

Output Filtering & Electromagnetic Noise Reduction

Application Note Assignment

14 November 2014

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Abstract

The motivation of this application note is to both review what is meant by electromagnetic noise and cover a number of filtering techniques employed in electronic devices. Measurement of both radiated and conducted emissions for the purpose of FCC approval will also be covered.

Keywords

electromagnetics, EMC, EMI, filters, ferrite, matching network, FCC

Contents

Introduction to Output Filtering	page 3
Introduction to Electromagnetic Noise Reduction	page 5
Capacitive, L-, T-, and PI-Filters	page 7
FCC and CISPR Regulations	page 10
Measurement of Radiated and Conducted Emissions	page 11
References	page 12

Introduction to Output Filtering

Output filtering is used in an enormous number of electronics, spanning DC/DC converters, inverters, power supplies, amplifiers, audio/video applications, and transducers of all varieties. This list of uses is non-exhaustive.

Electrical signals of all kinds go through a number of stages for the purpose of “conditioning” them from start to finish. In the case of an audio amplifier, for example, a digital file stored on a device is put through a digital-to-analog converter, then a pre-amplifier where it is prepared for amplification with minimal noise, brought to the gate of a biased transistor, and finally through an equalizer to balance the weight of different frequencies to produce a desired speaker output. In the described illustration, the equalizer is the final stage the signal travels through and represents the output filter. There are many options available to accomplish this, including the use of existing linear designs such as a Chebyshev, Butterworth, or elliptic filters (Figure 1), or an entirely new design. Each of these filters use a number of resistors, capacitors, and inductors, and can be cascaded for greater effectiveness in making a clean signal.

Output filtering is not limited to analog applications: it is used digitally as well. This can be done with a number of digital filtering techniques, such as a Lattice Wave filter whereby a series of addition, subtraction, and multiplication operations are combined with chosen coefficients to favor some frequencies over others (1).

In practice, output filters are used in more than just choosing a frequency from the audio band. They are also used to smooth out voltage ripple, clean a signal of harmonic distortion, and prepare a signal for the next stage. In the case of voltage ripple, an appropriately-sized capacitor across the output can charge and discharge in response to an alternating current to make a more uniform DC signal. One or more low- or band-pass filters may be used to stop higher frequencies and unwanted harmonics from making it through to the next stage. Conversely, a high- or band-pass filter could be implemented to only allow middle- and high-frequency signal through; this could be used just before a traditional speaker to prevent a DC-offset from causing over-excursion, which can be damaging.

Finally, output filtering can be used to prepare a signal for the next stage, such as when a DC voltage is stepped down before inversion. In building a DC/AC inverter, a DC input rail must oftentimes be stepped up or down using switching techniques. This process uses pulse width modulation to switch a supply on and off at tens of kilohertz that must be smoothed to create a relatively flat DC signal; the output filter in this design can potentially be very simple: one capacitor (2).

Many more output filters exist, which will be discussed later.

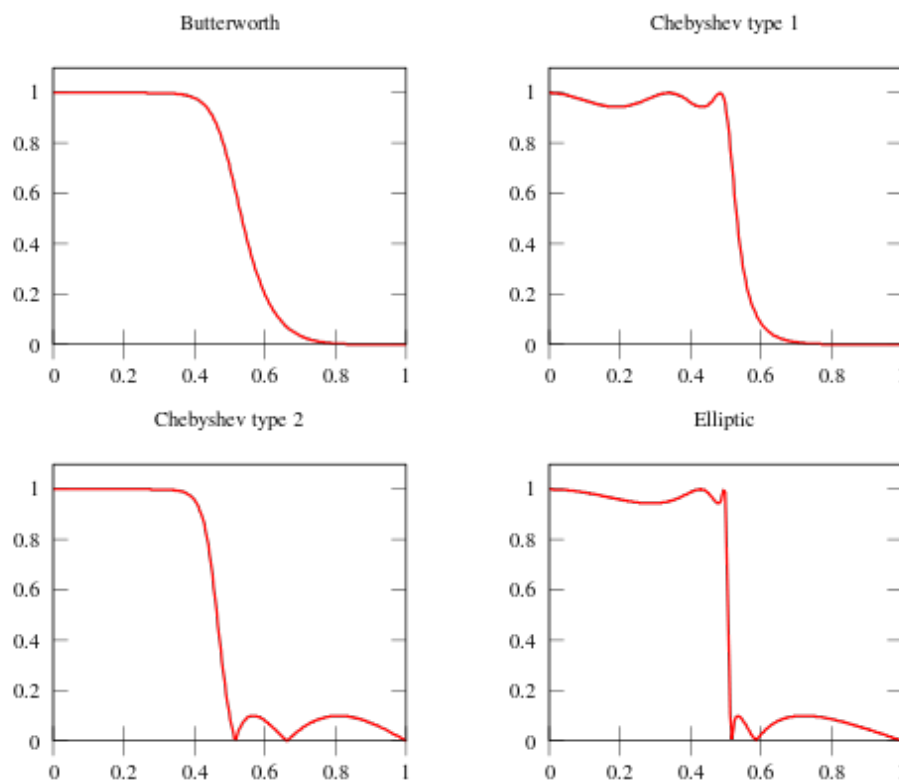


Figure 1: Butterworth, Chevyshev, and Elliptic Linear Filters

(http://en.wikipedia.org/wiki/Chebyshev_filter#mediaviewer/File:Electronic_linear_filters.svg)

Introduction to Electromagnetic Noise Reduction

Electromagnetic noise is an unfortunate byproduct of high speed circuitry that, if not properly dealt with, can interfere with the operation of other devices or even itself.

Electromagnetic interference, which occurs in the RF (radio frequency) spectrum (9 kHz - 300 GHz), that is strong enough can impose an electromagnetic field on part of a circuit. Antennas, ground planes, and long wires are all places on a circuit that are at risk of producing an electromagnetic-field-induced voltage; having unexpected voltages as a ground reference or on an antenna whose circuit is designed to amplify nano-volts poses obvious problems. Three non-filtering techniques of attenuating are the use of ferrite cores (Figure 2), deciphering common- and differential-mode currents, and employing shielding.

Ferrite cores are used by either being fit around a wire once or turning a wire around the core several times. Their characteristics include serving as a resistor at high frequencies and having little to no effect at DC- and low-frequencies (3). For this reason, they do well at serving as a low-pass filter and reducing electromagnetic noise. One of the benefits of using ferrite to reduce high frequency noise is that their effect, similar to a resistor, is compounded by adding multiple cores in series; this means that achieving greater attenuation in a desired frequency band is as simple as repeating the process. It is important to realize that different material make-ups of ferrite are better for attenuating some frequencies than others. For example, 15G material is best for attenuation frequencies from 10 - 100 kilohertz, while 75G acts on 400 kilohertz to 1.5 megahertz (4).



Figure 2, ferrite cores

Another option is the use of a ferrite bead, whose package include both wire and ferrite core and can simply be placed in series with an existing circuit.

Common- and differential-mode are two types of currents that may be present in a circuit. Common-mode includes current which are the same sign and polarity. The magnetic field produced by using these wires when near each other is added. Conversely, differential-mode currents may be in phase yet have opposite signs due to their orientation, meaning their fields are equal and opposite. The result of this arrangement is a cancellation of magnetic fields, which can pass through a choke unattenuated. Running common-mode currents through a choke, on the other hand, will double the attenuation, which is more effective at ridding the circuit of electromagnetic fields produced by high frequency signals (5).

Yet another method for reducing potential electromagnetic interference between devices is the use of shielding. Deciding on an adequate skin depth, which is the thickness of a conductor required for 8.7 decibels of reduction, is one design choice that must be made. Another is the material that will be used. It can be calculated using:

$$\delta = \sqrt{\frac{2\rho}{2\pi f\mu_R\mu_0}} \text{ (meters)}$$

where delta is skin depth, rho is resistivity of the material, f is the frequency of the material to be attenuated, mu_R is relative permeability, and mu_0 is the permeability of free space. As stated, for each skin depth that a shield is thick, another 8.7 dB reduction occurs at a specified frequency (6, 7).

Capacitive, L, PI, and T Filters

Many filter designs are in existence, and each carries its own set of benefits and drawbacks. They may require a large amount of math, be designed to minimize voltage ripple, have a very steep and coveted cut-off range, or be designed for the purpose of matching impedance for maximum power transfer. The filters discussed in this application note include single-capacitor, L-networks, T-networks, and PI-networks.

Capacitive filters are amongst the simplest to implement when trying to suppress high frequency noise. The basis of such a filter is to include a capacitor shorted to ground at the output of a circuit. The equation for impedance of a capacitor is:

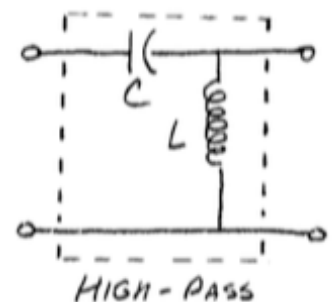
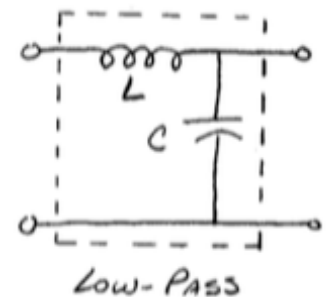
$$Z = 1 / j\omega C$$

where C represents the capacitance and ω is the frequency in radians. This means that as the frequency of a signal increases, the impedance of the capacitor drops. Higher frequencies signals will be split between the output load and the ground-shorted capacitor, preventing some (or most) high frequency noise from arriving at the output.

L-networks are similar to solely capacitive filters, with the exception of also including an inductor. This addition expands design choices by including its own impedance equation:

$$Z = j\omega L$$

Opposite the capacitor, the inductor, L, will have an increasing impedance with frequency, eventually appearing as an open circuit at very high frequencies. The combination of these circuit elements creates simple high- and low-pass filters depending on the arrangement (see right).

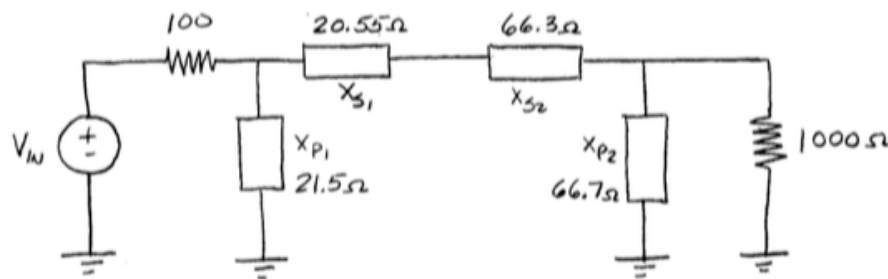


As an example, a 5-volt, 75 MHz signal is considered to be noise on a circuit, likely caused by harmonics created during the construction of a square wave. If a low pass L-network filter is built using a 10-ohm load, 1 mH inductor, and a 1 nF capacitor, their respective impedances at the given frequency will be 471239 and 2 ohms. Using current division, it is shown that nearly 5 amps passes through the capacitor to ground, while just 22 microamps go through to the load. At lower, more desirable frequencies such as those under 10 kHz, the opposite scenario occurs. The high frequency noise is attenuated and low frequencies are able to pass through to the load.

Yet another variation is the PI-network filter. An advantage of these filters is a high circuit Q, a circuit parameter which helps to outline the sharpness of the filter. Having a high circuit Q allows very specific frequency bands to be passed or stopped. This design uses 2 inductors and 2 capacitors to create a “virtual resistor” between input and output impedance for matching purposes. To begin the design, a number of equations are needed:

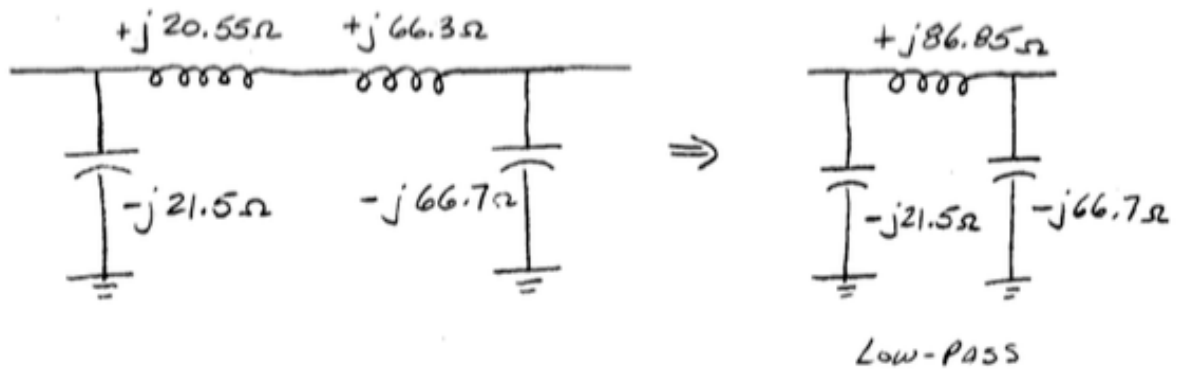
$$\begin{aligned}
 Q &= 2 * Q_0 \\
 R &= R_H / Q^2 + 1 \\
 Q &= R_L / X_{P2} = X_{S2} / R \\
 Q_{\text{left}} &= R_{TH} / X_{P1} = X_{S1} / R = \sqrt{(R_{TH}/R) - 1} \\
 Q_{\text{right}} &= \sqrt{(R_L/R) - 1}
 \end{aligned}$$

where Q is a filter parameter, Q₀ is the overall circuit Q, R is the virtual resistor, R_H is the resistor which is larger (either load or source), R_L is the resistor which is smaller, X_{P2} is the circuit element in parallel with the load, X_{S1} and X_{S2} are the circuit elements in series with the source and load resistance, R_{TH} is the resistance of the source, X_{P1} is the circuit element in parallel with the input voltage, and Q_{left} and Q_{right} determine the value of the filter parameter Q. An example source, matching filter, and load are shown below, and includes solved values:

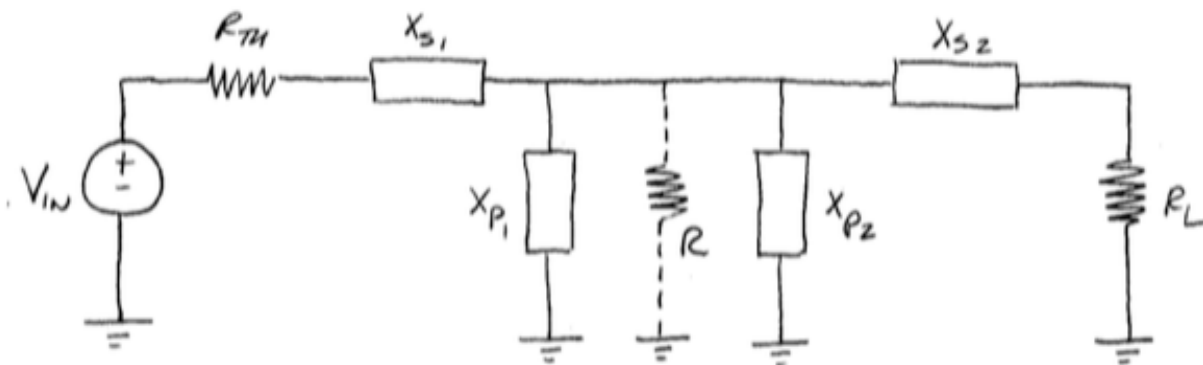


From here, the circuit element (inductor or capacitor) can be chosen for X_{S1} , X_{S2} , X_{P1} , and X_{P2} , to create either a low-, band-, or high-pass filter. Our likely choice is shown below:

DESIGN I



A T-network is similar to the previous filter with the exception of minor equation changes and a variation of the final filter layout, as shown:



The last two filters are especially useful when a high Q is required on top of needing the source to match the load (8).

FCC and CISPR Regulations

The Federal Communications Commission and Comité International Spécial des Perturbations Radioélectriques (CISPR) each have a set of rules laid out for handling electromagnetic radiation from high-speed circuits. These rules include that each device must accept any incoming radiation and also not interfere with other devices in the vicinity. One set of common regulations employed in the United States, FCC part 15, will be described.

The FCC defines radio frequencies to be signals which oscillate between 9 kHz and 3000 GHz; clocks and oscillators within this range are limited in how much power they can output in each range as not to disturb other devices as described previously (9). The limits imposed on these devices is split into commercial use, class-A, and residential use, class-B; commercial limits are more lenient as they are expected to be used in places where interference issues can be taken care of. The voltage limits of each class are laid out below, and varies between conducted (line) and radiated emissions:

FCC Conducted Emissions Limits (uV)		
Frequency	Class-A	Class-B
450 kHz - 1.705 MHz	1000 uV	250 uV
1.705 MHz - 30 MHz	3000 uV	250 uV

FCC Radiated Emissions Limits (dBuV/m) @ 3m		
Frequency	Class-A	Class-B
30 MHz - 88 MHz	49.5	40
88 MHz - 216 MHz	54	43.5
216 MHz - 960 MHz	56.5	46
960 MHz - 40 GHz	60	54

Measurement of radiated and conducted emissions

The measuring techniques required in order to sell electronic devices in the United States is outlined by the FCC. Different techniques are needed for measuring conducted and radiated emissions.

For conducted emissions, a LISN, or line-impedance-stabilization-network, is required. The AC power plug from the device being tested is inserted into the LISN, which generates voltages based on the current it receives at different frequencies for measurement purposes. These voltages can be used with a network analyzer to view which frequencies may be near or above the required limit.

Radiated emissions are a bit more complex. These require a calibrated antenna, semi-anechoic chamber or open field test site, and are measured from 10 meters away for devices aimed at passing class-A limits and 3 meters for devices aimed at passing class-B limits. Devices and antennas must be oriented with respect to each other to maximize power transfer, or display the worst case scenario conditions. The peaks from these signals are displayed on a network analyzer and measure electric, not magnetic, fields. The bandwidth of the receiver must be at least 100 kHz during measurement.

Finally, the FCC uses a method called “quasi-peak detection” instead of normal “peak detection”. This helps the test measure only continuous emissions at certain frequencies rather than sporadic peaks that seldom occur. This is because the signals which are considered most harmful are those which are notable and consistent (9).

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