MEASUREMENT AND FILTERING OF OUTPUT NOISE OF DC/DC CONVERTERS
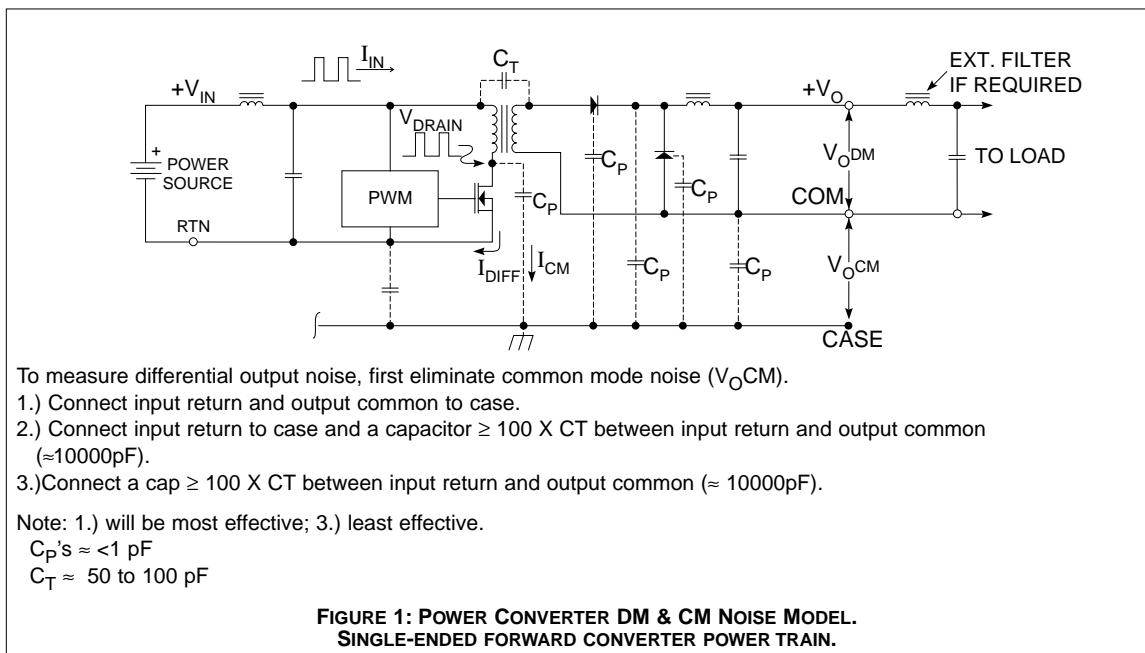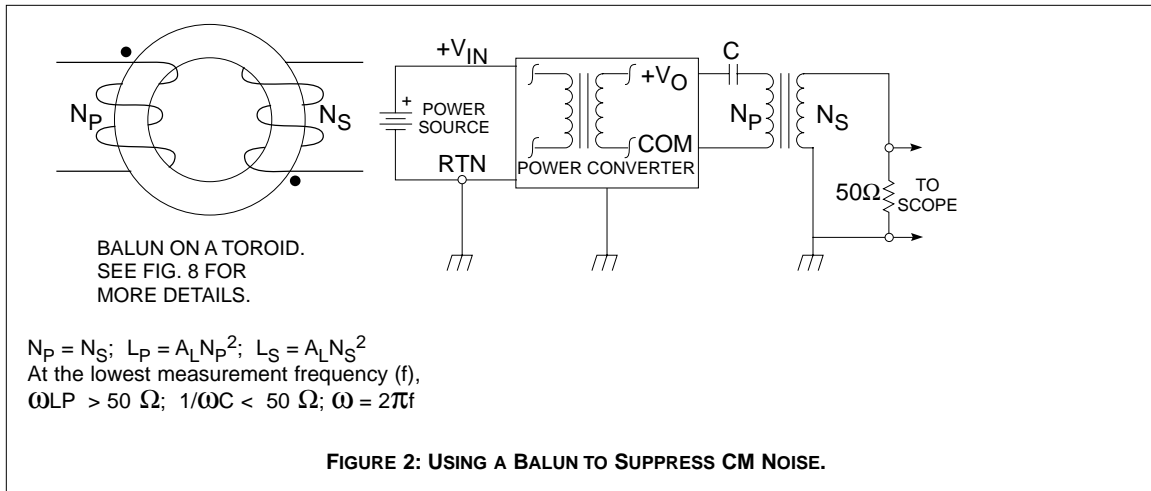
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DEFINING & MEASURING OUTPUT NOISE

In order to determine if an external output filter is needed for a switching power converter, an understanding of the nature of output noise and its proper measurement will be helpful. The two types of noise, differential mode (DM) and common mode (CM), are discussed in the following paragraphs with the aid of Figures 1 through 12.

Switching power converters are natural generators of narrowband spectral noise which will be present at the fundamental switching frequency and its higher order harmonics. For push-pull type converters it is possible to have a sub-harmonic component at one-half the switching frequency due to imperfect balance. This spectral noise will have both DM and CM components. DM noise is the normal mode noise that occurs between the output and its return line. See Figure 1. CM noise occurs between each of the output lines and, if isolated, the EMI reference, which is the power supply metal case. CM noise is due to CM currents being pumped through parasitic capacitances between the power train and the case. These capacitances, generally less than a picofarad, are a function of the dielectric constant of the ceramic substrate, which is on the order of 8. The substrate is back metalized and soldered to the metal base plate with the power train and other circuits on the substrate top side. The parasitic capacitances are then proportional to the product of dielectric constant and area used and inversely proportional to the substrate thickness.

To measure differential output noise, first eliminate common mode noise (V_OCM).

1.) Connect input return and output common to case.

2.) Connect input return to case and a capacitor $\geq$ 100 X CT between input return and output common ($\approx$10000pF).

3.) Connect a cap $\geq$ 100 X CT between input return and output common ($\approx$ 10000pF).

Note: 1.) will be most effective; 3.) least effective.
  C_P's $\approx$ <1 pF
  C_T $\approx$ 50 to 100 pF

**FIGURE 1: POWER CONVERTER DM & CM NOISE MODEL.
SINGLE-ENDED FORWARD CONVERTER POWER TRAIN.**

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APPLICATION NOTE

$N_P = N_S$; $L_P = A_L N_P{}^2$; $L_S = A_L N_S{}^2$
At the lowest measurement frequency (f),
$\omega L P > 50\ \Omega$; $1/\omega C < 50\ \Omega$; $\omega = 2\pi f$

FIGURE 2: USING A BALUN TO SUPPRESS CM NOISE.

The DM noise will generally have a magnitude of less than 50 millivolts. The CM noise, however, can have a magnitude of several volts, and may appear as DM mode noise due to poor CM rejection of the noise measurement equipment. CM noise is generally not important in most system applications but can cause misleading and excessive DM noise measurements. An oscilloscope is usually used to make noise measurements and may have a DM bandwidth of 100 MHz or more, but will usually have poor common mode rejection over this bandwidth. The power converter CM output noise spectrum will, however, have a bandwidth of several tens of MHz, and a magnitude significantly higher than the DM spectrum. An accurate DM noise measurement will usually require that the CM noise spectrum be suppressed prior to making the measurements.

The best way to suppress the CM output noise spectrum is to short out the power-train-to-case parasitic capacitances. The main CM output problem (refer to Figure 1) is the interwinding transformer capacitance which forms a high ratio capacitive divider with the output-to-case parasitics. Much of the high level pulses at the power FET drain appear as secondary noise common to both output lines. Shorting out the parasitic capacitances reduces the output to case common mode impedances, reducing the spectrum magnitude. To short out the parasitics, connect both input and output commons to the case and use the case as a single point ground. This is practical for bench measurements but may not be practical in the system. A good ceramic capacitor from output return to case, or ceramic capacitors from both output pins to case, may suffice if the unit is mounted on a PC card and direct connections are not possible. The capacitors should be greater than 10000 pF. The exact value can be determined experimentally. If the capacitors can't be connected to the case, connect them to the input common.

A balun, shown in Figure 2, can also be used to reject CM noise for measurement purposes. The balun should have minimal interwinding capacitance and a 1:1 turns ratio. A toroid, as shown, with segmented windings or a pot core with separated windings can be used.

The output DM noise is the noise voltage measured between the two output terminals. Refer to Figure 1. The measurement must be carried out at the pins using short leads to reduce the pickup of radiated noise. If an oscilloscope with a differential bandwidth of 100 MHz is used, and we use a 10X probe, it is important to be sure the connections to the test sample are good over this bandwidth. The probe ground lead, which is about 6 inches long, has a lead inductance of about 100 nanohenries. This inductance equates to 10 ohms reactive at 16 MHz, and increases at a 6 dB/octave rate with frequency. The
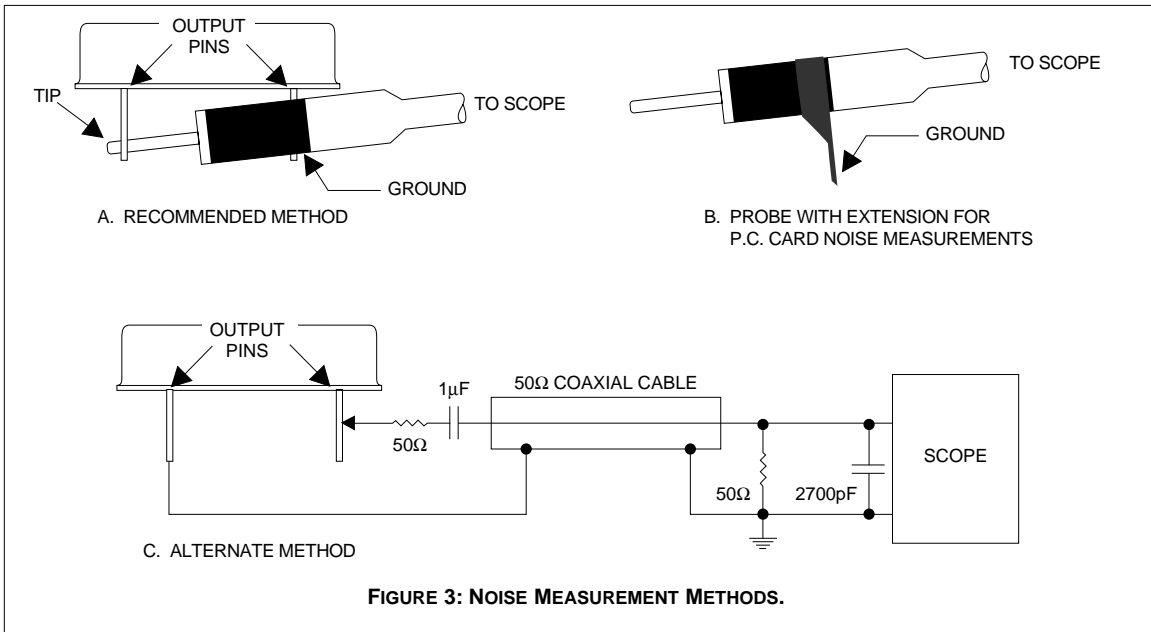
probe ground is not an acceptable ground connection for noise measurements, but rather is an excellent antenna for radiated noise pickup as well as a high impedance for any circulating ground loop currents to flow through (exactly what we don't want). To improve the situation, remove the ground lead and probe clip and use the probe tip and barrel ground lead as shown in Figure 3. To make noise measurements on a PC card where the power converter is installed, add the shortest possible lengths of wire to either the tip or the barrel ground to reduce series lead inductance. Using a rectangular cross section conductor for this purpose also reduces lead inductance as compared to round wire, also shown in Figure 3B.

Alternately, a 50-ohm coaxial cable can be used in lieu of the 10X probe. The same precautions about short leads also apply here. This setup, also in Figure 3, will require that the scope reading be multiplied by 2X. A 2700 pF capacitor can be used to reduce scope bandwidth to 2 MHz to allow observing the lower frequency components only. Excellent results for DM noise measurements on the bench can be achieved with the balun of Figure 2 or by tacking the primary to the power converter output pins on a PC card. The balun should be terminated in a low impedance, 50 ohms as shown.
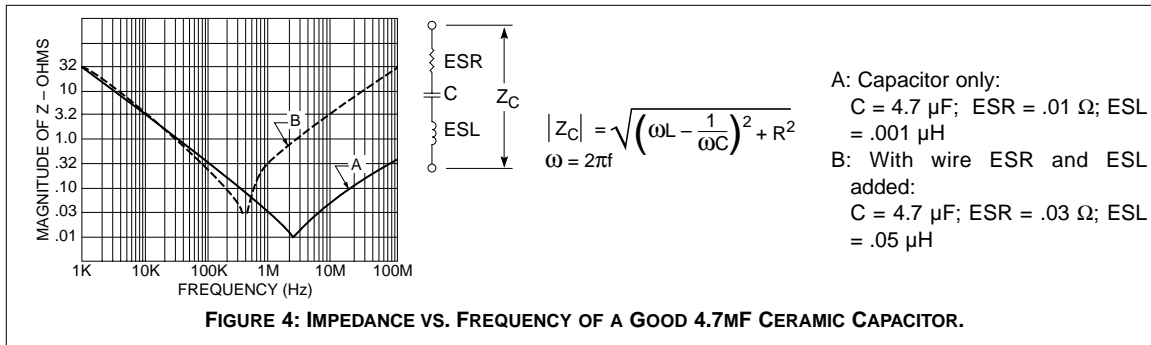
FILTERING OF DIFFERENTIAL MODE OUTPUT NOISE

Additional filtering, if required, can be as simple as adding an external capacitor. This may work where the higher frequency components are the problem and the required rejection is 12 dB or less. Only high quality low ESR ceramic capacitors are recommended. They should be connected to or near the common output return pin to form a single point ground, and to the other electrode as near the positive output pin as possible. Use the widest possible copper traces and take the load connections from the capacitor termination so that the wires or copper traces are between the capacitor and power converter output pins and not in series with the capacitor. This is important because the capacitor
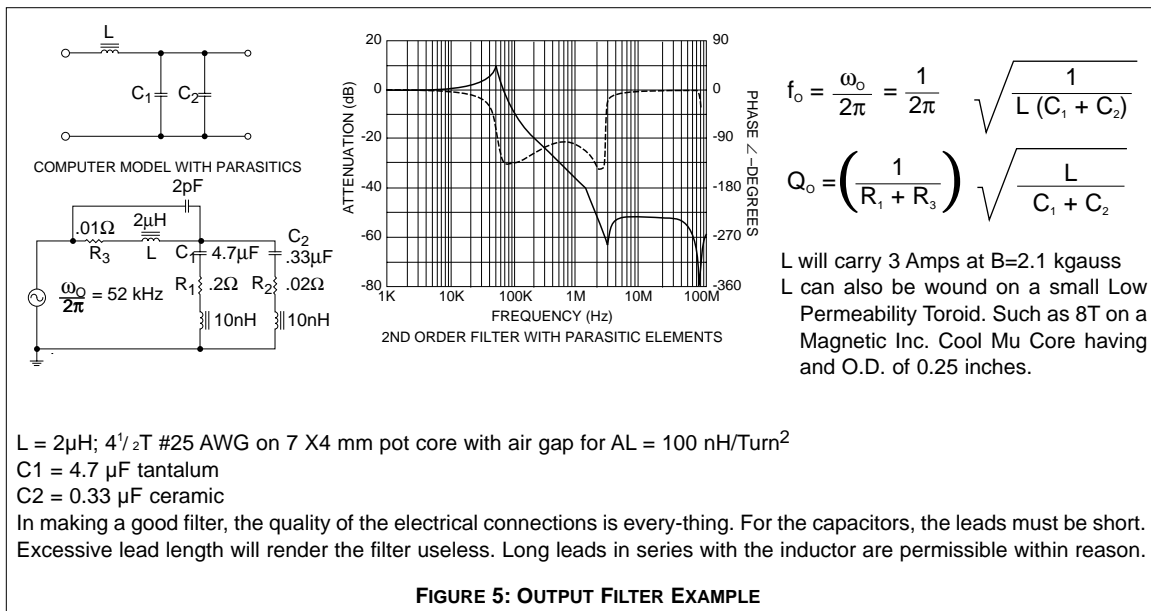

A. RECOMMENDED METHOD

B. PROBE WITH EXTENSION FOR
   P.C. CARD NOISE MEASUREMENTS

C. ALTERNATE METHOD

FIGURE 3: NOISE MEASUREMENT METHODS.

APPLICATION NOTE

A: Capacitor only:
C = 4.7 µF; ESR = .01 Ω; ESL = .001 µH

B: With wire ESR and ESL added:
C = 4.7 µF; ESR = .03 Ω; ESL = .05 µH

$$\left| Z_C \right| = \sqrt{\left(\omega L - \frac{1}{\omega C}\right)^2 + R^2}$$

$\omega = 2\pi f$

FIGURE 4: IMPEDANCE VS. FREQUENCY OF A GOOD 4.7MF CERAMIC CAPACITOR.

becomes useless if appreciable ESR and/or ESL is added in series with it. Figure 4 shows an example of the impedance vs. frequency of a good 4.7 µF ceramic capacitor, and how it can begin deteriorating at frequencies below 1 MHz due to additional trace ESR and ESL. The increase in these parameters is what can be expected with about 2 inches of small wire in series with the capacitor. It is important that the capacitor be of low impedance over the bandwidth of interest because it has to work against the power supply output impedance which will also be low.

Second-order low-pass LC filters will provide better and more predictable attenuation as a function of frequency. They are also more forgiving to imperfect layouts because of the inductor in series with the output. The inductor can also make the layout of the filter easier since the trace and wire length in series with the inductor will not compromise filter attenuation. Keep the capacitor lead and trace lengths as short as possible and make the load connections at the points where the capacitor is terminated. An example of a simple second-order LC filter is shown in Figure 5. The resonant frequency of 52 kHz is determined by the 4.7 µF tantalum capacitor and the
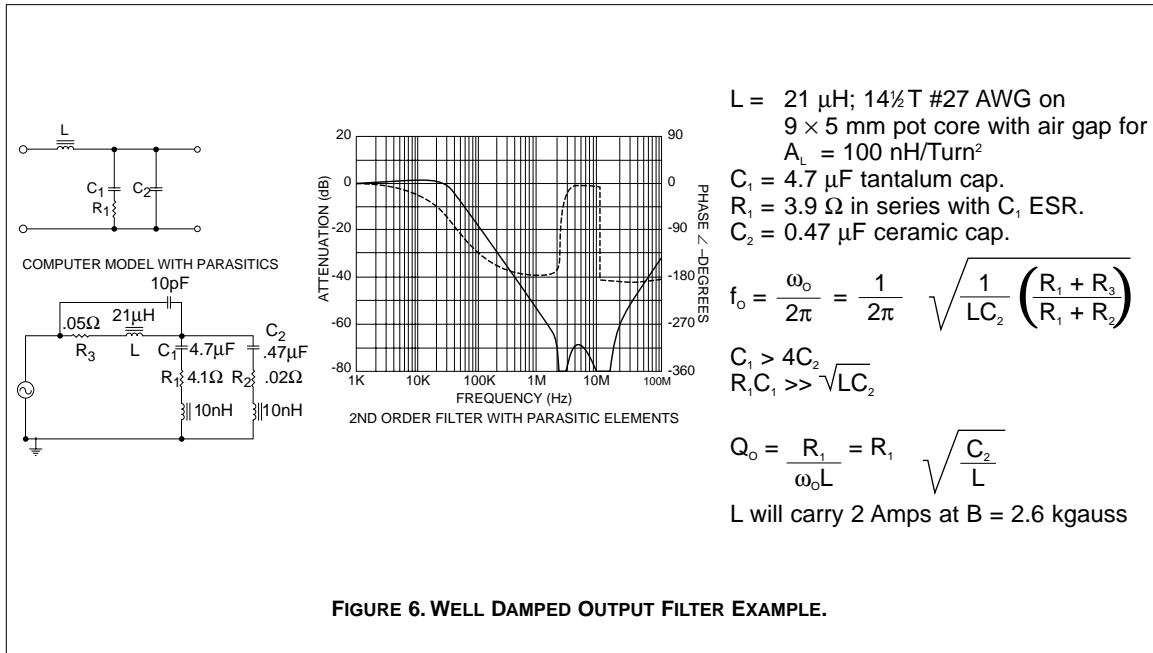

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{1}{L(C_1 + C_2)}}$$

$$Q_o = \left(\frac{1}{R_1 + R_3}\right) \sqrt{\frac{L}{C_1 + C_2}}$$

L will carry 3 Amps at B=2.1 kgauss
L can also be wound on a small Low Permeability Toroid. Such as 8T on a Magnetic Inc. Cool Mu Core having and O.D. of 0.25 inches.

L = 2µH; $4^1/_2$T #25 AWG on 7 X4 mm pot core with air gap for AL = 100 nH/Turn^2
C1 = 4.7 µF tantalum
C2 = 0.33 µF ceramic
In making a good filter, the quality of the electrical connections is every-thing. For the capacitors, the leads must be short. Excessive lead length will render the filter useless. Long leads in series with the inductor are permissible within reason.

FIGURE 5: OUTPUT FILTER EXAMPLE

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L = 21 μH; 14½ T #27 AWG on
    9×5 mm pot core with air gap for
    A_L = 100 nH/Turn^2
C_1 = 4.7 μF tantalum cap.
R_1 = 3.9 Ω in series with C_1 ESR.
C_2 = 0.47 μF ceramic cap.

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{1}{LC_2}\left(\frac{R_1 + R_3}{R_1 + R_2}\right)}$$

$C_1 > 4C_2$
$R_1C_1 \gg \sqrt{LC_2}$

$$Q_o = \frac{R_1}{\omega_o L} = R_1 \sqrt{\frac{C_2}{L}}$$

L will carry 2 Amps at B = 2.6 kgauss

COMPUTER MODEL WITH PARASITICS

2ND ORDER FILTER WITH PARASITIC ELEMENTS

FIGURE 6. WELL DAMPED OUTPUT FILTER EXAMPLE.

2 μH inductor. The 0.33 μF ceramic capacitor is used to compensate for the zero due to the tantalum capacitor's ESR and hence improve high frequency rejection. This type of filter has been used with Interpoint power converters in the past with excellent results. The actual attenuation and phase characteristics will be close to that of the computer model if it is designed and laid out as described in Figure 5 notes.

The simple example of Figure 5 has a disadvantage. The Q at resonance can be difficult to control because it is an inverse function of the ESR sum for L and C. Because of additional power loss, adding R in series with the inductor is not practical unless the output current is small. Making the $\sqrt{L/C}$ small may be impractical due to volume restrictions. An alternate filter design, shown in Figure 6, does not have

this disadvantage and also has improved high frequency response. The example shown uses approximately the same capacitor values shown in Figure 5, but a somewhat larger inductor value. The resonant frequency is a function of the 21 μH inductor and the 0.47 μF ceramic capacitor. The 4.7 μF tantalum capacitor and series resistor function as an AC load or parallel damping network.

An external LC filter can affect load regulation. Using the smallest L value possible and keeping the inductor ESR small will help. The LC filter also acts as a series resonant circuit across the power converter output terminals and can cause stability problems if the resonant frequency is inside the control loop bandwidth. Setting the resonant frequency above 30 kHz should suffice for any Interpoint power converters.

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APPLICATION NOTE

FILTERING COMMON MODE OUTPUT NOISE

Common mode noise can be of importance in analog circuits where sensitive devices such as high resolution A/D converters, high gain instrumentation amplifiers, and/or video displays are involved. Common mode output noise represents noise components which are in phase in both output lines with respect to a common reference. This can lead to radiation in addition to conducted noise problems if not corrected.

As discussed previously, the CM output noise problem is mainly due to the transformer interwinding capacitance, CT. The power train components also generate CM current components into the case due to the high dv/dt across their parasitic capacitances to the case. These CM currents are really a separate problem, but need to be considered in the overall CM noise problem solution. Refer again to the model of Figure 1.

The interwinding capacitance, CT, is distributed between the primary and secondary turns. For an input line voltage of 28 volts, the peak-to-peak (p-p) voltage excursion on the power switch drain will be approximately 50 volts. In the absence of any CM suppression, a large AC voltage will be commutated to all output lines of the same secondary winding by the interwinding capacitance, CT, and is referenced to the input power return. A magnitude of 20 volts p-p is a typical amplitude. This CM noise voltage can be suppressed by forming a capacitive divider with the interwinding capacitance, CT, and implemented by connecting a capacitor from output common to input return. If CT is 50 picofarads, then connecting a 50 nanofarad ceramic capacitor from output common to input return will reduce the CM noise from 20 volts to about 20 millivolts. This connection is often not allowable in an equipment specification. It also does nothing for the CM currents which are pumped into the case through the power train parasitic capacitances, and which belong back in the input return line. The solution is to use case bypass capacitors from both input return and output common to case, and also a balun to place a high CM impedance in the input lines. The input bypass directs the case CM currents back into the return line, reducing radiation. A bypass capacitor can be replaced by a direct connection where permitted in the equipment spec, and the balun may not be needed in all cases. A combined DM and CM filter, using the low pass section of Figure 5 and the CM filter just discussed, is shown in the example of Figure 7. Design of the balun is covered in the paragraphs which follow.

LOW NOISE OUTPUT FILTERS FOR DC-DC CONVERTERS

Very low noise output filters can be implemented using baluns in both the input and output lines of DC/DC power converters. These are particularly
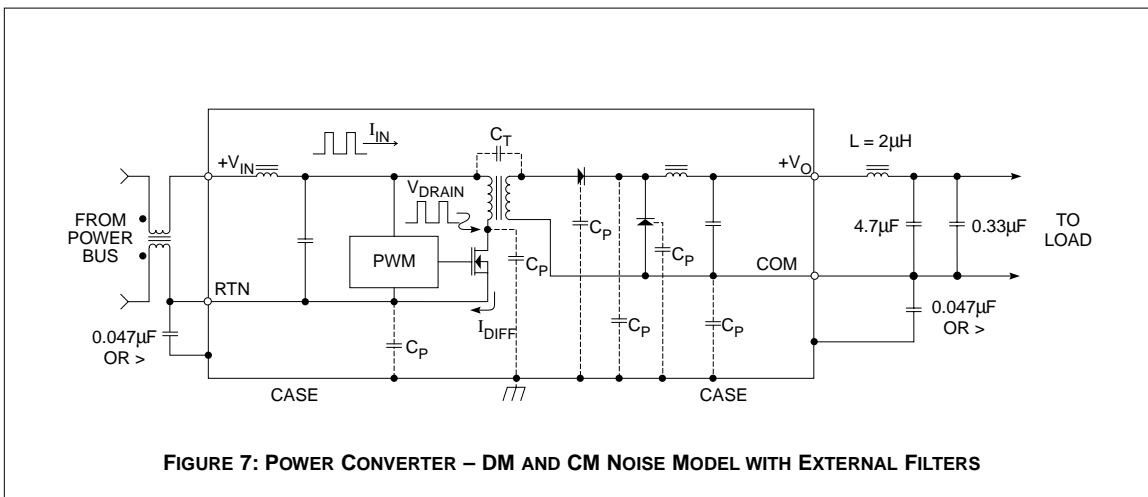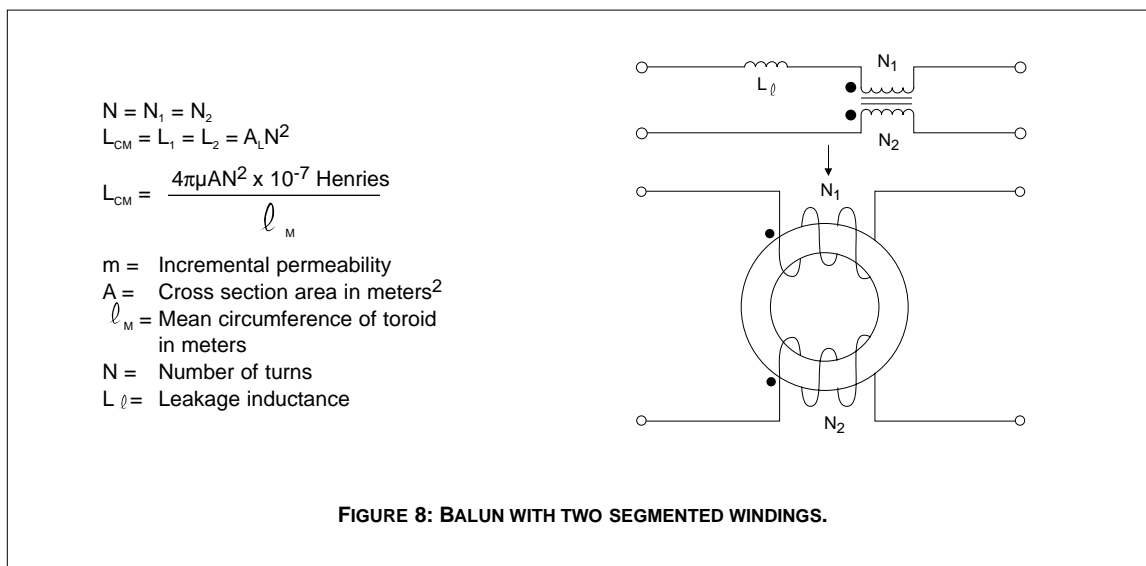

FIGURE 7: POWER CONVERTER – DM AND CM NOISE MODEL WITH EXTERNAL FILTERS
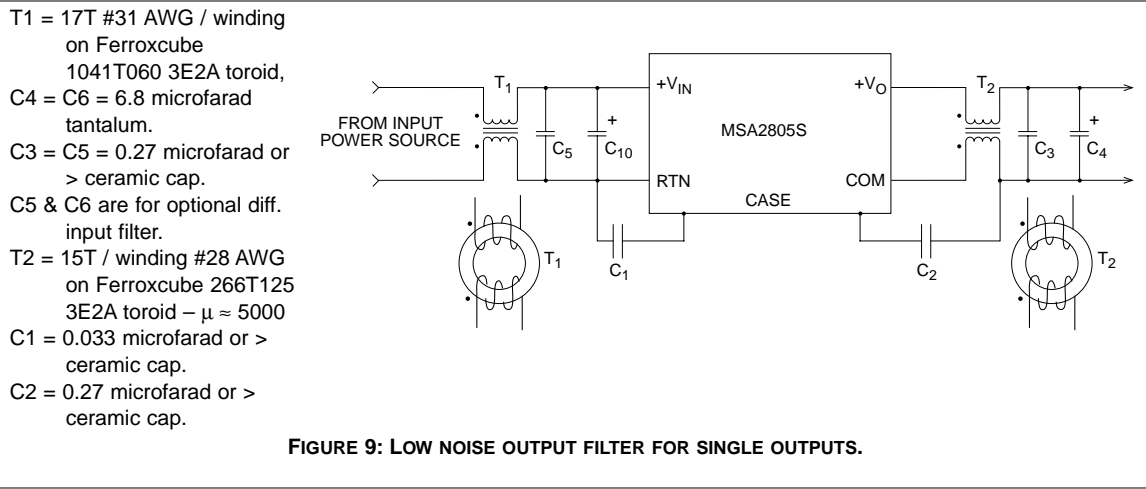
effective where long lines or traces run from the power converter to the load. These filters use baluns of the types shown in Figures 8 and 10. Single output power converters use a two winding balun, with a three winding balun used for dual output converters. The balun leakage inductance is used for the DM filter. The CM filter is implemented first with a ceramic bypass capacitor which forms a capacitive divider with the primary to secondary interwinding capacitance. Secondly the balun forms a high frequency CM filter which works with the stray capacitance of the load side of the balun. This can be particularly effective where the load is on the other end of a pair of long wires.

A low noise output filter for an isolated single output MSA2805S power converter is shown in Figure 9. Here the filter is implemented using baluns in both the input and output lines. The input balun and ceramic bypass capacitor are used to attenuate CM input currents. This can also be accomplished to a limited degree by shorting the input return to the case where permitted in the equipment specification.

Shunt capacitors can be used to work against the balun leakage inductance to create a differential filter section. Both baluns are wound on high permeability ferrite toroids, and are segment wound to create leakage inductance, each winding covering about 180 degrees of core circumference. When wound with equal turns on each winding, the net ampere turns in the core will always be zero when used as shown in Figure 7. A solid tantalum capacitor, paralleled with a ceramic capacitor for improved high frequency performance, is used for the DM filter.
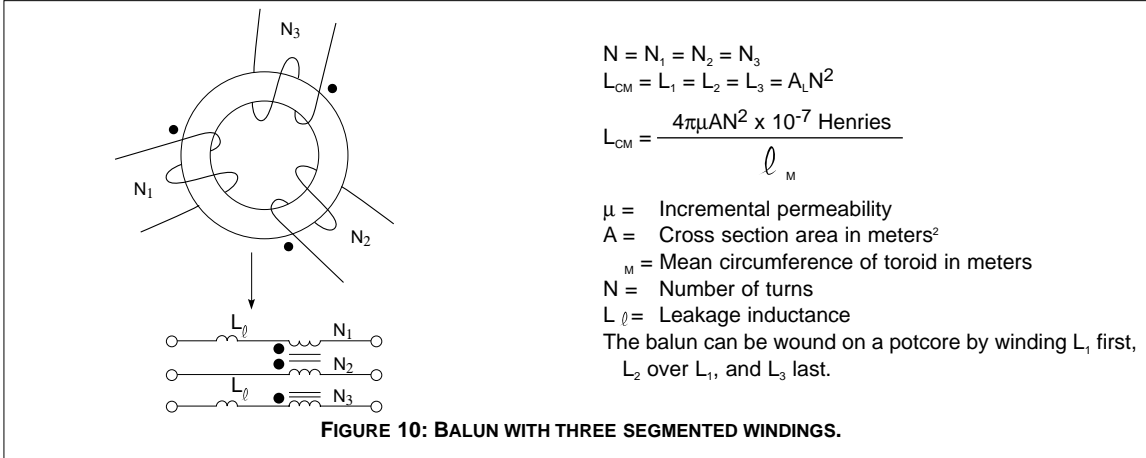
This is the DM filter of the Figure 5 example, where the leakage inductance replaces the series inductor. The leakage inductance, is however, in the air, not the core, and therefore cannot be saturated. The circuit of Figure 9 was built as described on copper clad vector board using readily available components, and layout techniques to minimize trace ESL and ESR in series with the capacitors. The result was a DM and/or CM output noise level of a few millivolts p-p. The measurement bandwidth was 100 MHz.

$N = N_1 = N_2$

$L_{CM} = L_1 = L_2 = A_L N^2$

$$L_{CM} = \frac{4\pi\mu A N^2 \times 10^{-7} \text{ Henries}}{\ell_M}$$

m = Incremental permeability
A = Cross section area in meters^2
ℓ_M = Mean circumference of toroid in meters
N = Number of turns
L_ℓ = Leakage inductance

FIGURE 8: BALUN WITH TWO SEGMENTED WINDINGS.

APPLICATION NOTE

T1 = 17T #31 AWG / winding
on Ferroxcube
1041T060 3E2A toroid,
C4 = C6 = 6.8 microfarad
tantalum.
C3 = C5 = 0.27 microfarad or
> ceramic cap.
C5 & C6 are for optional diff.
input filter.
T2 = 15T / winding #28 AWG
on Ferroxcube 266T125
3E2A toroid – $\mu \approx$ 5000
C1 = 0.033 microfarad or >
ceramic cap.
C2 = 0.27 microfarad or >
ceramic cap.

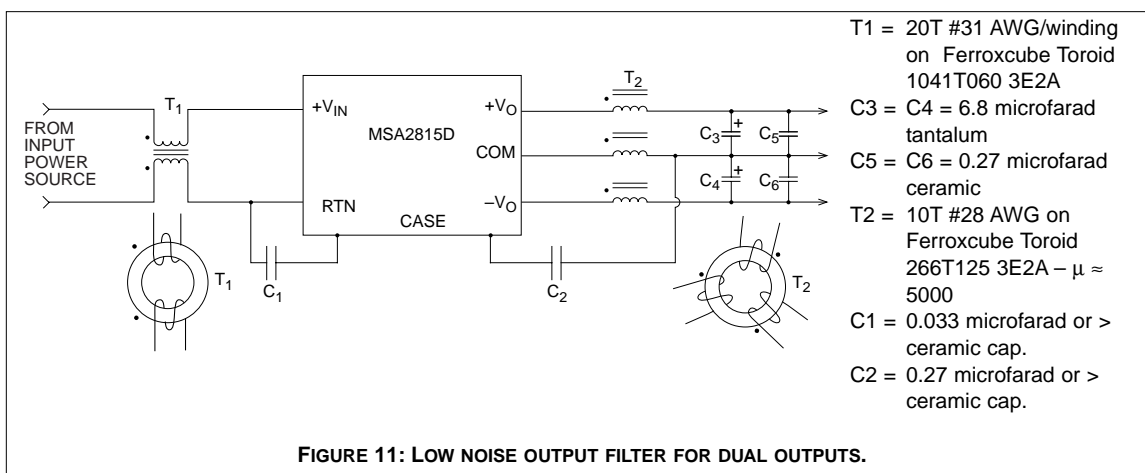**FIGURE 9: LOW NOISE OUTPUT FILTER FOR SINGLE OUTPUTS.**

A low noise output filter circuit for a dual MSA power converter is shown in Figure 11. This is similar to the Figure 9 case except for the three winding Balun and the two additional DM output capacitors. Here, the balun is also segment wound to create leakage inductance, each winding occupying about 120 degrees of core circumference. When phased as shown, and with equal turns on each of the three windings, the net ampere turns in the core will always be zero regardless of load distribution. This circuit was also built on copper clad vector board using readily available components with about the same results as for the Figure 9 case.

The baluns should be designed using Ferrite materials having a relatively high permeability of approximately 5000. Examples are "B Mat'l" by Ferronics Inc., "3E2A Mat'l" by North American Phillips/Ferroxcube, "HP-5000 Mat'l" by TDK, and "J Mat'l" by Magnetics Inc. The high permeability allows a high CM inductance with a minimal number of turns, resulting in reduced copper loss, distributed capacitance, and core size. Higher permeability ferrite materials will work even better, provided their curie point temperature is somewhat above the maximum system operating temperature. Since the

$$N = N_1 = N_2 = N_3$$
$$L_{CM} = L_1 = L_2 = L_3 = A_L N^2$$

$$L_{CM} = \frac{4\pi\mu A N^2 \times 10^{-7} \text{ Henries}}{\ell_M}$$

μ = Incremental permeability
A = Cross section area in meters[2]
ℓ_M = Mean circumference of toroid in meters
N = Number of turns
L_ℓ = Leakage inductance
The balun can be wound on a potcore by winding L_1 first, L_2 over L_1, and L_3 last.

FIGURE 10: BALUN WITH THREE SEGMENTED WINDINGS.

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T1 = 20T #31 AWG/winding on Ferroxcube Toroid 1041T060 3E2A

C3 = C4 = 6.8 microfarad tantalum

C5 = C6 = 0.27 microfarad ceramic

T2 = 10T #28 AWG on Ferroxcube Toroid 266T125 3E2A – $\mu \approx$ 5000

C1 = 0.033 microfarad or > ceramic cap.

C2 = 0.27 microfarad or > ceramic cap.

FIGURE 11: LOW NOISE OUTPUT FILTER FOR DUAL OUTPUTS.

Balun net ampere turns are always zero, when used as in Figures 9 and 11, the only thing limiting small size is copper loss/temperature rise, the availability of small cores, and how physically small the balun can be made.

A simplified equivalent circuit for a two winding balun is shown on Figure 8. The leakage inductance is shown as an additional series inductor. The common mode inductance is that of one winding, and can be calculated knowing the core permeability and dimensions using the formula in Figure 8. The leakage inductance is much smaller than the former, and should be measured on a sample balun by shorting one winding and measuring the inductance looking into the other. For the circuit example of Figure 9, the measured leakage inductance of the output filter balun was 3.5 μH at 0.5 MHz. The calculated CM inductance is 480 μH.

A simplified equivalent circuit for a 3 winding balun is shown in Figure 10. The CM inductance, the open circuit inductance of any of the windings, can be calculated from the formula in Figures 8 or 10. The leakage inductance, as shown, can be measured by shorting two of the windings and measuring the inductance looking into the third.

For the circuit example of Figure 11, the measured leakage inductance of the output filter balun was 1.44 μH at 0.5 MHz. This is the value of the com-

ponent shown in series with two of the three windings. The calculated CM inductance is 214 μH.

The filters of Figures 9 and 11 as configured, have the DM inductance limited to the output balun leakage inductance. This works for most applications, but where additional inductance is required, an inductor can be added in series with the leakage inductance shown on the balun equivalent circuits in Figures 8 or 10. The DM inductance will now be the sum of the leakage and added series inductance, which allows some added flexibility in the design of the DM output filter, such as the filter type of Figure 6 where a shunt damping network is used to control the Q. This can also allow the balun to be made on a pot or RM Core by bifilar or trifilar winding since the DM filter is not now solely dependent on leakage inductance. In this case, use a high permeability ferrite material and a core pair with no air gap for the balun. The added series inductor can be made on a small Molyperm toroid or air gapped pot core.

The input CM filter can be part of an EMI power line filter, but must be close to the power converter to be effective. Where a separate balun is used, the CM natural frequency should be placed two to three octaves or more below the switching frequency. Since this is a low pass filter, the exact frequency is not important. In Figures 9 and 11, where the switching frequency is nominally 500 kHz, the CM natural frequency has been placed at around 62 kHz.

APPLICATION NOTE

A CM inductance in the 100 to 500 µH area should be used with the largest practical value of ceramic capacitor available.

The output CM filter case bypass capacitor should be the largest practical value which can be used. It is only necessary to bypass the output common to case since the output lines are shorted together by the DM filter capacitors. The output balun CM inductance can be the largest practical value provided that interwinding capacitance is kept to less than approximately one picofarad. Stray capacitance on the load side of the balun, which determines the CM natural frequency with the CM inductance, can be expected to be no more than a few pF.

Designing the DM output filter requires knowledge of the amplitude of the power converter output noise so it can be ratioed with the required level at the filter output to determine the required filter attenuation. To determine the noise level, use the maximum value of the device specification, which is usually at a restricted bandwidth and does not include high frequency switching spikes. It defines the envelope of the first few spectral components which need to be addressed, since the low pass filter will automatically take care of the high frequency switching components. Alternately, measure the noise with an oscilloscope as a check against the data sheet and use the larger of the values to determine required attenua-

tion. Once the needed attenuation has been determined, the graph and equations of Figure 12 can be used to complete the DM output filter design. Assume a value of 0.20 ohms for the ESR to determine the location of the zero associated with the tantalum capacitor. The natural frequency of the filter can now be determined by calculation from the transfer function plot and the equations. Figures 4, 5, and 6 may also be helpful.

The DM filter natural frequency should not be set inside the control loop band width of the power supply to avoid instability. This is because the output filter appears to the power supply as a series resonant circuit and will act as a crowbar on the output at its natural frequency. For most Interpoint power converters, use 25 kHz as the lower limit. For earlier products such as MTO, MHE, MLP, MTW, and MFW, the filter natural frequency can be set as low as 10 kHz. In cases where the above guidelines don't produce enough attenuation, an additional second order DM filter section can be cascaded with the first. In doing this, place the natural frequency of the second section one or more octaves above that of the first. Use a small Molyperm toroid for the inductor and make sure its core flux is well below the saturation level at maximum load.

Output filters using loosely coupled baluns to provide very low CM and DM noise levels have been discussed. These filters are applicable to any switching power supply where low output noise is a requirement. The user should be aware that the output filter may cause additional dynamic regulation or other errors, and should be careful to test for these effects before committing to a final design.
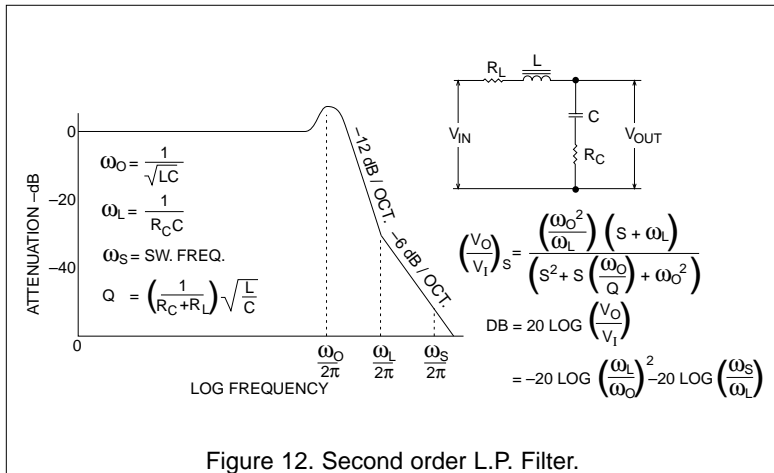

$$\omega_O = \frac{1}{\sqrt{LC}}$$

$$\omega_L = \frac{1}{R_C C}$$

$$\omega_S = \text{SW. FREQ.}$$

$$Q = \left(\frac{1}{R_C + R_L}\right)\sqrt{\frac{L}{C}}$$

$$\left(\frac{V_O}{V_I}\right)_S = \frac{\left(\frac{\omega_O{}^2}{\omega_L}\right)(S + \omega_L)}{\left(S^2 + S\left(\frac{\omega_O}{Q}\right) + \omega_O{}^2\right)}$$

$$DB = 20 \text{ LOG}\left(\frac{V_O}{V_I}\right)$$

$$= -20 \text{ LOG}\left(\frac{\omega_L}{\omega_O}\right)^2 - 20 \text{ LOG}\left(\frac{\omega_S}{\omega_L}\right)$$

Figure 12. Second order L.P. Filter.

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