Load Impedance and Stepped Attenuators

By Milan Uskokovic

This article looks at the impact of input resistance on the accuracy and resolution of stepped attenuators.

For those of you who may still be unclear about the whole point of making your own stepped attenuators, let me begin by listing some of their most important advantages over logarithmic volume potentiometers:

- lower noise level
- longer wear and life span
- excellent channel matching in dual (stereo) implementation
- better approximation of the log function
- better quality/price ratio
- flexibility to suit individual application requirements

Although these are tangible benefits that outweigh the potential drawbacks (such as lower resolution), the performance and reliability of their final products still remain a major source of confusion and frustration for many DIYers. In my experience, the highest potential for things to go very wrong occurs when not giving due consideration to the issue of load resistance. The effect of the (pre-)amplifier's input impedance is all too often overlooked or not managed properly, and this is precisely what introduces errors in the accuracy and resolution of amateur-made attenuators.

The rest of this article examines this issue in greater detail and shows you through examples how it can be successfully dealt with in practice. The article offers guidelines for proper calculation of attenuation and resistor values for series- and ladder-type attenuators and provides you with an Excel spreadsheet program that, unlike other such programs, takes into account the load impedance of the circuit following the attenuator.

RESOLUTION AND ACCURACY

The realization that stepped attenuators operate as resistor voltage dividers (*Fig. 1*) is not a new idea. The output voltage (Vout) of the voltage divider, measured at the resistor Ry, is defined as:

$$Vout = Vin\,\frac{Ry}{Rx + Ry} \qquad (1)$$

However, this calculation is valid for idealized cases only, in which the input impedance (Rina) of the circuit following the attenuator is essentially infinite. In practice, this is not the case, and the value of impedance may be equal to or lower than that of the resistor Ry (*Fig. 2*).

As a result, the output voltage is lower than when there is no load on the attenuator and it can be calculated as:

$$Vout = Vin\,\frac{Ry\|Rina}{Rx + Ry\|Rina} \qquad (2)$$

FIGURE 1: Unloaded voltage divider.

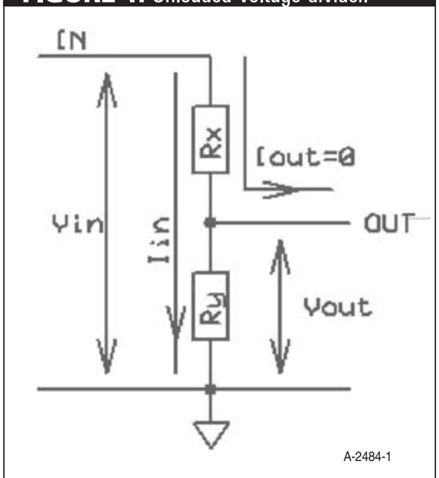


FIGURE 2: Loaded voltage divider.

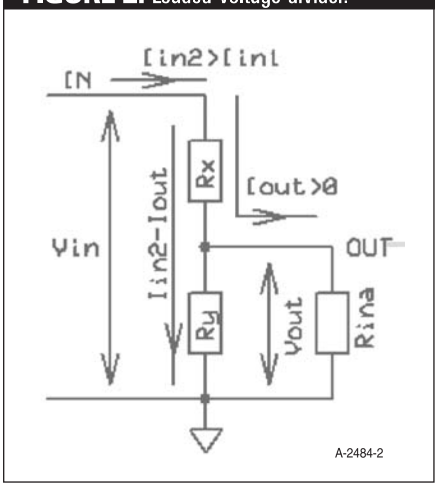
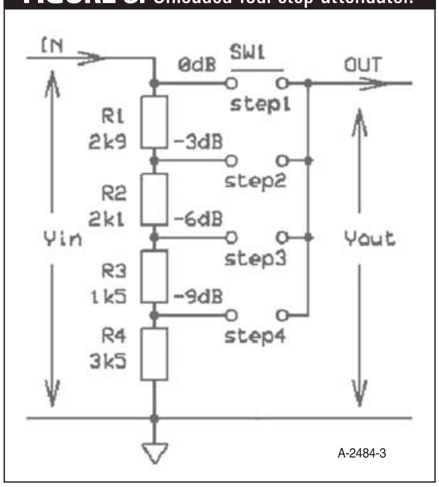


FIGURE 3: Unloaded four-step attenuator.



And here we come to an extremely important point, the one I raised earlier: It is absolutely critical that the input impedance (Rina, as defined by the above formula; usually an amplifier) also be figured in to avoid errors in the accuracy of resolution and attenuation calculations. Although there are two elements to input impedance, the real component (Rina) and the capacitive reactive component (Cina), you may safely omit the latter from the calculations because its effect on the attenuator accuracy in the audio bandwidth is negligible. The value of the component Rina is typically in the range of 1kΩ to 1MΩ.

I will use the four-step attenuator in *Fig. 3* to illustrate the error that may occur if the effect of the input impedance of the circuit following the attenuator is neglected. The assigned value of the total resistance (Rall) of the attenuator is 10kΩ, load impedance Rina is 10kΩ, and the steps are 0, –3, –6, and –9dB.

When the output of the attenuator is loaded with a resistance of, say, Rina = 10kΩ, the voltage on the output drops significantly below the desired value (*Fig. 4*).

The error per step is as much as 2dB in absolute terms (with the attenuation of –8dB for step 3, instead of the desired –6dB), while the maximum resolution error occurs between steps 1 and 2, and is 1.6dB.

It is evident that the attenuator accuracy becomes looser the lower the value of Rina, and that the effect of Rina on attenuator operation can be safely neglected only at values equal to or exceeding 10*Rall. Otherwise, it is of utmost importance that you consider the value of Rina when calculating resistor values (equation 2) in order to come up with the correct value of each individual resistor in the chain (*Fig. 5*).

The world's leading attenuator manufacturers, who are well aware of these considerations, specify Rina values for optimum performance of their products, often even providing spreadsheets for estimating errors should the product be loaded with a resistance value that is outside their specifications.

CALCULATION PROCEDURE

First, determine the nominal value

FIGURE 4: Accuracy and resolution error.

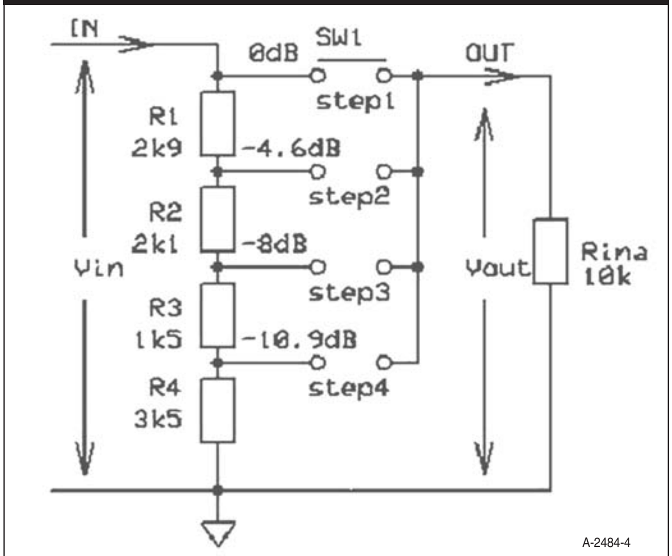
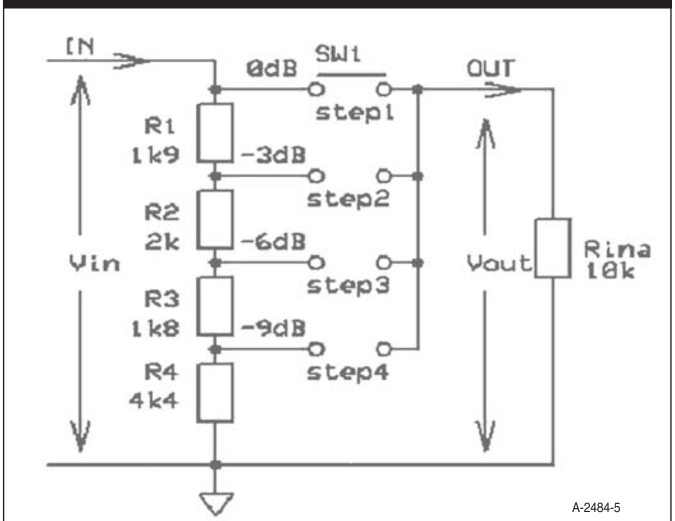


FIGURE 5: Correct resistor values.



of the attenuator Rall for a given value of Rina. In my experience, Rall should take on values between 10kΩ and 500kΩ, with the following condition holding:

5* Rina > Rall.

Thus, for the given value of Rina = 10kΩ, for instance, Rall looks to be between 10 and 50kΩ.

FIGURE 6: 24-step attenuator spreadsheet.

3	Ratt(kOhm)		Rina(kOhm)		Source Zout(kOhm)			
4	50		50,00		0			
5								
6								
7	Step	Sattn(dB)	Attn(k)	Rx		Rn(kOhm)	Rin(kOhm)	SinAtt(dB)
8	1	0	1,00	50,000	R1=	6,056	25,00	0,00
9	2	2	1,26	43,944	R2=	6,472	29,44	0,00
10	3	4	1,58	37,472	R3=	6,505	33,95	0,00
11	4	6	2,00	30,967	R4=	6,086	38,16	0,00
12	5	8	2,51	24,882	R5=	5,303	41,73	0,00
13	6	10	3,16	19,578	R6=	4,360	44,49	0,00
14	7	12	3,98	15,219	R7=	3,446	46,45	0,00
15	8	14	5,01	11,772	R8=	2,667	47,76	0,00
16	9	16	6,31	9,105	R9=	2,047	48,60	0,00
17	10	18	7,94	7,058	R10=	1,569	49,13	0,00
18	11	20	10,00	5,489	R11=	1,206	49,46	0,00
19	12	22	12,59	4,283	R12=	0,931	49,66	0,00
20	13	24	15,85	3,352	R13=	0,721	49,79	0,00
21	14	26	19,95	2,631	R14=	0,561	49,87	0,00
22	15	28	25,12	2,070	R15=	0,438	49,92	0,00
23	16	30	31,62	1,631	R16=	0,344	49,95	0,00
24	17	32	39,81	1,287	R17=	0,482	49,97	0,00
25	18	36	63,10	0,805	R18=	0,300	49,99	0,00
26	19	40	100,00	0,505	R19=	0,188	49,99	0,00
27	20	44	158,49	0,317	R20=	0,118	50,00	0,00
28	21	48	251,19	0,200	R21=	0,074	50,00	0,00
29	22	52	398,11	0,126	R22=	0,047	50,00	0,00
30	23	56	630,96	0,079	R23=	0,029	50,00	0,00
31	24	60	1000,00	0,050	R24=	0,050	50,00	0,00

A-2484-6

FIGURE 7: 12-step attenuator.

3	Ratt(kOhm)		Rina(kOhm)		Source Zout(kOhm)			
4	50		25,00		0			
5								
6								
7	Step	Sattn(dB)	Attn(k)	Rx		Rn(kOhm)	Rin(kOhm)	SinAtt(dB)
8	1	0	1,00	50,000	R1=	6,547	16,67	0,00
9	2	3	1,41	43,453	R2=	8,039	22,42	0,00
10	3	6	2,00	35,415	R3=	5,884	29,24	0,00
11	4	8	2,51	29,531	R4=	5,836	34,01	0,00
12	5	10	3,16	23,696	R5=	5,294	38,47	0,00
13	6	12	3,98	18,402	R6=	4,403	42,20	0,00
14	7	14	5,01	13,998	R7=	6,015	44,98	0,00
15	8	18	7,94	7,984	R8=	4,410	48,07	0,00
16	9	24	15,85	3,574	R9=	2,253	49,55	0,00
17	10	32	39,81	1,321	R10=	1,001	49,93	0,00
18	11	44	158,49	0,319	R11=	0,256	50,00	0,00
19	12	58	794,33	0,063	R12=	0,063	50,00	0,00
20	13	100	100000,00	0,001	R13=	0,000	50,00	0,00
21	14	100	100000,00	0,001	R14=	0,000	50,00	0,00
22	15	100	100000,00	0,001	R15=	0,000	50,00	0,00
23	16	100	100000,00	0,001	R16=	0,000	50,00	0,00
24	17	100	100000,00	0,001	R17=	0,000	50,00	0,00
25	18	100	100000,00	0,001	R18=	0,000	50,00	0,00
26	19	100	100000,00	0,001	R19=	0,000	50,00	0,00
27	20	100	100000,00	0,001	R20=	0,000	50,00	0,00
28	21	100	100000,00	0,001	R21=	0,000	50,00	0,00
29	22	100	100000,00	0,001	R22=	0,000	50,00	0,00
30	23	100	100000,00	0,001	R23=	0,000	50,00	0,00
31	24	100	100000,00	0,001	R24=	0,001	50,00	0,00

A-2484-7

You must now define the number of steps (preferably 24, but a cheaper 12-step version would also do nicely) and determine the attenuator resolution. Although the resolution of any step is adjustable to suit personal preferences, 2dB should normally be enough for the positions most frequently in use during operation (i.e., typically the mid-section), whereas the resolution of the low-volume steps may be coarser (*Fig. 6*).

Enter the data in column Satt(n) of the spreadsheet to calculate the right resistor values for each individual step of the attenuator (Column Rn).

Since resistors come in only standard values, each calculated resistor value will need to be approximated to the nearest value on the E96 list.

Column Rin gives the value of the total resistance that the attenuator presents to the signal source at a given attenuation step. When you enter the value of output resistance of the source device in column SourceZout, column SinAtt calculates the value of additional attenuation generated by the low, yet significant, output resistance of the source.

When you use the spreadsheet for attenuators with a smaller number of steps (12, 14, 16, and so on), enter a sufficiently large value (say, 100dB) in column Sattn(dB) fields for the steps that are not being used. It is important to note that you must choose the same value for all unused steps, as in the case of the 12-step attenuator shown in *Fig. 7*.

The results from column Rin reveal that the input resistance value of the attenuator/amplifier can vary greatly, depending on the switch position, and that it falls with decreasing attenuation. Although the literature and Internet resources available on the subject often characterize series attenuators such as this as presenting constant resistance to the source, it is worth noting that this holds true only if Rina > 10*Ratt.

You may use the spreadsheet (which you can download at www.audioXpress.com) for ladder-type attenuator calculations. In that case, only the second line is used to calculate resistor values by separately entering appropriate attenuation values for each step. Similarly, you

FIGURE 8: Ladder attenuator—"2dB" step.

3		Ratt(kOhm)		Rina(kOhm)	Source Zout(kOhm)			
4		50		50,00		0		
5								
6								
7	Step	Sattn(dB)	Attn(k)	Rx		Rn(kOhm)	Rin(kOhm)	SinAtt(dB)
8	1	0	1,00	50,000	R1=	6,056	25,00	0,00
9	2	2	1,26	43,944	R2=	43,944	29,44	0,00
10	3	100	100000,00	0,001	R3=	0,000	50,00	0,00

A-2484-8

FIGURE 9: Ladder attenuator—"6dB" step.

3		Ratt(kOhm)		Rina(kOhm)	Source Zout(kOhm)			
4		50		50,00		0		
5								
6								
7	Step	Sattn(dB)	Attn(k)	Rx		Rn(kOhm)	Rin(kOhm)	SinAtt(dB)
8	1	0	1,00	50,000	R1=	19,033	25,00	0,00
9	2	6	2,00	30,967	R2=	30,967	38,16	0,00
10	3	100	100000,00	0,001	R3=	0,000	50,00	0,00

A-2484-9

will need to enter a sufficiently large value (100dB) in column Sattn(dB) for the steps 3 through 24 (*Figs. 8* and *9*).

CONCLUSION

You must take into account input impedance of the circuit following the attenuator when designing stepped attenuators in order to avoid errors in attenuator accuracy and resolution. Otherwise, these errors may be so significant as to render useless all the work and resources put into the purchase of high-precision resistors for the project. Also, give due consideration to the proper calculation of steps in case of attenuators with fewer steps (for example, 12), because they have a greater likelihood of error than 24-step attenuators, as well as in cases in which the input impedance of the circuit following the attenuator is lower than the total resistance of the attenuator (Rall).

The Excel spreadsheet is a simple program intended to assist in the calculation of correct resistor values and attenuations. It is available for download at www.audioXpress.com, and may be customized to suit personal preferences. aX

Milan Uskokovic *has a Master's degree in electrical engineering and 15 years of experience in designing and building professional audio and video production and post-production systems for broadcasting. Currently, he is working as the chief technical officer at Croatia's Radio 101 and is a licensed project engineer for audio studios, post-production, and sound reinforcement systems.*

[You can find the spreadsheet program for Milan Uskokovic's article on our website (www.audioXpress.com). —Eds]