ARC Filters based on Lossy LC Ladder Prototypes

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Abstract: - The paper describes the new possibilities of synthesis method developed to goal–directed lossy ARC filter synthesis. If this new method is use, RLC filter ladder prototypes can be designed without any transfer function deviations due to finite quality factor of real filter elements. ARC filters based on goal–directed lossy RLC ladder prototypes then exhibit much better parameters then conventionally designed filters. Thus the new synthesis method enables to optimize ARC filter parameters. In some examples are here shown resulting parameters of designed filters with minimized element value spread, optimization of sensitivities, increasing of dynamic range and minimization of active elements (OAs) number.

Key-Words: - Filter, active, lossy, design, optimization, goal – directed lossy design, operational amplifier

1 Introduction

In the area of active RC (ARC), SC or digital filters are by filter design process very often used LRC ladder prototypes with regard to very low filter element sensitivities. On the other hand, these realizations have some disadvantages as attenuation in the pass-band, higher spread of element values in a case of one – sided terminated filters and above all requirement of an ideal lossless inductor and capacitor elements simulation.

The using of the lossy filter realizations with low number of active elements is possible only for low-Q (usually only low – pass) filters. However these filters exhibit many disadvantages as non-ideal magnitude response, relative high spread of element values and high decreasing of a dynamic range of active filter realizations. Classic LC ladder synthesis uses double-sided termination by resistors with equivalent resistance as internal source resistance and input resistance of the next block.

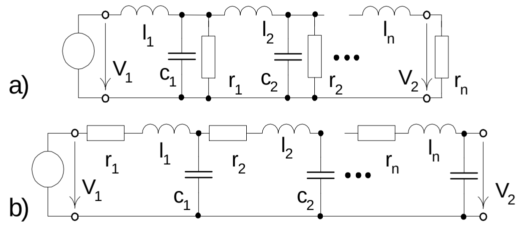
On the other hand, in the ARC filters are usually connected amplifiers with low output impedance as signal source and they are loaded by the high input impedance of the next amplifier. Consequently matching usually required and used by standard LC ladder prototypes and simulation of the ideal lossless L and C elements are not necessary in this case. The use of the LC ladder prototypes with spread losses to whole filter is preferable for ARC filters. Therefore in a last years were developed and published [4], [6] a new synthesis method witch enable to design goal–directed lossy LC prototypes which can be used very good to optimization process in area of active filter design.

2 The Goal – Directed Lossy LC Ladder Prototypes

In the circuit of any LC ladder filter there are many possibilities how to connect the dumping lossy resistors to LC structure. The main requirement is to select lossy structures with a simple and good function of ARC or ASC filters based on these prototypes. In the practice are used usually these structures:

1. Classical one-sided or double-sided terminated LC ladder prototypes with real lossy inductors and capacitors
2. Lossy ladder prototypes with spread of the losses of the inductors and capacitors :
   a) to parallel branches
   b) to serial branches
   c) to parallel and serial branches

First class of structures includes classical way with pre-correction of the real inductor losses for ladder with dominant losses in loading resistors. On the contrary to first group, the ladder filters from second group spread the necessary losses for definition of the Q-factor values of particular LC resonant circuits to resistors in whole ladder. By the active filter (ARC or SC) synthesis the LC ladder structures from Fig.1 are preferable, exhibit zero attenuation in pass-band, enable very easy to simulate ARC filters using generalised impedance converters (GIC) [2]. To date, it isn't known any analytical synthesis procedure for lossy prototype design, consequently to design of goal – directed lossy prototypes the programs SYNTLOSS using iteration synthesis process were developed [6]. The programs enable to design goal–directed lossy prototypes of standard approximation filter types to 10th filter order with losses spread to any branches (parallel, serial, or both - parallel and serial branches concurrently).



FFig. 1. Two modifications of the lossy ladder prototypes usable by active filter synthesis

Some examples of LC ladder lossy prototype parameters of the Bessel, Butterworth and Chebyshev approximation types in case of third, fifth and seventh filter order for different values of Q (lossy only in parallel branches – Fig. 1a) was ordered to the Tab. 1

Tab. 1 Normalized value prototype parameters

GOAL - DIRECTED LOSSY LC PROTOTYPES						
BESSEL	3	l	**1,3347**	**0,3014**	-	-
			1,2138	0,3107		
		c	**0,8968**	-	-	-
			0,9566			
	5	l	**1,2813**	**0,7318**	**0,1673**	-
			1,0798	0,7094	0,1731	
		c	**1,1403**	**0,4987**	-	-
			1,2762	0,5272		
	7	l	**1,2153**	**0,7546**	**0,4963**	**0,1084**
			0,9758	0,6877	0,4921	0,1120
		c	**1,1909**	**0,7281**	**0,3243**	-
			1,3892	0,7945	0,3400	
BUTTERWORTH	3	l	**1,2839**	**0,5257**	-	-
			1,0823	0,5553		
		c	**1,4780**	-	-	-
			1,6598			
	5	l	**1,1182**	**1,3123**	**0,3292**	-
			0,7830	1,2379	0,3524	
		c	**2,0793**	**0,9931**	-	-
			2,6193	1,1150		
	7	l	**0,9525**	**1,3819**	**1,0423**	**0,2384**
			0,5510	1,1361	1,0236	0,2564
		c	**2,4839**	**1,6934**	**0,7252**	-
			3,5788	2,0973	0,8091	
CHEBYSHEV	3	l	**1,4992**	**2,0081**	-	-
		c	**1,3255**	-	-	-
	5	l	**0,5242**	**2,6544**	**2,6743**	-
		c	**2,6227**	**1,6355**	-	-
	7	l	**0,6370**	**1,5815**	**1,8763**	**1,2866**
		c	**2,7040**	**2,5259**	**1,9218**	-
$Q_C = 10$ (5), $Q_L \rightarrow \infty$, $R_Z = 1\Omega$						

2 Optimization of LC Ladder Filter Parameters

The spread of LC values is very important parameter for filter realization, especially for integrated filters, minimization for lossless LC ladders was partly solved. Now the use of the lossy ladder prototypes brings new possibilities to further minimization of this spread. The values of spread coefficients k_L and k_C can be essentially minimized namely in the case of Bessel and also in the

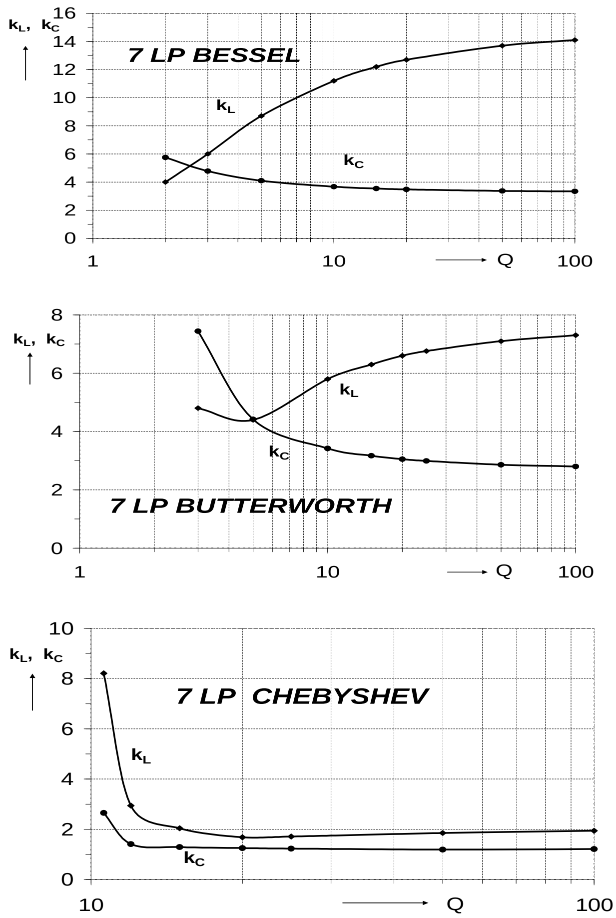


Fig. 2. The k_L and k_c spread coefficients in case of 7 nth order lossy filter prototypes

Butterworth approximation types (see Fig.2). On the other hand, in case of the Chebyshev approximation the spread of elements in comparison to classical (ideal elements) synthesis (Q infinitive) cannot be essentially diminished. For the Q values near of the minimum network required Q value, the spread of element value is increasing.

However in all cases (including Chebyshev filter types) the use of goal-directed lossy prototypes brings possibility to realize filters without any distortions due to finite Q factor of elements in frequency area as well as in time domain area how it is seen from an example in Fig.3. While filter responses of lossy design (Q factor defined Q = 15) are identical with ideal (Q factor of elements going to infinity), conventional designed filter exhibit great deviations. A comparison of the filter responses in time domain is evident from an example

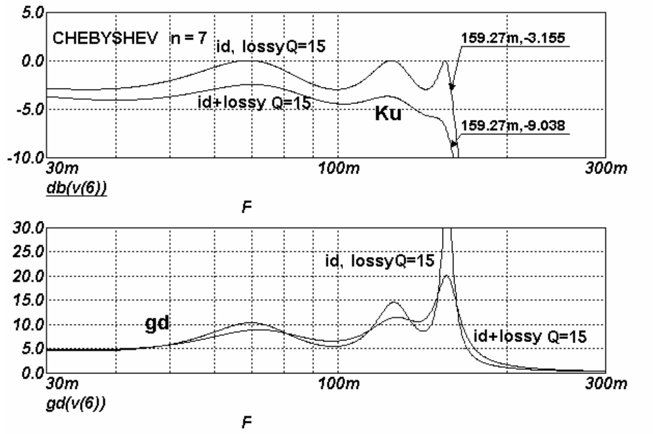


Fig. 3. The magnitude and group delay responses of the 7th order Chebyshev lossy filter prototype

of step responses of the Bessel filter in Fig. 6. The step response of lossy synthesized filter and ideal filter response are identical. The step response of the filter realized by classical way from ideal prototype (with real lossy elements) exhibits great distortion due to real lossy elements.

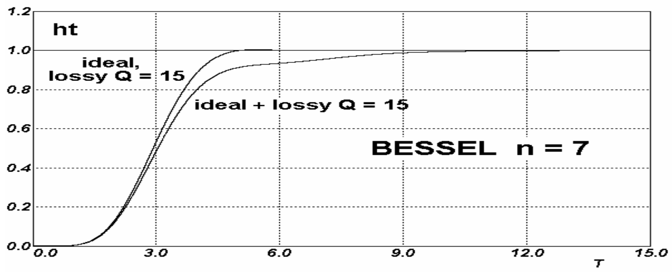


Fig. 4. The comparison of step responses of the 7th order Bessel filters

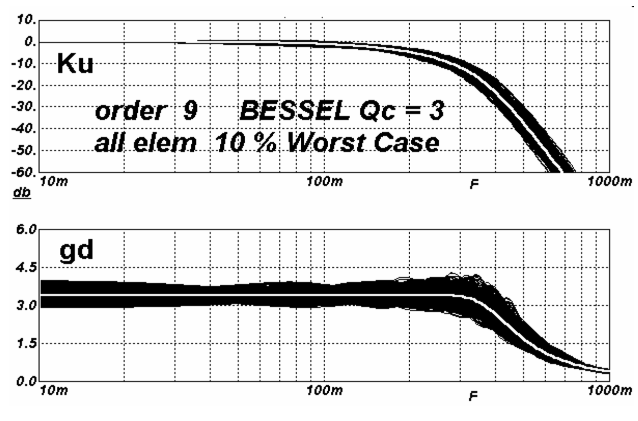


Fig. 5. The sensitivity analysis of the Bessel´s LP filter goal-directed lossy design

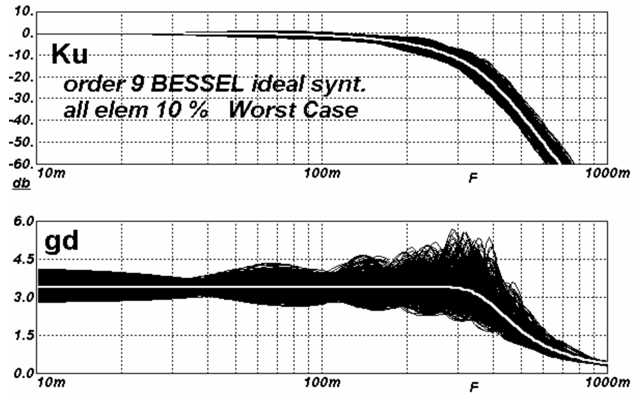


Fig. 6. The sensitivity analysis of the Bessel´s LP filter- conventional design

The results of sensitivity analysis declare, that filters designed using goal–directed lossy prototypes exhibit generally smaller sensitivity to changes of filter parameters then filters designed using loss–less prototypes. To comparison of sensitivity analysis here are presented results of sensitivity analysis using Monte Carlo (Worst Case) method in Fig. 5 and Fig. 6. How we can observe from figures, lossy designed filter exhibit much smaller sensitivity to changes of value parameters, the difference is very good seen namely from group delay curves comparison.

The goal–directed lossy prototypes can be used except above discussed low–pass filter types also to optimisation of other filter types as example of high – pass and band – pass filters using known filter frequency transformations. The resulting transfer response of an example of designed band–pass filter of Chebyshev´s type is presented in the Fig. 7. From the curves is clearly seen advantage of the goal lossy design (Q factor of inductors defined as Q = 20), with resulting transfer function without any deviations (transfer responses identical with pure ideal) in comparison to conventionally designed filter which exhibit great transfer response deviations.

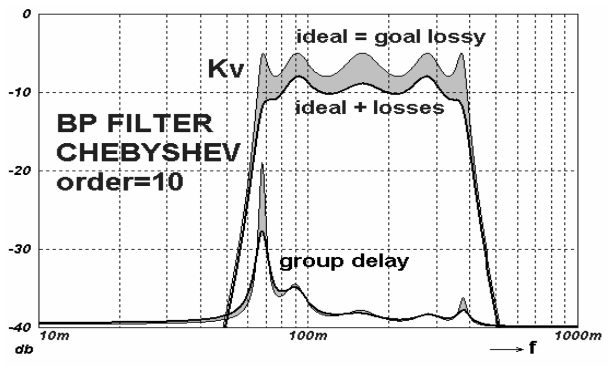


Fig. 7. The analysis of resulting responses of Chebyshev band-pass filters

3 ARC Filters Design by Lossy Ladder Prototypes

The design of Butterworth low – pass filter with corner frequency f_c = 10 kHz (filter order n = 5) is here presented as an example of the goal–directed lossy design. The circuit diagram of passive lossy LCR ladder prototype (Fig. 8a) was converted to active realization according Bruton´s transformation (Fig. 8b). As active elements the lossy GICs with one operational amplifier (with defined Q factor Q = 3) were designed.

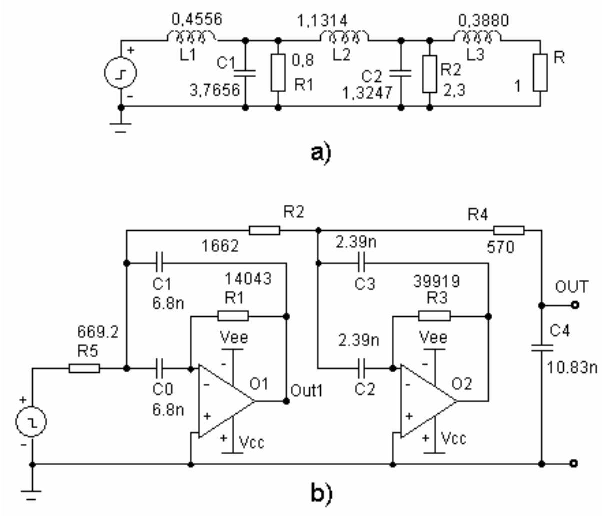


Fig. 8. The goal–directed lossy LP filter:
a) LRC ladder prototype, b) resulting ARC filter

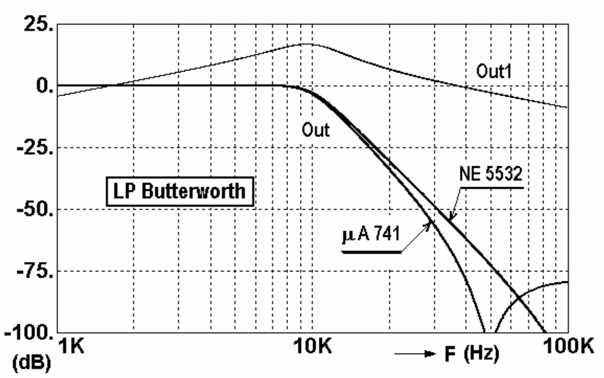


Fig. 9. The simulated response of ARC filter by use of different types of OAs

The selection of proper type of operational amplifier (with sufficient high GBW parameter) by filter design must be respected, how it was indicated using PC counter simulations (see Fig. 9), where low value of GBW causes a parasitic pole of resulting transfer response. Resulting measured transfer response of designed filter (Fig. 10) is fully agreeing with modeled responses. Further examples of lossy designed ARC filters of different orders were investigated in comparison to conventional designed filters. Except above discussed advantages the filters designed by goal – directed lossy prototypes exhibit also essentially better dynamic range then standard designed filters [6].

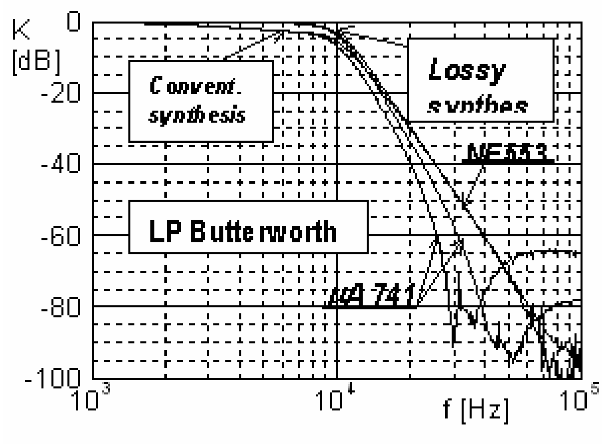


Fig.10. The measured response of ARC filter by use of different types of OAs

4 Conclusion

This contribution presents the new way to improving of ARC filters and further type of filters, based on LC ladder prototypes. The new synthesis method based on goal–directed lossy ladder prototypes is applied for proposed aim. Developed method of filter design enables minimization of element value spread, optimization of sensitivities, minimization of number of operational amplifiers (OAs) and increasing of dynamic range.

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