Keeping Drives Electrically Quiet: Ferrites, Shielding and Grounding

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Motion control systems often combine high power drive signals in close proximity (or even within the same cable) with lower level signals, like encoders. You will often see ferrite beads added around cables; their effectiveness in minimizing noise is greatly affected by how they are deployed. This involves which signals are grouped, what are the drive characteristics, and how shielding and grounding are handled in the system.

Real life magnetic cores are not typically covered in many engineering courses. The idealized magnetic core has a significant complexity involved. Permeability, saturation, coupling, losses, etc. are all significant complexities. Trying to look at these devices over broad ranges of frequencies with exact equations and models turns into a significant exercise. We will start with the basic equations for idealized parts, followed by talk about the departures, and finally rule-of-thumb heuristics.

A ferrite core is commonly placed over a cable in an attempt to reduce noise — both radiated and as it interacts internally to the system, and to reduce the received noise. The ferrite forms a common mode coupled inductor / transformer for each of the signals passing through it. The range of frequencies of the coupling is dependent upon the type of material used in the bead, how many turns are wound, and how the turns are physically wound. The inductance also depends on the physical geometry of the ferrite material.

First, we will begin with the basic textbook equations for the inductance of a wire passing through a core; the inductance can be calculated as:

$$L = \mu N^2 A / 2\pi r$$

Where

μ = permability of the core
N = number of turns
A = cross-sectional area of core
$2\pi r$ = mean path length arond the core

To change this to word problem format: the inductance goes up with the square of the number of turns, with the permeability of the core and with the cross-section of the core. Inductance goes down with the mean path length (average circumference of the path around the wires).

Using the same material, a thick bead (large area) with a small internal hole (smaller radius *r*) has a significantly higher inductance than a thin ring (small area) with a large hole (large *r*). A few turns can significantly increase the impedance if they can fit through the core. Winding is important to prevent capacitive coupling between the turns from “bypassing” the bead impedance. In general, use the bead with the smallest hole available that will fit the cable.

Reality adjustment: Many of the ferrite beads commonly used for filtering have large resistive losses and are not simple inductors. However, this is often a good thing as lossy ferrites convert the electrical noise issues into heat; as long as the heating is not excessive, this keeps the noise from just being conducted or radiated elsewhere. An even worse effect is when the noise is resonated, which can significantly increase the effects of the noise. (Note that resonance is used intentionally when trying to radiate RF energy in a radio transmitter!)

There are many different ferrite “recipes” or blends available, targeted for many diverse purposes. The blends used for a high-efficiency switching power supply often would not be the best for use in filtering power cables, for example. According to the frequency of the switcher, the materials and often their processing will also commonly vary. Higher permeability materials allow for significant impedances at lower frequencies but are also more easily saturated in that their permeability drops rapidly as the net current through the aperture of the bead increases.

A simple fix that allows the use of these higher permeability cores while avoiding the saturation is to form common mode inductors where the currents are fairly balanced so that the ***sum*** of the currents through the wires is fairly low. As only the net current through the core gives rise to the magnetic field in the core, the field is reduced considerably reducing chances of saturation. The coupled inductor that results from passing sets of signals through a ferrite bead can be used in multiple ways to reduce noise issues.

The first example using the bead as a BALUN (Fig. 1) – a contraction of **BAL**anced-**UN**balanced. A Balun configuration can be used to convert balanced signal lines into an unbalanced line or visa versa. The driver to the motor is unbalanced as one half bridge driving the motor switches while the other does not (generally) simultaneously switch in the opposite direction. This is contrasted to an RS-485 which is balanced: the transitions in the two signals are (approximately) equal and opposite.

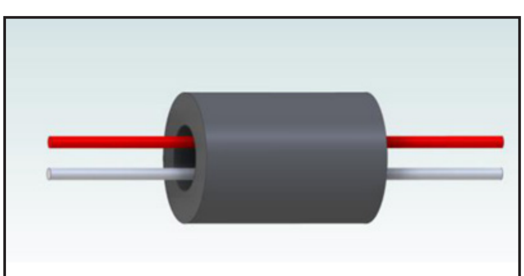

Figure 1 Using a Ferrite bead as a BALUN to match an unbalanced drive circuit to balanced wiring.

We will draw this configuration for a 2-wire system, but the same concept also applies to a 3-phase system. The schematic (Fig. 2) is simplified and depicts the phase that is not switching as being grounded, while the phase that is switching at this time is shown as a pair of transistors. Not shown is the capacitance between the wires, nor from the wires to the surrounding environment, nor the load of the motor windings.

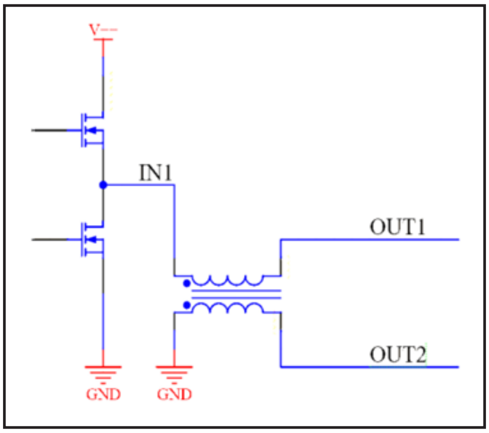

Figure 2 Simplified schematic of a bridge driver showing only the elements about to change state feeding wiring through a balun.

When the signal at IN1 takes a positive step (switching the upper transistor on), a current flows into OUT1 wire to charge the capacitances associated with IN1 wiring. This current causes a positive to negative voltage drop from IN1 to OUT1 due to the rapid change in current interacting with the inductance of the ferrite bead. (That is, the inductance of the bead opposes the rapid change in current through it.) This voltage drop reduces the size of the step at OUT1, as compared to the step size at IN1. This same negative voltage step (from the transformer function of the bead) appears OUT2. If the step is sufficiently fast compared to the bead inductance, the output will be (instantaneously) nearly balanced: OUT1 will step to half of V++, while OUT2 will go to minus one-half of V++. The voltage between the two conductors at the output will still be essentially the same as the voltage between the two conductors at the input.

While the average voltage of the two wires at the input jumped to one-half the supply voltage V++, the average of the wires at the output remained close to zero volts (for the high-frequency components of the waveform immediately following switching). This balancing of the signals by the ferrite bead greatly reduces the coupling to nearby signals, as the high frequency components of the signals from OUT2 nearly cancel those from OUT1. A similar balancing of the currents is also present for high frequencies, reducing the net high frequency components of the H-field (magnetic field) from the pair of wires.

The use of a ferrite is commonly paired with using twisted pairs (or triples for 3 phase). If the signals are fairly well balanced, the average voltage (at high frequencies) will be fairly low. The twists in the wire will alternate which wire – OUT1 or OUT2 is closer to the test wire (victim signal), significantly reducing the noise coupled to it. The magnetic field emissions are reduced by a similar method: the magnetic field is produced from the small loops from each half of the twist will tend to cancel out the magnetic field from the adjacent loop formed by half of the twist, as the sense of the turn is reversed. Again, this cancellation is improved by having the signals balanced, at least for frequencies of interest.

But how about the shield? A shield is often added (Fig. 3) around the driven wires between the driver and the motor to reduce the electric field from the drive wires from radiating. The question always arises as to where and how to ground the power cable shield.

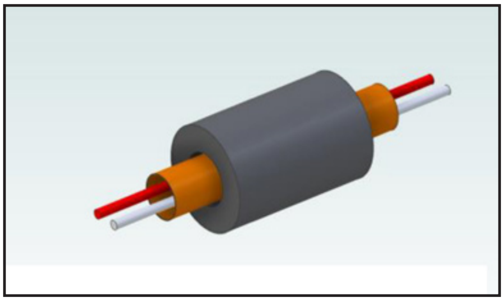

Figure 3 A BALUN for shielded wiring pair (often shielded twisted pair).

We have found that grounding the shield — either directly or through a significant capacitance — at the drive, and also grounding the driver signals shield at the motor significantly reduces the radiated noise from the drive. Note that while the power supply return is often not directly connected to the chassis ground, generally EMI filters are present which add a capacitance from the DC rails to the chassis. This is not shown for simplification, but these return paths for high-frequency signals from the chassis to the power supply rails are still normally present.

The first thought is that this configuration is forming a ground loop through the chassis as the driver and motor are both connected to the chassis, and thus it should be avoided! For feedback signals that do not inject (significant) current into the chassis, this is certainly the case — ground one end of the shield (generally at the controller end of the cable). For the motor, the extra capacitance between the motor windings and the stator changes the situation. A ferrite bead over the whole cable can greatly reduce the currents coupled from the windings to the stator and to the system chassis ground.

Let's first look at what would happen if the shield connection to the motor were not present (Fig. 4). A positive step at IN1 will cause OUT 1 to go positive and OUT2 to go negative, but the extra capacitance of the shield will give an additional current path through the ferrite bead and it will not work as nicely balanced as the previous balun example. The motor windings have a capacitance to the stator of the motor, which is commonly tied to the local chassis. The step in the average voltage to the winding will induce a current through this capacitance into chassis ground when the driver takes a step. The only return path for this current is through the chassis, and so there will be a loop through the cable to the motor, and back through the chassis. The noise will be radiated by the loop formed by the cable and the chassis ground return path.

Now let's see what happens if the chassis *is* connected at both the driver and to the motor. The ferrite will "attempt" to minimize the net change in current through the bead. In this example, a 100 ohm bead is used, i.e. approximately 100 ohms at 10 MHz. The current from the step on IN1 will cause a small negative voltage on the output side of the shield conductor, such that most of the current capacitively coupled from the windings to the motor stator will be drawn back through the shield.

To greatly simplify: current that passes in one direction through the beads has to pay the 100-ohm toll (bead impedance) to flow, while that current which returns back though the bead does not pay the 100-ohm toll, as the magnetic fields produced by the two (ore more) wires will cancel. This makes the return path through the shield going through the ferrite bead the much preferred path.

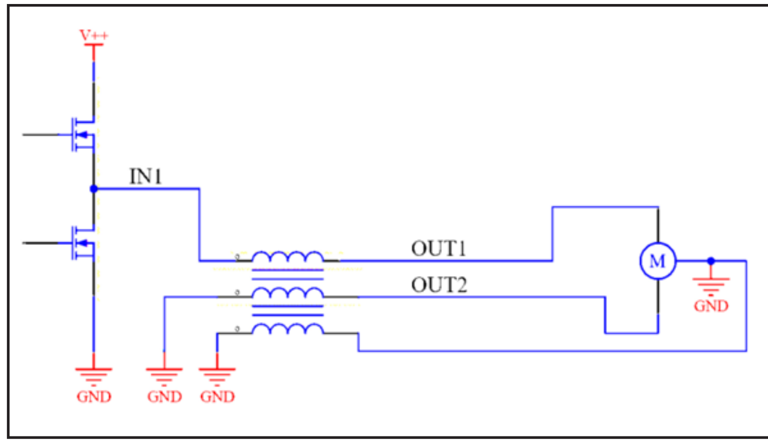

Figure 4 **Simplified schematic of a bridge driver showing only the elements about to change state feeding shielded wiring through a balun.**

Actual testing in a system with a hybrid motor showed the current to the chassis without the shield connection was on the order of 1A, with a fast switching driver. The current through the chassis dropped to approximately 20 mA with the shield grounded and a ferrite bead over the whole cable — or about a 35dB improvement! Almost 98% of the current returned via the preferred path. This is reduction is most effective at higher frequencies, which are also the most likely to radiate.

Looking at the bead as providing a 100-ohm impedance to the net current, the current that passes out through the bead to the motor and to the chassis which then bypasses the bead sees 100 ohms; while the current that returns through the shield and back through the bead cancels the field from the outgoing current, and thus returns with no "impedance toll" needing to be paid.

Simply grounding the shield at both sides without the presence of the ferrite bead would provide a path for some of the current coupled from the coils to the stator to return back to the driver. This is a preferred return, as the area of the resulting loop (driver ground, to driver, to wire to motor coil, to stator, to shield, to driver ground) is very small as the shield surrounds the driven wires. However, the current divides according to the impedance of both paths, and the chassis commonly has a lower impedance.

Another way of looking at this is the reverse drop across the bead produces a voltage at the output side of the shield such that the shield is "pulling" the current injected by the switching phase charging the winding capacitance back through the shield (as well as the rest of the driver lines) back to the driver chassis. The impedance "toll bridge" of the ferrite bead only applies to one-way currents — not to balanced currents.

As to circulating currents from the ground loop, these see the bead impedance and thus are significantly attenuated so that the bead breaks the loop at high frequencies. The optional series capacitor will break the loop at DC and low frequencies, if that is an issue in your system.

So — balun or shield with bead?

My experience is that if you must choose one, the shield and the bead does more than the balun alone to reduce noise; however, you are free to choose both. A small through board U and I core close to the drivers but capturing all of the driver lines can make a small but effective balun, while still using a shielded cable with a bead to the motor.

What beads should I use? I have primarily used type 31 suppression ferrite, as well as type 43 suppression ferrite materials from Fair-rite, but there are many ferrite sources. Lossy ferrites are useful in that they convert the noise into heat rather than just reflecting the energy or resonating it. A small amount of heat is vastly preferable to radio emissions or coupling-switching noise into other nearby circuits.

QuickSilver Controls uses multiple techniques to reduce noise, allowing use of our products in RF-sensitive environments as well as in high-RF environments such as RF susceptibility test chambers. These techniques also allow QCI to use single cables for both motor signals and encoder signals, tested to 200 feet (61 meters) — although we normally suggest shorter runs. **For more information**. Questions or comments regarding this article? Contact Don Labriola at *don_labriola@quicksilvercontrols.com*. **PTE**

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