

AF120 Generalized Impedance Converter, GIC

General Description

The AF120 contains a pair of operational amplifiers and four precision thin film resistors connected as shown below. A gyrator may be formed by adding one external capacitor; or a frequency dependent negative resistance FDNR may be formed by adding two external capacitors. In the gyrator mode, $Z_{IN} \propto j\omega C$, which is equivalent to a grounded inductor. In the FDNR mode, $Z_{IN} \propto -1/\omega^2 C_1 C_2$. The AF120 may also be used in pairs to form ungrounded inductors or inductor networks. Thus, with appropriate transformations, the GIC makes possible an active realization of any low-frequency ladder filter network. The advantage of ladder filters being, of course, that they exhibit lower sensitivity to component variations than any other type of filter realization. Temperature coefficient of the internal resistors is equal and opposite in sign to that of poly-

styrene capacitors, thus RC products exhibit approximately zero TC.

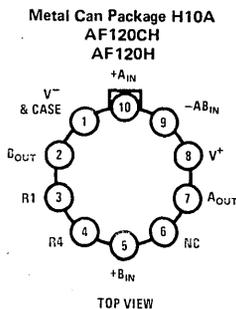
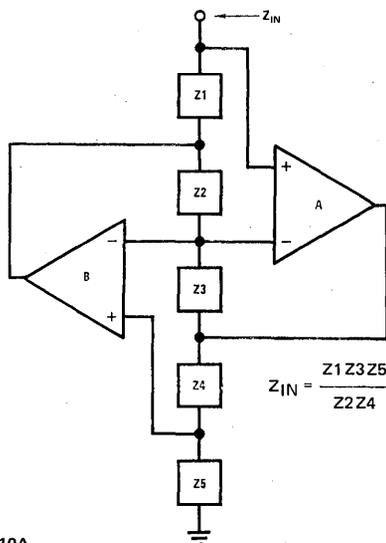
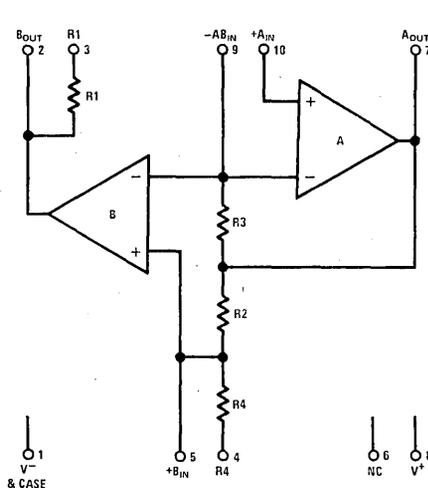
Features

- Matched internal resistors 7500Ω ±0.1%
- Resistor TC = +110 ±30 ppm/°C
- Supply voltage ±5 to ±18V
- Input impedance 7500Ω

Applications

- Gyrator, $Z \propto s$
- Frequency dependent negative resistance, $Z \propto 1/s^2$
- Use in low-frequency active ladder filter networks

Schematic and Connection Diagrams



Absolute Maximum Ratings

Supply Voltage, V_S	$\pm 18V$
Power Dissipation, $T_A = 25^\circ C$	500 mW
Derate 18 mW/ $^\circ C$ above $60^\circ C$	
Operating Temperature, T_A	
AF120	$-55^\circ C$ to $+125^\circ C$
AF120C	$-25^\circ C$ to $+85^\circ C$
Storage Temperature, T_{STG}	$-65^\circ C$ to $+150^\circ C$
Lead Temperature (Soldering, 10 seconds)	$300^\circ C$

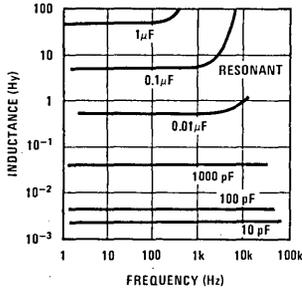
Electrical Characteristics $T_A = 25^\circ C, V_S = \pm 5.0V$ to $\pm 15V$, except as noted

PARAMETER	CONDITIONS	AF120			AF120C			UNITS
		MIN	TYP	MAX	MIN	TYP	MAX	
$ Z_{IN} $	Input Impedance	7425	7500	7575	7350	7500	7650	Ω
θ	Phase (Note 1)	89.5	90	90.5	89	90	91	DEG.
V_{OS}	DC Voltage measured at Input Terminal		1	8		1	10	mV
R1, R2, R3, R4		7485	7500	7515	7470	7500	7530	Ω
R2/R3		0.999	1.000	1.001	0.998	1.000	1.002	
TC	Resistor Temp. Coeff.	80	110	140	50	110	170	ppm/ $^\circ C$
V_O	Op Amp Output Voltage	$V_S = \pm 15V, R_L = 2k$	± 10	± 13	± 10	± 13		V
I_{SC}	Op Amp Short-Circuit Output Current	$V_S = \pm 15V$	20			20		mA
I_S	Supply Current	$V_S = \pm 15V$	3	5.6		3	5.6	mA

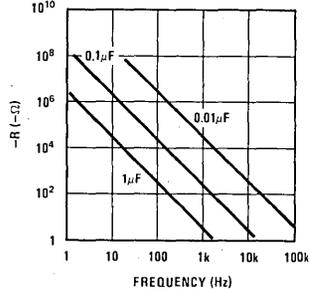
Note 1: 90° indicates that connection actually simulates a pure inductor.

Typical Performance Characteristics

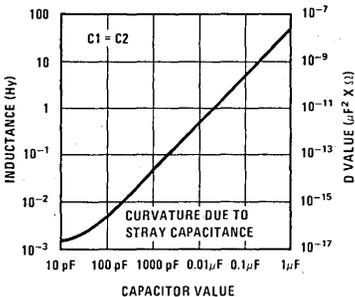
Equivalent Inductance vs Frequency



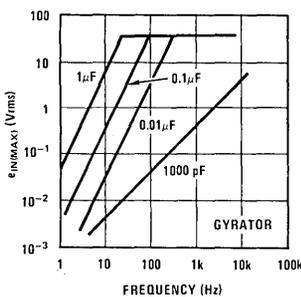
FDNR Value vs Frequency



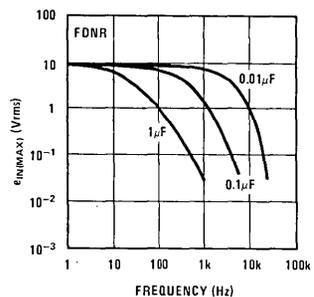
Equivalent L and D vs Capacitor Values



Maximum Terminal Voltage vs Frequency



Maximum Terminal Voltage vs Frequency



Applications Information

The generalized impedance converter GIC is a versatile tool for realization of inductive components in low-sensitivity filters. The driving point impedance is $Z_i(s) = k(s) Z_L(s)$. The input impedance of the AF120 is

$$Z_i = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4} \quad (\text{Refer to Figure 2})$$

which reduces to

$$Z_i = \frac{Z_1 Z_5}{Z_2}$$

since $Z_3 = R_3$, $Z_4 = R_2$ and $R_2 = R_3$. No more than one or two of Z_1 , Z_2 and Z_5 may be external capacitors. Internal resistor R_4 is available for use as Z_5 , and internal resistor R_1 may be used as either Z_1 or Z_2 . External resistors of other values may be substituted for R_1 or R_4 if proper attention is paid to temperature coefficients. The TC of internal resistors is +110

$\pm 30 \text{ ppm}/^\circ\text{C}$ to compensate for the TC of polystyrene capacitors.

The AF120 may be used for the following impedance conversions:

Positive impedance converter (PIC) — $k(s)$ is positive and real

$$Z_2 = R_1, Z_5 = R_4, k = R_4/R_1 = +1,$$

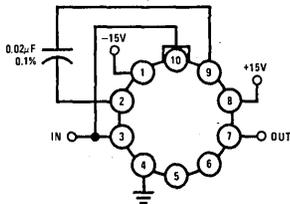
$$Z_i(\omega) = Z_1(\omega) \quad (\text{trivial case})$$

Positive impedance inverter (PII) — $k(s)$ is positive and real

$$Z_1 = R_1, Z_5 = R_4, k = R_1 R_4 = (7500)^2$$

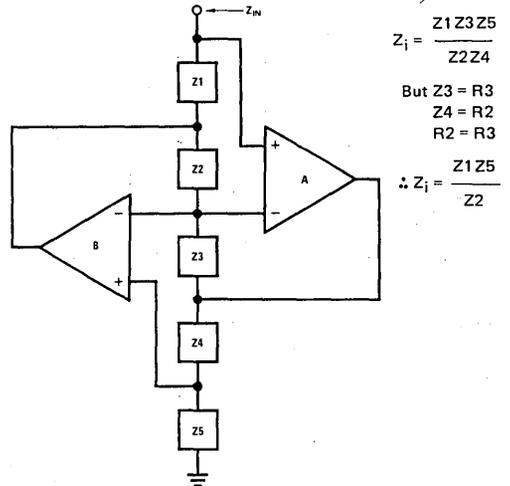
$$Z_i(\omega) = R_1 R_4 / Z_2(\omega)$$

If Z_2 is an external capacitor, then $Z_i(\omega) = R_1 R_2 j\omega C$, and $Z_i(s) \propto (s)$



$V_{IN} \leq 1V_{rms}$ @ 1053 Hz

FIGURE 1. Test Circuit

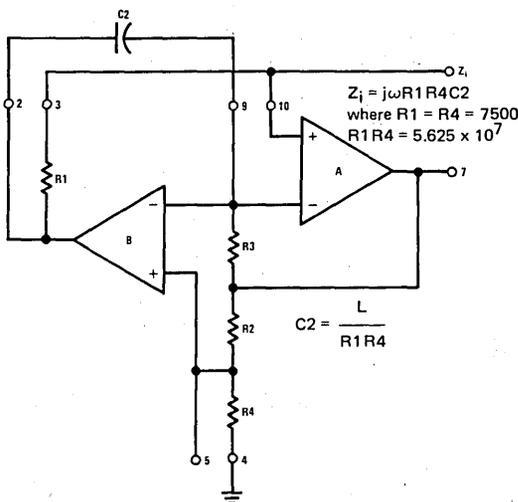


$$Z_i = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$$

But $Z_3 = R_3$
 $Z_4 = R_2$
 $R_2 = R_3$

$$\therefore Z_i = \frac{Z_1 Z_5}{Z_2}$$

FIGURE 2. GIC Circuit

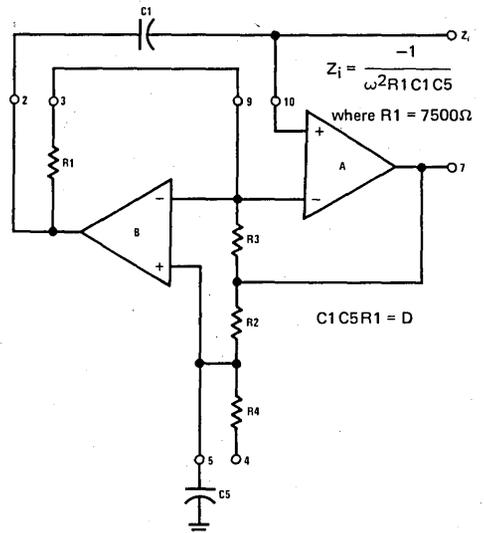


$$Z_i = j\omega R_1 R_4 C_2$$

where $R_1 = R_4 = 7500$
 $R_1 R_4 = 5.625 \times 10^7$

$$C_2 = \frac{L}{R_1 R_4}$$

FIGURE 3. Gyration (Inductive Element)



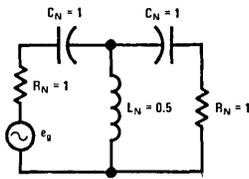
$$Z_i = \frac{-1}{\omega^2 R_1 C_1 C_5}$$

where $R_1 = 7500\Omega$

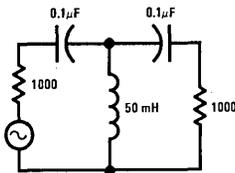
$$C_1 C_5 R_1 = D$$

FIGURE 4. FDNR (D Element)

Applications Information (Cont'd.)



(a) Prototype

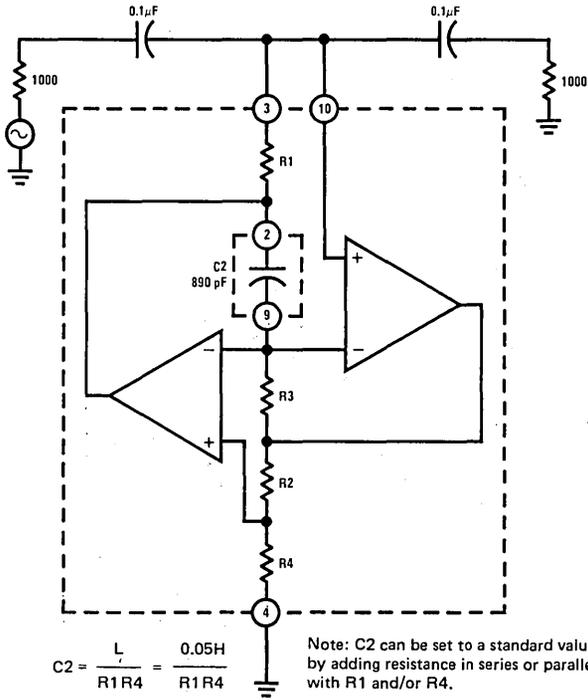


$$R_O = 1 \text{ k}\Omega$$

$$f_c = 1590 \text{ Hz}$$

$$\omega_c = 10^4$$

(b) Filter after Frequency and Impedance Transformation



$$C2 = \frac{L}{R1 R4} = \frac{0.05H}{R1 R4}$$

(c) GIC Active Realization

FIGURE 5. Third-Order Butterworth Highpass Filter

Frequency dependent negative resistance (FDNR)

$$Z2 = R1, k = 1/R1$$

$$Z1 = Z1(\omega)Z5(\omega)/R1$$

If Z1 and Z5 are both external capacitors, then $Z1 = -1/R1\omega^2 C1C5$, and $Z1(s) \propto -1/s^2$

GIC elements are especially useful for active simulation of low-sensitivity passive ladder filters. Symmetrically terminated ladder filters exhibit an exceptionally low sensitivity to changes in network element value; in fact, they exhibit the lowest sensitivity of any filter type. This means that practical realization of multistage filter functions may be achieved with moderate tolerance components, and that component shifts due to temperature variations will have minimal effect on the filter transfer function. Additionally, a great deal of ladder filter design information exists in handbook form; hence the value of the GIC as a network element. Several examples are given on the following pages for the realization of filters with grounded inductors, with ungrounded inductors, and with both grounded and ungrounded inductors.

Highpass Filter (with Grounded Inductors)

Figure 5 shows the development of the GIC active realization of the prototype ladder filter of Figure 5(a). The network is first designed with normalized values for all components. Next, the component values are transformed according to the desired characteristic impedance and cutoff frequency of the filter. To transform from prototype normalized values where $R_O = 1$ and $\omega_c = 1$,

$$\left. \begin{array}{l} \text{Multiply all R and L by } R_O \\ \text{Divide all C by } R_O \\ \text{Divide all L and C by } \omega_c \end{array} \right\} \text{to obtain } \left\{ \begin{array}{l} R = R_O R_N \\ L = R_O L_N / \omega_c \\ C = C_N / R_O \omega_c \end{array} \right.$$

where N subscripts indicate original normalized values.

Lowpass Filter (with Ungrounded Inductors)

Since the simple GIC realization of an inductor results only in a grounded inductor, a network transformation is necessary in order to use the GIC in a lowpass filter. Figure 6 shows the frequency and impedance transformation of the prototype lowpass filter, followed by a 1/s impedance transformation. When this 1/s transformation is made, the performance of the filter is unchanged, therefore the transformation is valid. The

Applications Information (Cont'd.)

resultant circuit shown in *Figure 6(c)* allows the realization of the prototype ungrounded inductor circuit with a grounded D element (FDNR). To make the $1/s$ transformation, each impedance is multiplied by $1/s$ so that

- each R is replaced by a $C = 1/\omega_c R$,
- each L is replaced by an $R = \omega_c L$, and
- each C is replaced by a $D = C/\omega_c$.

Examination of the GIC realization of an FDNR in *Figure 4* will reveal that a resistive path from FDNR terminal 10 must exist to ground in order to supply bias current to the internal amplifiers. The circuit of *Figure 6(c)* is, therefore, incomplete as no resistive path exists from D element to ground. If a large R were shunted across D, that R would appear in *Figure 6(b)*

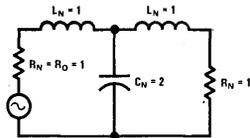
as an inductor across the C. The solution is to place large R's across the C's in *Figure 6(c)* which appear as large inductors across R_O of *Figure 6(b)*, and thus do not significantly affect the transfer function except near $\omega = 0$. The resultant network appears in *Figure 6(d)*. The transfer function at $\omega = 0$ is $T(0) = 0.5$, therefore resistors R_A and R_B must be chosen to affect this value. Then $T(0) = 0.5 = R_B / (R_A + R_B + 2R_O)$.

The GIC realization of the lowpass filter, complete with low-frequency compensation appears in *Figure 6(e)*. Note again, that C1 and C5 can be varied or can be unequal just so long as $C1C5R1 = D$. Also note that in the final transformation of *Figure 6(c)*

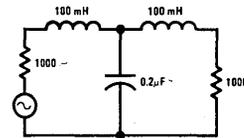
$$D = C_N / \omega_c^2 R_O$$

$$R = R_O L_N$$

$$C = 1 / \omega_c R_O R_N$$



(a) Prototype

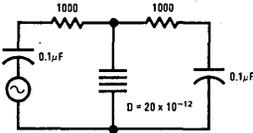


(b) Filter after Frequency and Impedance Transformation

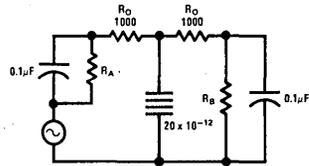
$$R_O = 1 \text{ k}\Omega$$

$$f_c = 1590 \text{ Hz}$$

$$\omega_c = 10^4$$



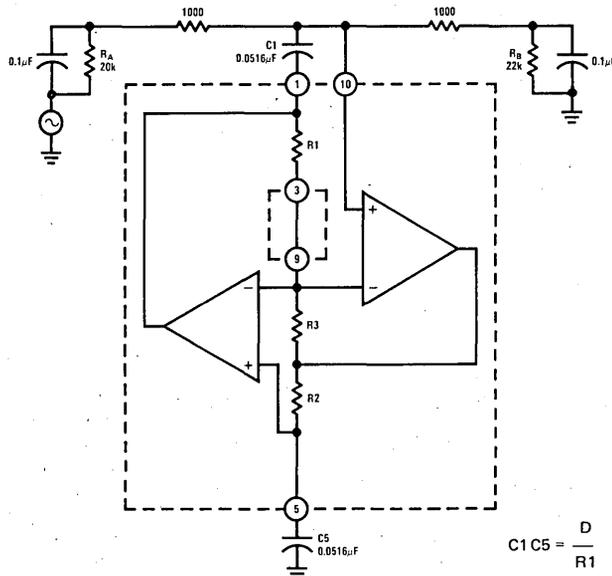
(c) Filter after 1/s Transformation



(d) Final Circuit with Low-Frequency Compensation

$$R_A, R_B \gg R_O$$

$$R_B = R_A + 2R_O$$



(e). Active Realization

$$C1 C5 = \frac{D}{R1}$$

FIGURE 6. Third-Order Butterworth Lowpass Filter

Applications Information (Cont'd.)

GIC Embedding

Ungrounded inductors may be simulated by embedding an ungrounded resistor between two GIC's as shown in *Figure 7(a)*. Actually, the embedded element may be any 2 or 3-terminal network and the GIC may be given any of its realizable impedance transformations $Z(s)$, $Z(s^{-2})$, $Z(s^{-1})$ or $Z(s^2)^*$.

Bandpass Filter (with Grounded and Ungrounded Inductors)

Direct RC active simulation of this filter requires the use of GIC embedding techniques (as described above) because there is no transformation which will eliminate all ungrounded L or D elements. *Figure 8* shows the step-by-step realization of a 6-pole Butterworth bandpass filter.

The filter circuit of *Figure 8(c)* constructed with AF120 and with R and C values shown performed as indicated

in the plot of *Figure 9*. Note that the band center and cutoff frequencies occur at the design points as indicated by the phase measurements at 0°C and ±135°C.

The circuit of *Figure 8(c)* is simplified with a shorthand notation for the GIC's. This shorthand circuit is equivalent to the GIC as shown in *Figure 10*.

The final circuit for the bandpass filter of *Figure 8* contains six capacitors, one for each pole of the 6-pole network. This circuit then contains a minimum number of reactive elements to satisfy the prototype design. A dc path to ground exists for all GIC elements in this design so no additional resistors are needed for dc compensation. Note also that even though one and two percent components have been used throughout the circuit and the $C_D C_C$ product is in error by 3%, performance is as designed. It should be clear from this exercise that ladder networks of virtually any complexity may be realized using the AF120 GIC circuit.

* $Z(s^2)$ is not realizable with the AF120.

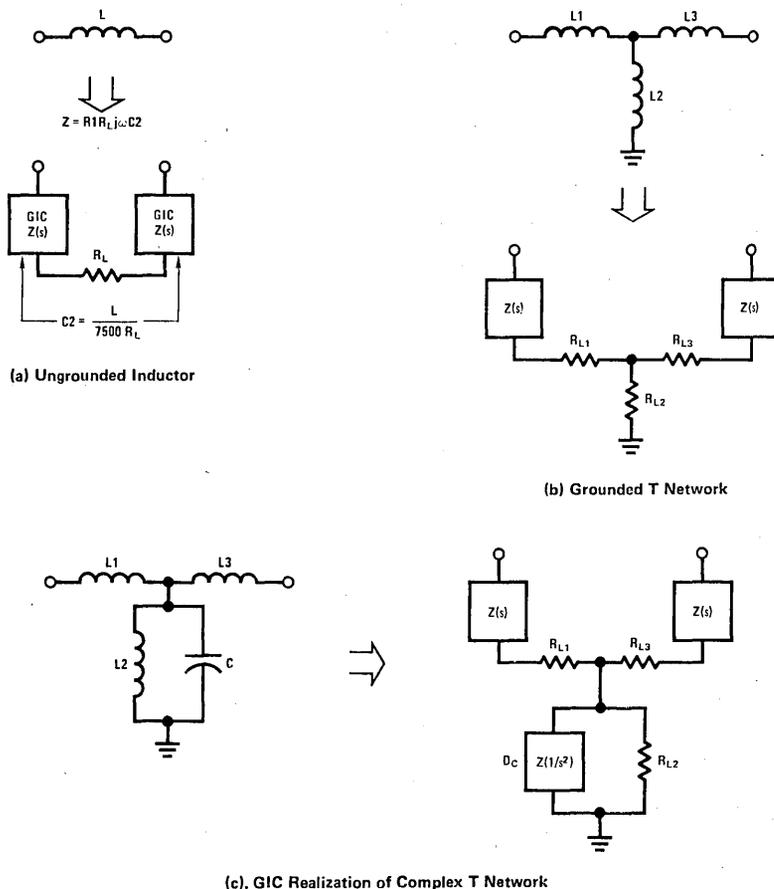
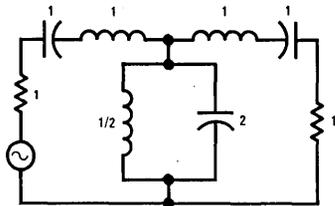
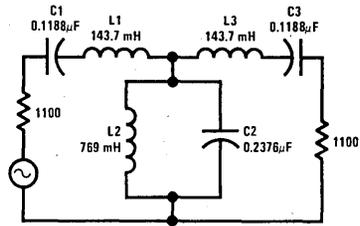


FIGURE 7. GIC Realization of Ungrounded Inductors and T Networks

Applications Information (Cont'd.)

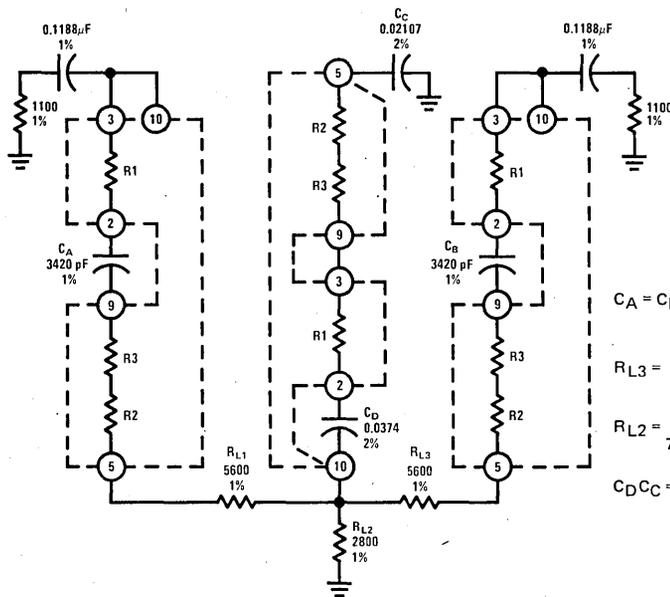


(a) Prototype



$R_O = 1100\Omega$
 $f_O = 1218 \text{ Hz}$
 $f_L = 752.8 \text{ Hz}$
 $f_H = 1970.8 \text{ Hz}$

(b) Filter after R_O and ω_O Transformations



$$C_A = C_B = \frac{L_1}{7500 R_{L1}} = 3420 \text{ pF}$$

$$R_{L3} = \frac{L_3}{7500 C_A} = 5600\Omega$$

$$R_{L2} = \frac{L_2}{7500 C_A} = 2800\Omega$$

$$C_D C_C = C_A C_2 = 812 \times 10^{-6} \mu\text{F}^2$$

(c) GIC Realization

FIGURE 8. 6-Pole Butterworth Bandpass Filter

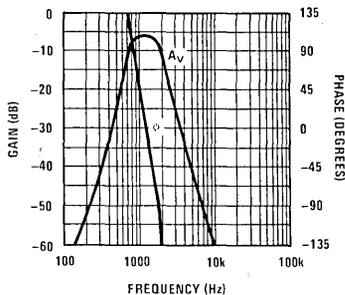


FIGURE 9. Gain and Phase Transfer Functions of the Filter of Figure 8(c).

Applications Information (Cont'd)

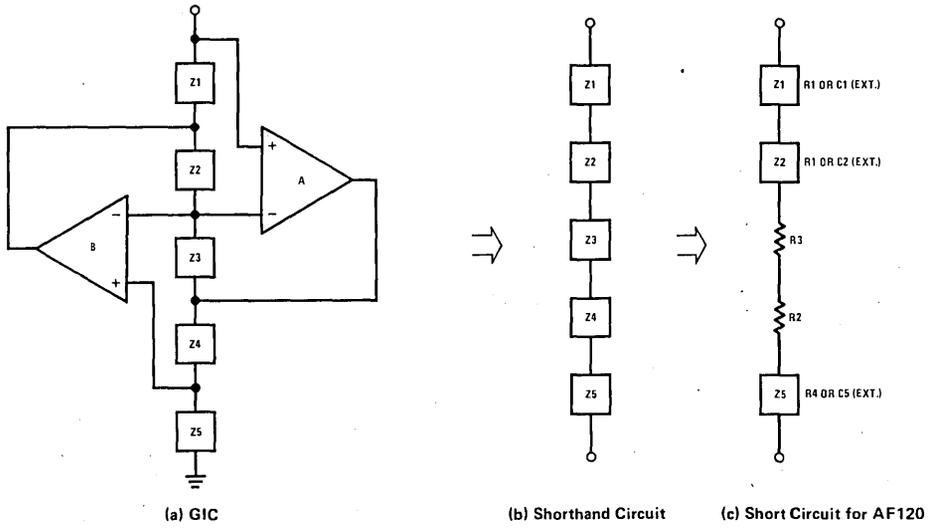


FIGURE 10. Development of GIC Shorthand Circuit