THE GRAPHICAL ATTENUATION CALCULATION METHODOLOGY

This graphical technique for predicting the attenuation of a filter indicates possibilities for design improvement and is most useful in power line filter design.

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INTRODUCTION

A graphical technique for predicting the attenuation of a filter relies upon impedance paper and the use of several simple identities. This method can determine the attenuation of any multisection filter and gives the engineer an intuitive insight into both the operation of the filter and possibilities for its improvement. Although this method does not predict the effects of high "Q" resonances in the filter, it is most useful for power line filter design.

BACKGROUND

A filter operates as an impedance mismatching device. Different filter topologies and different combinations of source and load impedance for a given topology will result in different attenuations.[1] Virtually all manufacturers' data sheets give the attenuation performance of a filter for a resistive 50 Ω source and load impedance. When this filter is used with a switching supply which has a noise source impedance of anything but 50 Ω, the attenuation of the filter will vary significantly. While a computer circuit simulation will allow the prediction of the overall attenuation and the effects of parasitics on attenuation, it yields no information on either optimizing the efficiency of a filter or on designing to overcome the effect of parasitics. The graphical attenuation calculation aids the designer with both these problems.

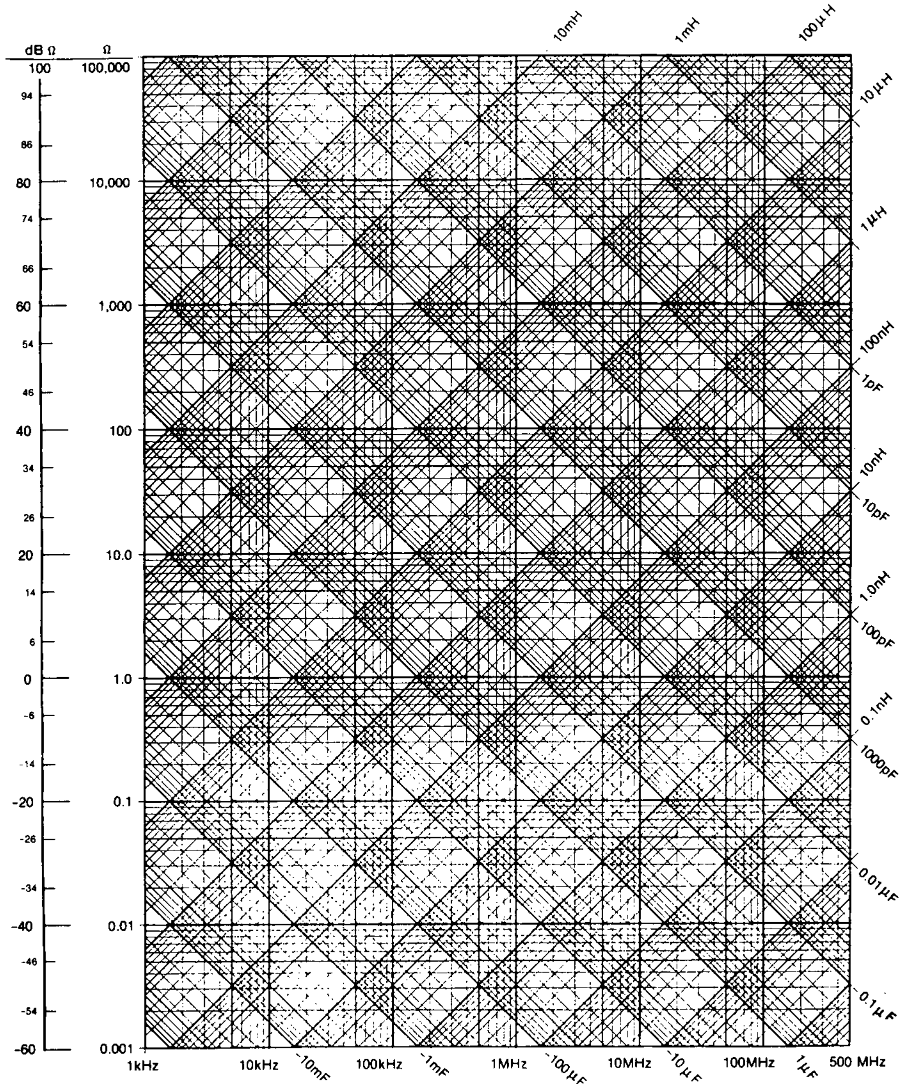

Figure 1. Impedance Paper

THE GRAPHICAL ATTENUATION CALCULATION METHOD

With the graphical attenuation methodology, a designer uses the concept of the single element filter and reactance paper to plot attenuation. The more complex filter topologies and may be reduced piece-by-piece to the simple series or shunt filter model by use of the sequential element theorem. Reactance paper has three variables plotted against a log-scale frequency axis: impedance (in units of ohms and dB ohms), capacitive reactance and inductive reactance. A sample of impedance paper is shown in Figure 1.

The basic concept behind the graphical method is to plot the filter element impedance and the reference impedance on a log scale. The reference impedance is Z_{sum} for a series filter element and Z_p for a shunt filter element. In terms of the source impedance, Z_s, and the load

* See Reply Card on Page 65

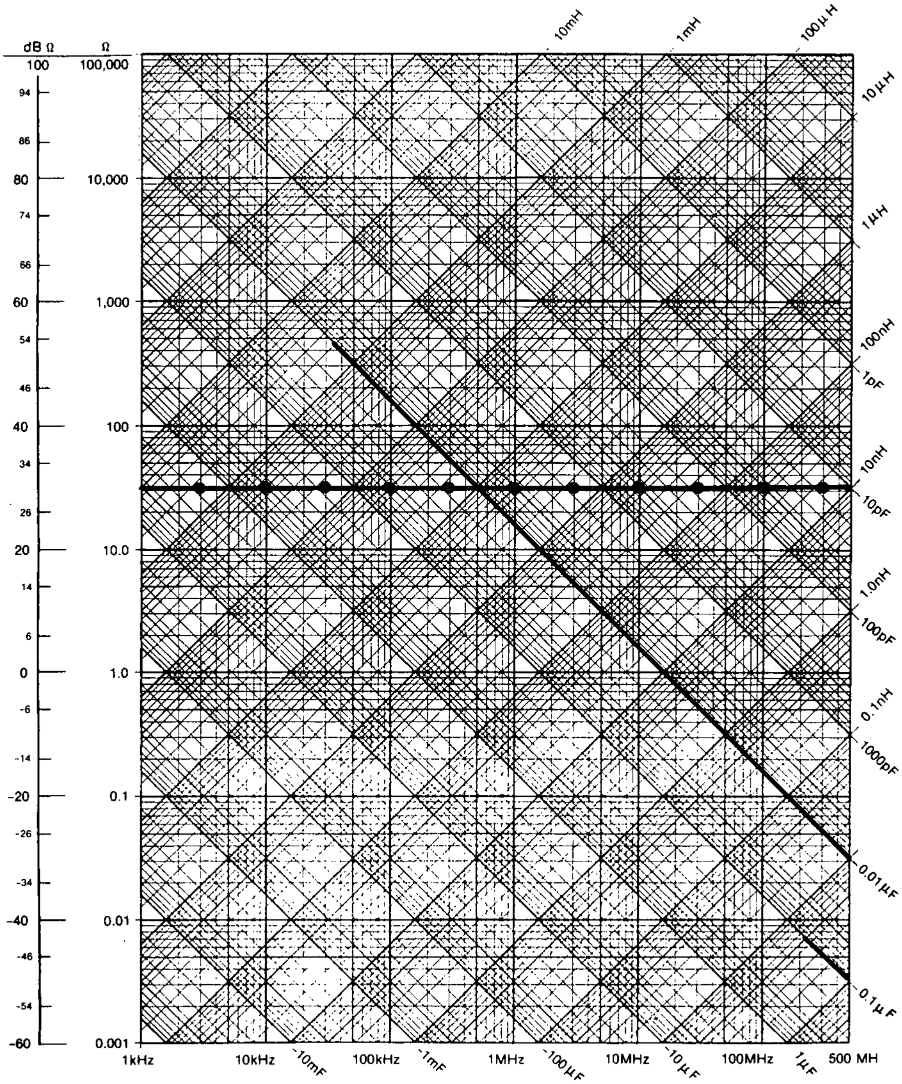

Figure 2. Graphical Attenuation Calculation for a Shunt Capacitor.

impedance, Z_l, $Z_{sum} = Z_s + Z_l$, $Z_p = Z_s//Z_l$. For a low pass filter, the shunt element of a filter is presumed to be a capacitor with an impedance of Z_{cap}. The series element is presumed to be an inductor, with an impedance of Z_{ind}.

By plotting the reference impedance and the filter element impedance, the impedance mismatch (and hence attenuation) can be read directly from the graph paper. A more rigorous explanation is possible by considering the expression[2] for attenuation for a shunt element filter.

$$A = 20 \text{ Log}_{10} [1 + Z_p/Z_{cap}] = 20 \text{ Log}_{10} [Z_p + Z_{cap}/Z_{cap}] \quad \textbf{(1)}$$

$$A = 20 \text{ Log}_{10} [Z_p + Z_{cap}] - 20 \text{ Log}_{10} [Z_{cap}] \quad \textbf{(2)}$$

Careful consideration of the above expression will reveal that as Z_{cap} becomes smaller, the attenuation increases. Also, as Z_{cap} becomes larger, the expression for attenuation approaches 0 dB. If an additional limitation is imposed, that the expression will only be valid for $Z_{cap} < Z_p$, an additional simplification may be made:

$$A = 20 \text{ Log}_{10} [1 + Z_p/Z_{cap}] \approx 20 \text{ Log}_{10} [Z_p/Z_{cap}] \quad \textbf{(3)}$$

which may be expressed as

$$A = 20 \text{ Log}_{10} [Z_p] - 20 \text{ Log}_{10} [Z_{cap}] \quad \textbf{(4)}$$

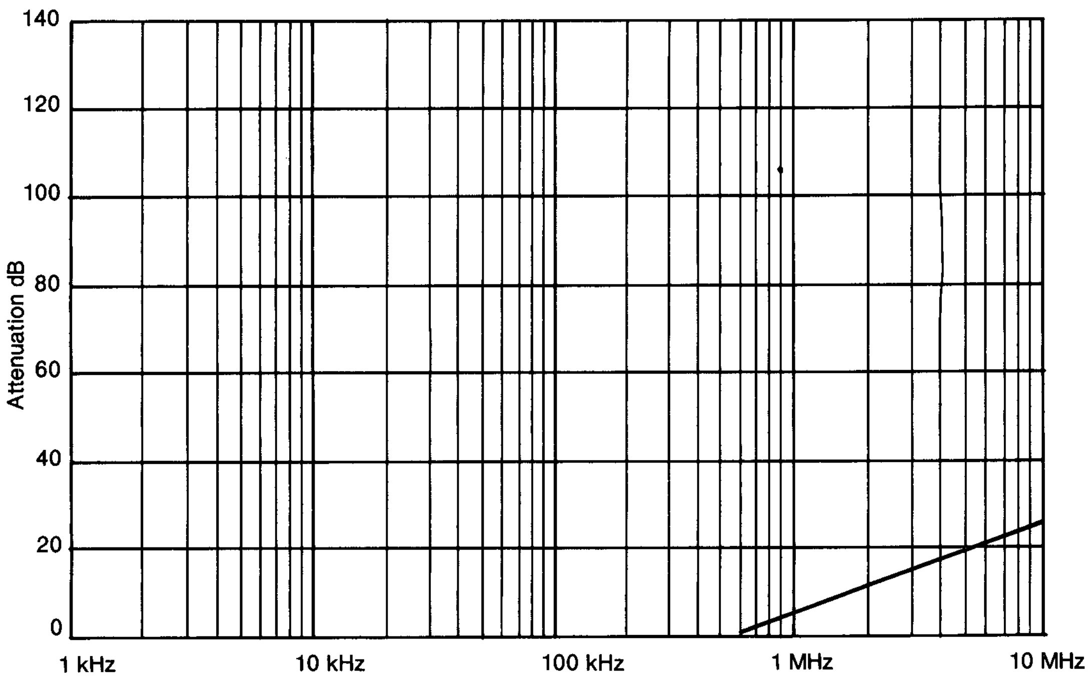

Figure 3. Plot of Attenuation for a 0.01 μF Capacitor in a 50 Ω System.

Above is the expression which allows direct use of the graphical attenuation method for a shunt capacitor.

A similar derivation for the expression of attenuation of a series inductor gives the result that

$$A = 20\,\mathrm{Log}_{10}\,[Z_{ind}] - 20\,\mathrm{Log}_{10}\,[Z_{sum}] \qquad \mathbf{(5)}$$

Again, for a series inductor, attenuation only occurs when Z_{ind} is greater than the reference impedance, Z_{sum}.

GRAPHICAL ATTENUATION FOR A SINGLE ELEMENT CAPACITIVE FILTER

Using impedance paper, one may employ the following method to estimate attenuation versus frequency.

1. Plot the source and load impedance on impedance paper (Z-paper).
2. Use a dotted line to mark the parallel combination (Z_p) of the source and load impedance.
3. Plot the impedance of the filter capacitor, (Z_{cap}), versus frequency.
4. The attenuation region due for shunt filter (Z_{cap}) is the region in which the filter impedance (Z_{cap}) is less than Z_p. The attenuation is approximately 20 Log $[Z_p/Z_{cap}]$ in this region.

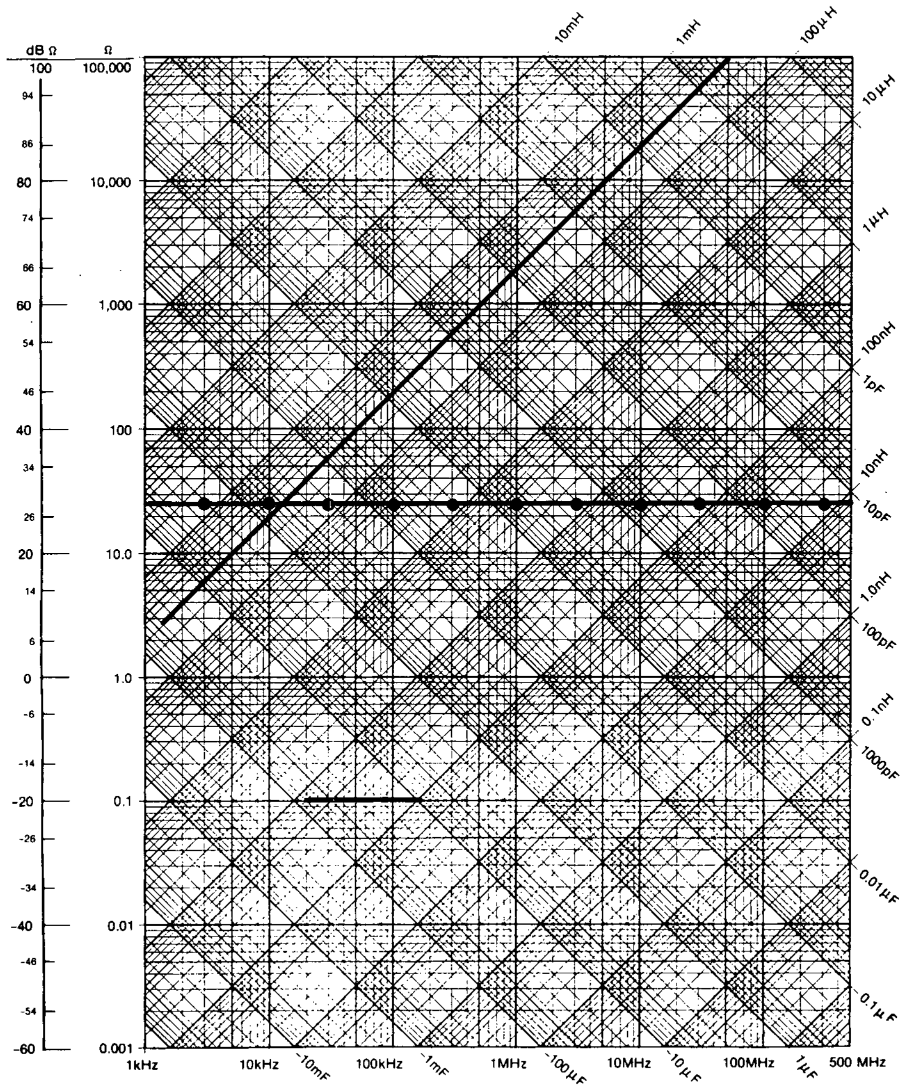

Figure 4. Graphical Solution to Common Mode Choke Attenuation.

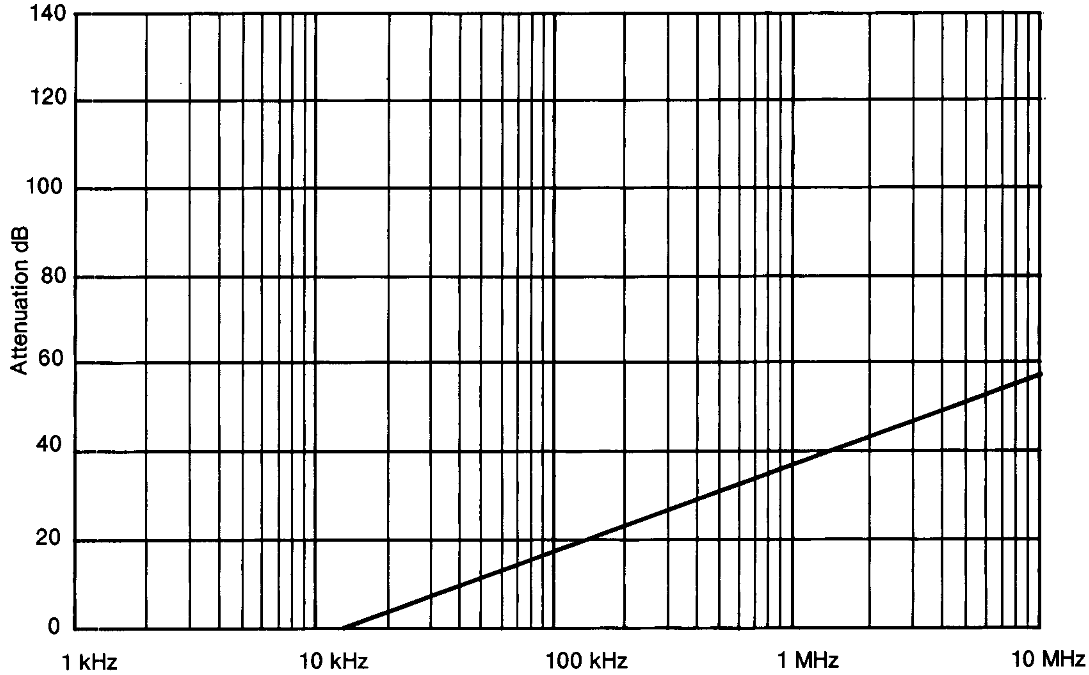

Figure 5. Plot of Attenuation for a Common Mode Choke.

Example Problem 1: Attenuation of a Shunt Capacitor in a 50 Ω System

An oscilloscope has a 50 Ω input. A 50 Ω coaxial cable is connected to the oscilloscope and to a homemade probe which has 0.01 μF shunt capacitance. The probe is used to monitor the output of a signal generator (50 Ω output impedance).

1. Calculate the attenuation due to the capacitance of the scope probe at 10 kHz and 10 MHz.
2. Calculate the attenuation at 10 MHz if the capacitance is 0.1 μF.

Solution:

(Part 1)

It is known that the attenuation for a shunt filter is

$$A_{dB} = 20 \text{ Log } [1 + Z_g//Z_l/Z_{cap}] \approx 20 \text{ Log } [Z_p/Z_{cap}] \quad \mathbf{(3\text{-}1)}$$

First mark Z_p (25 Ω) on the impedance paper then mark Z_{cap} = (0.01 μF) on the impedance paper. Reading off values of Z_{cap}, one finds

Frequency	Impedance	Attenuation
10 kHz	≈1700 Ω	$20 \text{ Log} \left[1 + \frac{25}{1700}\right] \approx 0$
10 MHz	≈ 1.8 Ω	$20 \text{ Log} \left[\frac{25}{1.8}\right] \approx 23$ dB

Likewise, one can read off the impedance (in dBΩ) of Z_{cap} and Z_p (also in dBΩ) from the Z-paper directly and can substract impedances to find the attenuation (Figure 2). This approach follows equation (4).

(Part 2)

From the Z-paper, the impedance of 0.1 μF at 10 MHz is ≈ 0.2 Ω, or −14 dBΩ. Z_p is 28 dBΩ. The attenuation is then 28 − (−14) = 44 dB. An exact solution is

$$A_{dB} = 20 \text{ Log } [1 + 20/0.18] = 43 \text{ dB}$$

A plot of the attenuation of the capacitor is shown in Figure 3.

GRAPHICAL ATTENUATION FOR A SINGLE ELEMENT INDUCTIVE FILTER

On impedance paper, one may use the following procedure to calculate the attenuation for a series inductor.

1. Plot the source and load impedance on Z-paper.
2. Using a dotted line, mark the sum of Z_g and Z_l (Z_{sum}).
3. Plot the inductive impedance versus frequency Z_{ind}.
4. The attenuation region due to the inductor, Z_{ind}, is the region in which Z_{ind} is greater than Z_{sum}. The attenuation is 20 Log [Z_{ind}] − 20 Log [Z_{sum}] in this region.

Example Problem 2: Attenuation of a Common Mode Choke

The common mode source impedance of a supply is determined to be 0.1 Ω at 100 kHz. The common mode impedance of the LISNs is 25 Ω. A 300 μH common mode choke is to be used as a filter. Calculate the attenuation at 100 kHz.

Solution:

The method for inductors is applied:

1. First plot the source and load impedance on Z-paper.
2. The reference impedance, Z_{sum}, is marked with a dotted line.
3. Plot the impedance of the 300 μH choke.
4. The attenuation at 100 kHz is

$$A_{dB} = 20 \text{ Log } [200\ \Omega] - 20 \text{ Log } [25\ \Omega] = 46 \text{ dB}\Omega - 28 \text{ dB}\Omega = 18 \text{ dB}.$$

The graphical solution is shown in Figure 4. A plot of attenuation versus frequency is shown in Figure 5.

GRAPHICAL ATTENUATION CALCULATIONS FOR MULTIPLE ELEMENT FILTERS

The Sequential Element Theorem results in a very slight modification of the technique. After using the sequential element theorem, the attenuation of each element is calculated separately. All of the individual attenuations are added together for the total attenuation.

SOLVING FOR ATTENUATION WITH PARASITICS USING THE GRAPHICAL ATTENUATION METHODOLOGY

One of the strengths of the Graphical Attenuation Calculation Methodology is the ease in which the effects of parasitics, the variation of permeability with frequency, and other non-idealities may be handled. The most common parasitics of interest are capacitor lead inductance and inductor parasitic capacitance. The key to accounting for parasitics is simply to modify the magnitude of the impedance of the filtering element to reflect the parasitics. Consider a 300 μH inductor with a shunt resistance of 100 pF. The impedance of the 300 μH choke will increase to roughly 2 kΩ before the 100 pF shunt capacitance begins to short out the inductor. As the net impedance becomes capacitive and decreases with increasing frequency, the attenuation is reduced accordingly. ■

REFERENCES

1. EMC Services Seminar notebook on "Filter Design for SMPS."
2. EMC Services, Inc., "Graphical Attenuation Calculations with Applications to Power Line Filters and Digital Interfaces."