

Design of active power filter for narrow-band power line communications

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Abstract. In power line communication (PLC), couplers such as coupling transformers and band-pass matching coupling circuits are usually required for coupling, band-pass filtering, and impedance matching. However, the cost and size of transformers prevent them from being an economic and compact solution for PLC couplers. In addition, passive band-pass matching coupling circuits need accurate impedance matching and possibly incur power losses. In this paper, a 6th order multiple feedback (MFB) active power filter with the minimum number of components was designed for narrow-band PLC, which has high input impedance and low output impedance, allowing outstanding performance in main voltage isolation, suppressing the current-harmonics and compensating the reactive power simultaneously. Finally, simulations were conducted in the range of 95 kHz-125 kHz (CENELEC “B-band”), which confirmed that the new filter met the CENELEC requirements for transmission and disturbance levels.

1 Introduction

Power line communication (PLC) is one of the most economical solutions to data transmission, as it utilizes existing power lines as the communication medium. As an environmentally friendly, cost-effective, and energy-efficient communication strategy, PLC technology has been widely used in smart grids, such as automatic meter reading[1], grid monitoring[2], smart home[3], etc.

However, due to the extremely noisy environment of power line channel, data communication over power line may be difficult. Since supply current and communication signal exist in the same power line channel, the quality and reliability of PLC are always interfered by high-order harmonic or pulse jamming caused by non-linear end electric devices. As a band-pass filter (BPF), PLC coupler is usually required for allowing the communication signal to pass through as much as possible while filtering out band noises and main voltages.

The coupling transformer and band-pass matching coupling circuits are two typical kinds of PLC couplers. Among them, coupling transformer design [4-6] involves so many parameters, which make coupling transformer fabrication an imprecise and experimental procedure. For the more, the cost and size of transformers prevent them from being an

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economic and compact solution for PLC couplers. In addition, band-pass matching coupling circuits[7-9] are often fabricated by passive components, which need accurate impedance matching and possibly incur power losses.

In this paper, for overcoming these problems an active power filter was designed for suppressing the current-harmonics and compensating the reactive power simultaneously. The active power filter is a Butterworth filter using a multiple feedback topology which has a fairly flat pass-band characteristic and a relatively sharp attenuation outside the pass-band. It should be noted that although the new active filter design focuses on the CENELEC B band (95 kHz-125 kHz) as an example, the same principles will hold for any of the CENELEC bands.

2 CENELEC requirements and typical analog filters

2.1 CENELEC band allocation

The European PLC standard was approved by CENELEC, which divides frequency (3 kHz-148.5 kHz) into four different sub-bands, and provides maximum transmission and disturbance levels for different bands when transmitting data over power line. Table 1 lists the PLC frequency bands and their maximum transmission and disturbance levels [10].

Table 1. The maximum transmission and disturbance levels.

Bands	Frequency range(kHz)	Maximum Transmission Level(dBuV)	Maximum Disturbance Level(dBuV)
A	3-95	134-120	89-75.5
B	95-125	116	75.5-65.97
C	125-140	116	75.5-65.97
D	140-148.5	116	75.5-65.97

CENELEC-A band is exclusively for utility providers and the other three (CENELEC-B, C, D) bands are open for end user applications. In this paper, an active power filter was designed based on the CENELEC B band (95 kHz-125 kHz).

2.2 Review of typical analog filters

2.2.1 Multiple-Feedback filter topology

Multiple-Feedback (MFB) topology is one of the simplest circuits with the minimum number of components, which is often implemented with 2th order response for single operational amplifier. Figure 1 is a 2th order MFB band-pass filter.

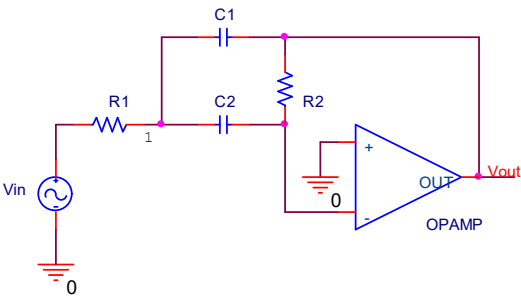


Fig. 1. 2nd Order MFB band-pass filter.

The standard form for transfer function[11] of all 2th order band-pass filters is

$$H(j\omega) = H_0 H_{BP}(j\omega) = H_0 \frac{(j\omega / \omega_0) / Q}{1 - (\omega / \omega_0)^2 + (j\omega / \omega_0) / Q} \quad (1)$$

where Q is quality factor, ω_0 and H_0 are the resonant frequency and resonant gain, respectively.

As shown in figure 1, node equations can be expressed as Eq.(2) and Eq. (3).

$$V_{out} = -sR_2C_2V_1 \quad (2)$$

$$\frac{V_{in} - V_1}{R_1} + \frac{V_{out} - V_1}{1/sC_1} + \frac{0 - V_1}{1/sC_2} = 0 \quad (3)$$

According to Eq. (2) and Eq. (3), the transfer function of this MFB band-pass filter is illustrated in Eq. (4)

$$H(j\omega) = \frac{V_{out}}{V_{in}} = \frac{-j\omega R_2C_2}{1 - \omega^2 R_1R_2C_1C_2 + j\omega R_1(C_1 + C_2)} \quad (4)$$

Comparing Eq. (4) with Eq. (1), the proper filter characters can be obtained when designing a MFB band-pass filter.

$$\begin{cases} H_0 = \frac{-R_2 / R_1}{1 + C_1 / C_2} \\ Q = \frac{\sqrt{R_2 / R_1}}{\sqrt{C_1 / C_2} + \sqrt{C_2 / C_1}} \\ \omega_0 = \frac{1}{\sqrt{R_1R_2C_1C_2}} \end{cases} \quad (5)$$

In order to simplify the calculation, equation $C_1 = C_2 = C_0$ is usually assumed established. The Eq. (5) can be expressed as Eq. (6).

$$\begin{cases} H_0 = -2Q^2 \\ Q = \frac{\sqrt{R_2 / R_1}}{2} \\ \omega_0 = \frac{1}{\sqrt{R_1R_2 \times C_0}} \end{cases} \quad (6)$$

The MFB band-pass filter design equations are shown in Eq. (7).

$$\begin{cases} R_1 = \frac{1}{2\omega_0QC_0} \\ R_2 = \frac{2Q}{\omega_0C_0} \end{cases} \quad (7)$$

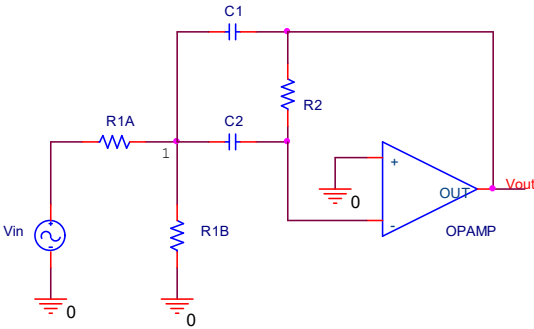


Fig. 2. MFB band-pass filter for $H_0 < 2Q^2$.

As shown in figure 2, a voltage divider can be used to replace R_1 in order to design a MFB filter for $H_0 < 2Q^2$. The corresponding design equations are shown in Eq. (8).

$$\begin{cases} R_{1A} = \frac{Q}{H_0 \omega_0 C_0} \\ R_{1B} = \frac{R_{1A}}{(2Q^2 / H_0 - 1)} \\ R_2 = \frac{2Q}{\omega_0 C_0} \end{cases} \quad (8)$$

2.2.2 Cascade design of MFB filter

Each MFB filter stage with one operational amplifier will be 1st or 2nd order, which should be cascaded to achieve higher order MFB filter. In order to design a 6th order MFB band-pass filter, three 2nd order MFB filter stages are cascaded. According to Eq. (8), the design of each 2nd order stage needs the parameters of quality factor Q , resonant frequency ω_0 and resonant gain H_0 , which can be obtained from cumbersome polynomial equations.

Thankfully there are some resources can be used to look up when designing a MFB band-pass filter rather than dealing with cumbersome polynomial equations. Each type of filter (such as Butterworth, Chebychev, Bessel) has its own coefficient table based on the desired filter order number. The coefficients table serve as a quick design reference of designing a proper filter instead of complex mathematical calculations.

3 The design of the 6th order MFB Band-pass Filter

The designed MFB band-pass filter is focused on the CENELEC “B band” (95 kHz-125 kHz), whose resonant frequency $f_0 = \sqrt{95 \times 125} = 109\text{kHz}$, and bandwidth $BW = 30\text{kHz}$. In order to reduce the influence of fluctuating power line impedance, the MFB filter should be adjusted to the demand of zero gain ($H_0 = 0\text{dB}$). A 30 dB attenuation both at 70 kHz and 170 kHz is required to meet the CENELEC disturbance levels.

Step 1 The calculation of Quality factor

According to the resonant frequency and bandwidth of the designed active band-pass filter, the equation of the quality factor is: $Q_{bp} = \frac{f_0}{BW_{3dB}} = \frac{109\text{kHz}}{30\text{kHz}} = 3.633$.

Step 2: The Selection of stages

Assuming $f_{l1} = 70\text{kHz}$, $f_{u1} = \frac{f_0^2}{f_{l1}} = \frac{109^2}{70} \approx 169\text{kHz}$ can be calculated; as same as $f_{u2} = 170\text{kHz}$, $f_{l2} \approx 70\text{kHz}$. Therefore, $\Delta f_1 = f_{u1} - f_{l1} = 99\text{kHz}$, and $\Delta f_2 = f_{u2} - f_{l2} = 100\text{kHz}$. Therefore, the steepness coefficient $A_s = \frac{\Delta f_2}{BW} = 3.33$ and the stage of the Butterworth LPF is

3.

Step 3: The parameters of each stage

The normalized Butterworth LPF with stage $n=3$ has two complex poles ($\alpha = 0.5, \beta = 0.866$) and one real zero ($\alpha_0 = 1$). After dealing with cumbersome polynomial equations, the pole (zero) frequency f , quality factor Q and resonant gain H for each filter stage can be derived.

(1). For the first stage, $f_1 = 96$, $Q_1 = 7.325$, and $H_1 = 2.12$

(2). For the second stage, $f = 124$, $Q_2 = 7.325$, and $H = 2.12$

(3). For the third stage, $f_3 = 109\text{kHz}$, $Q_3 = 3.633$, and $H_3 = 1$

Step 4: The Calculation of Component Values for Each Stage

According to Eq. (8), assuming $C_0 = 10nF$, the component values for each stage can be calculated which are illustrated in table 2.

Table 2. Component values for each stage.

Stages	R(Ω)		
	R _{1A}	R _{1B}	R ₂
Stage 1	573	11.55	2.43k
Stage 2	439.55	8.94	1.88k
Stage 3	530.74	20.9	1.06k

4 Simulation results and analysis

The simulation was conducted in PSPICE. Figure 3 illustrates the 6th order MFB filter topology, which includes three 2nd order MFB filter stages. The calculation process of each stage (see section 3) is complex even with the simplified coefficient table, previously given.

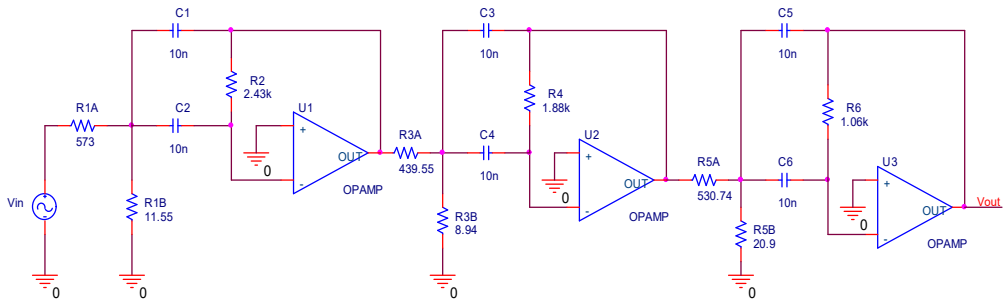


Fig. 3. The designed 6th order MFB band-pass filter.

The magnitude responses of the 6th Order MFB Filter are illustrated in figure 4. As shown in figure 4, the 6th MFB filter has an excellent flat pass-band located in CENELEC B band and a -30 dB attenuation both at 70 kHz and 170 kHz, which meets the CENELEC specifications.

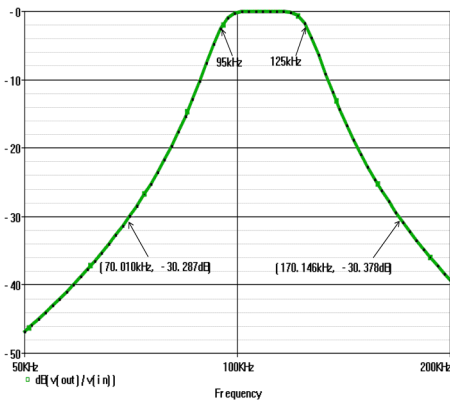


Fig. 4. Magnitude responses of the MFB filter.

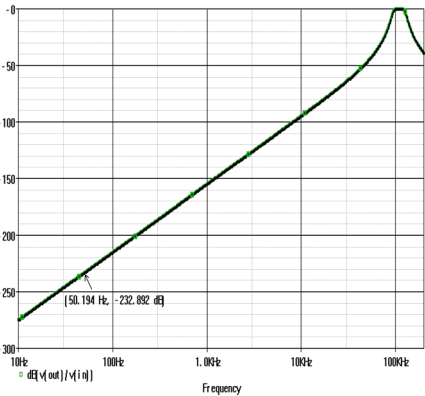


Fig. 5. Attenuation of the MFB filter at 50Hz.

As shown in figure 5, the attenuation of the 6th order MFB filter at 50 Hz is approximately -230 dB. If a 50 Hz, 340V peak voltage is resident at the input side of the MFB filter, the disturbance level is about 1 nV_{peak} , which is much lower than the CENELEC

maximum disturbance levels (see table. 1) and exhibits outstanding performance in main voltage isolation.

5 Conclusion

In this paper, a 6th order active MFB filter was designed for narrow-band PLC to achieve the CENELEC specifications. Although the new active filter design focuses on the CENELEC B band (95 kHz-125 kHz) using a MFB topology as an example, the same principles is adequate for any of the CENELEC bands. The active filter was analyzed with a series of simulations, which exhibits an excellent flat pass-band and meets the CENELEC requirements for transmission and disturbance levels.

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