-sensed or *sensorless* control, this additional noise at low speed interferes with the sensing of the induced voltage waveform which is needed for extracting motor phase.

From Driver to Amplifier

As motor-drive technology is refined, improvement of power driver performance leads to its morphogenesis into an amplifier not unlike an audio amplifier. The performance requirements and conditions of use of both are remarkably similar. They have the same frequency range and both drive electromechanical power conversion devices with windings. Speakers are a kind of linear motor and have the same characteristic series-RL impedance in series with an induced voltage source. For both, it is a design goal to drive each with a precise waveform. For audio, amplifier imperfection results in the tangible effect of displeasing sound. For motor-drives, it results in displeasing torque or force manifested in the motion it causes.

Earlier audio power amplifiers were linear and of low efficiency. Linear amplification was necessary to achieve high *fidelity* -- that is, low distortion and noise over the audible frequency range. This *undesirability* can be quantified as total harmonic distortion plus noise (THD+N), as measured by equipment such as that produced by the world's leading audio test equipment manufacturer, Audio Precision. http://www.api.com As power electronics has advanced, switching (or *Class-D*) amplifiers have become commercially available. They are often implemented as a half-bridge followed by an LC low-pass filter, to remove switching current ripple. Audio waveforms are input to a PWM generator. The result is that over each switching period, the average voltage output by the half-bridge is a scaled replica of the input voltage, and is $D \cdot V_g$ where V_g is the supply voltage. A multi-pole low-pass filter is necessary to reduce the current ripple. This scheme is sufficient in performance for many less-demanding audio power amplifier applications.

By making the switching frequency much higher than the audio bandwidth, ripple amplitude is proportionally reduced, as is filter performance, size, and cost. If the audio source is digital, the half-bridge can be driven directly from digital processing without conversion to an analog waveform. It is also desirable to store as much audio data as possible on a CD or other medium and this pushes toward use of the lowest sampling frequency commensurate with good sound reproduction. Thus, audio oversampling is not excessive and sample interpolation could be required to increase the sampling frequency of the PWM driving the half-bridge.

Analog PWM generators are usually implemented with a ramp generator and comparator, with input waveform applied to the comparator noninverting input. The comparator output is *trailing-edge PWM* because the on-time ends when the level transitions from high to low. If inverted, it is *leading-edge PWM*. If the ramp is replaced by a triangle-wave, then the PWM is *centered PWM* and expands and contracts from the middle of the switching period with changes in *D*. Note that one edge is fixed within the time interval, T_s, while the other varies with *D*.

For all of these PWM variants, the incremental (small-signal) model of a PWM generator -- an inherently nonlinear function -- as used in a current-control feedback loop is that of a current-ripple sample and hold, as Ray Ridley http://www.ridleyengineering.com perceptively observed.

There is no need to stop the progression of refinement with these PWM generators. Δ-Σ ADCs are similar in implementation in that a single comparator is used to servo a digital output controlling what is essentially current ripple resulting from the difference between input and feedback quantities. The Δ-Σ concept has been extended to higher-order implementations with the result that it is increasingly easier to filter out the undesirable aspects (noise) of the resulting waveform. The Δ-Σ function can be used as an ADC (as is the PWM generator) with digital output pulse frequency or width proportional to the analog input.

Selective Harmonic Elimination

A fixed-frequency PWM scheme has only one free variable, *D*. One edge is constrained to occur at some fixed time within the switching period. If it were not constrained in time but only in sequence, then this opens the possibility for use of a technique called *selective harmonic elimination*, as it is called in the electric power industry, another industry seemingly far removed from audio. Power distribution waveforms, like motor-drive and audio waveforms, are also subject to the criterion of analog precision. If leading and trailing edges are precisely placed in time relative to each other, it is possible to eliminate from the resulting digital waveform, binary in value though it be, all harmonics up to some high number. This is accomplished through substantial calculation, by solving with high precision a system of equations involving Chebycheff polynomials. To do this in real time is DSP-intensive, but DSPs exist to do it. A refinement of harmonic elimination techniques consequently should be expected at the leading edge of audio, power distribution, and motor-drive technologies.

Closure

When the more basic criteria of a given area of technology are revealed, they are found to be not unlike the criteria in other areas, seemingly unrelated in their historical development and goals. For audio, motor-drives, and even power distribution, all share in the quest for analog waveform-processing perfection. The conceptual distinction between analog (continuous) and digital (discrete) lessens when the precision processing of waveforms is considered irrespective of the means by which that processing is accomplished.

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