Fixing EMI Across the Board

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An ounce (okay 2 ounces!) of prevention are always better than cure. So here we look at some of the practical design aspects involved in controlling and testing EMI.

**The Role of the Transformer in Radiated Emissions (EMI)**

Very often an engineer resolves a stubborn EMI problem by just 'playing' with the transformer. The transformer comes into the picture in the following ways

- With its windings carrying high-frequency current, the transformer becomes an effective H-field antenna. These fields can impinge upon nearby traces and cables, and enlist their help in getting transported out of the enclosure via conduction or radiation.
- As parts of the windings have a swinging voltage across them, they can also become effective E-field antennas.
- The parasitic capacitance between the Primary and Secondary carries noise across the isolation boundary. Since the Secondary side ground is usually connected to the chassis, this noise returns via the Earth plane, in the form of CM noise. So we want to couple the Primary and Secondary very close to each other in order to reduce leakage inductance, but this also increases their mutual capacitance, and thus the CM noise.

Here are some standard techniques that help prevent the above (see Figure 1)

- In a safety-approved transformer, there are three layers of safety-approved polyester ('Mylar®') tape between the Primary and Secondary windings, for example the popular #1298 from the 3M Company. In addition to these layers, a copper 'Faraday shield' may be inserted to 'collect' the noise currents arriving at the isolation boundary, and diverting them (usually to the Primary ground). Note that this shield should be a very thin piece of copper to avoid eddy current losses and also to keep leakage inductance down. It is typically 2-4 mils thick, consisting of one turn wound around the center limb. A wire is soldered close to its approximate geometric center and goes to the Primary ground. Note that the ends of the copper shield should not be galvanically connected, as that would constitute a shorted turn as far as the transformer is concerned. Some designs also use an additional Faraday shield on the Secondary side (after the 3 layers of insulation), and that is connected to the Secondary ground. However, most commercial ITE power supply designs don't need these shields, provided adequate thought has gone into the winding and construction, as we will discuss.
- There is usually also a circumferential copper shield (or 'flux band') around the entire transformer. It serves primarily as a radiation shield. It is often left floating in low cost designs, though it may be connected to the Secondary ground if desired. If so connected, safety issues may need to be considered in regards to the requirement of reinforced insulation between Primary and Secondary, and also the required Primary to Secondary 'creepages' (distance along the insulating surface) and 'clearances' (shortest distance through air) as applicable. When the transformer uses an air gap on its outer limbs, the fringing flux emanating from the gap causes severe eddy current losses in the band. So this band is also usually only 2-4 mil thick. Note that the ends of this band can, and should be, soldered together, because this is an outer shield, and can never constitute a shorted turn for the transformer. But like the Faraday shield, this too can be omitted by good winding techniques.
- From the point of view of EMI, a flyback transformer should be preferably center-gapped. i.e. no gap on its outer limbs. The fringing fields from exposed air gaps become strong sources of radiated EMI besides causing significant eddy current losses in the flux band.

- There is usually an auxiliary winding present on the Primary side which provides a low voltage rail for the controller and related circuitry. One end of it is connected to Primary ground. Therefore, it can actually double over as a crude Faraday shield if we a) wind it spread out over the available bobbin width, and b) we help it collect and divert more noise by AC coupling its opposite end (i.e. the diode end) to Primary ground, through a small 22pF-100pF ceramic capacitor as shown in Figure 1. We don't need to draw any current from this 'Faraday winding'. So it need not even be used by the circuitry. We could just wrap a few spaced-out turns of thin wire, with one end connected to Primary ground, and the other end with the small 22pF cap to ground
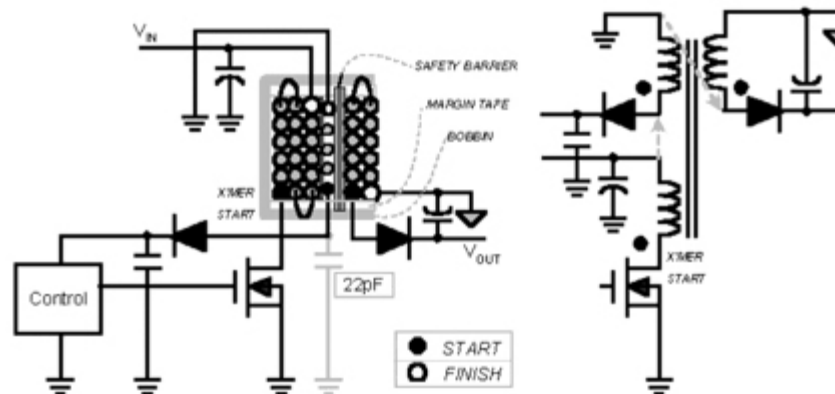
Figure 1: Flyback Transformer of Low Noise Construction

- Since the Drain of the Fet is swinging, it is a good idea to keep this end of the Primary winding buried as deep as possible, i.e. it should be the first layer to be wound. The outer layers then tend to shield the field emanating from this. The Drain end of this winding should definitely not be adjacent to the 'safety barrier' (the three layers of tape). Noise current injected is proportional to the net dV/dt across the two 'plates' of the parasitic capacitor. Since we really cannot reduce the capacitance much, without adversely impacting the leakage inductance, we should at least try to reduce the net dV/dt across this capacitor.
- Comparing the diagram on the left of Figure 1 with its schematic on the right, we see that the start and finish ends of any winding have been indicated. In particular, the start ends have been shown with dots in the schematic. In a typical production sequence, the coil winding machine always spins the bobbin in the same direction for every winding placed, therefore a) all the start ends (dotted ends) are magnetically equivalent (so if one dotted end goes high, the other dots also go high at the same moment, as compared to their opposite ends). We can also see that from the point of view of actual physical proximity, every dotted end of a winding is close to the non-dotted end of the next winding.
- This means that for the flyback transformer of Figure 1, the diode end of the Secondary winding will necessarily fall adjacent to the safety barrier. Therefore, we have a very small dV/dt on the Primary side, though we have some dV/dt on the Secondary side, and therefore a small net dV/dt across the barrier. But this dV/dt is much smaller than if the Drain end of the Primary winding was adjacent to the safety barrier. The latter situation can be created by winding the transformer the 'wrong' way, i.e. reversing all the start and finish ends shown in Figure 1). With that arrangement, we would have a healthy dose of CM noise injected directly into the chassis/Earth.
- The transformer in Figure 1 has the advantage that the quiet end (ground) of the Secondary is now the outermost layer. That is by itself a good shield. So we may be able to drop the ubiquitous circumferential shield (copper band).
- When we go through the same reasoning for a forward converter transformer, we will find that with the described winding sequence, we will automatically have the quiet ends of both Primary and Secondary overlooking each other across the safety barrier. This is good from the viewpoint of conducted EMI since very little noise will be injected through the parasitic capacitance. But the outermost layer is not 'quiet' anymore, and we could have a radiation problem. In this case, the circumferential shield becomes necessary.
- A way out of this forward converter outer surface radiation problem is to ask our production to reverse the direction of the Secondary winding (only). So for example, if till that point the machine was spinning clockwise, for the Secondary we specify an anticlockwise direction. With this, the reasoning given above for the flyback will apply to the forward converter transformer too. We would then have a quiet exterior (without a shield).

- A forward converter transformer has no (or very small) air gap, so it is generally considered 'quieter' to start with. Also by interleaving as per proximity effect analysis, we can significantly reduce the magnetomotive force that gives rise to leakage flux and EMI
- When the transistor is mounted on the chassis, there is a technique that is used to try and cancel the current injected through the heatsink capacitance. This done by placing another winding, equivalent to the main winding and opposite in phase (though it can be of much thinner wire). The idea is that if the noise current is being pushed out from the primary winding, in the cancellation winding it gets pulled in. Therefore in effect the injected current does a quick U-turn back to the source.
- Rod inductors are often used in post-filtering LC stages on the output. Because of their open structure, they have been called 'EMI cannons'. But they are still used because of their low cost and the low real estate they need. But they should be placed vertically (as they normally are). If two such rods are being used on a given output, we should wind the two rods identically, but reverse the current flow in one of them compared to the other by suitable modification of the PCB. So looking from the top, one should be carrying current clockwise and the other anticlockwise. This helps redirect the flux from one inductor straight into the other, so there is much less spilled around.

EMI from Diodes

We list some remaining things to know and try out

- Diodes are a potent source of low to high-frequency noise. Slow diodes (like those in a typical input bridge) can also contribute such noise.
- For medium to high power converters, snubbers are usually placed across the ultrafast catch diode. Such diodes can be selected to have softer reverse recovery characteristics to reduce EMI. Note that a Schottky diode has no reverse recovery time in principle, but its body capacitance is relatively large and can end up resonating with trace inductances. So an RC snubber is also helpful for them. If the layout is 'terrible', we will need snubbers even for very low power converters.
- If a diode has fully recovered (i.e. zero current) before the voltage across it starts to swing, there is no reverse recovery current. This is true for any diode used in a (properly designed) RCD snubber or clamp. Therefore such diodes really don't have to be 'super super fast'.
- As compared to the diode turn-off (recovery) speed, the Fet turn-on should be 2 to 3 times slower. Otherwise the Fet will force high current spikes through these yet unrecovered diodes. This will produce strong H-fields. Therefore it is not uncommon to intentionally degrade the Fet switching speed by adding a resistor (say 10Ω to 100Ω) in series with the gate (maybe with a diode across the resistor so as to leave the turn-off speed unaffected for efficiency reasons.
- Small capacitors may be placed across the Fet (Drain to Source). But this can create a lot of dissipation in the Fet, since every cycle the capacitor energy is dumped into the Fet. ($P=1/2 x C x V^2$ (f_{SW}).
- Fast diodes can also have very high forward voltage spikes at turn-on. So momentarily the diode forward voltage may be 5 to 10V rather than the expected 1V or so. Usually, the snappier the reverse recovery, the worse is this forward spike too. At Fet turn-off, the diodes become strong E-field sources, whereas at Fet turn-on, the diodes will generate strong H-fields. Any small R-C snubber present across the diode essentially controls these forward voltage spike too.
- In integrated switchers, access to the gate of the Fet may not be available. In that case, the turn-on can be slowed by inserting a resistor of about 10Ω to 50Ω in series with the bootstrap capacitor. The bootstrap cap is in effect the voltage source for the internal floating driver stage. At turn-on, it is asked to provide the high current spike required to charge up the gate capacitance. So a resistor placed in series with this capacitor simply limits the charging current somewhat, and thereby slows the turn-on.
- Ferrite beads (of nickel-zinc type) are often placed in series with catch diodes, such as the output diode of a flyback. These beads must be very small, as they can have a great effect on the power supply efficiency. Correctly chosen, the good results obtained with regards to EMI and output ripple are well worth the 1-2% drop in efficiency.
- A comment about split/sandwich windings. We often split windings for various reasons. In general series splitting works fine. Putting windings in parallel is not always a good idea. For example, if the Secondary winding is split in parallel to increase its current handling capability, since the two windings are usually physically apart on either side of the Primary winding, they are actually magnetically slightly different. This can lead to a lot of ringing on the output and can also affect the EMI spectrum. If this paralleling is really needed, it is better to use them as shown in Figure 2. Here the diode forward drops help to 'ballast' the windings and thus they 'iron out' any inequality between the two halves.
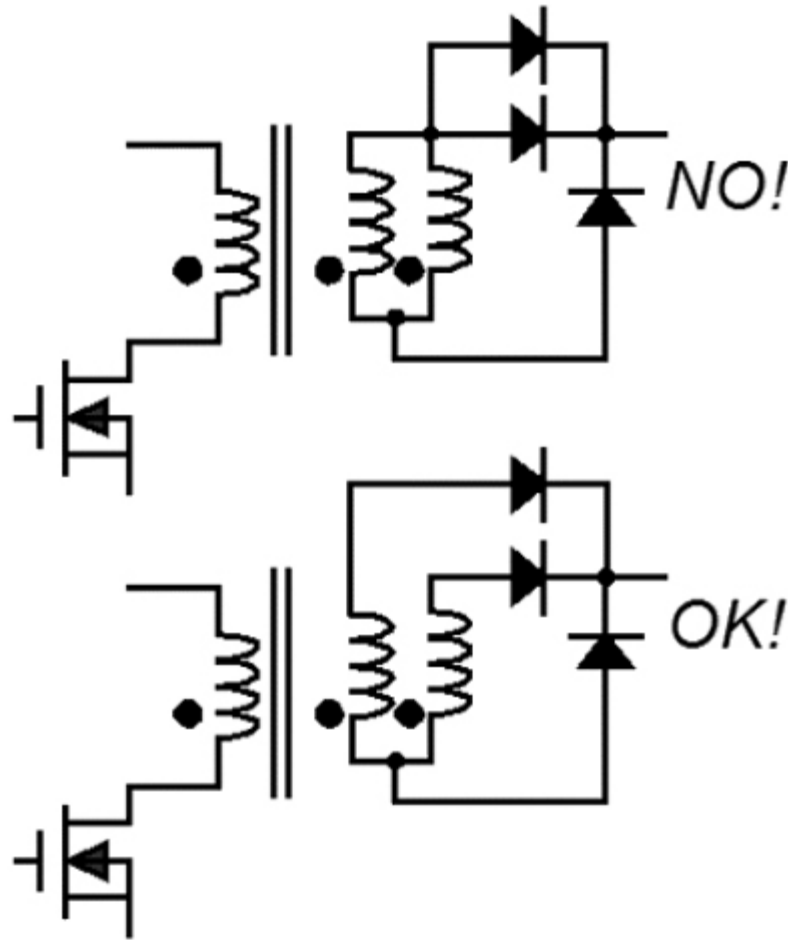
Figure 2: Alternative Ways of Paralleling Secondary Windings

Layout guidelines

We should examine each topology carefully to figure out which PCB trace segments are 'critical'. Those traces in which current is forced to either start flowing or stop flowing (suddenly) at the instant of turn-on or turn-off, will produce inductive spikes. At each transition we get a very high dI/dt across this trace segment, and so from the thumb rule of '20nH per inch of trace' we get a voltage spike as per V=LdI/dt. The areas of these high frequency current loops must be minimized. They don't just produce EMI but can infiltrate into the control sections of integrated switchers causing erratic behavior.

We need to be careful about inadvertently making traces that have a swinging voltage on them too wide, as then they become good E-field antennas. The prime example is the trace at the switching node of any topology. We may need to increase its copper area for the purpose of lowering its inductance and/or helping dissipate heat from the Fet or catch diode, but we must do this judiciously.

The ground plane is a very effective method of bringing down the overall level of the EMI emissions. On a multi-layer board, if the very next plane to the side containing the power components and their associated traces is a ground plane, the EMI can drop by 10-20 dB. This is clearly more cost-effective than opting for a 'cheap' one/two sided board, and having to use bulky filters instead. However the integrity of such a ground plane should be maintained. Return currents tend to travel by the shortest straight line path at low frequencies, but the higher harmonics tend to image themselves directly under the forward trace on the opposite layer. Currents, given a chance, therefore automatically try to reduce the area they enclose, as this lowers the self-inductance of the trace containing them, and thereby provides the current the lowest impedance route. So if ill-considered cuts are made in the ground plane with the intention of 'conveniently' routing some other trace, the return currents of the power converter stage (which really need this ground plane) will get diverted along the sides of the intervening cuts, and in doing so, will form effective slot antennas.

Last-ditch Troubleshooting

It is helpful to separate the CM and DM components to be able to study them and debug a bad spectrum. The LISN reading only provides a certain weighted sum of the total conducted noise, and therefore unless special accessories are available (including a modified LISN), we can only guess which part of the EMI scan is mainly DM and which is CM. So we may not know the root cause either. In Figure 3 we have shown two current probes, wired up in such a way that they are actually performing 'simultaneous equation' math to separate the CM and DM components. By doing these two measurements at the same time rather than one after another, we have also retained valuable information about the relative phase relationship existing between the CM and DM components.

$$\left(I_{dm} + \frac{I_{cm}}{2}\right) + \left(-I_{dm} + \frac{I_{cm}}{2}\right) = I_{cm} \qquad \left(I_{dm} + \frac{I_{cm}}{2}\right) - \left(-I_{dm} + \frac{I_{cm}}{2}\right) = 2 \times I_{dm}$$

$$I_{dm} + \frac{I_{cm}}{2}$$

$$-I_{dm} + \frac{I_{cm}}{2}$$

$$I_{cm}$$

Ensure current probe does not saturate here (because operating current is also adding up !)
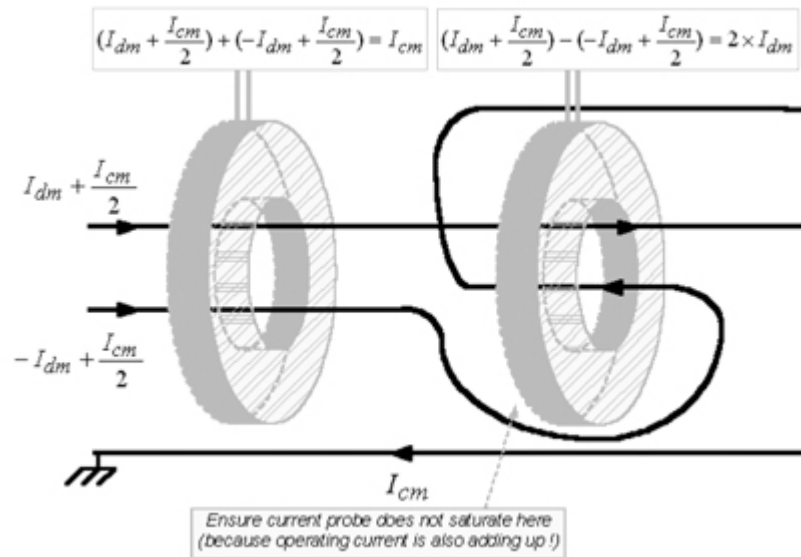
Figure 3: Math Algorithm Implementation for Separating CM and DM Components