Understand and reduce dc/dc-switching converter ground noise

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Dc/dc-switching power converters are notorious for physically disrupting otherwise carefully designed systems and circuit schematics. These converters drive unwanted charge onto electrical ground, causing false digital signals, flip-flop double clocking, electromagnetic interference, analog-voltage errors, and potentially harmful high voltages. As the complexity of these designs increases and applications become more densely populated, the physical-circuit implementation begins to play a critical role in the electrical integrity of the system. To address these issues, you need to learn how to reduce two major sources of ground noise.

Ground Noise: Problem number 1

Figure 1 shows an ideal buck converter with a constant load current. Switches $S_1$ and $S_2$ toggle back and forth, chopping the input voltage across the buck inductance and the buck capacitance. Neither inductor current nor capacitor voltage can change instantaneously, and the load current is constant. All switching voltages and currents should successfully span buck inductance or pass through the buck capacitance, respectively, because an ideal buck converter produces no ground noise. But experienced designers know that a buck converter is a notorious noise source. This fact means that the circuit in Figure 1 is missing some important physical elements.

Whenever charge moves, a magnetic field develops. Current in a wire, a resistor, a transistor, a superconductor, or a capacitor’s plate-to-plate displacement creates a magnetic field. Magnetic flux is a magnetic field passing through a current-loop area and equals the product of the field cutting the loop surface at a right angle: $\varphi_b = B \times A$, where $\varphi_b$ is the magnetic flux, $B$ is the magnetic field, and $A$ is the current-loop area. The magnetic field at a distance encircling a wire is directly proportional to the wire’s electrical current, $B = \mu_0 I / 2 \pi r$, where $r$ is the magnetic field at a distance.
Electrical components have length, and charge must flow from one device to the next in the various wire segments. Moving charge creates a magnetic field, however, so you can improve the circuit in Figure 1. Figure 2 shows a better model of a simple buck converter. In Figure 2, the wire remains ideal in every way, except that current must flow some distance in each segment while traveling from one electrical component to the next. As this charge flows, magnetic field wraps around the energized wires and is magnetic flux passing through the $S_1$ and $S_2$ switch loops.

Changing $S_1$ and $S_2$ current-loop areas is the first major source of switching-converter ground noise. Magnetic flux in the input-voltage-to-$S_1$-to-ground loop grows and collapses on every switch cycle. That changing flux induces voltage everywhere in that loop, including the ideal ground-return line. No amount of copper, not even a superconductor, can eliminate this induced voltage. Only a reduction in the changing magnetic flux will help.

Changing magnetic flux has three factors: rate of change, magnetic-field strength, and loop area. Because the clock frequency and the maximum output current may be design requirements, minimizing loop area becomes the best approach. Inductance is proportional to magnetic flux.

Figure 3 shows an electrical model for Figure 2 in which changing current in parasitic inductor $L_{P1}$ causes ground noise, whereas constant current in parasitic $L_{P2}$ does not. Although Figure 3 presents the problem in a familiar way, it makes a poor substitute for the physically enhanced model in Figure 2. Figure 3 shows parasitically induced voltage across $L_{P1}$ and $L_{P2}$, whereas the arrangement induces voltage everywhere in a loop enclosing changing magnetic flux. This circuit element, however, still serves the purpose of showing how to reduce induced ground noise.
In Figure 3, ground-return current flows and changes in \( L_{p1} \), and it causes a voltage-bounce problem. A carefully placed input capacitor reduces the parasitic magnetic-flux area and routes changing buck current in a path that does not include ground return (Figure 4). In this case, current in parasitic inductors \( L_{p1} \) and \( L_{p2} \) is constant, so the ground voltage is stable. The reduction in this magnetic-flux area also proportionally reduces EMI and all other unwanted, induced loop voltages.

The first important source of switching-converter ground noise is a result of changing magnetic-flux area. Good PCB design uses both trace routing and careful bypass-capacitor placement to minimize changing current-loop areas and changing current in a ground-return path.

**Ground Noise: Problem Number 2**

The second major ground-noise problem results from parasitic inductor capacitance (Figure 5). Voltage cannot instantaneously change across a capacitor, and current cannot instantaneously change through an inductor. So, voltage changes on the LX node couple directly across both the parasitic buck-inductor capacitance, \( C_L \), and the buckfilter capacitor, \( C_{BUCK} \), to appear across parasitic ground inductors \( L_{p1} \) and \( L_{p2} \).
No charge initially flows, but, in the next moment, current builds in all of these components until the energy in the parasitic buck-inductor capacitor, \( E_{CL} = \frac{1}{2} C_L V_L^2 \), transfers to the wiring's parasitic magnetic field, \( E_{LP} = \frac{1}{2} L_P I_{CHANGINGMAX}^2 \), where \( L_P \) is the sum of all parasitic loop inductors. That unwanted energy then passes back and forth from the electric to the magnetic field until it radiates or dissipates in resistive elements.

Both the peak voltage and the duration of a groundnoise oscillation are problems. The peak voltage, measured at node \( V_{GB} \), is a function of the \( V_L \) node's voltage change, the parasitic buck-inductor capacitance, and additional parasitic trace capacitance. A large parasitic buck-inductor capacitance stores more energy, so using a smaller one is a better approach. After selecting the buck inductor's inductance and current rating, choose an inductor with the highest self-resonating frequency to limit the capacity of \( C_L \). An inductor's self-resonating frequency is expressed as \( \frac{1}{2\pi\sqrt{L_C C_L}} \). Doubling the self-resonating frequency reduces the parasitic inductor capacitance and, therefore, the groundnoise energy, by a factor of four.

When performance takes priority over cost, maintain the same value of inductance by replacing the single buck inductor in Figure 5 with two series-connected inductors, each having half the value of the buck inductor (Figure 6). For a manufacturer's series of inductors, the parasitic capacitance is typically proportional to the rated inductance, so one-half the inductance results in one-half the parasitic capacitance. With series-connected inductors, their values add to increase inductance, but parasitic capacitors add as the inverse sum of inverse values to decrease total parasitic capacitance. In two series-connected one-half-buck-inductance inductors, total inductance will be \( L_{BUCKNEW} \) and total parasitic capacitance will drop by a factor of four to one-quarter of buck-inductor capacitance. This reduction in parasitic inductance in turn reduces ground bounce.
By exploring the models and understanding the two sources and mechanisms of ground noise that the ubiquitous dc/dc-switching converter induces, engineers can minimize the effects in the early stages of design, component selection, and layout and can reduce the number of subsequent production headaches and re-spins.

Acknowledgment
This article originally appeared on EDN’s sister site, Power Management Designline.

Author’s biography
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