Band pass filter design
Part 8. Compensating for inductor losses

1. Introduction

In Part 6 we looked at the effects of the inevitable losses in practical inductors. The higher circulating currents in the resonators towards the edges of the pass band cause increased power loss and a rounding of the frequency response. This Part presents a method for compensating for the degradation of the response caused by the inductor losses. The “q & k” design method is used, as described in Part 2 of this series. As will be seen, there is a price to be paid for the improved frequency response – the overall losses within the filter are deliberately increased.

2. Compensating for inductor losses

The losses in inductors can be compensated by a technique called “pre-distortion” which uses amended values for q & k. Tables of pre-distorted q & k values have been calculated for various inductor Q factors for a wide range of filter responses (Ref. 1). All of the inductors must have the same value and Q factor. It is unlikely that q & k values will be available for the Q of the inductor to be used, so the nearest tabulated Q value must be used or the values extrapolated. The tables also predict the overall loss of the filter.

The losses of the end resonators are absorbed into the input and output terminating resistors. In a two-resonator design this means that the pre-distorted values are the same as the standard q & k values. A two-resonator loss-compensated design was examined in Part 7.

The first filter we will examine is a three resonator Chebychev design with a pass band ripple of 0.1dB, with a centre frequency of 10MHz, a bandwidth of 500kHz using toroid inductors with an inductance of 1uH and a Q_L of 200. Chebychev designs with 0.1dB ripple are popular because of the almost flat response over the pass band.

Firstly we must calculate the value of the normalised unloaded resonator Qo which is given by:-

$$Qo = \frac{Q_L}{Q_{BP}}$$

where Q_{BP} is the ratio of the filter frequency to the 3dB bandwidth

$$Q_{BP} = \frac{Fo}{F_{3dBBW}}$$

If Q_L =200, Fo = 10MHz and F_{3dBBW} = 500kHz, then Q_{BP} = 20 and so Qo = 10.

Table 1 contains normalised values of q1, k12. k23 and q2 (from Ref. 1) for a three resonator filter with a Chebychev response and with a pass band ripple of 0.1dB. Seven different values for Qo are listed and so the Qo closest to the calculated value must be used.

Looking at the Qo column in Table 1, the closest tabulated value is 9.6. The predicted insertion loss is 3.2dB. The rest of the row gives the q1, k12, k23 and q2 values and are all that is necessary to design a pre-distorted filter. Notice that unless the filter is lossless, it is no longer symmetrical i.e. q1 is not equal to q2, and k12 is not equal to k23.

Qo	Insertion Loss (dB)	q1	k12	k23	q2
Lossless	0	1.4328	0.6618	0.6618	1.4328
28.7	0.9	1.2184	0.6539	0.6667	1.8511
14.3	2.0	1.1922	0.6311	0.6807	2.0522
9.6	3.2	1.1907	0.6029	0.6966	2.2158
7.2	4.6	1.2013	0.5703	0.7138	2.3595
5.7	6.2	1.2202	0.5329	0.7325	2.4887
4.8	8.2	1.2461	0.4897	0.7527	2.6045
4.1	10.8	1.2789	0.4380	0.7751	2.7052

Table 1. Lossless and pre-distorted q & k values for Chebychev 0.1dB 3-resonator filter

The calculations are shown below. Qo is 10 for the filter under consideration – the pre-computed tables have Qo = 9.6 as the nearest value and so the pre-distorted values for that Qo are used. A simple spreadsheet can be set up to make the calculations.

Parameter	Formula	Lossless	Q_L = 200
Fo	Filter centre frequency	10MHz	10MHz
F_{3dBBW}	3dB bandwidth	500kHz	500kHz
L	Chosen inductor value (all inductors)	1 uH	1 uH
Q_L	Inductor Q at Fo	Infinity	200
Q_{BP}	$Q_{BP} = Fo / F_{3dBBW}$	20	20
Qo	$Qo = Q_L / Q_{BP}$	Infinity	10 (9.6 used)
q1	*From Table 1*	*1.4328*	*1.1907*
k12	*From Table 1*	*0.6618*	*0.6029*
K23	*From Table 1*	*0.6618*	*0.6966*
q2	*From Table 1*	*1.4328*	*2.2158*
Cnode	$Cnode = 1/((2\pi\ Fo)^2\ L)$	253.3 pF	253.3 pF
R_{TERM1}	$R_{TERM1} = 2\pi\ Fo\ L\ Q_{BP}\ q1$	1,801 Ohms	1,496 Ohms
R_{TERM2}	$R_{TERM2} = 2\pi\ Fo\ L\ Q_{BP}\ q2$	1,801 Ohms	2,784 Ohms
Rs	$Rs = 2\pi\ Fo\ L\ / Q_L$	0	0.314 Ohms
Rp	$Rp = Q_L / (2\pi\ Fo\ Cnode)$	Infinity	12,566 Ohms
R1	$R1 = Rp\ R_{TERM1} / (Rp - R_{TERM1})$	1,801 Ohms	1,699 Ohms
C1	C1 = Cnode – C12	244.9 pF	245.7 pF
C12	$C12 = Cnode\ k12 / Q_{BP}$	8.4 pF	7.6 pF
C2	C2 = Cnode – C12 – C23	23.5 pF	236.8 pF
C23	$C23 = Cnode\ k23 / Q_{BP}$	8.4 pF	8.8 pF
C3	C3 = Cnode – C23	244.9 pF	245.7 pF
R2	$R2 = Rp\ R_{TERM2} / (Rp - R_{TERM2})$	1,801 Ohms	3,577 Ohms

Table 2. Formulae and component values for loss less and pre-distorted filter

The circuit diagram of the loss less filter, drawn using a SPICE simulator (Ref. 2) is shown in Fig 1.

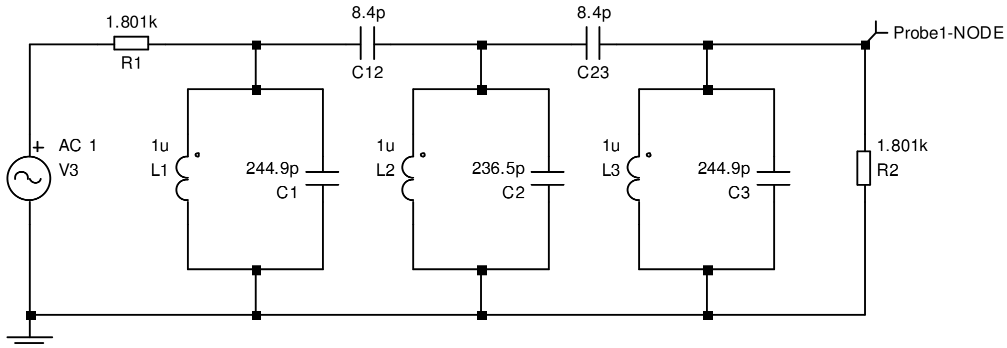
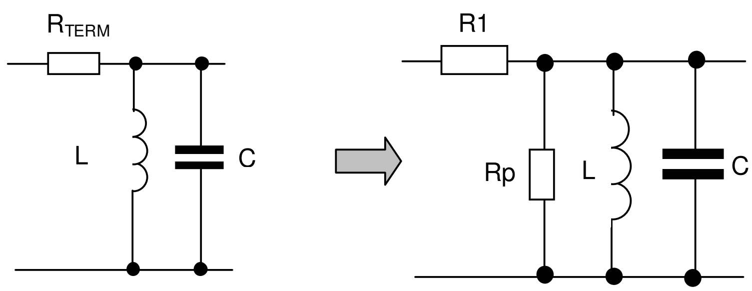


Fig. 1. Lossless filter

In Table 2, R1 and R2 are the input and output terminating resistors and the values have been calculated to give the required termination resistances when the loss resistances of the input and output resonators are taken into account – see part 6 of this series. The loss in an inductor can be represented by a series resistance Rs. When an inductor forms part of a resonator (or tuned circuit), then at the resonant frequency the loss can instead be represented by a parallel resistance Rp, with a value given by

$$Rp = \frac{L}{C\ Rs}$$

The filter requires specific input and output terminating resistances. This is made up by the parallel loss resistance of the input and output resonators in parallel with the actual physical input and output resistors



$$R1 = \frac{Rp\ R_{TERM}}{(Rp - R_{TERM})}$$

Fig 2. Compensation for loss in the end resonators

The final filter is shown in Fig 2.

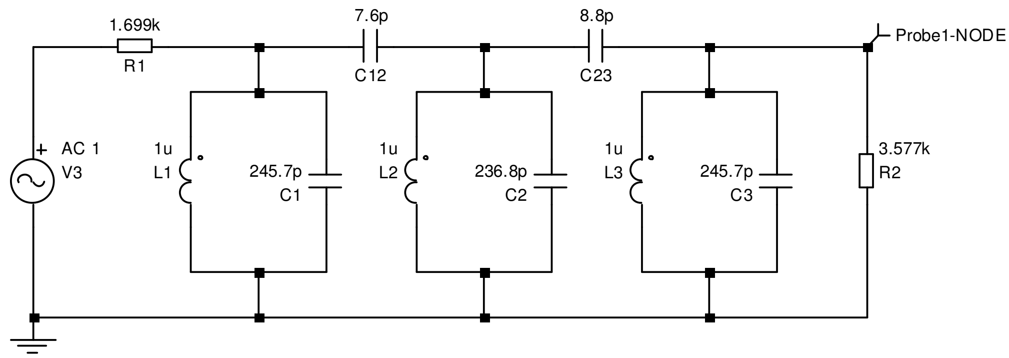


Fig. 3. Pre-distorted Chebychev 0.1dB filter for Q_L = 200

The insertion losses of the loss less filter in Fig. 1, the uncompensated filter and the compensated filter in Fig 2 are shown in Fig 3.

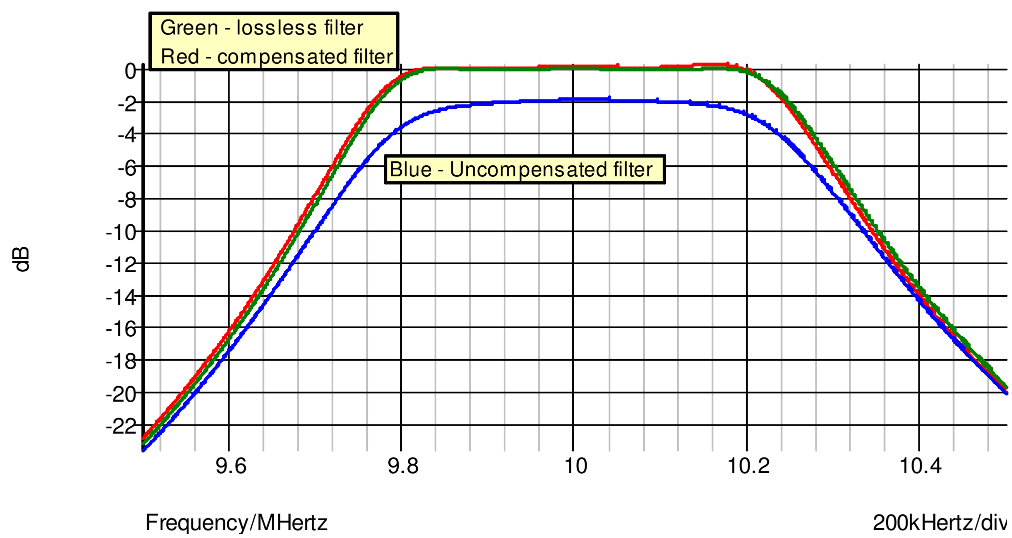


Fig. 4. Filter insertion losses

Fig. 4 shows that the response of the pre-distorted filter and it is almost identical to the loss less filter. The uncompensated filter has more loss and shows the rounded response towards the extremes of the pass band. Notice that the pre-distorted filter response is to all intents identical to the loss less design, yet the insertion loss is predicted to be 3.2dB. How can this be? The reason is simply that the terminating resistances are no longer equal and there is a voltage gain equal to the square root of these terminating resistors namely 3.0dB, so the difference is only 0.2dB.

3. Conclusion

The degradation of the frequency response of band pass filters caused by inductor losses can be compensated by pre-distortion. The output voltage of the pre-distorted filter may still be almost identical to that of a loss less design due to the higher output terminating resistance.

4. References

1. Anatol I. Zverev, "Handbook of Filter Synthesis", Wiley Interscience. This book was first published in 1967 and is regarded as a classic and is quoted as a reference in a great many articles about filter design. It is available new in paperback form. Personally, I find it quite hard going.

2. www.simetrix.co.uk An excellent free evaluation version of SPICE.