Mathematical Modeling of Twin -T Notch Filter using Floating Admittance Matrix

Sanjay Kumar Roy¹, PhD. Scholar at Lovely Professional University and Head (Power Distribution), OMQ Division, TATA Steel Ltd, India
Kamal Kumar Sharma, Professor, Electronics and Communication, Lovely Professional University, Phagwara, Punjab, India
Brahmadeo Prasad Singh, Professor Adjunct, Electronics and Communication, Netaji Subhas University of Technology, New Delhi, India

corresponding author: sanjay.roy@tatasteel.com

Abstract - A novel article presents the RC-notch filter function using the floating admittance matrix approach. The main advantages of the approach underline the easy implementation and effective computation. The proposed floating admittance matrix (FAM) method is unique, and the same can be used for all types of electronic circuits. This method takes advantage of the partitioning technique for a large network. The sum property of all the elements of any row or any column equal to zero provides the assurance to proceed further for analysis or re-observe the very first equation at the first instant itself. This saves time and energy. The FAM method presented here is so simple that anybody with slight knowledge of electronics but understating the matrix maneuvering can analyze any circuit to derive all types of transfer functions. The mathematical modelling using the FAM method allows the designer to adjust their design at any stage of analysis comfortably. These statements provide compelling reasons for the adoption of the proposed process and demonstrate its benefits.

Keywords: Notch filter, Floating Admittance Matrix (FAM), Twin-T Network.

I. INTRODUCTION

The development of technology at an incredible pace over decades forced the society to employ electronics at an unimaginable proportion of human activities. This necessity induces a constant improvement in the existing and further development of new electronic equipment. Electronic networks such as bridge-T, twin-T, lattice equalizer, and general purposes filter circuits [1]-[6] find a wide application in communication systems.

The parallel combination of an RC low-pass and an RC high-pass forms a band-pass filter. The band-pass filter passes a band of frequencies of either side of the low-pass or high-pass filter. Combining the same low-pass and high-pass filter can reject a band of frequencies. This type of filter should completely block a band of frequencies or drastically reject the band of frequencies. A unique subset of the band-reject filter is the notch-filter, which rejects extremely low-band of frequencies as in Fig. 1 [7], [8]. A twin-T network forms the parallel combination of two-T complementary RC structures. The twin-T network is used as a notch filter for rejecting (offering the highest attenuation) the signal at only one frequency, called the notch frequency ($f_o$) and passes all frequencies on both sides of the notch frequency.

![Fig. 1 Band Reject Filter](image-url)
The other names of the band-stop filter are the band-
elimination, band-reject, or notch filters. Like the band-
pass design, we connect the two filter sections 
(LP and HP) in parallel with each other instead of 
them in series.

The twin–T network is a handy circuit for the 
selection of a particular frequency very precisely. 
One of the parallel twin–T passes the signals without 
any attenuation, whereas the other does not function 
in this frequency range. The other parallel twin–T 
takes over just after the frequency range; the first 
twin–T network passed the output signal.

This way, for a very narrow range of frequency, 
neither the first twin–T nor the second twin–T 
network function, and the signal at the twin–T output 
gets drastically attenuated. For this reason, its name 
is a notch filter because it rejects only a notch of 
frequency.

Notch filters are highly selective because it is a 
high-Q form of the bandstop filter that can reject a 
single or very-small band of frequencies rather than a 
whole bandwidth of frequency. For instance, it may 
be necessary to reject or attenuate a specific 
frequency drastically generating electrical noise 
(such as mains hum) which comes from the inductive 
load as that of a motor or ballast used in tube light 
ballast of lighting Circuit, or the removal of 
harmonics etc.

The musicians in sound equipment such as 
graphic equalizers, synthesizers, and electronic 
crossovers use a variable type of notch filter to deal 
with narrow peaks in the systems’ acoustic response. 
So, we see that notch filters behave in much the same 
way as low-pass and high-pass filters.

II. METHOD

Figure 2 shows a general circuit of a twin-T network 
[1]-[8]. The low-pass filter section comprises of \( Y_1 = Y_2 = R \), and \( Y_6 = sC \) in a twin-T configuration. 
Similarly, the other parallel filter is the high-pass 
section comprising of \( Y_3 = Y_4 = C \) and \( Y_5 = R \) in the 
complementary-T configuration. The combined 
arrangement forms a twin-T filter, giving a sharp 
response to the following ratios’ component values.
The component values for the Twin-T band-stop (an 
extremely small range of frequency) filter are:

\[
G_1 = 2G \\
C_1 = 2C
\]

We assume that \( g_s = Y_L = 0 \), i.e., source and load 
impedances are very high for further analysis.

A notch filter design has a very narrow and very 
deep stop band around its center frequency. Its 
selectivity factor \( Q \) describes the notch’s width precisely the same way the RLC circuit peaks 
at one frequency.

The most common name of the notch filter design 
is the twin-T-notch filter. In its basic form, the 
twin-T, is the parallel-tee consists of two RC 
branches of two tee sections. Each T-section uses 
either two resistors and a capacitor or two capacitors 
and one resistor, as in Fig. 2. We are analyzing the 
twin-T network shown in Fig. 2 to select the 
particular frequency using the floating admittance 
matrix approach. For the generalized analysis, we put 
all capacitors or all resistors in the form of 
admittances such as \( Y_1, Y_2, Y_3, Y_4, Y_5 \) and \( Y_6 \).

The floating admittance matrix of Fig. 2 results [9]-
[15] as:

\[
\begin{bmatrix}
1 & 2 & 3 & 4 & 5 \\
G + sC & -sC & 0 & -G & 0 \\
-sC & 2G + sC & -sC & 0 & -2G \\
0 & -sC & G + sC & -G & 0 \\
-G & 0 & -G & 2G + sC & -sC \\
0 & -2G & 0 & -2sC & 2G + 2sC
\end{bmatrix}
\]

Substituting \( Y_1 = Y_2 = G, Y_3 = Y_4 = sC, Y_5 = G_1 = 
2G, Y_6 = sC_1 = 2sC, g_s = Y_L = 0, \) then Eq. (1) yields:

\[
\begin{bmatrix}
1 & 2 & 3 & 4 & 5 \\
G + sC & -sC & 0 & -G & 0 \\
-sC & 2G + sC & -sC & 0 & -2G \\
0 & -sC & G + sC & -G & 0 \\
-G & 0 & -G & 2G + sC & -sC \\
0 & -2G & 0 & -2sC & 2G + 2sC
\end{bmatrix}
\]

The voltage transfer function between its terminals 3 
& 5 and 1 & 5 in Fig. 2 can be written (9)-[15] as:

\[
A_{p_{135}}^{15} = sgn(3 - 5) sgn(1 - 5)(1-14)^2 \frac{y_{15}^{15}}{y_{15}^{15}}
\]

\[
\begin{bmatrix}
-sC & 2G + 2sC & 0 \\
0 & -sC & -G \\
-G & 0 & 2G + 2sC \\
-sC & G + sC & -G \\
0 & -G & 2G + 2sC
\end{bmatrix}
\]

\[
= (s^2C^2 + G^2)(G + sC) \\
\begin{bmatrix}
2G + 2sC & -sC & 0 \\
-sC & G + sC & -G \\
0 & -G & 2G + 2sC
\end{bmatrix}
\]
\[
A_{v115} = \frac{2G + sC}{2G + sC} = \frac{G}{G + 2sC} = \frac{1 - sC}{1 - sC + 2R/2H} \]

\[
= 2(G + sC)(s^2C^2 + 4sCG + G^2)
\]

\[
A_{v215} = -\frac{2(G + sC)(s^2C^2 + G^2)}{2(G + sC)(s^2C^2 + 4sCG + G^2)}
\]

\[
= -\frac{(1 + s^2R^2)}{s^2C^2R^2 + 4sCR + 1} = -\frac{\frac{s^2 + 1}{CR^2}}{s^2 + 2s\Delta \omega + \Delta \omega^2} \quad (4)
\]

\[
= -\frac{(s^2 + 1)}{s^2 + 2s\Delta \omega + \Delta \omega^2} \quad (5)
\]

\[
= -\frac{1 - s^2R^2}{1 - s^2R^2 + j2\Delta \omega R + \Delta \omega^2} \quad (6)
\]

where the passive notch filter has notch frequency \(\omega_0 = \frac{1}{RC}\), bandwidth \(\Delta \omega = \frac{\omega_0}{Q}\) and the quality factor \(Q_{\text{passive}} = \frac{1}{Q}\). For the fixed value of \(R\) and \(C\), the output voltage is a function of the input voltage frequency.

The absolute value of the transmission coefficient is given as:

\[
|A_{v115}| = H_{\text{passive}}(\omega) = \frac{1 - \omega^2}{\sqrt{1 - \frac{\omega^2}{\omega_0^2} + \left(\frac{\omega}{\omega_0}\right)^2}} \quad (7)
\]

Fig. 3 shows the dependence of the output voltage or \(|A_{v115}| = H_{\text{passive}}(\omega)\) on frequency.

The plot reveals that the voltage ratio \(|A_{v115}| = H_{\text{passive}}(\omega)\) ceases to zero at only one frequency i.e.

\[
f_0 = \frac{1}{2\pi RC}\]

The circuit of Fig. 1 functions as a resonant network in the vicinity of this frequency \(f_0\). This type of circuit is especially suitable at low frequency where the LCR equivalent requires a very large value of \(L\) and \(C\). Figure 4 is the practical circuit for such a conceived network.

![Fig. 4 Twin-T Network with inverting Amplifier](image)

One of the shortcomings of this basic twin-T notch filter design is that the maximum value of the output voltage \(v_{35}\) below the notch frequency is normally less than the maximum value of the output voltage w.r.t. that of the output voltage above the notch frequency. This is mainly due to two series resistances (2R) in the low-pass filter section providing higher losses than those of the two series capacitors (C) reactances in the high-pass T-section.

Along with the uneven gains on two sides of the notch frequency, another shortcoming of this basic design is that it has a very low and fixed \(Q\) value of 0.25, of the order of –12 dB. The current flow through each series of LP section is 180° apart from the current flow in the each series arm of the HP section of the twin-T network at the notch frequency. This is because of the currents flowing in each series arm, one being 2R and 2C, are 180° out of phase, at the notch frequency.

The positive feedback may improve the notch filter by making it more selective. Instead of connecting the junction of R/2 and 2C to the ground, i.e. 0V, it may connect it to a variable point of the voltage divider network fed from the output voltage as in Fig. 5. The voltage divider network decides the amount of feedback that determines the value of \(Q\), which in turn decides the extent of the depth of the notch.

Very frequently, the problem arises in the response of the twin-T circuits due to the lack of precision of passive components used in the network. Also, the quality factor of the circuit is very low as it uses only passive components. It has been observed that the circuit response increases drastically using active circuits of the twin-T network.

Hence, we give a relook for selecting precise values of resistances and capacitances used in the twin-T filter.

The common terminal in Fig. 5 is not grounded. Instead, it is connected to a potentiometer that functions as a voltage divider composed of \(R_1\) and \(R_4\) to form a positive feedback loop. The fraction of the output voltage \(v_o\) fed back is given as:
\[
 v_5 = \beta v_o = \frac{R_3}{R_3 + R_4} v_o \tag{9}
\]

Now, substituting \(H(j\omega)\) from Eq (5) in Eq.(13) results:

\[
 H_{active}(j\omega) = \frac{v_o}{v_i} = \frac{H(j\omega)(R_3 + R_4)}{R_3 + H(j\omega)R_4}
\]

\[
 = \frac{(R_3 + R_4)(s^2 + \frac{1}{R_2 C})}{(s^2 + \frac{1}{R_2 C} + js\frac{1}{RC})} \left( s^2 + \frac{1}{R_2 C} + js\frac{1}{RC} \right)
\]

\[
 = \frac{(s^2 + \frac{1}{R_2 C}) + s\Delta\omega_{active}}{s^2 + \frac{1}{R_2 C} + s\Delta\omega_{active}}
\]

\[
 = \frac{s^2 + \frac{1}{R_2 C}}{s^2 + \frac{1}{R_2 C} + js\Delta\omega_{active}}
\]

where the quality factor and the bandwidth of the active filter with positive feedback are given as:

\[
 Q_{active} = \frac{R_3 + R_4}{4R_3} = Q_{passive} \left( \frac{R_3 + R_4}{R_3} \right).
\]

And

\[
 \Delta\omega_{active} = \frac{\omega_0}{Q_{active}} \tag{16}
\]

This Eq. (16) suggests that we can adjust the quality factor and the bandwidth of the filter by changing the value of \(R_3\) and \(R_4\).

III. EXPERIMENTAL VERIFICATION

Three circuits of Figs. 6 and 9 have been designed for practical verifications of the responses. Fig. 9 included an additional inverter in the feedback loop, and its responses are plotted as in Figs. 10 and 11.

The outcome of the second type of twin-T filter in Fig. 10 gives the notch frequency and the notch depth inside the block of the plot. Fig. 11 shows the 3dB frequencies of the second type of twin-T filter using two Op. Amp inverters.

The response of Fig. 6 is given in Figs. 7 and 8. The outcome of notch depth and notch frequency from the plot is inside the block of the plot.
Fig. 7 Indicates notch depth and notch frequency without feedback in the box of the plot.

Fig. 8 Indicates 3 dB frequencies without feedback in the box of the plot.

Fig. 10 Indicates notch frequency and notch depth using one Op Amp feedback in the box of the plot.

Fig. 11 Indicates 3dB frequencies using two Op-Amp feedback in the box of the plot.

IV. RESULT AND DISCUSSIONS

The plots of a twin-T network of Figs. 6 and 9 reveals a close corroboration of the theoretical results. Resistances and capacitances also play important roles in producing very closely related output functions. For that, the precise value of resistances and capacitances must be considered.

Generally, the resistors are available with tolerances of ±1%, ±2%, ±5%) and adequate in less critical circuits. But, for the twin-T notch filter, tolerances less than these values may be required. Carbon track resistor may be suitable if its measured values on Wayne-Kerr Bridge is taken. The other suitable resistor for such a circuit could be the Cermet...
track variable resistor that gives better reliability. However, a bridge for the exact value of the resistor could be used.

The Silver Mica capacitors have tolerances of ±1%, but the maximum value available is limited to only 4.7 nF. They have good temperature stability. Hence, such capacitors are suitable where the filter has to operate in an environment of wide temperature range of variation. The Polystyrene capacitors are most suitable for filters on account of their close tolerances and are available in a large capacitance range. They also have excellent temperature stability. From three forms of ceramic capacitance, metallized, resin dipped, and disc types, the metallized ceramic capacitor has good tolerance (±2%) and temperature stability. The polyester type may be of choice for large capacitor values, but their tolerances fall between (5% to (10%) and their temperature stability is also very poor.

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