P1000 TX Application Circuit Description- Line Coupling Circuit

Don Whitney
Plan 9, Inc.
1 Mar 2021
18 Aug 2022

The following is a description of the derivation of the application circuit component values as well as some suggested configurations. The description will discuss the components needed for the P1000 transmitter and the line coupling/interface circuitry for various standards. This APP Note describes how to size the line coupling components to work with standard requirements and possible loading conditions.

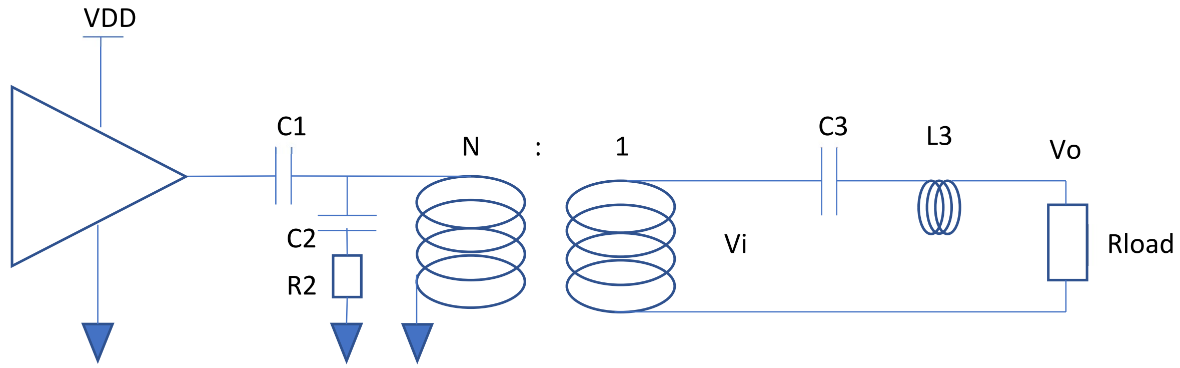
The Line Coupling Circuit

There are several functions of the Line Coupling Circuit. Unfortunately, there are constraints by Standards, application space, and component manufacturers. Here is a list of the functions/goals-

1) Connect the Line Driver to the Line
2) Isolate the low voltage from the high voltage domains
    a. The transformer isolates the high voltage from the low voltage
3) Reduce the 50 or 60Hz mains signal at the low voltage circuitry
    a. Provided primarily by the C3 and the transformer HV Secondary inductance.
4) Provide band shaping of the output signal where necessary.
    a. Primarily C3, L3, and the Load. C1, XFMR also have a role.
5) Results in band shaping of the input signal
    a. C3, L3, Load
6) Optimize the power / overhead voltage / signal level to provide highest signals at lowest power
    a. Line driver supply, XFMR ratio
7) Comply with requirements and standards
    a. C3 is limited by VAR loading on the line
    b. TX Line signal and out of band noise maximum levels
8) Work with component non-idealities
    a. Transformers have inductance leakage which will attenuate the signal at higher frequencies
    b. Attenuation with low impedance loads due to series resistances of the XFMR and other components
9) Protect against surges (discussed in another section)

For this application, only number 3,4, and 5 will discussed. The line interface gain makes a difference to other considerations, so it should be determined first. The challenge is to provide the most signal transfer at various loads, even down to 1 Ohm, without having to increase the signal level. That is difficult; however, solutions for certain standards can be optimized and this paper illustrates a systematic way of deriving component values. Of course, there might be some room for optimization over the course of determining the rest of the components.

The standard schematic for the Line Coupling (without) protection looks like the Figure below.



Steps to take to design a line interface circuit-

1) Determine the maximum value of C3
2) Determine bandwidth/Standards requirement
3) Adding a HV section BPF filter to help shape the band to better fit the standard, if necessary.
4) Determine transfer function of Line Coupling Circuit
5) Understand transformer properties (another app note)
6) Balance the Vout, Vload, transformer ratio, signal levels, and line driver temperature rise. Perhaps iterate. (another app note)

1) Determine C3

This cap value is determined not by the desired low pass filter characteristics, but by the amount of reactive load the PLC modem circuit will place on the electrical mains source. Compliance to this limit is required. Below is derivation of the equation to calculate it.

$$Power_{reactive} = VAr = \frac{Vrms^2}{\frac{1}{2\pi * freq * C3}}$$

There is a maximum reactive power (VAr), so rearranging the equation, we get-

$$VAr \geq \frac{Vrms^2}{\frac{1}{2\pi * freq * C3}}$$

Solving for the C3

$$C3 \leq \frac{VAr}{Vrms^2 * 2\pi * freq}$$

Here is a table of possible C3 capacitance maximum values-

Max VAr	Vrms	Frequency	Cap Value
10	240	50	5.53E-07
10	120	60	1.84E-06
10	240	60	4.61E-07

2) Bandwidth Requirements

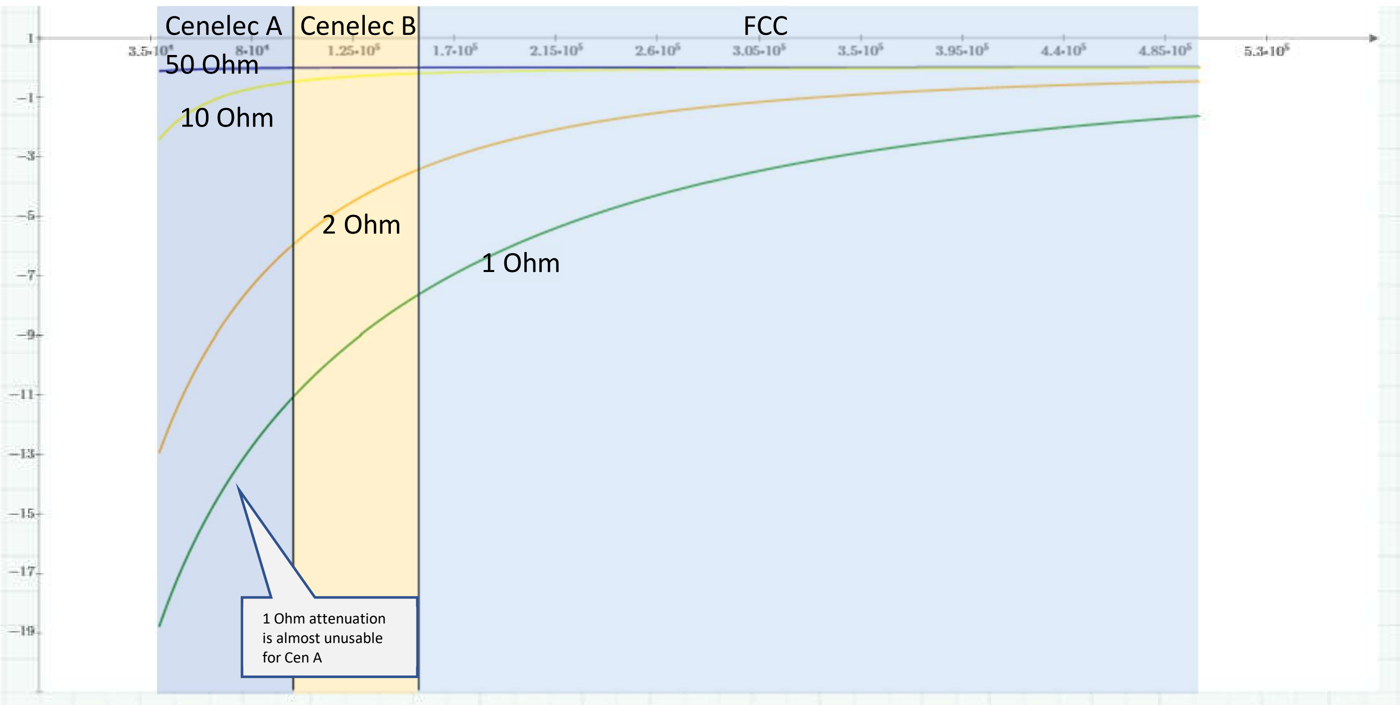
Given the upper limit of the C3 capacitance and the load value range, and not using L3 yet, calculate the High Pass Filter on the HV side using the below equation.

$$F3dBHPF = \frac{1}{2\pi * C3 * Load}$$

The Cutoff frequency is shown below.

Load	Cap	Cutoff Freq
50	4.70E-07	6.77E+03
10	4.70E-07	3.39E+04
2	4.70E-07	1.69E+05
1	4.70E-07	3.39E+05
50	2.20E-07	1.45E+04
10	2.20E-07	7.23E+04
2	2.20E-07	3.62E+05
1	2.20E-07	7.23E+05

The graph below shows some of the results of just the C3 cap and the Load for the Celelec A, Celelec B, and the FCC range. As you can see the transfer functions for 1 Ohm and 2 Ohm load has large attenuation, especially in Cenelec A and B. The attenuation renders the configuration without the inductor L3 practically useless for low loads for all standards. In addition, without some consistency over the load impedance, the driver set to drive the 1 Ohm load could be overdriving the 50 Ohm load and exceeding the signal density specifications.



3) Adding HV BPF Filter

To improve the RC high pass filter cutoff frequency, the addition of an inductor (L3) to turn the RC LPF into a 2nd order LRC BPF can decrease the high pass filter pole and shift the center frequency to reduce the attenuation of the low frequency signals. The cost is additional attenuation at the high frequency side (since it is a Band pass filter), but with some work, a balance can be achieved.

$$Gain = \frac{\frac{Rload}{L3} * s}{s^2 + \frac{Rload}{L3} * s + \frac{1}{L3 * C3}}$$

$$fcenter = \frac{1}{\sqrt{L3 * C3}} * \frac{1}{2 * \pi}$$

$$fbw = \frac{Rload}{L3} * \frac{1}{2 * \pi}$$

$$f_{-3dB}, f_{3dB} = \frac{1}{2\pi} * \frac{1}{\sqrt{L3 * C3}} * \left(\sqrt{1 + \left(\frac{1}{2 * \frac{L3}{Rload} * \frac{1}{\sqrt{L3 * C3}}} \right)^2} \mp \frac{1}{2 * \frac{L3}{Rload} * \frac{1}{\sqrt{L3 * C3}}} \right)$$

Using the above equations and the bands for several standards, the values for L3 and C3 are determined for each load (1, 2, 10, 50 Ohms). As the load becomes smaller, C3 wants to increase, but it is limited by the max C3 calculation. Thus, L3 can be the only variable. The goal is to improve the 1 Ohm and 2 Ohm BW and Gain since they are the limiting cases. Determining L3 to maximize the BW at 1 Ohm while keeping the Center frequency in the center of the standards band is what is shown on the far right of the chart. Picking the 1 Ohm case for each standard will guarantee that the BW of any of the higher load will only yield a larger bandwidth centered at the same Center Frequency. The values will have to be adjusted for commercially available inductors and capacitors.

						This L is dependent on the BW and Load	This C is dependent on the previous L and the Center Freq	Max Cap is dependent on the max reative load VAr	Max or cal	Current BW using L needed	New Center Freq using Lneeded and Cap used			Change L to comply with C limits and keep the original Center Freq	New BW using New L3 can C limit			Since L is the smallest for the 1 Ohm case, the BW is only larger for the higher R loads, choose New L and "Cap used" for design.	
BAND	**Lower**	**Upper**	**Bandwidth**	**Center**	**Load**	**L needed**	**Cneeded**	**Max Cap**	**Cap used**	**Bandwidth**	**Center Freq**	**Lower**	**Upper**	**New L3**	**New BW**	**New Lower**	**New Upper**	**CAP C3**	**Inductor L3**
Cenelec A	35900	90000	54100	62950	50	1.47E-04	4.35E-08	4.70E-07	4.35E-08	54100	62950	35900	90000	1.47E-04	54100	35900	90000		
Cenelec A	35900	90000	54100	62950	10	2.94E-05	2.17E-07	4.70E-07	2.17E-07	54100	62950	35900	90000	2.94E-05	54100	35900	90000		
Cenelec A	35900	90000	54100	62950	2	5.88E-06	1.09E-06	4.70E-07	4.70E-07	54100	95707	68657	122757	1.36E-05	23405	51248	74652		
Cenelec A	35900	90000	54100	62950	1	2.94E-06	2.17E-06	4.70E-07	4.70E-07	54100	135350	108300	162400	1.36E-05	11702	57099	68801	4.70E-07	1.36E-05
Cenelec B	98000	154000	56000	126000	50	1.42E-04	1.12E-08	4.70E-07	1.12E-08	56000	126000	98000	154000	1.42E-04	56000	98000	154000		
Cenelec B	98000	154000	56000	126000	10	2.84E-05	5.61E-08	4.70E-07	5.61E-08	56000	126000	98000	154000	2.84E-05	56000	98000	154000		
Cenelec B	98000	154000	56000	126000	2	5.68E-06	2.81E-07	4.70E-07	2.81E-07	56000	126000	98000	154000	5.68E-06	56000	98000	154000		
Cenelec B	98000	154000	56000	126000	1	2.84E-06	5.61E-07	4.70E-07	4.70E-07	56000	137707	109707	165707	3.39E-06	46883	102558	149442	4.70E-07	3.39E-06
FCC	154000	487000	333000	320500	50	2.39E-05	1.03E-08	4.70E-07	1.03E-08	333000	320500	154000	487000	2.39E-05	333000	154000	487000		
FCC	154000	487000	333000	320500	10	4.78E-06	5.16E-08	4.70E-07	5.16E-08	333000	320500	154000	487000	4.78E-06	333000	154000	487000		
FCC	154000	487000	333000	320500	2	9.56E-07	2.58E-07	4.70E-07	2.58E-07	333000	320500	154000	487000	9.56E-07	333000	154000	487000		
FCC	154000	487000	333000	320500	1	4.78E-07	5.16E-07	4.70E-07	4.70E-07	333000	335802	169302	502302	5.25E-07	303344	168828	472172	4.70E-07	5.25E-07
ARIB	10000	450000	440000	230000	50	1.81E-05	2.65E-08	4.70E-07	2.65E-08	440000	230000	10000	450000	1.81E-05	440000	10000	450000		
ARIB	10000	450000	440000	230000	10	3.62E-06	1.32E-07	4.70E-07	1.32E-07	440000	230000	10000	450000	3.62E-06	440000	10000	450000		
ARIB	10000	450000	440000	230000	2	7.23E-07	6.62E-07	4.70E-07	4.70E-07	440000	272943	52943	492943	1.02E-06	312438	73781	386219		
ARIB	10000	450000	440000	230000	1	3.62E-07	1.32E-06	4.70E-07	4.70E-07	440000	386000	166000	606000	1.02E-06	156219	151890	308110	4.70E-07	1.02E-06

4) Determine Transfer Function

The goal is, of course, is the lowest loss over the entire band of interest given that the curves will not all be flat over the entire band. Using the above filter equation which includes the C3 cap, the possible addition of L3, and the load, Rload, the total gain at any specific frequency can be calculated. The integration of the magnitude of this transfer function over the applicable frequency range and normalized is the suggested figure of merit. The average gain ranges from 0 to 1 (V/V) and is a reasonable figure of merit of how good the overall transfer function is.

Below is the figure of merit equation-

$$AVGgainHVBPF(fql, fqh, Rload, C3, L3) := \frac{\int_{fql}^{fqh} \left| \left(\frac{C3 \cdot Rload \cdot (1j \cdot 6.2832 \cdot fq)}{C3 \cdot L3 \cdot (1j \cdot 6.2832 \cdot fq)^2 + C3 \cdot Rload \cdot (1j \cdot 6.2832 \cdot fq) + 1} \right) \right| dfq}{fqh - fql}$$

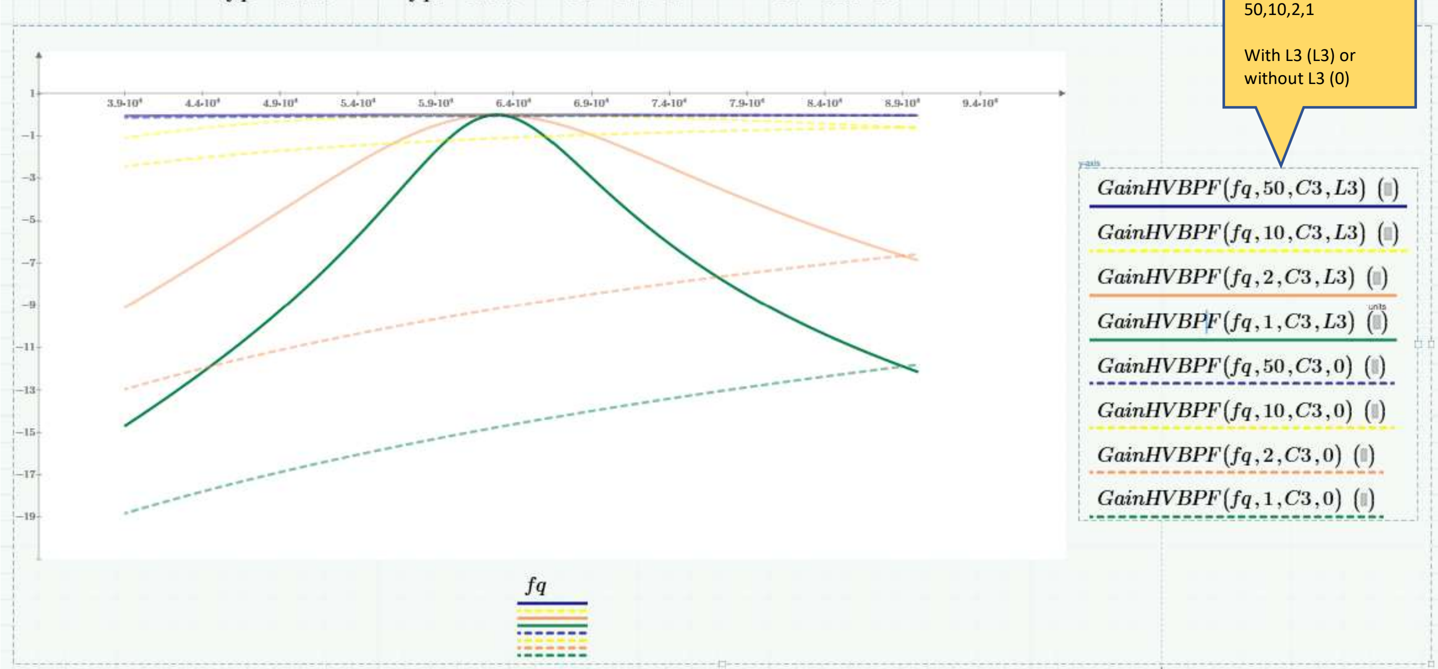
Fqh- Standard upper frequency in Hz
Fql- Standard lower frequency is Hz

Also, to compare how good each solution is for all four load conditions (50, 10, 2, 1 Ohms), all four results are added together as another figure of merit. The perfect score is a 4. Below are plots of just the RC HPF and the LRC BPF Gain vs. frequency for the four load conditions. Cenelec A, Cenelec B, and FCC standards are included.

Cenelec A L3=13.6uH (calculated in previous section)

Solid lines are with L3 (BPF) and dashed are without (HPF).

$fql := 39000$ $fqh := 90000$ $C3 := 470 \cdot 10^{-9}$ $L3 := 13.6 \cdot 10^{-6}$



The average filter transfer function in V/V and the totals are shown below:

LOAD IN OHMS	HPF WITHOUT L3 FOM	BPF WITH L3 FOM	COMMENTS
50	**0.99**	**1**	
10	**0.87**	**0.97**	
2	**0.35**	**0.69**	***Significantly improved***
1	**0.19**	**0.5**	***Significantly improved***
TOTAL OF 4 FOM	**2.4**	**3.16**	

For the Cenelec A configuration, the addition of the L3 inductor makes a significant difference. The gains are much more consistent and usable.

Cenelec B L3=3.4uH

Solid lines are with L3 (BPF) and dashed are without (HPF).

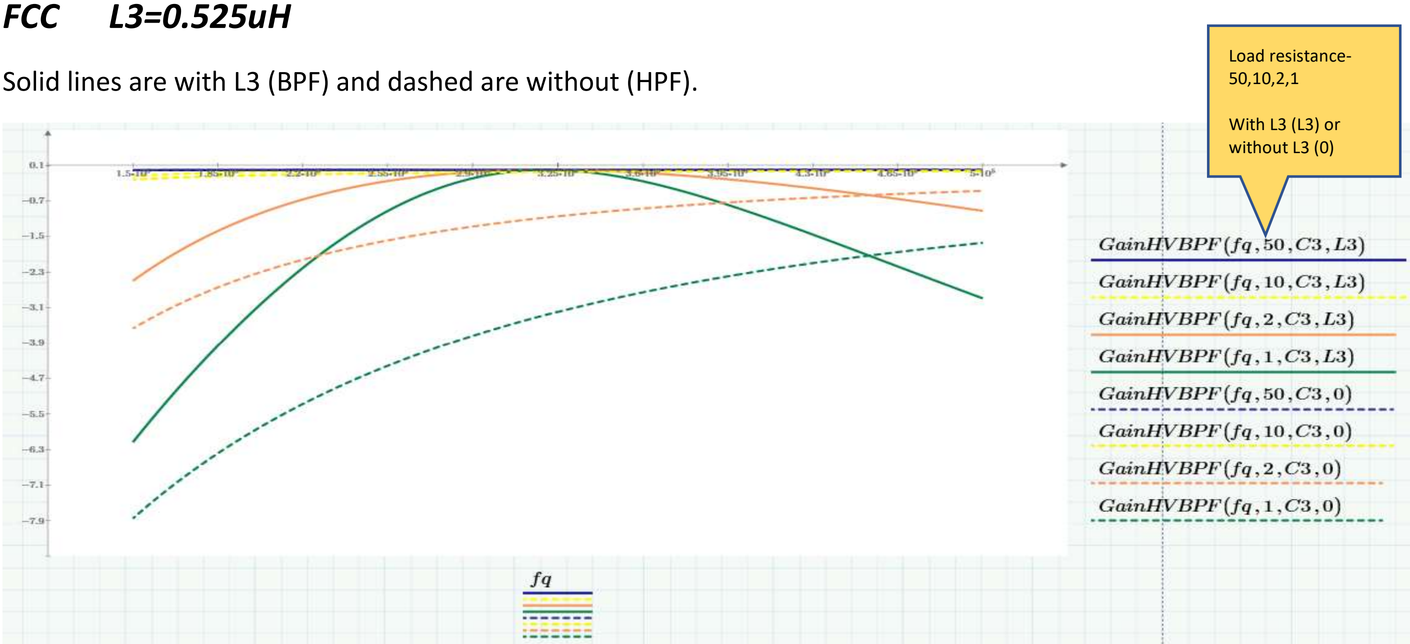
The Component Transfer function in V/V

LOAD IN OHMS	HPF WITHOUT L3 FOM	BPF WITH L3 FOM	COMMENTS
50	**1**	**1**	
10	**0.96**	**1**	
2	**0.59**	**0.95**	***Significantly improved***
1	**0.35**	**0.85**	***Significantly improved***
TOTAL OF 4 FOM	**2.90**	**3.79**	***Significantly improved***

Again, a significant improvement in average gain at lower impedance loads.

FCC L3=0.525uH

Solid lines are with L3 (BPF) and dashed are without (HPF).



The Component Transfer function (c used in below spreadsheet)

LOAD IN OHMS	*HPF WITHOUT L3 FOM*	*BPF WITH L3 FOM*	*COMMENTS*
50	***1***	***1***	
10	***0.99***	***1***	
2	***0.86***	***0.95***	***improved***
1	***0.66***	***0.85***	***improved***
TOTAL OF 4 FOM	***3.52***	***3.80***	***improved***

The addition of L3 for the FCC version helps, especially at a 1 Ohm load. The leakage inductance of the transformer is close to this value of L3 and it might provide some or all the band shaping and an additional L3 is not needed. Cost might be an issue also, so the final solution depends on various factors.

Conclusion

Given the messy reality of most line connections, an optimized solution is needed to achieve the signal level goals. Such is life. However, with these above tools, potentially a better solution can be obtained. Given that C3 is limited by capacitive loading requirements, then L3 can be added to create a bandpass filter and thus shape the pass band frequency response to provide for a higher average gain through the line coupling circuit.