BY DAVID TORMEY • COPLEY CONTROLS

Using PWM servo amplifiers in noise-sensitive applications

DIGITAL PWM SERVO AMPLIFIERS ARE SMALLER, MORE EFFICIENT, LESS EXPENSIVE, AND EASIER TO USE THAN THEIR LINEAR COUNTERPARTS.

A motor-drive servo amplifier's output voltage has a fundamental frequency and amplitude that corresponds to the motor speed, torque, and number of motor poles. PWM amplifiers, by their nature, also produce higher frequency voltage components that mainly correspond to the PWM rise and fall times and repetition rate. The fast edges that appear on the PWM output can capacitively couple noise currents to nearby conductors unless the system designer takes steps to reduce or eliminate coupling paths.

Designers must take care, therefore, when designing PWM amplifiers in noise-sensitive applications. Noise-sensitive applications include those that use high-resolution encoders, ultrasonic transducers, or other low-level, medium-frequency signal producers. Grounding, shielding, and other circuit-design techniques mitigate most noise problems. The most noise-sensitive applications may require additional noise-reduction methods, such as PWM edge filters. Simple design guidelines ensure effective management of capacitively coupled currents and help you to reap the full range of benefits that PWM servo amplifiers offer.

PWM APPROACH

PWM encodes analog signals within a digitally compatible, bi-level pulse train. Variations of PWM exist, but servo amplifiers most commonly use varieties with a constant carrier frequency. Typical PWM carrier frequencies for servo amplifiers are 10 to 20 kHz. Variations in the pulse width encode the analog-signal information in the PWM pulse train. For fixed-frequency PWM, designers sometimes describe the pulse width in terms of duty cycle: the ratio of the pulse width to the PWM period.

In the frequency domain, the PWM drive voltage has two primary frequency components. The first is the fundamental motor-drive component, which corresponds to the motor speed and number of motor poles. This fundamental component creates the torque-producing motor current. The second frequency component is at the PWM carrier frequency. Because this voltage does not correlate with the fundamental motor-drive frequency, any current that the PWM component of the motor-drive voltage produces does not contribute to motor operation. Any current at this frequency only creates power loss in the motor. Fortunately, the PWM frequency is typically high enough that the motor's inductive impedance is large at the PWM frequency. Because current equals the voltage divided by the impedance, the current at the PWM frequency is usually small.

The primary motivations for using PWM motor drives are size reduction and efficiency improvement. The IGBTs (insulated-gate bipolar transistors) or power MOSFETs that convert the dc input voltage to a motor-drive voltage operate most efficiently when they operate as switches. The PWM signal drives the IGBTs or MOSFETs either fully on or fully off with rapid tran-

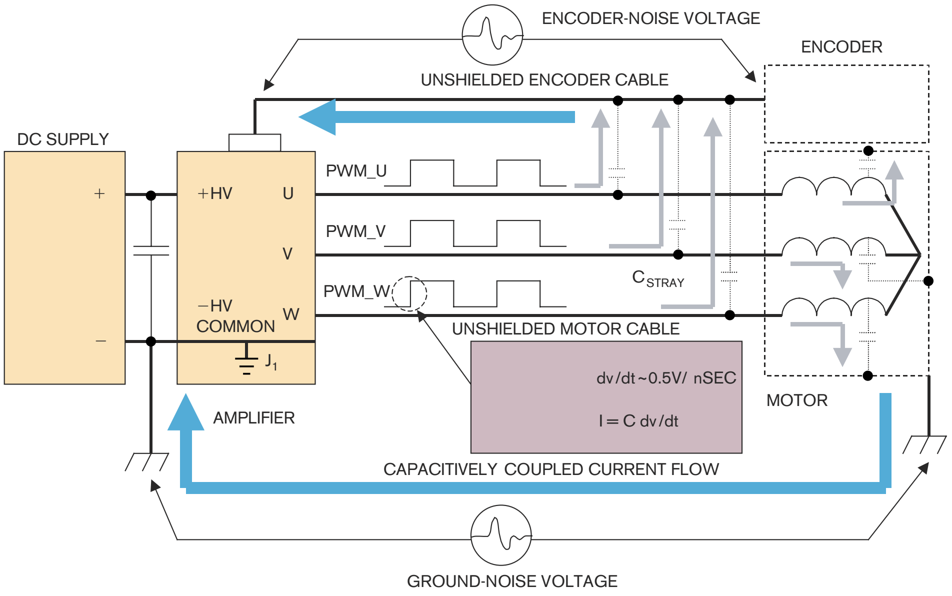

Figure 1 Drive-signal edges capacitively couple noise from unshielded cabling to other signal leads, such as those that carry shaft-encoder information.

sitions between the two states. In linear amplifiers, these devices operate in their linear region, and, as a result, the drive amplifier's power losses and overall size are larger.

CAPACITIVE COUPLING

While the transistors are switching between their on- and off-states, they pass through their linear region and dissipate energy. The faster the transistors switch, the less energy they dissipate, and the more efficient the amplifier is. If high efficiency were the amplifier design's sole requirement, the goal would be to as quickly as possible switch the transistors. There is a trade-off, however. The high dv/dt that accompanies rapid switch transitions can couple noise onto nearby circuits. In general, faster switching translates into higher noise levels. The amplifier designer must strike a compromise, then, between efficiency and noise levels.

The noise couples through the parasitic capacitance between the motor-cable conductors and the adjacent circuits (**Figure 1**). The **figure** shows a generic servo-motor application with a dc-powered PWM servo amplifier driving a brushless motor. The amplifier receives position feedback from an incremental encoder. In this example, neither the motor cable nor the encoder cable is shielded.

The amplifier PWM output-voltage waveforms on phases U, V, and W are in-phase, and their duty cycle is 50%. This in-phase and duty-cycle condition is typical when the system is holding position; the motor current and speed are near zero. The lower half of the **figure** shows a detailed view of a rising edge on the phase W output. Note

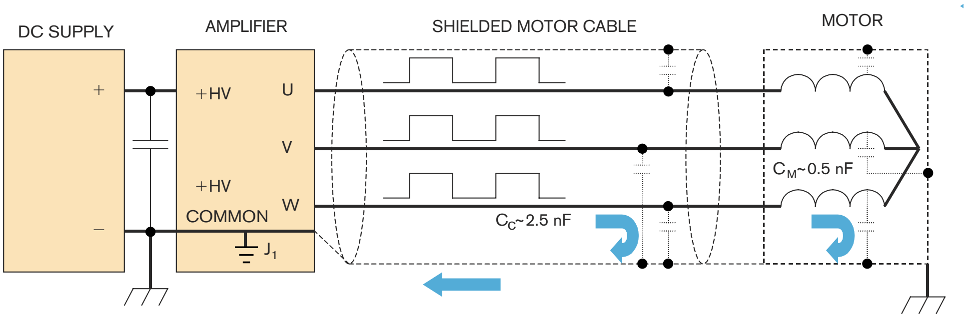

Figure 2 Shielding the drive cable safely shunts the noise currents to ground.

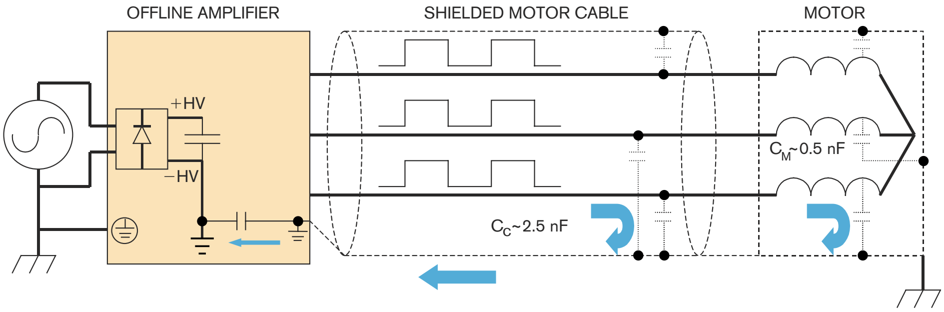

Figure 3 An offline-powered amplifier's negative supply is not directly available as a return path for noise currents. Instead, a high-voltage capacitor internal to the amplifier must shunt the negative supply rail to earth ground.

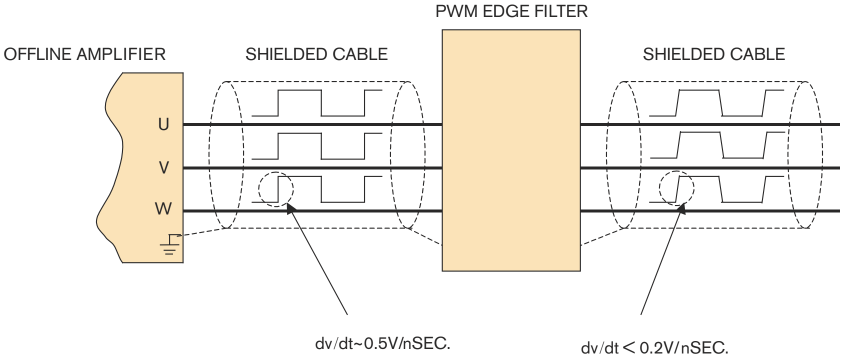

Figure 4 Edge filters reduce the drive signal's dv/dt and thereby attenuate the noise at its source. The extent to which you filter, however, is a compromise between noise reduction and overall drive efficiency.

that this edge has a finite rise time; a typical dv/dt is on the order of 0.5V/nsec. Below this rising-edge detail is a waveform showing the shape of the noise-current coupling through the parasitic capacitance to adjacent circuits as a result of the PWM rising edge.

The size of the parasitic capacitance between the motor conductors and an adjacent conductor depends on the size, shape, orientation, and proximity of the adjacent conductors. The equation I=C dv/dt calculates the amount of noise current that flows, where dv/dt is the rate of change of PWM voltage, and C is the value of the stray capacitance. Whether this noise current causes circuit-function problems depends on the exact path it follows and the sensitivity of adjacent circuits.

The noise current returns to its source, the amplifier, by the path of least impedance. For the frequencies generated by the PWM edges, this path usually means the path of least inductance. In the case of a system without any shielding in place, the path of least impedance is not well-defined. The noise currents may flow in nearby conductors, such as encoder cables and other circuits that have a common circuit ground with the amplifier. When these currents flow in encoder wires, a voltage develops between the encoder and the amplifier ends of the wire. If this voltage is large enough, the amplifier's encoder-receiver circuit falsely detects or masks a true encoder transition, resulting in a missing or an extra encoder count. Similarly, these noise currents can develop voltage drops across ground conductors and thereby introduce noise on other signal lines.

The noise currents are largest when the motion-control system is holding position. The rising and falling edges of all three waveforms coincide in this condition. The current spikes that result from the PWM edges thus all occur at the same point in time. The net peak current that capacitively couples to external circuits is then the sum of the individual currents contributed from the U, V, and W phases. On the other hand, when the motor is moving and producing torque, the PWM duty cycle of each phase changes, and the rising and falling edges no longer coincide. In this condition, the current spikes appear at a higher frequency but with lower amplitude.

THE SHIELD DOES NOT ELIMINATE BUT RATHER CONTROLS CAPACITANCE SO THAT THE COUPLING TERMINATES AT THE SHIELD AND NOT AT THE EXTERNAL CIRCUITS.

MANAGING CAPACITIVELY COUPLED CURRENTS

You can reduce problems related to capacitively coupled PWM noise by using cable shields and proper grounding techniques. There are two main objectives of grounding and shielding. The first is to force the capacitively coupled currents to flow in a well-defined path; the second is to ensure that any noise voltage developed across that path does not disturb critical signals. A motor-cable shield connected to both the motor frame and the amplifier ground establishes a controlled path through which capacitively coupled currents flow (**Figure 2**). The shield does not eliminate but rather controls capacitance so that the coupling terminates at the shield and not at the external circuits. The ideal overall shield, enclosing all three conductors, provides 100% coverage and a zero-impedance path for the high-frequency noise currents. A zero-impedance path ensures no voltage drop along the shield and that the entire shield is at the high-voltage-common potential.

TABLE 1 RECOMMENDED GROUNDING AND SHIELDING PRACTICES

Recommendation	Comments/rationale
Keep motor cables as short as possible.	Capacitance is a function of cable length whether or not a shield is used. Keeping cables short minimizes capacitively coupled currents.
Use a motor cable with a high-quality shield.	The best shield provides complete coverage of the enclosed conductors and is also a good, high-frequency conductor. A combination braid-and-foil shield is best but not necessary for all applications.
At the motor end of the cable, make a low-impedance connection between the shield and the motor frame.	If the motor has a metal shell connector, then you can tie the shield directly to the metal shell of the mating connector. Otherwise, the connection between the cable shield and the motor frame should be as short as possible.
At the amplifier end of the cable, make a low-impedance connection between the shield and the amplifier's common potential for nonisolated, dc-powered amplifiers only. For offline-powered amplifiers, connect the shield to the chassis ground.	The connection should be as short as and have the lowest inductance possible. In the case of pc-board-mounted amplifiers, the pc-board trace from the shield to the amplifier's common should be short and wide. Also, the connection should be directly to the positive-high-voltage common at the amplifier power connector.
Avoid running sensitive signal cables, such as encoders, small signal transducers, and others, in the same cable bundle with the motor cable.	Capacitive coupling is a function of proximity. Separating sensitive signals from the motor cable reduces capacitive coupling to the sensitive signals.
Use shielded cable for the sensitive signals. Connect this shield to the high-voltage common only at the amplifier end for nonisolated, dc-powered amplifiers only. For offline-powered amplifiers, connect the shield to the chassis ground.	The overall shield on the motor cable should prevent coupling to sensitive signals. An overall shield on cables with sensitive signals provides a second line of defense.
Add capacitance across the high-voltage dc bus to keep switching currents local to the amplifier.	The PWM switching also draws transient currents from the dc supply. For some amplifier models, additional capacitance connected to and close to the amplifier's positive-high-voltage and positive-high-voltage common terminals is recommended. Refer to the amplifier data sheet for details.
Refer to the amplifier data sheets for model-specific considerations regarding wiring best practices.	Each PWM amplifier model has noise-related characteristics depending on the amplifier topology and basic construction–pc-board-mount amplifiers versus panel-mount types, and offline versus dc-powered, for example.

The shield connection to the motor frame terminates the capacitive coupling between the motor windings and motor frame. In this way, the motor frame provides an overall shield for the motor windings. The cable shield provides a path for these currents to return to the amplifier's common, as well.

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Typical values for shielded-cable capacitance and motor-winding-to-frame capacitance are on the order of 250 pF/ft and 0.5 nF, respectively. The cable capacitance is a measured value for four #16 AWG conductors with a foil shield. If you use a PWM rising-edge rate of 0.5V/nsec, the peak current flow in the overall shield is $I=Cdv/dt=(2.5\text{ nF}+0.5\text{ nF})0.5\text{V/nsec}=1.5\text{A}$ peak. On the PWM falling edge, the same calculation holds, except the polarity of the current is reversed. So, when the motor is just holding position, you could expect a peak current of 3A p-p flowing in the cable shield. **Table 1** presents recommendations for grounding and shielding practices.

EDGE FILTERS

An offline-powered amplifier takes ac power from the mains and uses an internal rectifier to supply a dc bus (**Figure 3**). The negative side of the dc bus is not available for connection to the motor-cable shield, as is the case with nonisolated dc-powered amplifiers. In this topology, the bus is typically 100V or more below earth-ground potential, and connecting the cable shield to this potential would constitute a safety hazard.

Nonisolated, dc-powered amplifiers operate from line-isolated dc-power supplies; the negative rail of these supplies commonly connects directly to earth ground. In such arrangements, connecting the cable shield to the common bus is safe, practical, and effective.

In the case of the offline-powered amplifier, the shield connects to the amplifier chassis ground. A high-voltage, safety-rated capacitor internal to the amplifier bypasses the bus to chassis ground. This connection provides a path for the noise currents flowing in the shield to return to their source—the bus.

Offline-powered amplifiers usually operate from higher voltages than dc-powered amplifiers, and, as a result, the dv/dt of their PWM outputs tends to be higher than that of dc-powered amplifiers. Furthermore, because the cable-shield currents flow through the internal capacitor before returning to the bus of the amplifier, cable shielding tends to be less effective than in the dc-powered arrangement. These facts make PWM noise issues more difficult to address in systems using offline-powered amplifiers.

For noise-sensitive applications that use offline-powered amplifiers, you can use another noise-abatement tool: the PWM edge filter. PWM edge filters use passive components to reduce the dv/dt of the amplifier PWM edges (**Figure 4**).

The PWM edge filter connects in series between the amplifier and the motor and increases the rise and fall times of the PWM edges. The edge filter reduces the peak amplitude of all capacitively coupled currents. Again, there is a trade-off in edge-filter design between overall efficiency and filter effectiveness. Filter designs that reduce the rise and fall times by an order of magnitude or more are too large and dissipate too much power. Edge filters that provide a more modest reduction in rise and fall times are effective in real-world applications. The example in the **figure** depicts the effect of a practical edge filter in which the dv/dt decreases from 0.5 to less than 0.2V/nsec. The noise current decreases by the same factor: $I=Cdv/dt=(2.5\text{ nF}+0.5\text{ nF})\times 0.2\text{V/nsec}=0.6\text{A}$.

To maximize the edge filter's effectiveness, locate it as close to the amplifier as possible. Shield the section of cable connecting the edge filter to the amplifier and make it as short as possible. Maintain the shield on the section of cable between the edge filter and the motor and ensure continuity between the shields of each cable section. EDN

AUTHOR'S BIOGRAPHY

David P Tormey is senior design engineer at Copley Controls Corp (Canton, MA), where he designs PWM amplifiers and accessory products. He received bachelor's and master's degrees in electrical engineering from Worcester Polytechnic Institute (Worcester, MA). In his spare time, he enjoys running and travel.