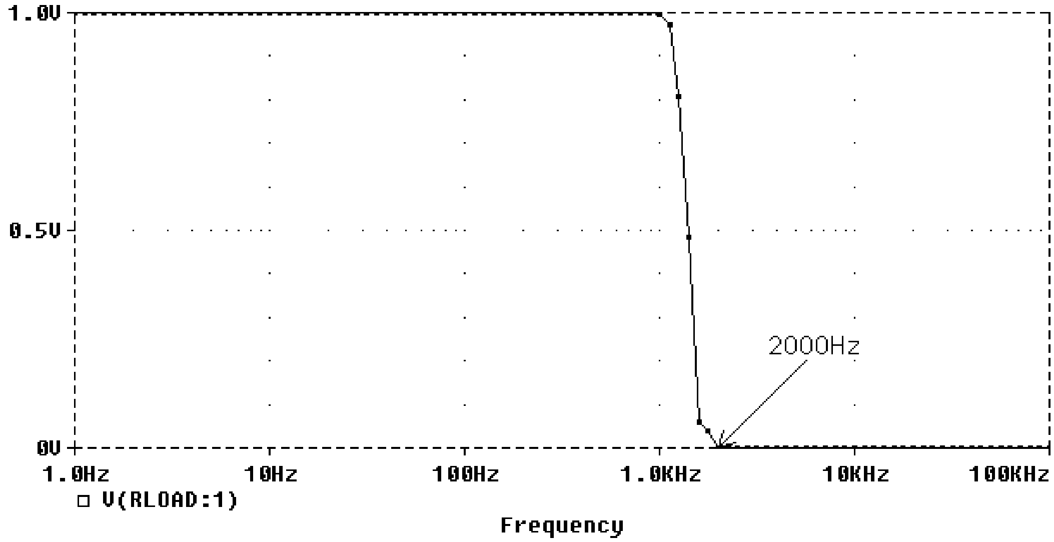
AUTOMATIC SYNTHESIS OF ELECTRICAL CIRCUITS USING DEVELOPMENTAL GENETIC PROGRAMMING

PART 2 — EXAMPLES — PASSIVE CIRCUITS

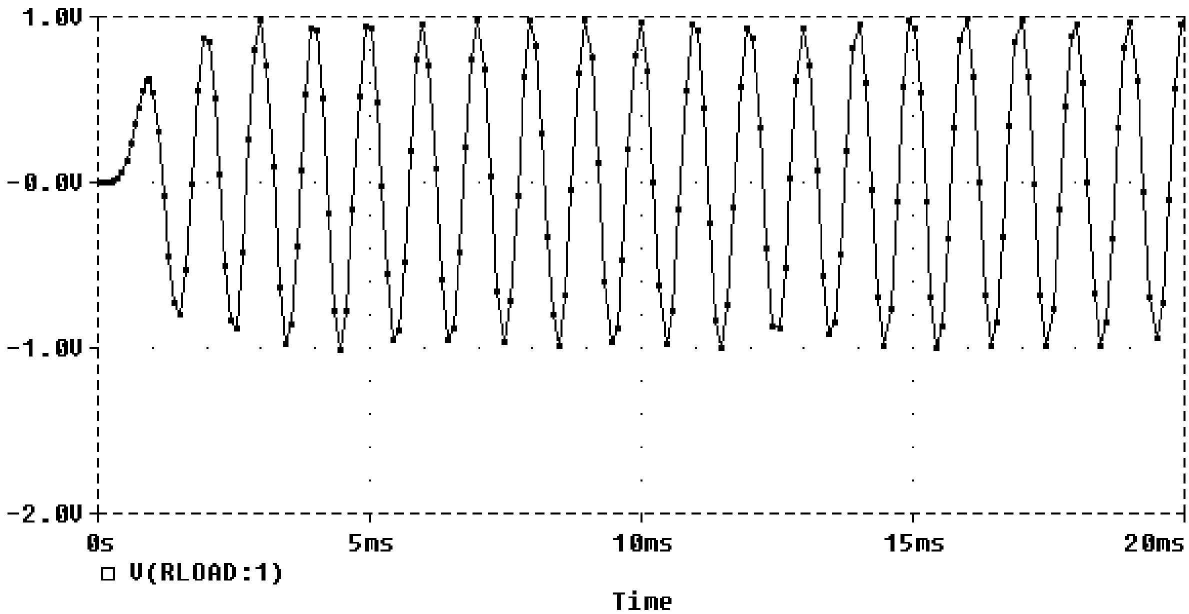
DESIGN GOALS FOR ONE-INPUT, ONE-OUTPUT LOWPASS FILTER CIRCUIT



- **One-input: incoming 2 volt AC signal**
- **One output**
  - Pass signal to output port if frequency is less than 1,000 Hertz
  - Suppress signal if frequency is greater than 1,000 Hertz
- **Source and load resistance: 1,000 Ohms**
- **Ideal output is 1 volt in passband and 0 volts in stopband**
- **Passband ripple of less than 30 millivolts**
- **Stopband attenuation so that there is no more than 1 millivolts in stopband**

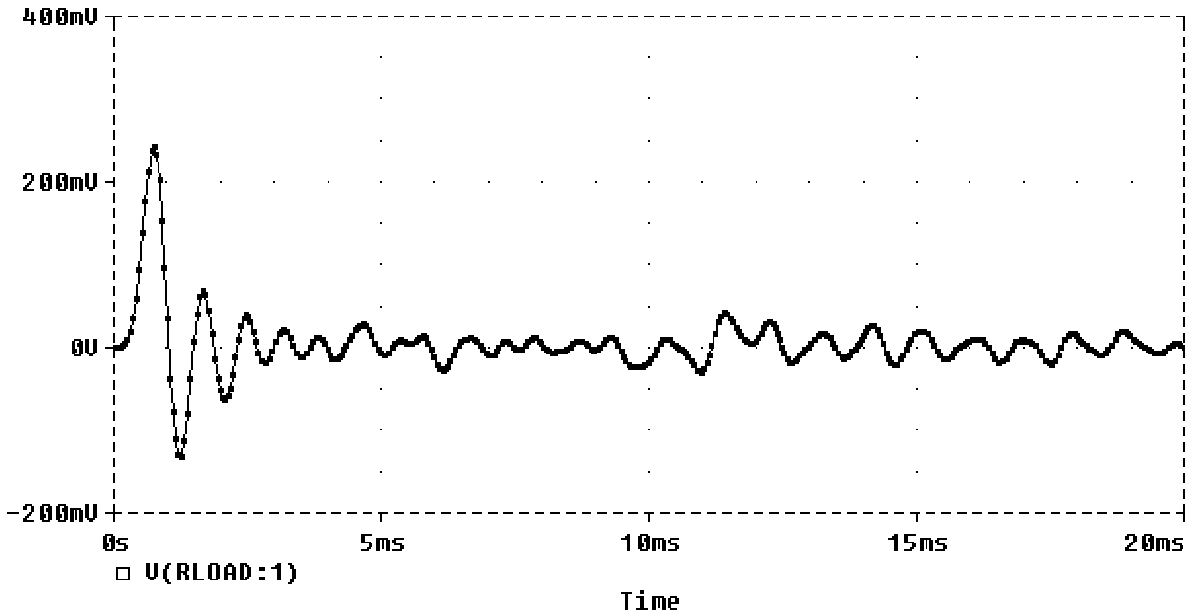
TIME DOMAIN TRANSIENT RESPONSE TO A 1,000 HZ SINUSOIDAL INPUT SIGNAL

(BOG 212 - LPF)

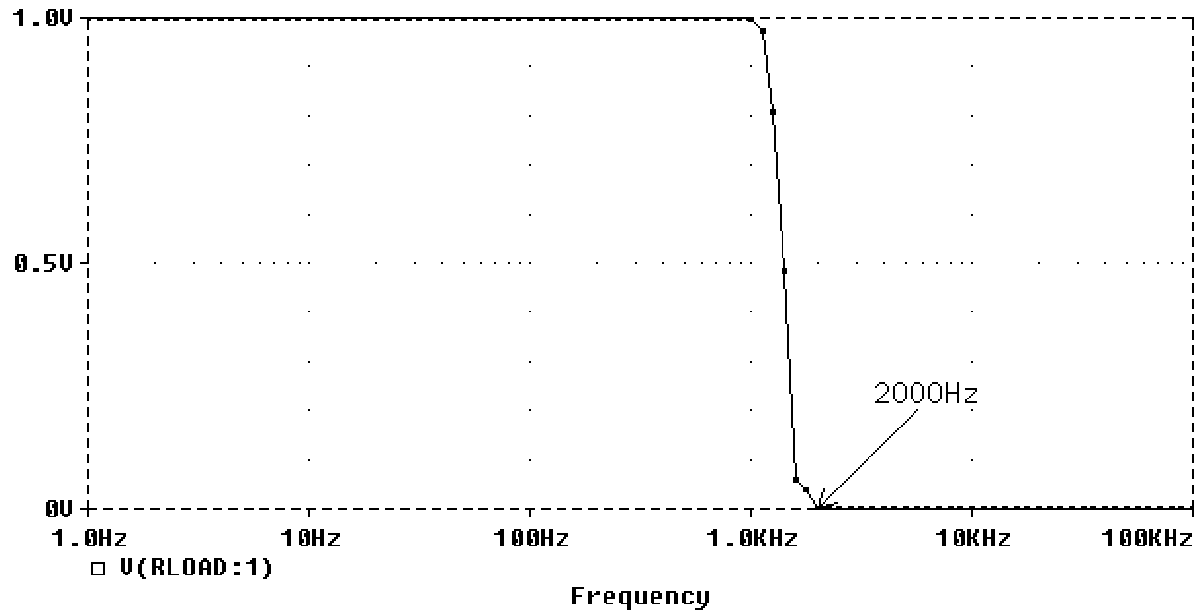


TIME DOMAIN TRANSIENT RESPONSE TO A 2,000 HZ SINUSOIDAL INPUT SIGNAL

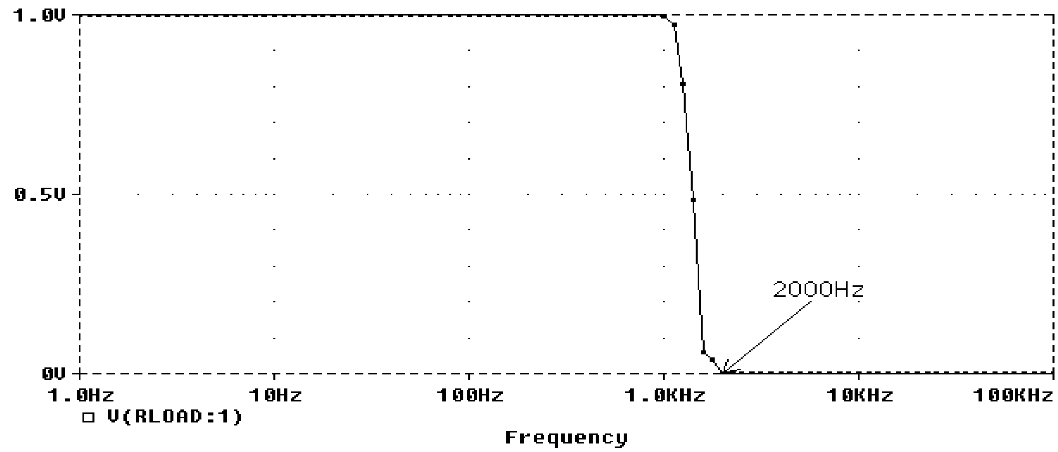
(BOG 212 - LPF)



FREQUENCY DOMAIN BEHAVIOR (BOG 212 - LPF)



BEHAVIOR OF A LOWPASS FILTER IN THE FREQUENCY DOMAIN



- **Examine circuit's behavior for each of 101 frequency values chosen over five decades of frequency (from 1 Hz to 100,000 Hz) with each decade divided into 20 parts (using a logarithmic scale). The fitness measure**
  - does not penalize ideal values
  - slightly penalizes acceptable deviations
  - heavily penalizes unacceptable deviations
- **Fitness is sum** $F(t) = \sum_{i=0}^{100} [W(f_i)d(f_i)]$
  - $f(i)$ is the frequency of fitness case i
  - $d(x)$ is the difference between the target and observed values at frequency of fitness case i
  - $W(y,x)$ is the weighting at frequency x

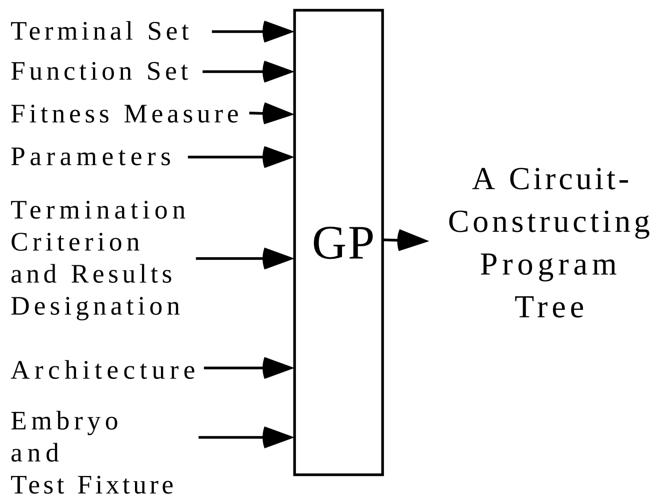
LOWPASS FILTER – CONTINUED

- **61 points in the 3-decade interval from 1 Hz to 1,000 Hz**
  - For voltage equaling the ideal value of 1.0 volts, the deviation is **0.0**
  - For voltage between 970 and 1,000 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of **1.0**
  - For voltage less than 970 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of **10.0**
- **35 points from 2,000 Hz to 100,000 Hz**
  - For voltage equaling the ideal value of 0.0 volts, the deviation is **0.0**
  - For voltage between 0 millivolts and 1 millivolt, the absolute value of the deviation from 0 millivolts is weighted by a factor of **1.0**
  - For voltage above 1 millvolt, the absolute value of the deviation from 0 millivolts is weighted by factor of **10.0**

LOWPASS FILTER – CONTINUED

- **5 "don't care" points between 1,000 Hz and 2,000 Hz**
- **Unsimulatable programs = 10^8 penalty**
- **Hits is number (0–101) of compliant points (i.e., those getting weight of 1.0)**

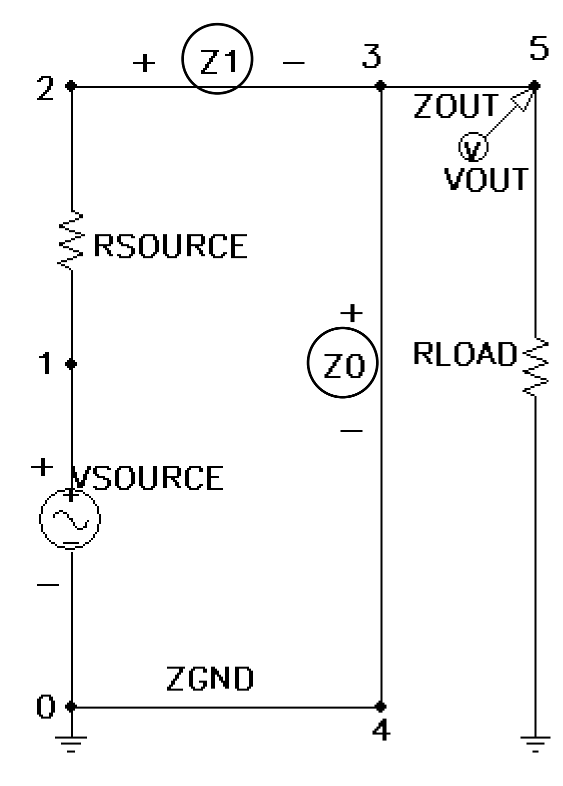
SEVEN MAJOR PREPARATORY STEPS FOR A PROBLEM OF CIRCUIT SYNTHESIS



SEVEN MAJOR PREPARATORY STEPS FOR DEVELOPMENTAL GENETIC PROGRAMMING

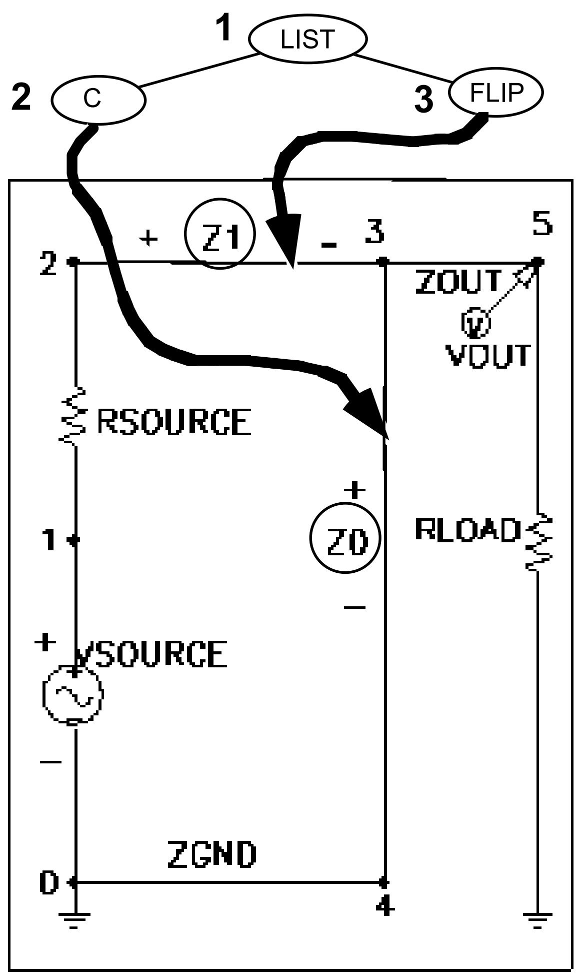
- **determining the set of terminals**
- **determining the set of functions**
- **determining the fitness measure**
- **determining the parameters**
- **determining method for designating a result and criterion for terminating a run**
- **determining the architecture of the circuit-constructing program tree (either specified by user or determined by the architecture-altering operations dynamically during the run)**
  - number of automatically defined function (ADFs)
  - number of arguments for each ADF
  - hierarchical references, if any, among the ADFs
- **determining the initial circuit**

INITIAL CIRCUIT



ARCHITECTURE OF CIRCUIT-CONSTRUCTING PROGRAM TREE

- **The circuit-constructing program tree has one result-producing branch for each modifiable wire in the embryo. Thus, it consists of two result-producing branches joined by a connective `LIST` function here.**



ARCHITECTURE OF CIRCUIT-CONSTRUCTING PROGRAM TREE - CONTINUED

- **No automatically defined functions (ADFs). Hence, there is no need, for this example, to address the issues of**
  - number of arguments possessed by each ADF
  - possible hierarchical references among ADFs
  - origin of ADFs and their number of arguments (i.e., possible use of architecture-altering operations)

FUNCTION AND TERMINAL SETS

- **Function set, F_{ccs}, for each construction-continuing subtree**

F_{ccs} = {C, L, SERIES, PARALLEL0, FLIP, NOP, GND, VIA0, VIA1, VIA2, VIA3, VIA4, VIA5, VIA6, VIA7}

- **Terminal set, T_{ccb}, for each construction-continuing subtree**

T_{ccs} = {END}

- **Function set, F_{aps} for each arithmetic-performing subtree**

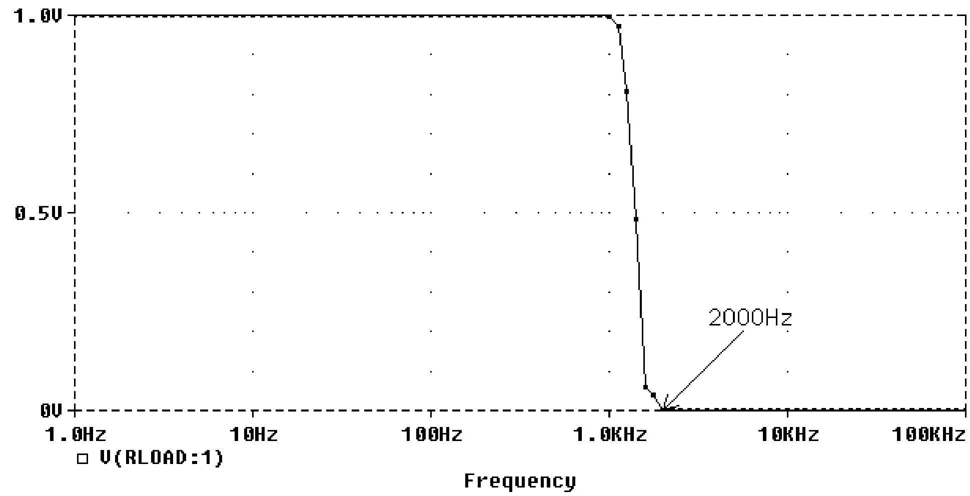
F_{aps} = {+, -}

- **Terminal set, T_{aps}, for each arithmetic-performing subtree**

$T_{aps} = \{\Re\}$

FITNESS MEASURE

- **Examine circuit's behavior for each of 101 frequency values chosen over five decades of frequency (from 1 Hz to 100,000 Hz) with each decade divided into 20 parts (using a logarithmic scale)**



- **Choose a fitness measure that**
  - does not penalize ideal values
  - slightly penalizes acceptable deviations
  - heavily penalizes unacceptable deviations
- **We use our modified version of SPICE (217,000 lines of C source code)**

FITNESS MEASURE

$$F(t) = \sum_{i=0}^{100} d(f_i)\, W(f_i, d(f_i))$$

- **f_i is the frequency (in Hertz) of fitness case i**
- **$d(x)$ is the absolute value of the difference between the target and observed values for frequency f_i of fitness case i**
- **$W(y, x)$ is the weighting at frequency x**

FITNESS MEASURE – BELOW 1,000 HERTZ

- **61 points in the 3-decade interval from 1 Hz to 1,000 Hz**
  - For voltage equaling the ideal value of 1.0 volts, the deviation is 0.0
  - For acceptable (compliant) voltages between 970 and 1,000 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of 1.0
  - For unacceptable (non-compliant) voltages less than 970 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of 10.0

FITNESS – ABOVE 2,000 HERTZ

- **35 points from 2,000 Hz to 100,000 Hz**
  - For voltage equaling the ideal value of 0.0 volts, the deviation is 0.0
  - For acceptable voltages between 0 millivolts and 1 millivolt, the absolute value of the deviation from 0 millivolts is weighted by a factor of 1.0
  - For unacceptable voltages above 1 millvolt, the absolute value of the deviation from 0 millivolts is weighted by factor of 10.0

FITNESS – 1,000 TO 2,000 HERTZ

- **5 "don't care" points in the transition band between 1,000 Hz and 2,000 Hz**

FITNESS MEASURE

- **Unsimulatable programs = 10^8 penalty**

- **Hits is number (0–101) of compliant points (those getting a weight of 1.0)**

CONTROL PARAMETERS

- **Population size, *M*, of 320,000 (sometimes 30,000, 40,000, 640,000, or 1,000)**
- **Maximum number of generations, *G*, is large (i.e., we monitor run manually)**
- **Maximum of 200 points (functions and terminals) for each result-producing branch**
- **For each generation**
  - 10% reproductions
  - 1% mutations
  - 89% crossovers
- **Secondary parameters are default values in Koza, Bennett, Andre, and Keane 1999 (appendix D)**

TERMINATION CRITERION AND RESULTS DESIGNATION

- **Terminate on 101 hits (i.e., 101 compliant points – 100% compliance)**

- **Best-so-far individual is designated as the result of the run**

TABLEAU — LOWPASS FILTER (WITHOUT ADFs OR ARCHITECTURE-ALTERING OPERATIONS)

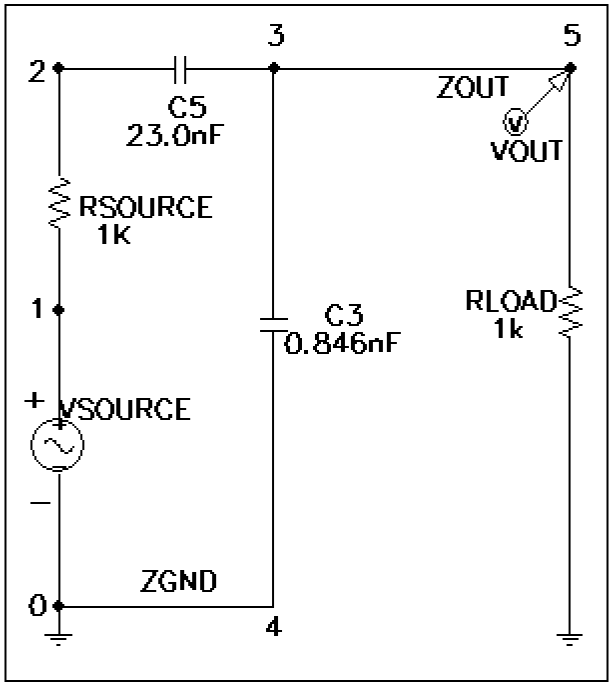
Objective:	**Design a lowpass filter composed of inductors and capacitors with a passband below 1,000 Hz, a stopband above 2,000 Hz, a maximum allowable passband deviation of 30 millivolts, and a maximum allowable stopband deviation of 1 millivolt.**
Test fixture and embryo:	**One-input, one-output initial circuit with a source resistor, load resistor, and two modifiable wires.**
Program architecture:	**Two result-producing branches, `RPB0` and `RPB1` (i.e., one RPB per modifiable wire in the embryo).**

Initial function set for the result-producing branches:	**For construction-continuing subtrees:** **$F_{ccs\text{-}rpb\text{-}initial}$ = {`C`, `L`, `SERIES`, `PARALLEL0`, `FLIP`, `NOP`, `TWO_GROUND`, `TWO_VIA0`, `TWO_VIA1`, `TWO_VIA2`, `TWO_VIA3`, `TWO_VIA4`, `TWO_VIA5`, `TWO_VIA6`, `TWO_VIA7`}.** **For arithmetic-performing subtrees:** **F_{aps} = {`+`, `-`}.**
Initial terminal set for the result-producing branches:	**For construction-continuing subtrees:** **$T_{ccs\text{-}rpb\text{-}initial}$ = {`END`}.** **For arithmetic-performing subtrees:** **T_{aps} = {$\leftarrow_{smaller\text{-}reals}$}.**
Fitness cases:	**101 frequency values in an interval of five decades of frequency values between 1 Hz and 100,000 Hz.**

Raw fitness:	**Fitness is the sum, over the 101 sampled frequencies (fitness cases), of the absolute weighted deviation between the actual value of the output voltage that is produced by the circuit at the probe point and the target value for voltage. The weighting penalizes unacceptable output voltages much more heavily than deviating, but acceptable, voltages.**
Standardized fitness:	**Same as raw fitness.**
Hits:	**The number of hits is defined as the number of fitness cases (out of 101) for which the voltage is acceptable or ideal or that lie in the "don't care" band.**
Wrapper:	**None.**

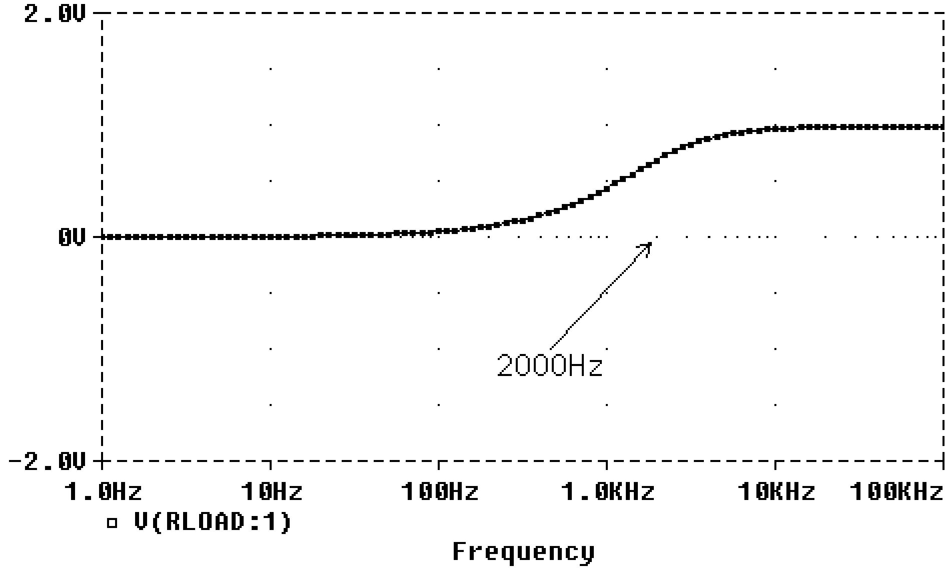
Parameters:	**M = 1,000 to 320,000. G = 1,001. Q =1,000. D = 64. B = 2%. N_{rpb} = 2. S_{rpb} = 200.**
Result designation:	**Best-so-far pace-setting individual.**
Success predicate:	**A program scores the maximum number (101) of hits.**

WORST SIMULTABLE CIRCUIT OF GENERATION 0 – LOWPASS FILTER

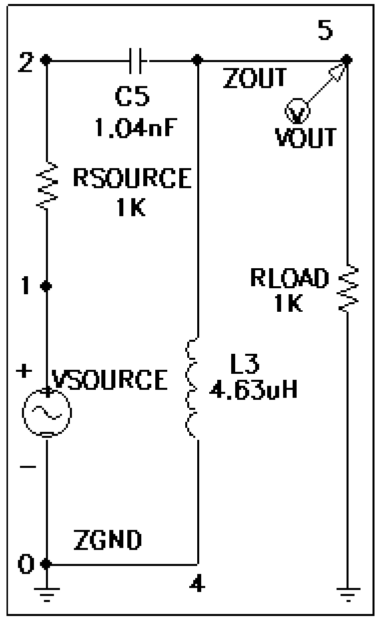


- **NOTE: Unsimulatable programs = 10^8 penalty**

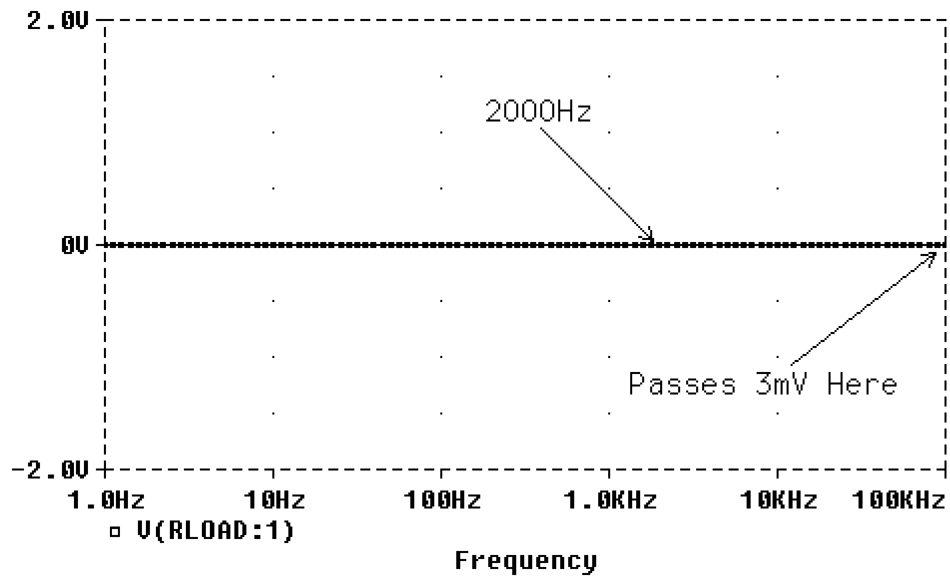
WORST SIMULTABLE CIRCUIT OF GENERATION 0 – LOWPASS FILTER



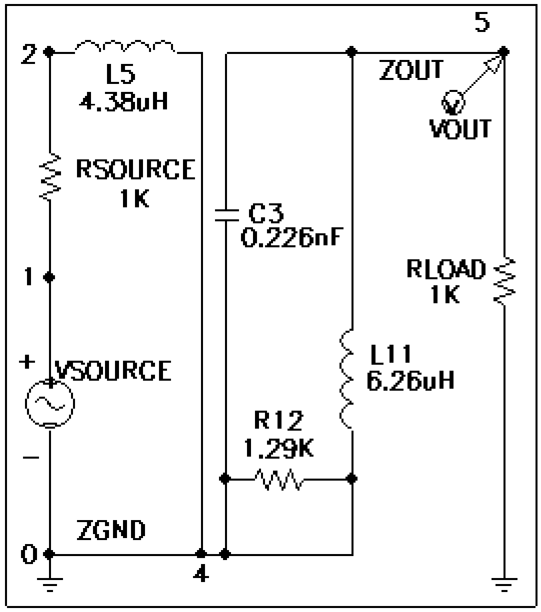
25TH PERCENTILE CIRCUIT OF GENERATION 0 – LOWPASS FILTER



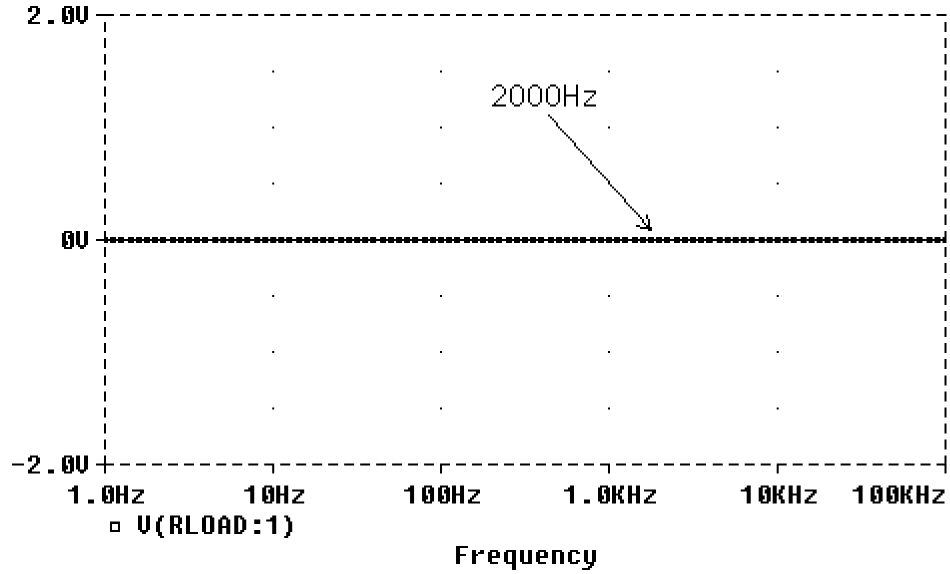
25TH PERCENTILE CIRCUIT OF GENERATION 0 – LOWPASS FILTER



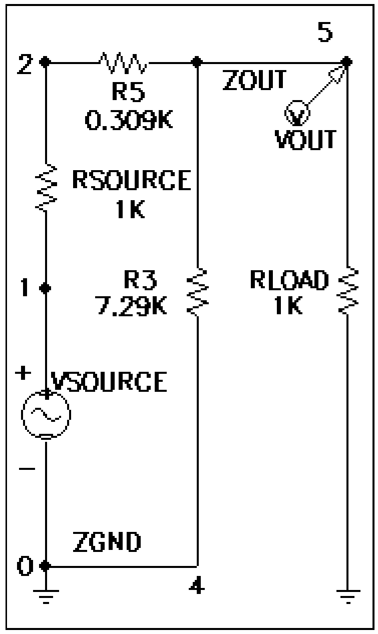
MEDIAN CIRCUIT OF GENERATION 0 – LOWPASS FILTER



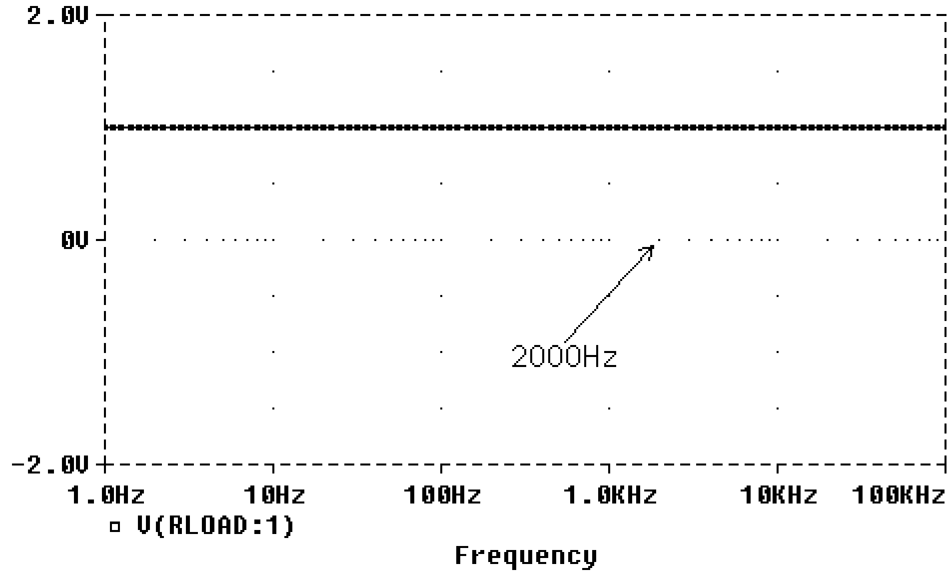
MEDIAN CIRCUIT OF GENERATION 0 – LOWPASS FILTER



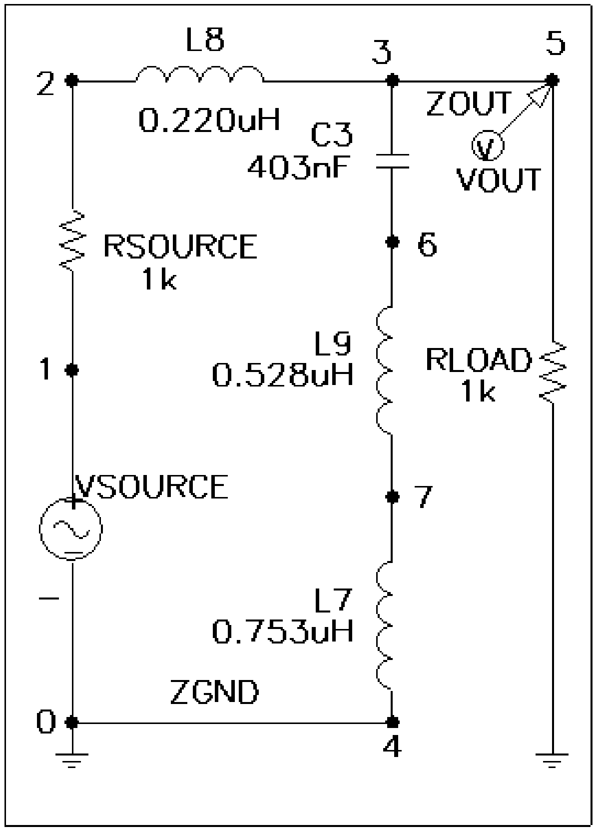
75TH PERCENTILE CIRCUIT OF GENERATION 0 – LOWPASS FILTER



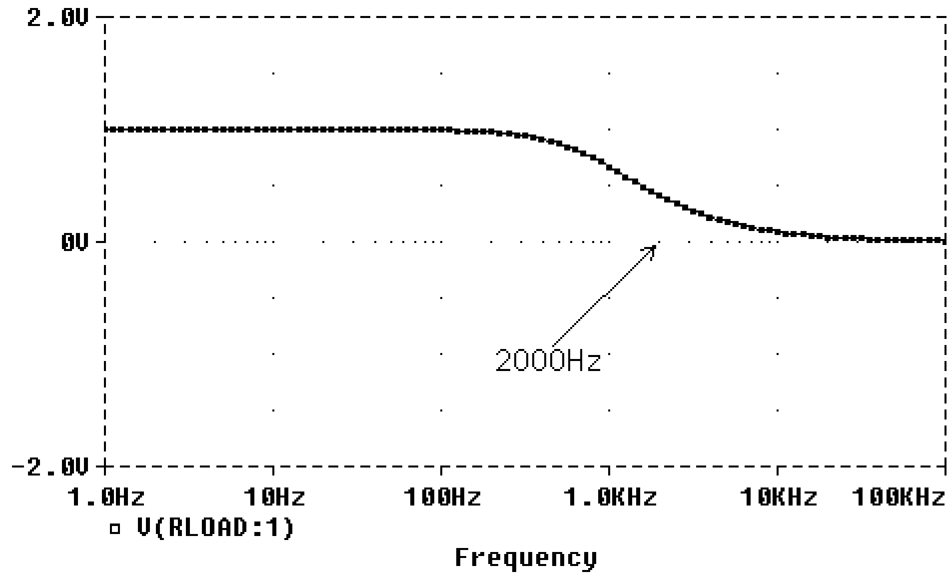
75TH PERCENTILE CIRCUIT OF GENERATION 0 – LOWPASS FILTER



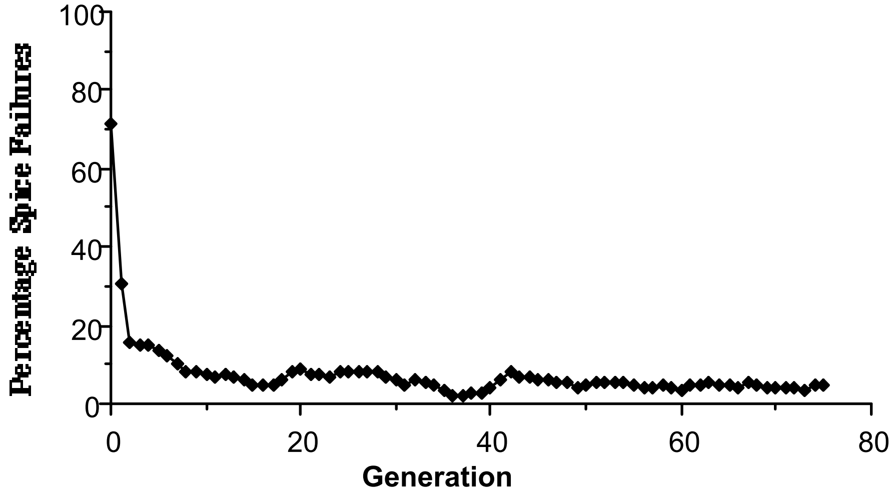
BEST-OF-GENERATION INDIVIDUAL FROM GENERATION 0 – LOWPASS FILTER



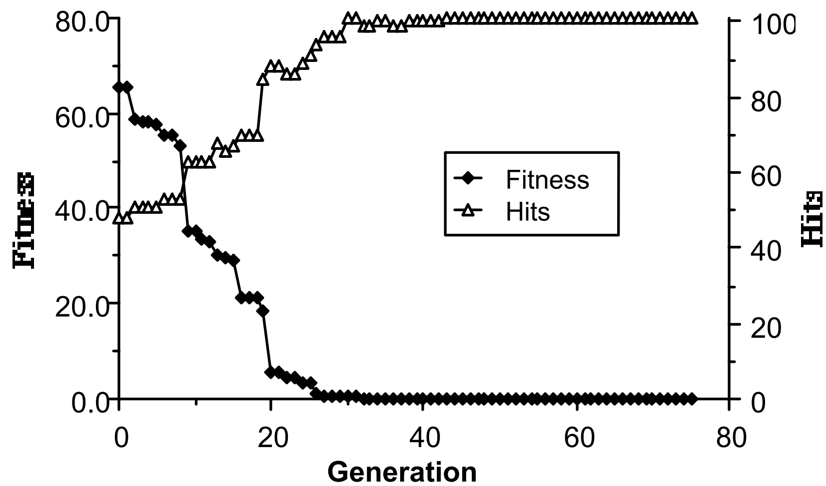
BEST-OF-GENERATION INDIVIDUAL FROM GENERATION 0 – LOWPASS FILTER



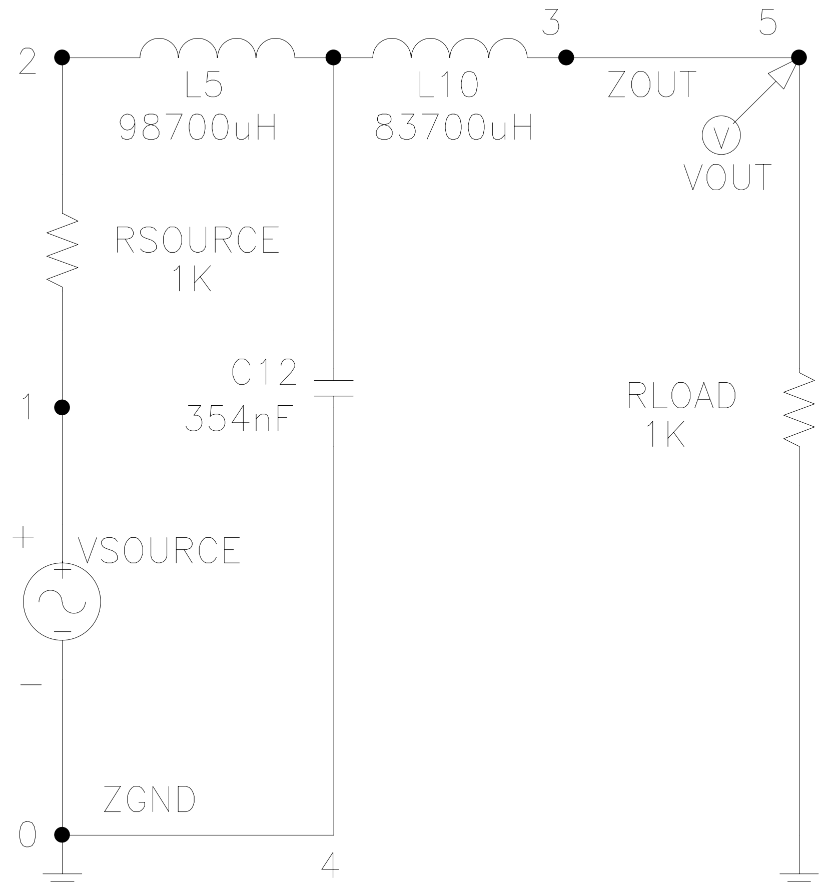
PERCENTAGE OF UNSIMULATABLE PROGRAMS



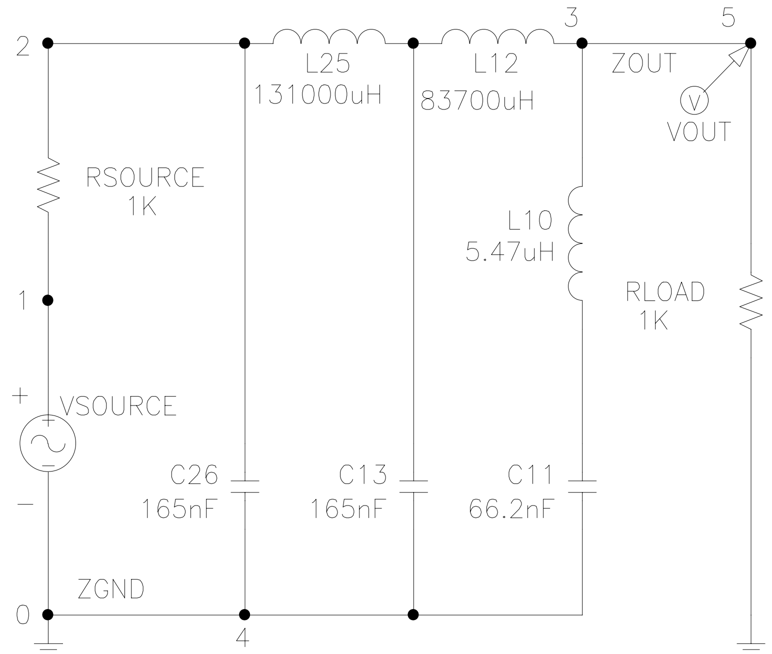
FITNESS AND HITS



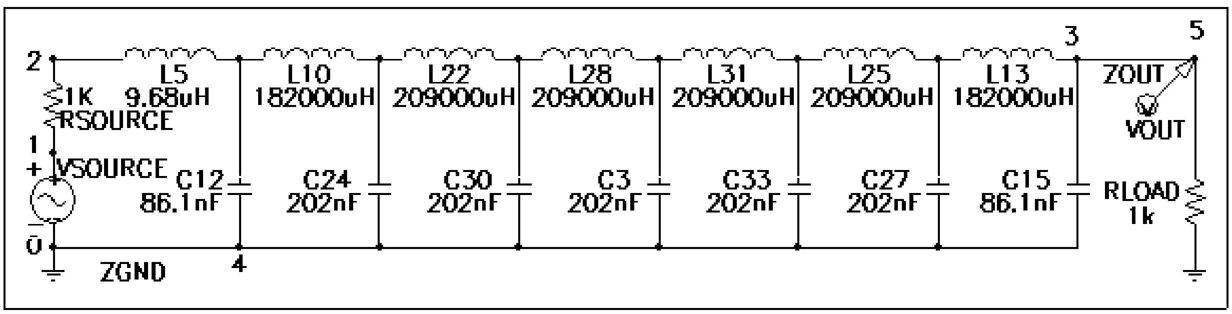
BEST-OF-GENERATION CIRCUIT FROM GENERATION 10 – LOWPASS FILTER



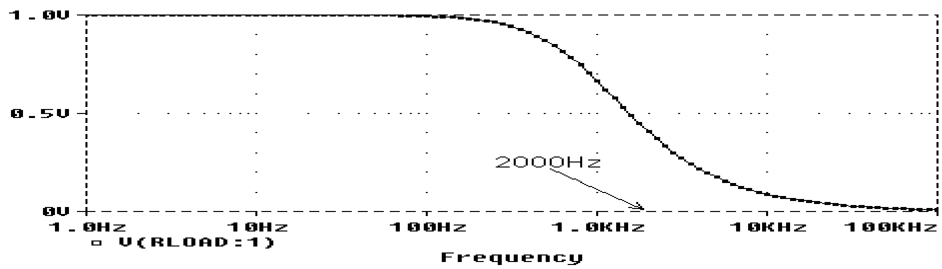
BEST-OF-GENERATION CIRCUIT FROM GENERATION 15 – LOWPASS FILTER



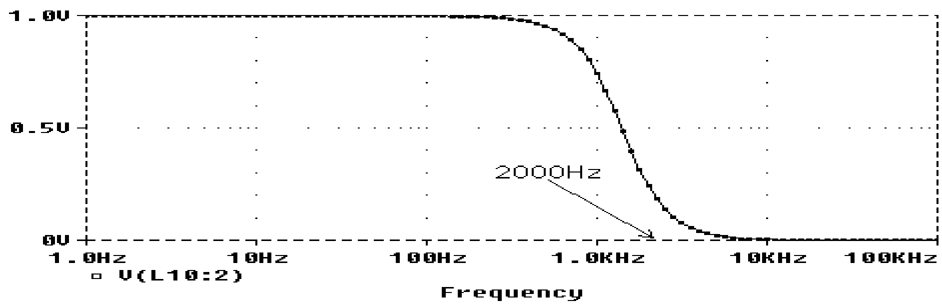
100%-COMPLIANT SEVEN-RUNG CAMPBELL LADDER CIRCUIT – BEST-OF-GENERATION 49 – LOWPASS FILTER



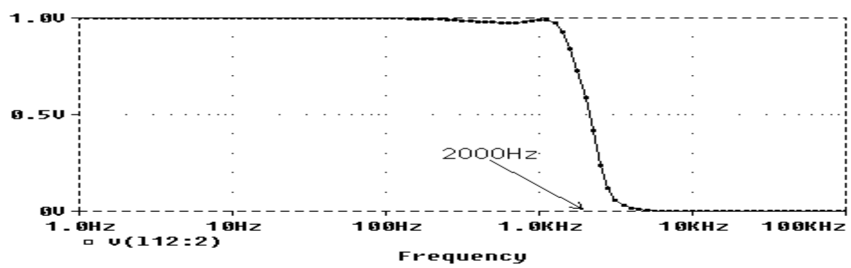
FREQUENCY DOMAIN BEHAVIOR OF BEST CIRCUITS OF GENERATION 0



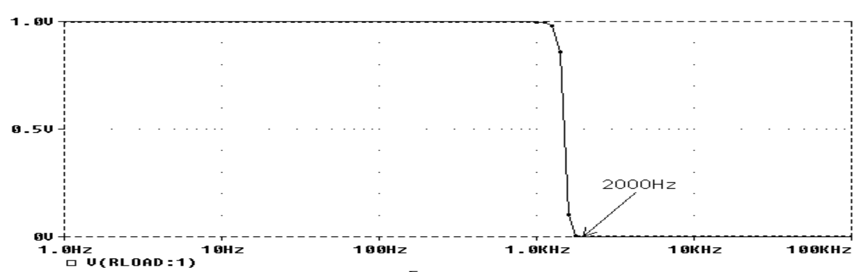
GENERATION 10



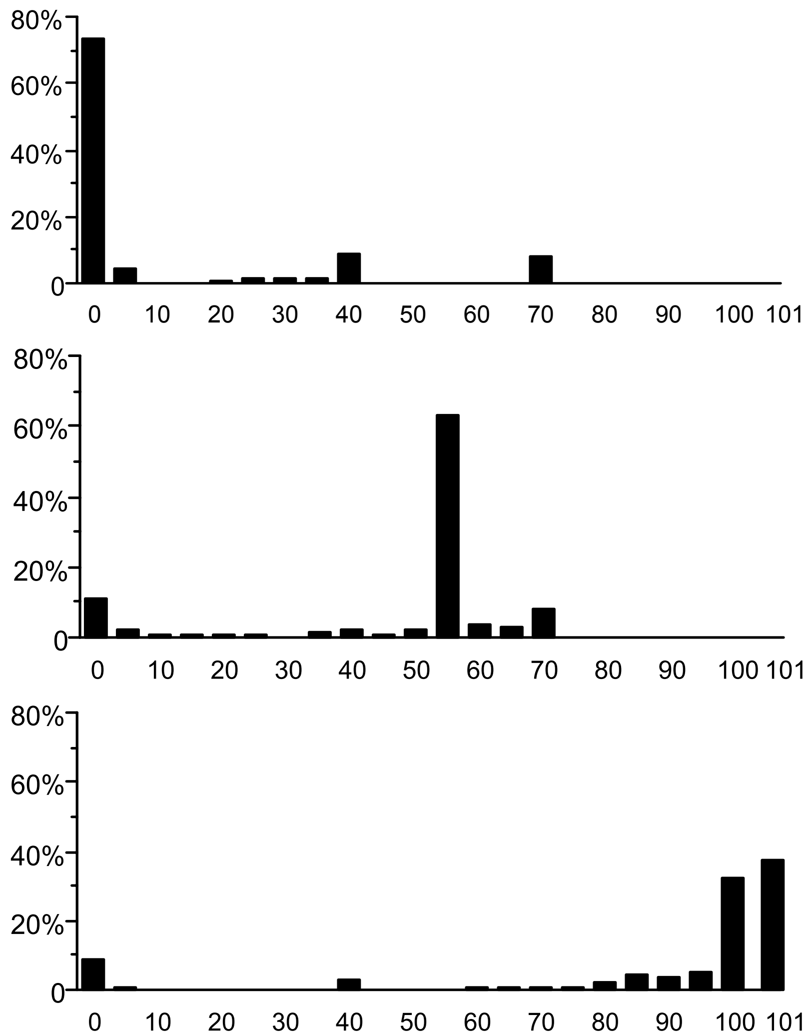
GENERATION 15



GENERATION 49



HITS HISTOGRAMS – GENERATIONS 0, 10, 50



NETLIST OF BEST OF GENERATION 49

```
* BEST-OF-GENERATION OF GENERATION 49
V0 2 0 SIN(0 2 166 0 0) AC 2
C3 3 0 2.02e+02nF
L5 4 5 9.68uH
R6 2 4 1.00K
R8 1 0 1.00K
L10 5 6 1.82e-05uH
C12 0 5 8.61e+01nF
L13 1 7 1.82e-05uH
C15 0 1 8.61e+01nF
L22 6 8 2.09e-05uH
C24 6 0 2.02e+02nF
L25 7 9 2.09e-05uH
C27 7 0 2.02e+02nF
L28 8 3 2.09e-05uH
C30 8 0 2.02e+02nF
L31 9 3 2.09e-05uH
C33 9 0 2.02e+02nF
* Component_count = 17
.AC DEC 20 1 100000
.PLOT AC VM(1)
.OPTIONS NOPAGE NOMOD
.END
```

SEVEN-RUNG LADDER FROM GENERATION 49

- **George Campbell of American Telephone and Telegraph received U. S. patent 1,227,113 in 1917 entitled *Electric Wave Filter***

  My invention in one or more of its embodiments has important applications in connection with wireless telegraphy, wireless telephony, multiplex high frequency wire telephony, composite telegraph and telephones lines, and in particular with telephone repeater circuits, wherein it is highly important that means be provided for selecting a range or band of frequencies, such as, for instance, the range or band of frequencies necessary for intelligible telephonic transmission of speech, while at the same time excluding from the receiving or translating device currents of all other frequencies.

CLAIM 2 OF CAMPBELL 1917 PATENT

An electric wave filter consisting of a connecting line of negligible attenuation composed of a plurality of sections, each section including a capacity element and an inductance element, one of said elements of each section being in series with the line and the other in shunt across the line, said capacity and inductance elements having precomputed values dependent upon the upper limiting frequency and the lower limiting frequency of a range of frequencies it is desired to transmit without attenuation, the values of said capacity and inductance elements being so proportioned that the structure transmits with practically negligible attenuation sinusoidal currents of all frequencies lying between said two limiting frequencies, while attenuating and approximately extinguishing currents of neighboring frequencies lying outside of said limiting frequencies.

PATENTS

- **The legal criteria for obtaining a U. S. patent are that the proposed invention be "new" and "useful" and that**

> **"… the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would (not) have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains." (35 *United States Code* 103a)**

CASCADE OF SIX π-SECTIONS

- **Modify the seven-rung ladder circuit from generation 49 in four minor ways.**
  - Replace 9.68 μH inductor L5 with a wire.
  - Replace each of the five identical 202 nF capacitors (C24, C30, C3, C33, C27) by a composition of two parallel 101 nF capacitors.
  - Note that the two 86.1 nF capacitors (C12 and C15) at the two ends of the ladder are each approximately equal to the (now) ten 101 nF capacitors. Replace each of these 12 approximately equal capacitors by 12 equal capacitors with capacitance equal to their average value (98.5 nF).
  - Replace the six non-trivial inductors (L10, L22, L28, L31, L25, and L13) by six equal inductors with inductance equal to their average value (200,000 μH).
- **The behavior in the frequency domain is substantially unchanged and is still 100%-compliant (i.e., it still scores 101 hits).**

CASCADE OF SIX π-SECTIONS - CONTINUED

- **The modified circuit is what is now known as a cascade of six identical symmetric π-sections.**
  - Each π-section consists of an inductor of inductance *L* (where *L* equals 200,000 μH) and two equal capacitors of capacitance *C*/2 (where *C* equals 197 nF).
  - In each π-section, the two 98.5 nF capacitors constitute the vertical legs of the π and the one 200,000 μH inductor constitutes the horizontal bar across the top of the π.

CASCADE OF SIX π-SECTIONS - CONTINUED

- **π-sections are characterized by two key parameters. The first parameter is the section's characteristic impedance (resistance). This should match the circuit's fixed load resistance (1,000 Ω).**
- **The second parameter is the nominal cutoff frequency which separates the filter's passband from its stopband. This second parameter should lie somewhere in the transition region between the end of the passband (1,000 Hz) and the beginning of the stopband (2,000 Hz).**
- **The characteristic resistance, *R*, of each π-section is given by the formula**

$$R = \sqrt{(L / C)}$$

  - When the inductance, L, is 200,000 μH and the capacitance, C, is 98.5 nF, this formula yields an R of 1,008 Ω.

CASCADE OF SIX π-SECTIONS - CONTINUED

- **The nominal cutoff frequency, f_c, of each of the π-sections of a lowpass filter is given by**

$f_c = 1 / (\pi \sqrt{(LC)})$

  - This formula yields a nominal cutoff frequency, f_c, of 1,604 Hz (i.e., roughly in the middle of the transition region between the passband and stopband of the desired lowpass filter).

- **Equivalent to the formulae in U. S. patent 1,227,113 (Campbell 1917).**

GEORGE CAMPBELL 1917 PATENT

- **The differences between the evolved circuit of generation 49 and the circuit taught by George Campbell in U. S. patent 1,227,113 (1917) are minor and unsubstantial.**
- **Legal criteria for U. S. patent is that the invention be "new" and "useful" and**

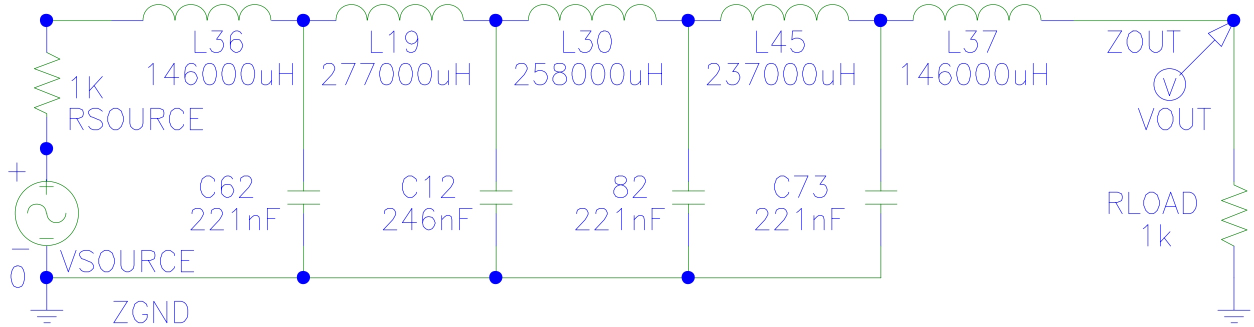
  ... the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would [not] have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. (35 *United States Code* 103a).

- **Arthur Samuel's criterion (1983) for artificial intelligence and machine learning:**

  The aim [is] ... to get machines to exhibit behavior, which if done by humans, would be assumed to involve the use of intelligence.

CASCADE OF FOUR T-SECTIONS

100%-COMPLIANT CIRCUIT FROM GENERATION 38 OF ANOTHER RUN



- **Modify the evolved circuit in three ways.**
  - Replace each of four nearly equal capacitors by a capacitor with capacitance equal to average value (227 nF).
  - Replace three largest inductors by a series composition of two equal inductors whose inductances are half of the replaced inductor
  - Replace (now) eight nearly equal inductors by an inductor equal to average (133,000 μH).
- **Yields a cascade of four identical symmetric T-sections with two equal *L/2* inductors (*L* = 266,000 μH) and one capacitor of capacitance *C* (where *C* = 227 nF).**

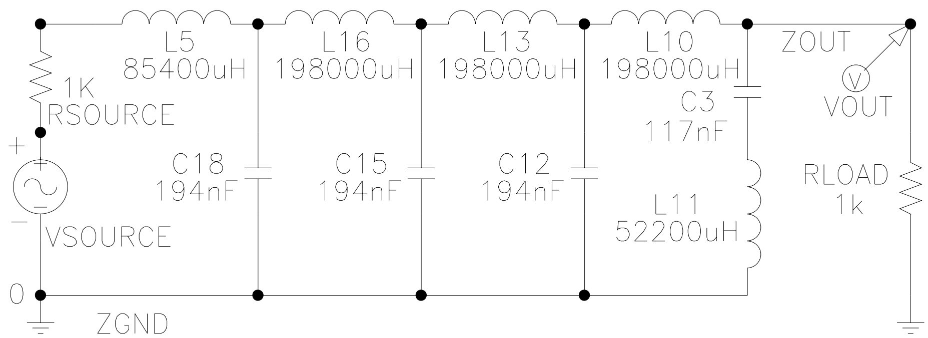
CASCADE OF FOUR T-SECTIONS - CONTINUED

- **T-sections are characterized by two key parameters**
  - The characteristic resistance, *R*, of each of the T-sections is $\sqrt{(L/C)}$ and this formula yields 1,083 Ω
  - The nominal cutoff frequency, f_c, of each T-section of a lowpass filter is g $1 / (\pi \sqrt{(LC)})$ and this formula yields 1,295 Hz

ZOBEL'S "*M*-DERIVED HALF SECTION" AND"CONSTANT K" FILTER SECTIONS

100%-COMPLIANT CIRCUIT FROM GENERATION 34 OF ANOTHER RUN

- **Replace the two 0.138 μH inductors of the evolved circuit by wires.**



- **Replace each of the three 198,000 μH inductors in the figure with a series composition of two 99,000 μH inductors.**
- **Replace the (now) seven approximately equal inductors by an inductor with inductance equal to the average (97,000 μH).**

ZOBEL'S FILTER — CONTINUED

- **After the above changes, the circuit is approximately equivalent to what is called a cascade of three identical symmetric T-sections and an "*M*-derived half section."**
- **Each T-section consists of an incoming inductor of inductance *L/2* (where *L* equals 194,000 μH), a junction point from which a capacitor of capacitance *C* (where *C* equals 194 nF) is shunted off to ground, and an outgoing inductor of inductance *L/2*. The first three symmetric T-sections are referred to as "constant K" filter sections. The characteristic resistance, *R*, of each of each of the three T-sections is $R = \sqrt{(L/C)}$ and is 1,000 Ω here. The nominal cutoff frequency, f_c, of each of the three T-sections of a lowpass filter is $f_c = 1 / (\pi \sqrt{(LC)})$ and is 1,641 Hz here.**

ZOBEL'S FILTER — CONTINUED

- **The remaining half section of the evolved circuit closely approximates what is called an "*M*-derived half section". In the derivation, *m* is a real constant between 0 and 1. Let *m* be 0.6 here. In a canonical "*M*-derived half section" that is derived from the above "constant K" prototype section, the value of the capacitor in the vertical shunt of the of an "*M*-derived half section" is given by the formula *mC*. This formula yields a value of 116.4 nF, while the actual value of C3 in the evolved circuit is 117 nF.**
- **The value of the inductor in the vertical shunt of an "*M*-derived half section" is given by the formula**

$L\ (1 - m^2) / (4m)$.

This formula yields a value of 51,733 while the actual value of L5 is 52,200 μH.

ZOBEL'S FILTER — CONTINUED

- **The frequency, f_∞, where the attenuation first approaches infinity, is given by the formula**

$f_\infty = f_c / \sqrt{(1 - m^2)}$.

This formula yields a value of f_∞ of 2,051 Hz. This value is near the beginning of the desired stopband.

ZOBEL'S FILTER — CONTINUED

- **Otto Zobel of the American Telephone and Telegraph Company invented the idea of adding an "*M*-derived half section" to one or more "constant K" sections and described it in U. S. patent 1,538,964 (Zobel 1925),**

> **The principal object of my invention is to provide a new and improved network for the purpose of transmitting electric currents having their frequency within a certain range and attenuating currents of frequency within a different range. . . . Another object of my invention is to provide a wave-filter with recurrent sections not all of which are alike, and having certain advantages over a wave-filter with all its sections alike.**

ZOBEL'S FILTER — CONTINUED

Claim 1 of Zobel's 1925 patent covers,

> **A wave-filter having one or more half-sections of a certain kind and one or more other half-sections that are M-types thereof, M being different from unity.**

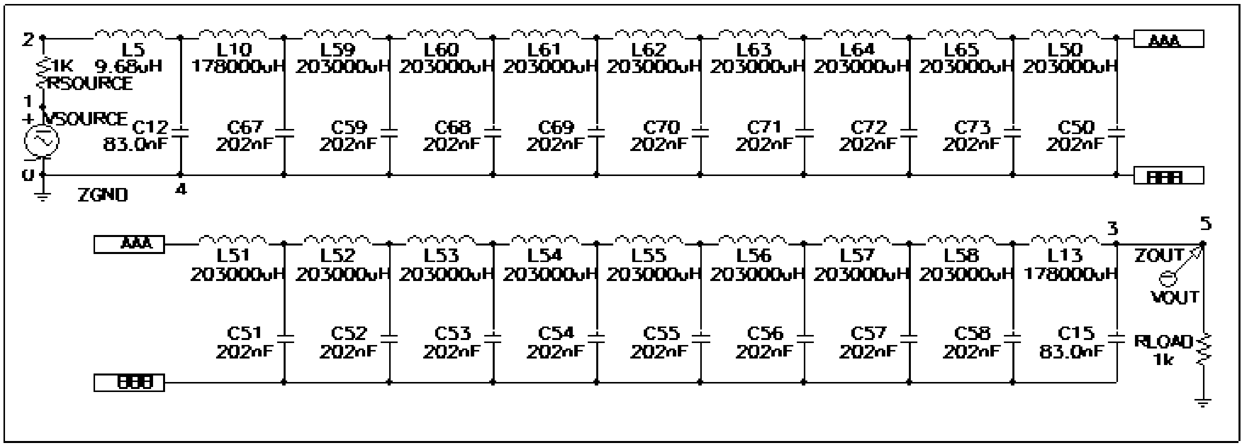
Claim 2 covers,

> **A wave-filter having its sections and half-sections so related that they comprise different M-types of a common prototype, M having several values for respectively different sections and half-sections.**

Claim 3 goes on to cover,

> **A wave-filter having one or more half-sections of a certain kind and one or more half-sections introduced from a different wave-filter having the same characteristic and the same critical frequencies and a different attenuation characteristic outside the free transmitting range.**

100%-COMPLIANT "19-RUNG LADDER" CIRCUIT – BEST-OF-RUN INDIVIDUAL FROM GENERATION 76 – LOWPASS FILTER (RUN A)



"BRIDGED T" CIRCUIT

- **Invented by Kenneth S. Johnson of Western Electric Company and received U. S. patent 1,611,916 in 1926.**

  In accordance with the invention, a section of an artificial line, such as a wave filter, comprises in general four impedance paths, three of which are arranged in the form of a T network with the fourth path bridged across the transverse arms of the T. The impedances of this network, which for convenience, will be referred to as a bridged T network, bear a definite relationship to a network of the series shunt type, the characteristics of which are well known.

"BRIDGED T" CIRCUIT - CONTINUED

In the forms of the invention described herein, the arms of the bridged T network consist of substantially pure reactances. Its most useful forms are found to be wave filter networks in which there is a substantially infinite attenuation at a frequency within the band to be suppressed and the network may be designed so that this frequency is very near the cut-off frequency of the filter, thus producing a very sharp separation between the transmitted and suppressed bands.

"BRIDGED T" CIRCUIT - CONTINUED

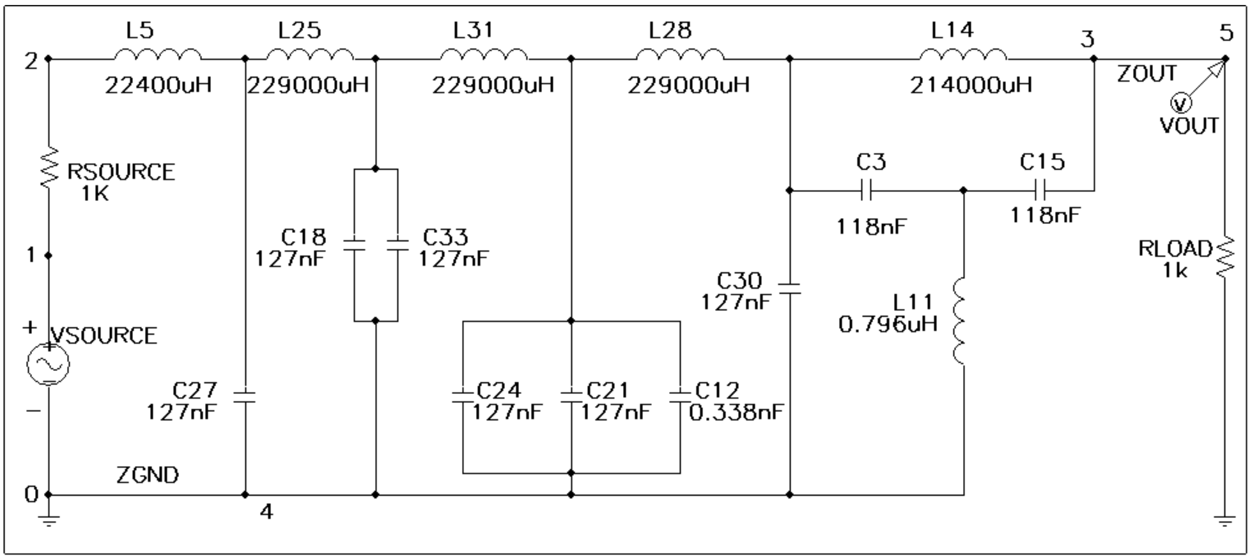
Claim 1 of patent 1,611,916 covers,

An electrical network comprising a pair of input terminals and a pair of output terminals, an impedance path connected directly between an input terminal and an output terminal, a pair of impedance paths having a common terminal and having their other terminals connected respectively to the terminals of said first path, and a fourth impedance path having one terminal connected to said common terminal and having connections from its other terminal to the remaining input terminal and output terminal, each of said paths containing a substantial amount of reactance, the impedances of said network having such values that said network is the equivalent of a series-shunt network having desired transmission characteristics.

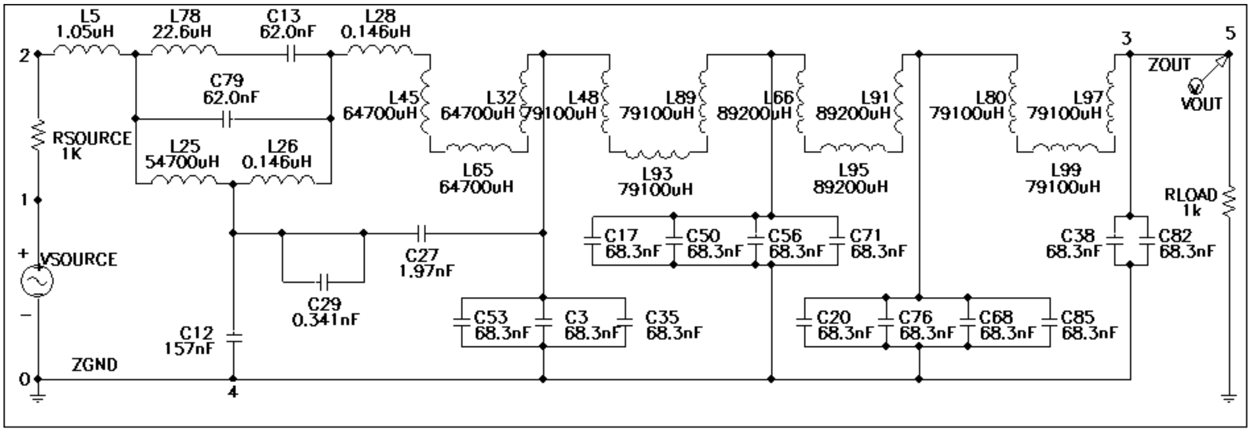
THE "BRIDGED T" CIRCUIT - CONTINUED

- **General topological form of Johnson's "bridged T" filter has been repeatedly evolved by genetic programming; however, none of these 100%-complaint filters have the substance of a bona fide "bridged T" filter.**

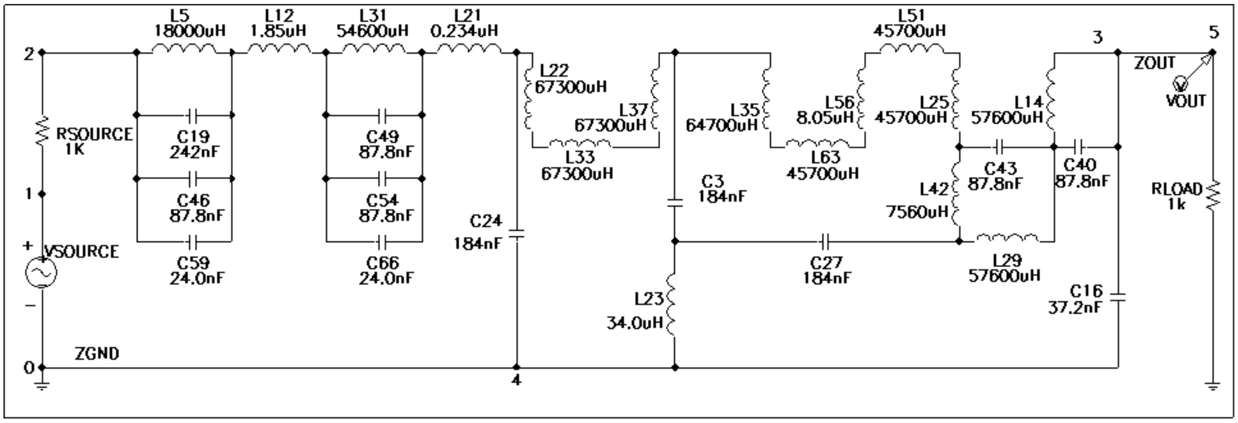
NOMINAL "BRIDGED T" CIRCUIT BEST-OF-GENERATION 64 – 100%-COMPLIANT CIRCUIT – LOWPASS FILTER



BEST-OF-RUN INDIVIDUAL FROM GENERATION 58 – 100%-COMPLIANT CIRCUIT – LOWPASS FILTER



BEST-OF-RUN INDIVIDUAL FROM GENERATION 212 – 100%-COMPLIANT CIRCUIT – LOWPASS FILTER



HIGHPASS FILTER

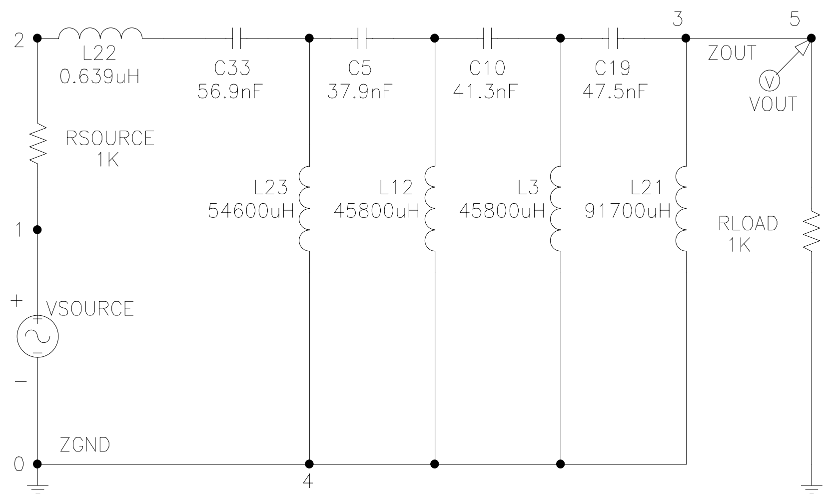
- **Six of the seven preparatory steps are the same for this highpass filter as they were for the lowpass filter. Only the fitness measure is different.**
- **The fitness cases for the highpass filter are the same 101 points in the five decades of frequency between 1 Hz and 100,000 Hz as for the lowpass filter**
- **For each of the 61 points in the three-decade interval between 1 Hz and 1,000 Hz (the desired stopband of the highpass filter)**
    - If the voltage equals the ideal value of 0.0 Volts in this interval, the deviation is **0.0**.
    - If the voltage is between 0 millivolts and 1 millivolt, the absolute value of the deviation from 0 millivolts is weighted by a factor of **1.0**.
    - If the voltage is more than 1 millivolt, the absolute value of the deviation from 0 millivolts is weighted by a factor of **10.0**.

HIGHPASS FILTER - CONTINUED

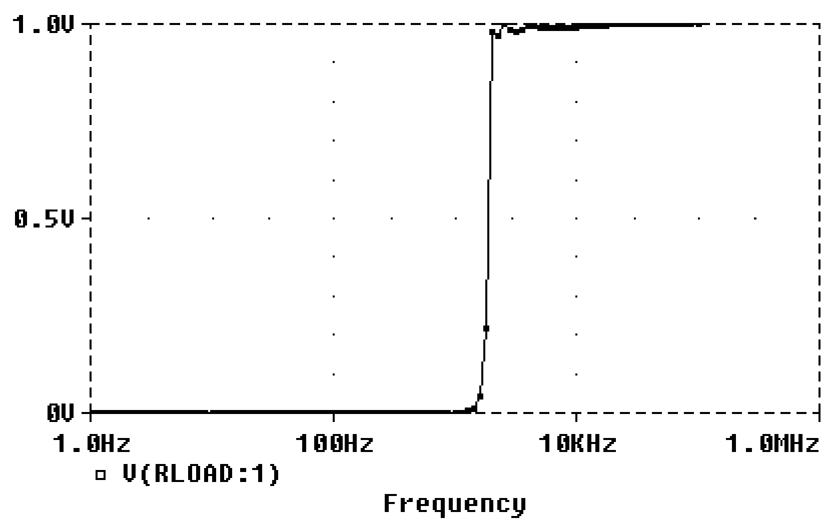
- **For each of the 35 points in the interval from 2,000 Hz to 100,000 Hz (the desired passband of the highpass filter)**
  - If the voltage equals the ideal value of 1.0 Volts in this interval, the deviation is 0.0.
  - If the voltage is between 970 millivolts and 1,000 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of 1.0.
  - If the voltage is less than 970 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of 10.0.

HIGHPASS FILTER - CONTINUED

FOUR-RUNG LADDER HIGHPASS FILTER FROM GENERATION 27



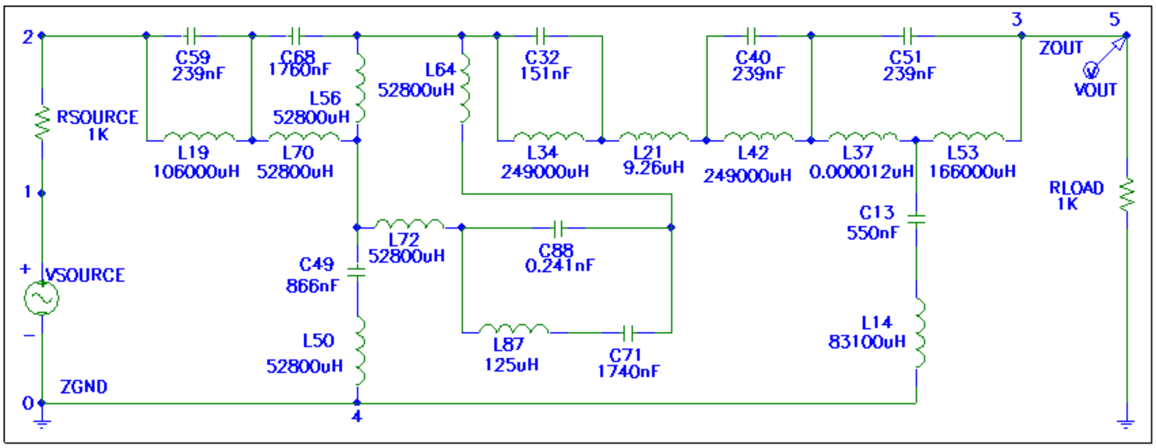
FREQUENCY DOMAIN BEHAVIOR



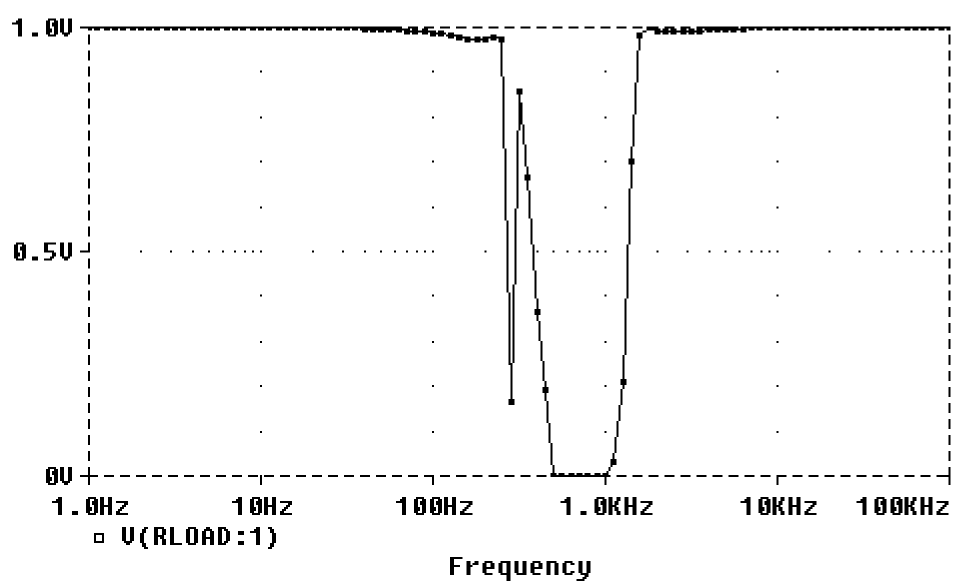
BANDSTOP (NOTCH, BAND-REJECT, BAND-ELIMINATION FILTER) FILTER

- **Stops all frequencies in a specified range while passing all other frequencies.**
- **Design a bandstop filter whose stopband lies between 500 Hz and 1,000 Hz**
- **There are two passbands, one stopband, and two transition bands.**
  - Suppose that the first passband of the desired bandstop filter runs from 1 Hz to 250 Hz and the second one runs from 2,000 Hz to 100,000 Hz.
  - Suppose further that the first transition ("don't care") band lies between 250 Hz and 500 Hz and the second one runs from 1,000 Hz to 2,000 Hz.
  - The desired stopband lies between 500 Hz and 1,000 Hz.
  - The acceptable deviation in the two passbands is 30 millivolts and is 1 millivolt in the stopband between 500 Hz and 1,000 Hz

100%-COMPLIANT BANDSTOP FILTER FROM GENERATION 101



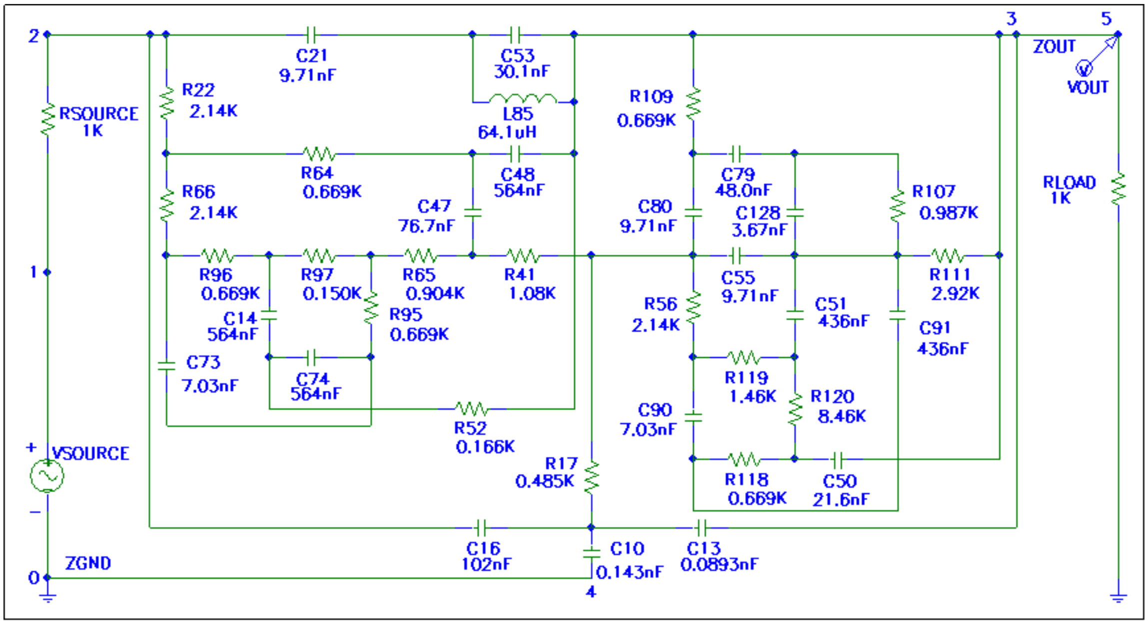
FREQUENCY DOMAIN BEHAVIOR



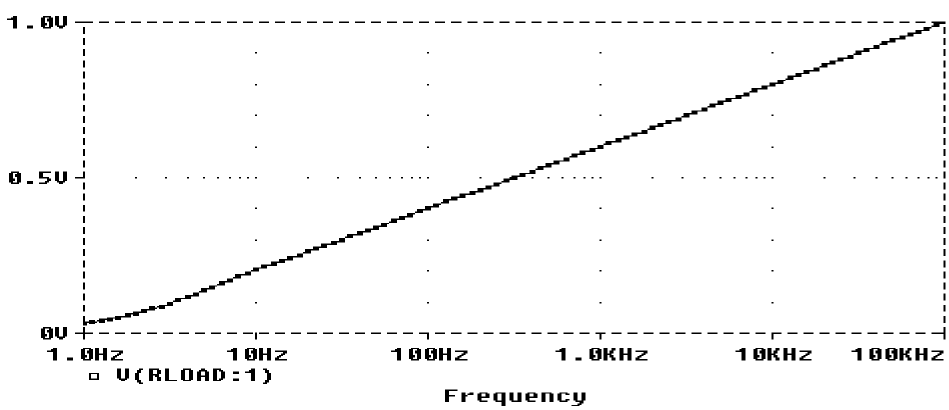
FREQUENCY-MEASURING CIRCUIT

- **Frequency-measuring circuit whose output in millivolts (from 1 millivolt to 1,000 millivolts) is linearly proportional to the logarithm of the frequency of the incoming signal (between 1 Hz and 100,000 Hz).**

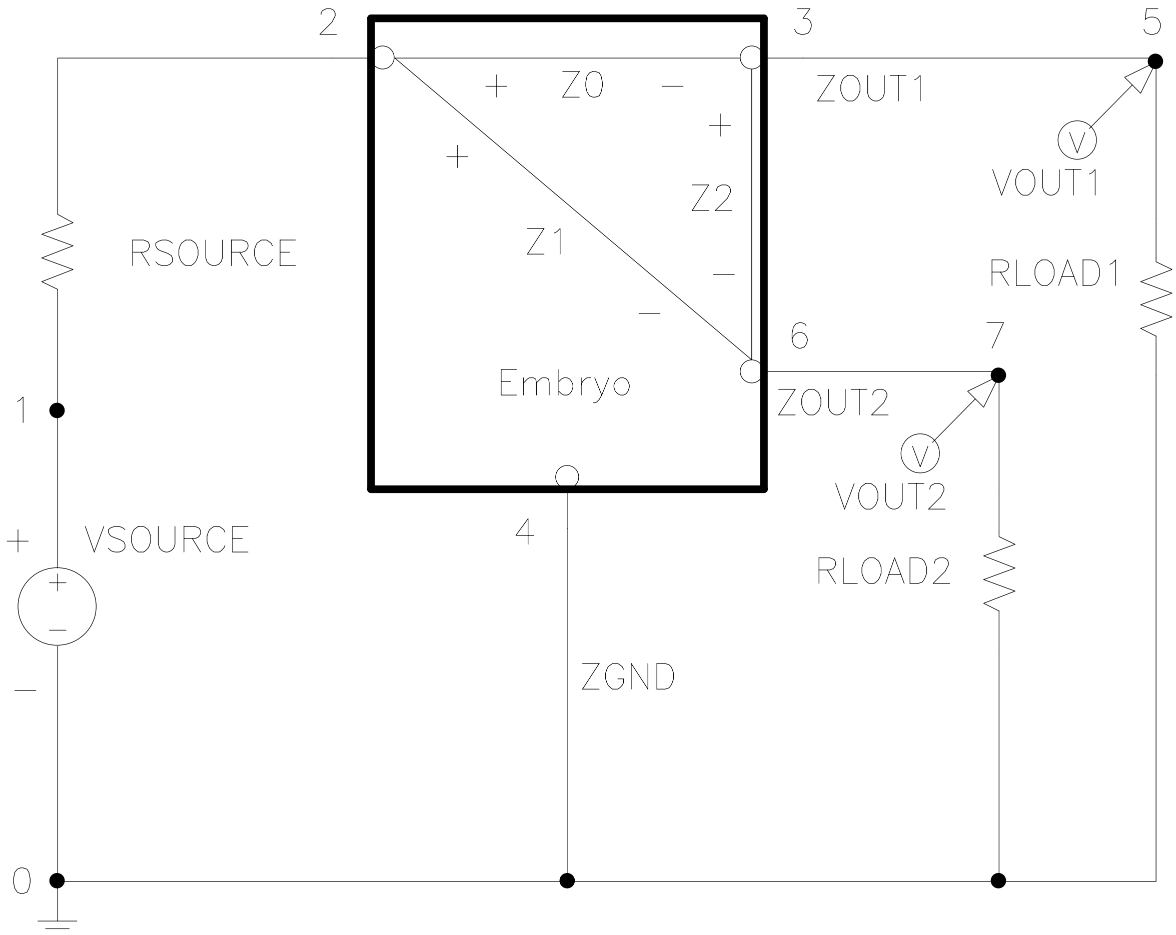
EVOLVED CIRCUIT OF GENERATION 56



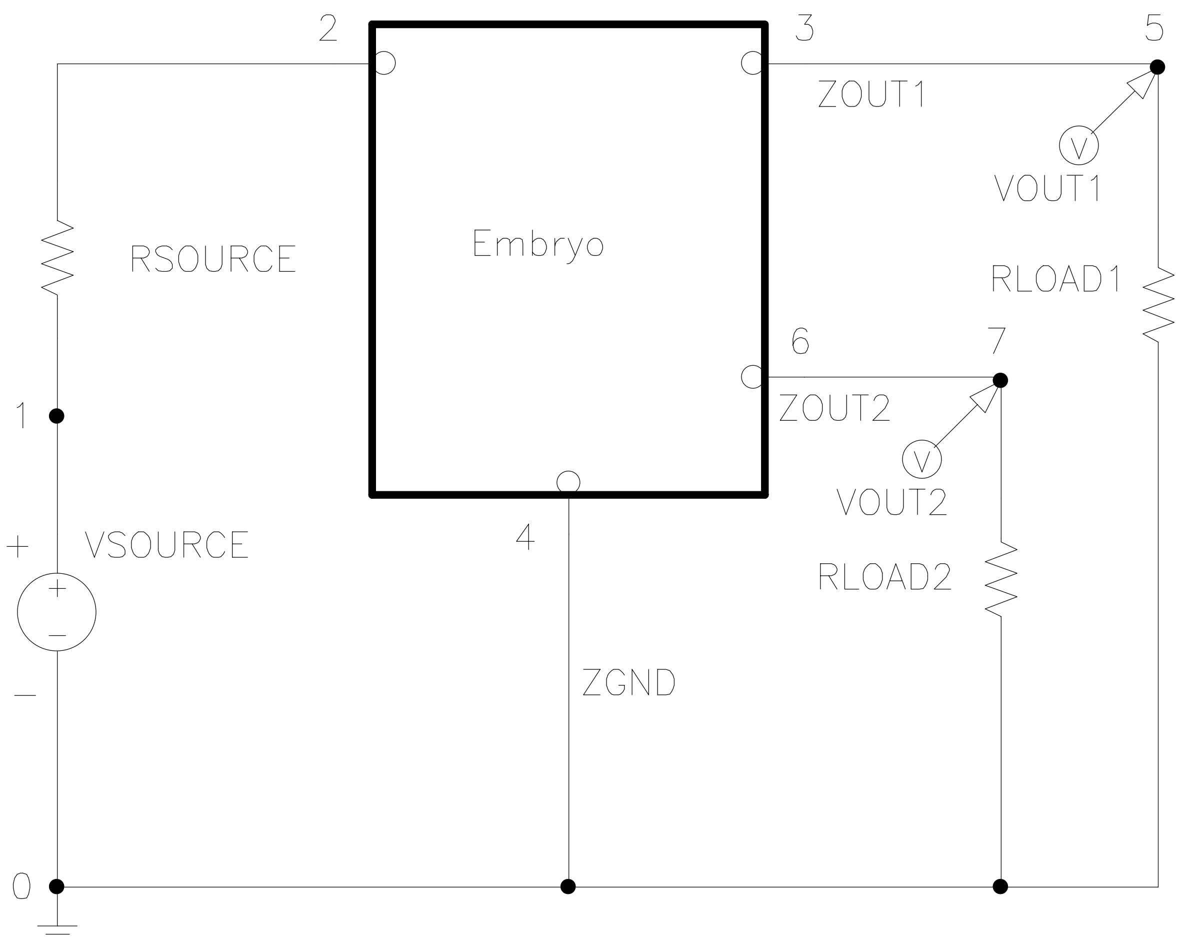
FREQUENCY DOMAIN BEHAVIOR



INITIAL CIRCUIT FOR A TWO-BAND CROSSOVER (WOOFER AND TWEETER) FILTER



INITIAL CIRCUIT FOR EVOLVING A TWO-OUTPUT CIRCUIT



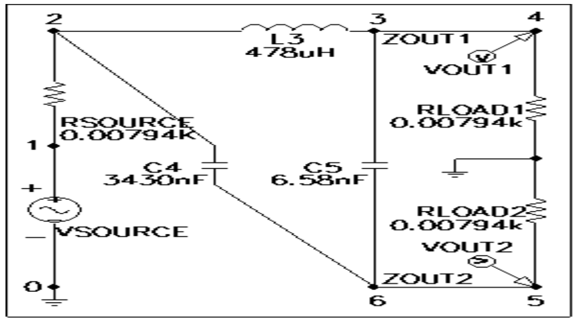
SEVEN PREPARATORY STEPS

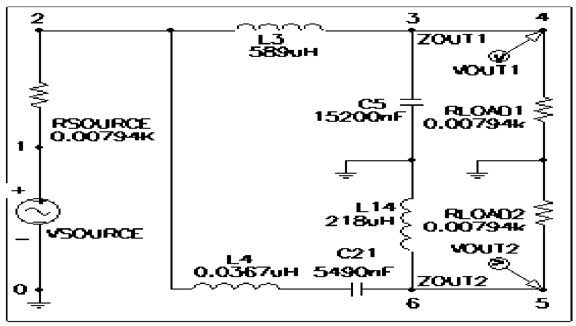
- **determining the set of terminals**
- **determining the set of functions**
- **<u>determining the fitness measure</u>**
- **determining parameters**
- **determining method for designating a result and criterion for terminating a run**
- **determining the architecture of the circuit-constructing program tree (either specified by user or using architecture-altering operations)**
- **<u>determining the initial circuit</u>**

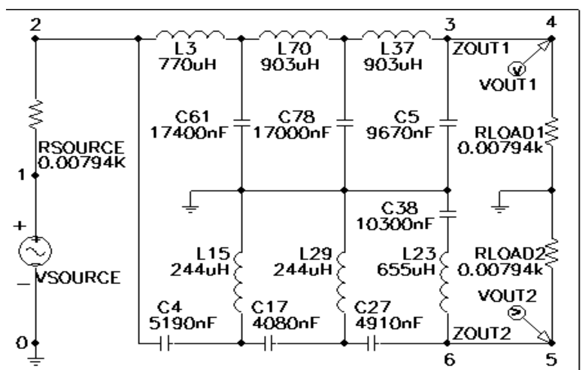
FITNESS FOR A TWO-BAND CROSSOVER FILTER

$$F(t) = \sum_{i=0}^{100} [W_1(d_1(f_i), f_i)d_1(f_i) + W_2(d_2(f_i), f_i)d_2(f_i)]$$

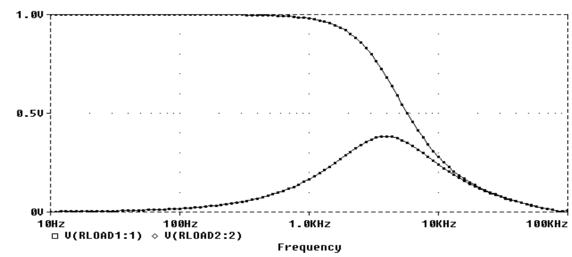
BEST OF GEN 0, 20, AND 137

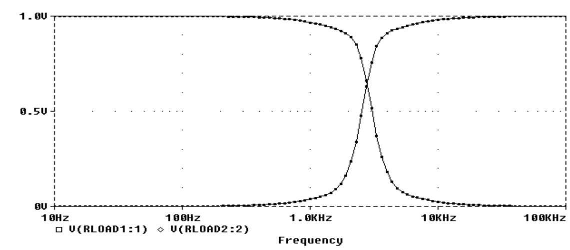


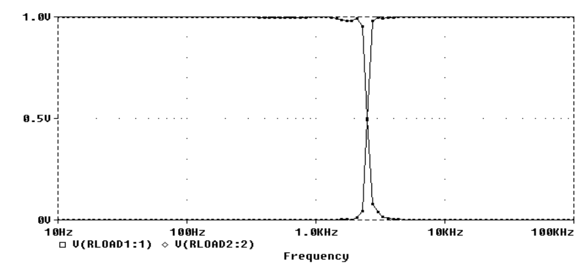




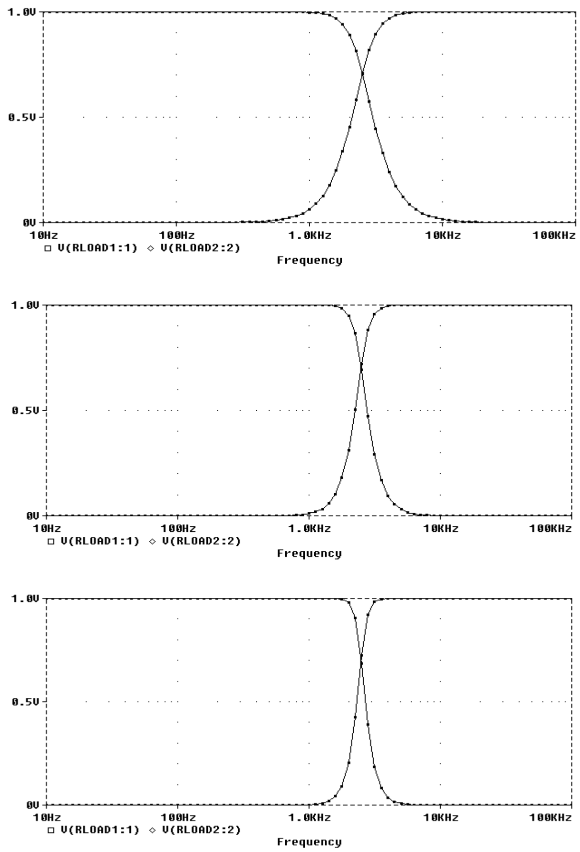
FREQUENCY DOMAIN BEHAVIOR OF THE BEST CIRCUIT OF GENERATION 0, 20, AND 137 FOR A TWO-BAND CROSSOVER FILTER



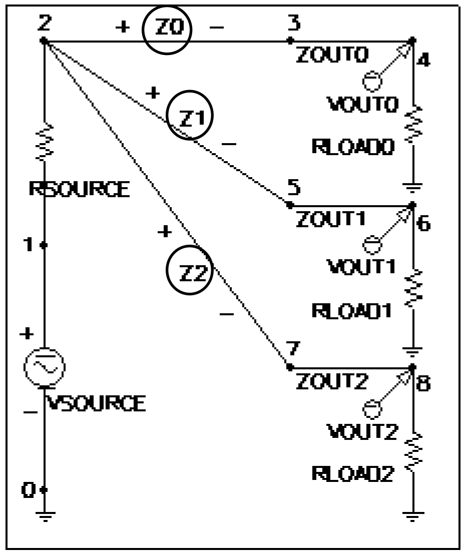




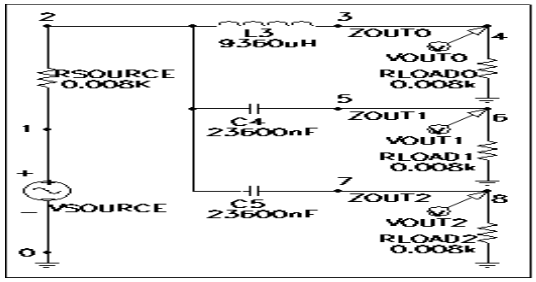
FREQUENCY DOMAIN BEHAVIOR OF BUTTERWORTH 3, 5, AND 7 FILTERS

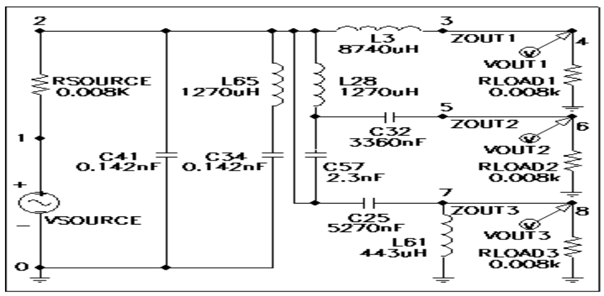


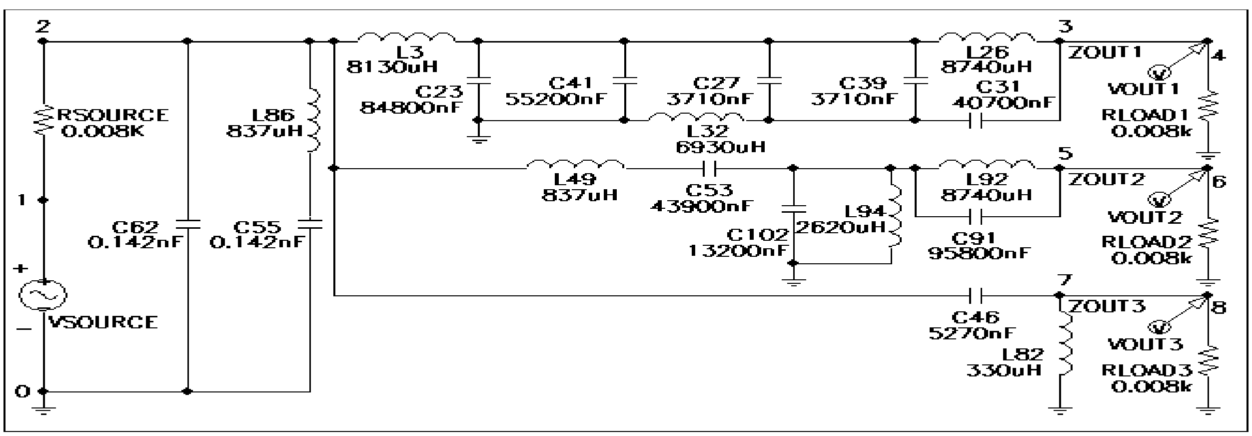
INITIAL CIRCUIT FOR A THREE-BAND CROSSOVER (WOOFER-MIDRANGE-TWEETER) FILTER



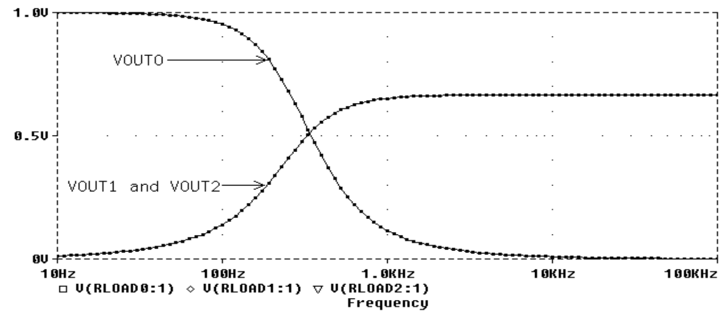
BEST CIRCUITS OF GENS 0, 54, 174

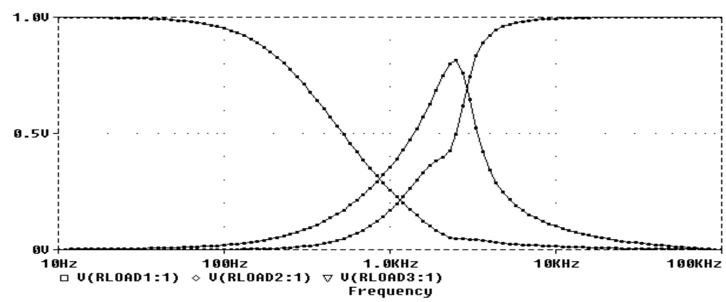


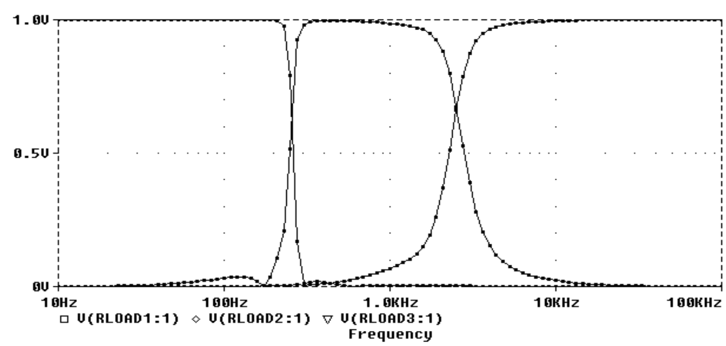




FREQ – BEST OF GENS 0, 54, 174

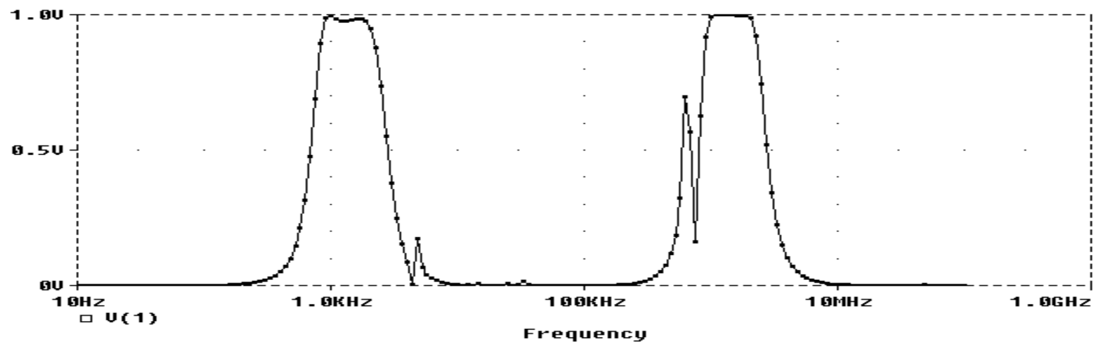




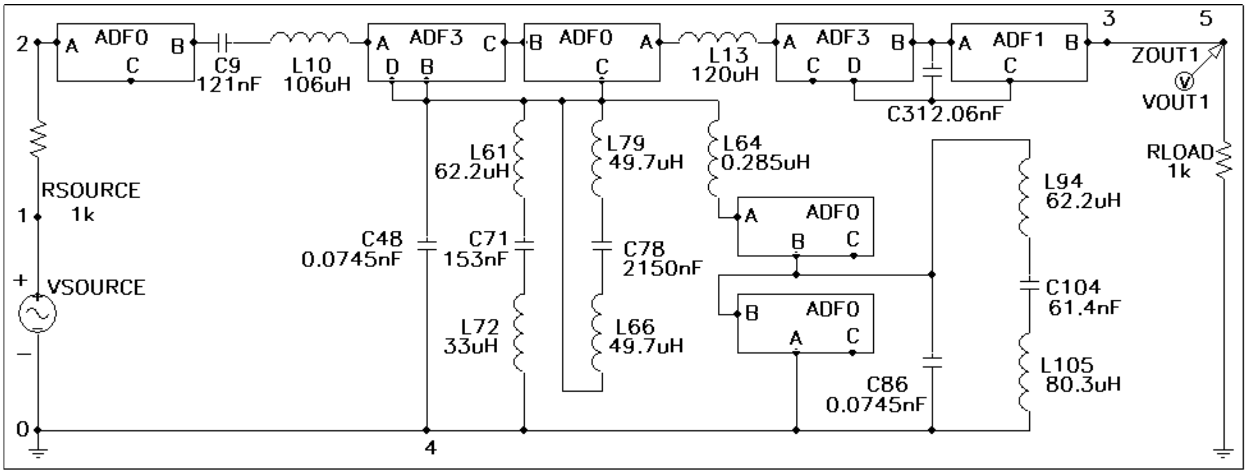


DOUBLE-BANDPASS FILTER (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

GENERATION 89 – FREQUENCY DOMAIN BEHAVIOR OF THE BEST-OF-RUN CIRCUIT

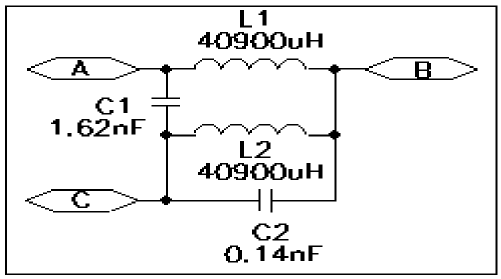


GENERATION 89 – BEST-OF-RUN CIRCUIT

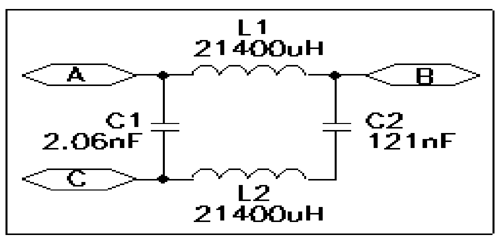


GENERATION 89 – BEST-OF-RUN CIRCUIT

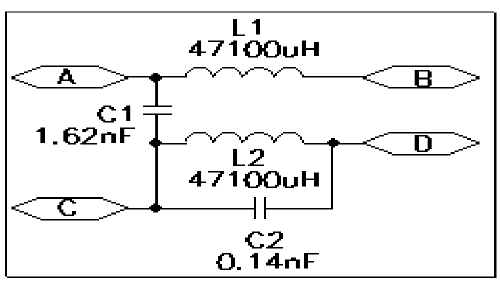
THREE-PORTED QUADRUPLY-CALLED ADF0



THREE-PORTED ADF1



FOUR-PORTED TWICE-CALLED ADF3



FUNCTION AND TERMINAL SETS

- **For RPBs, function set for construction-continuing subtree**

$F_{ccs\text{-}rpb}$ = {**ADF0**, **ADF1**, **ADF2**, **ADF3**, C, L, SERIES, PARALLEL0, FLIP, NOP, THGND, CUT, THVIA0, THVIA1, THVIA2, THVIA3, THVIA4, THVIA5, THVIA6, THVIA7}

- **For RPBs, terminal set for construction-continuing subtree**

$T_{ccs\text{-}rpb}$ = {END, CUT}

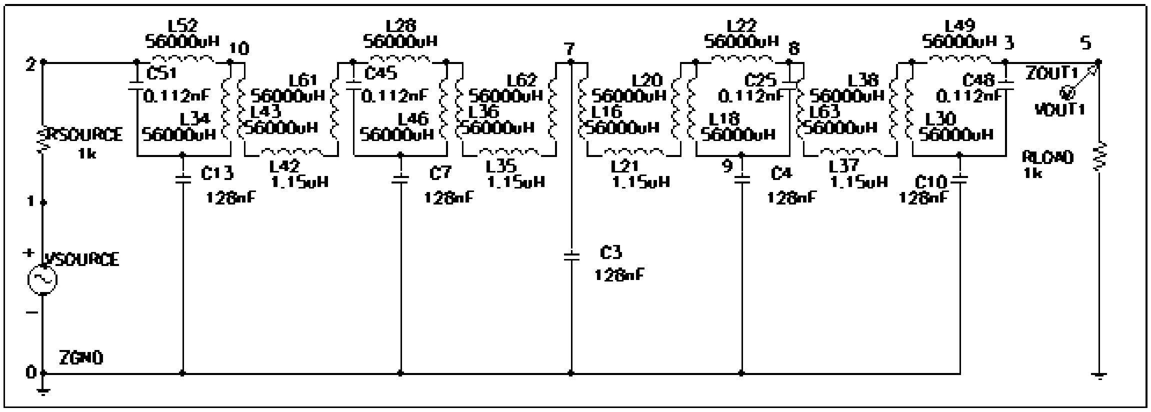
- **For ADFs, function set for construction-continuing subtree**

F_{ccs} = {C, L, SERIES, PARALLEL0, FLIP, NOP, THGND, CUT, THVIA0, THVIA1, THVIA2, THVIA3, THVIA4, THVIA5, THVIA6, THVIA7}

- **For ADFs, the terminal set for construction-continuing subtree**

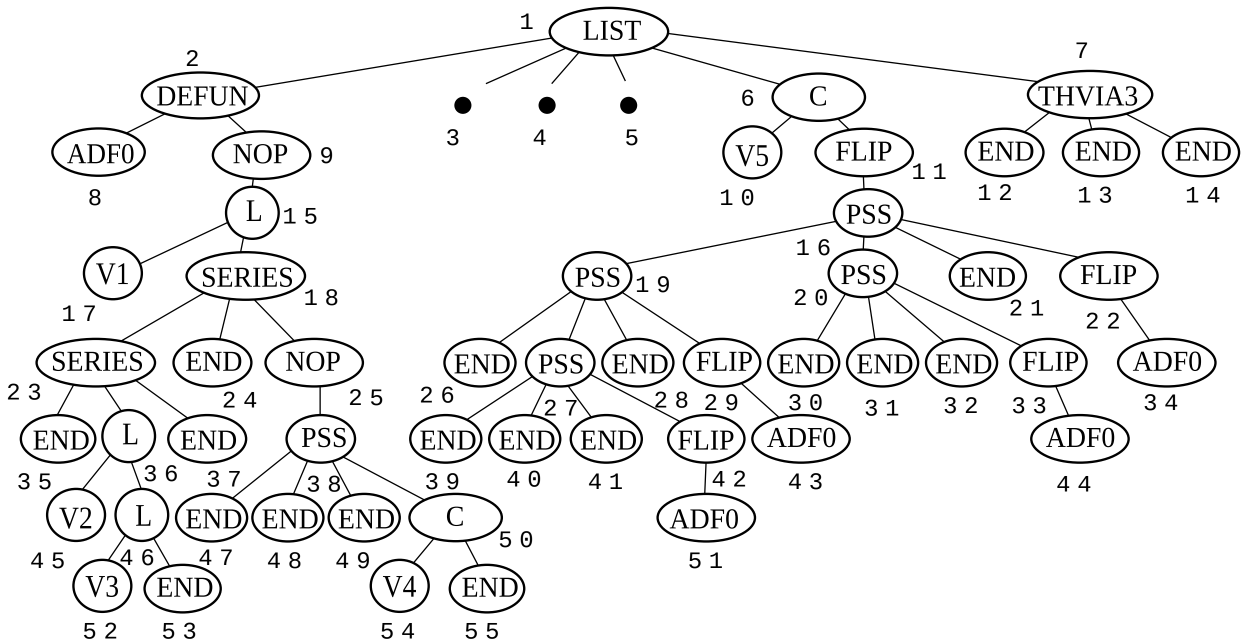
$T_{ccs\text{--}adf}$ = {END, CUT}

BEST-OF-RUN CIRCUIT FROM GENERATION 35 USING ADFs

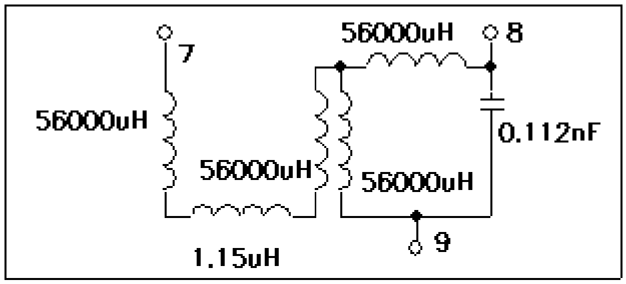


NOTE SYMMETRY

BEST-OF-RUN PROGRAM TREE FROM GENERATION 35 USING ADFs



EDITED VERSION OF `ADF0` FROM BEST-OF-RUN PROGRAM TREE FROM GENERATION 35 USING ADFs



FUNCTION AND TERMINAL SETS USING ARCHITECTURE-ALTERING OPERATIONS

- **For RPBs, function set for construction-continuing subtree**

$F_{ccs\text{-}rpb}$ = {`C`, `L`, `SERIES`, `PARALLEL0`, `FLIP`, `NOP`, `THGND`, `CUT`, `THVIA0`, `THVIA1`, `THVIA2`, `THVIA3`, `THVIA4`, `THVIA5`, `THVIA6`, `THVIA7`}

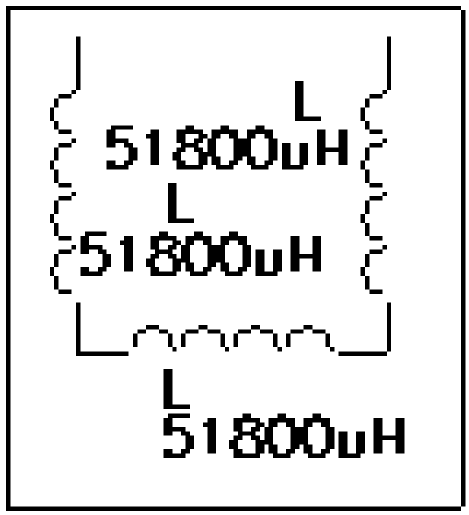
- **For RPBs, terminal set for construction-continuing subtree**

$T_{ccs\text{-}rpb}$ = {`END`, `CUT`}

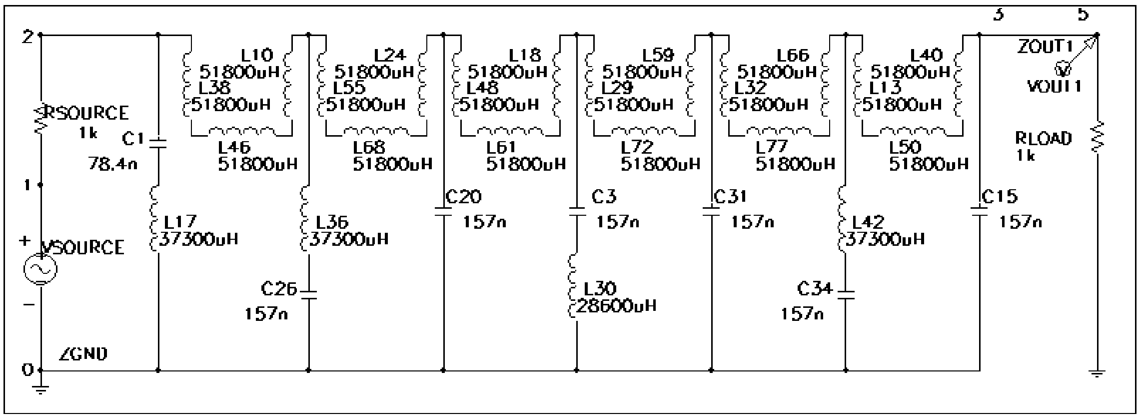
- **For the new ADFs, the set of potential new functions, $F_{ccs\text{-}pot}$, is**

$F_{ccs\text{-}pot}$ = {`ADF0`, `ADF1`, `ADF2`, `ADF3`}

AUTOMATICALLY DEFINED FUNCTION `ADF0` OF BEST-OF-RUN CIRCUIT FROM GENERATION 77 USING ARCHITECTURE-ALTERING OPERATIONS

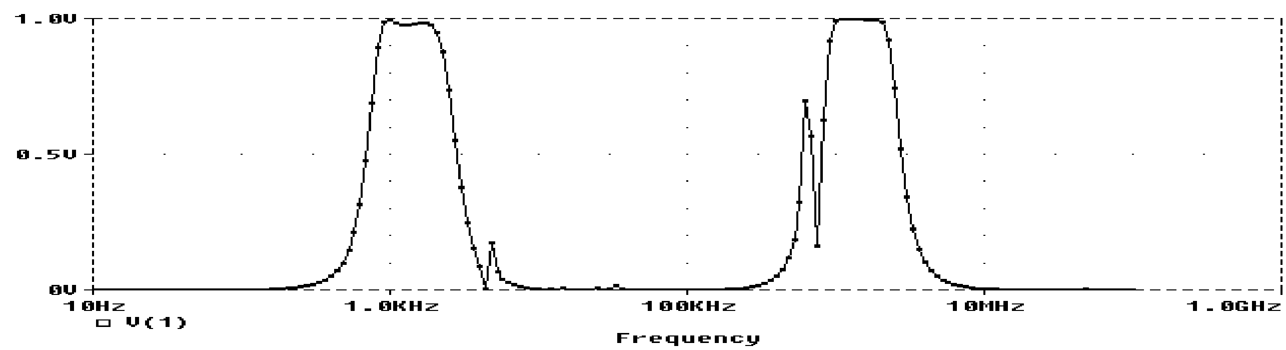


BEST-OF-RUN CIRCUIT FROM GENERATION 77 USING ARCHITECTURE-ALTERING OPERATIONS

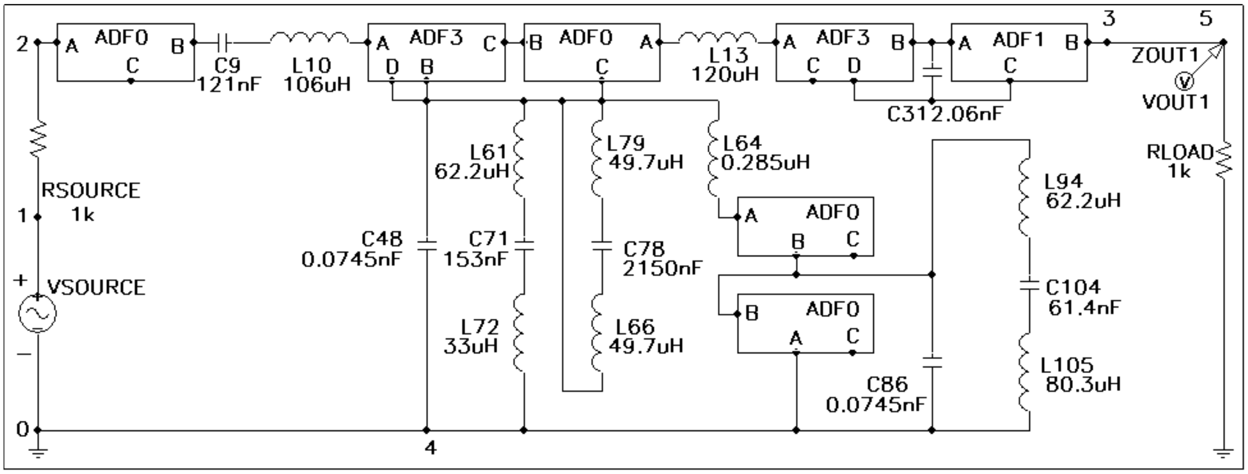


EVOLVING A DOUBLE-BANDPASS FILTER USING ARCHITECTURE-ALTERING OPERATIONS

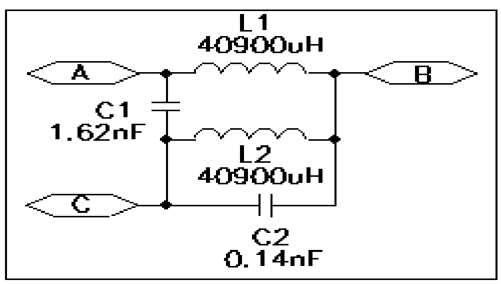
GENERATION 89 – FREQUENCY DOMAIN BEHAVIOR OF THE BEST-OF-RUN CIRCUIT



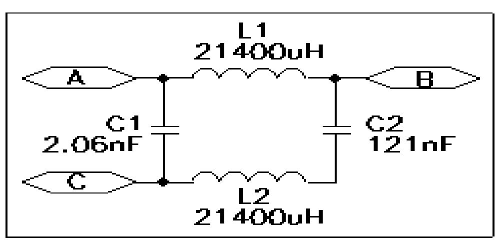
GENERATION 89 – BEST-OF-RUN CIRCUIT



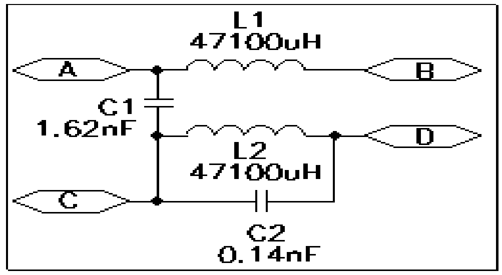
THREE-PORTED QUADRUPLY-CALLED ADF0



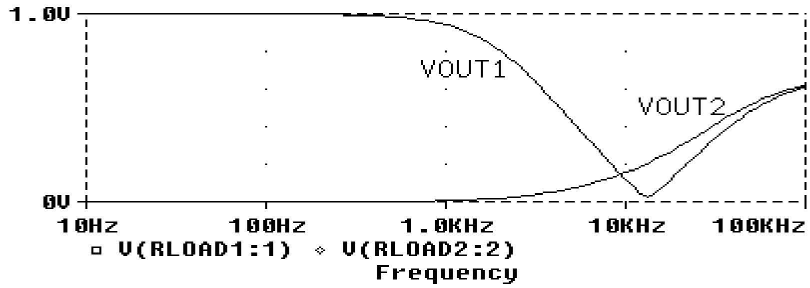
THREE-PORTED ADF1

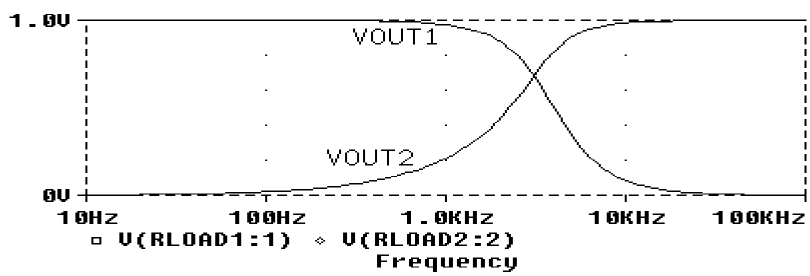


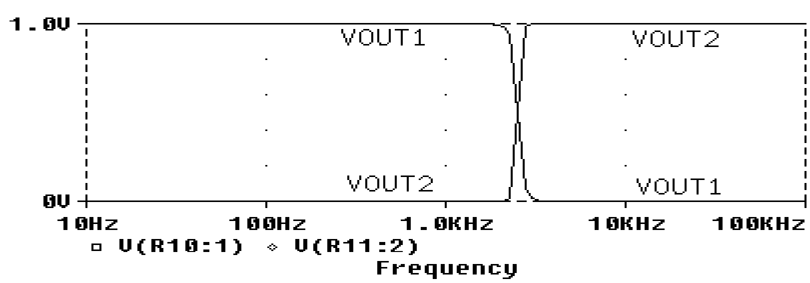
FOUR-PORTED TWICE-CALLED ADF3



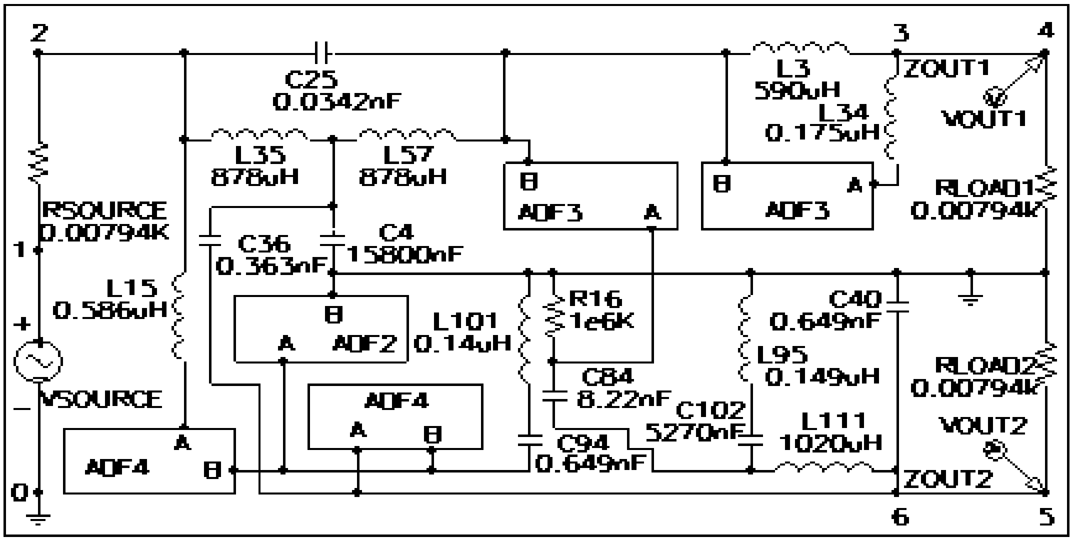
FREQUENCY DOMAIN BEHAVIOR OF BEST CIRCUIT OF GENERATIONS 0, 8, AND 158 FOR A TWO-BAND CROSSOVER FILTER



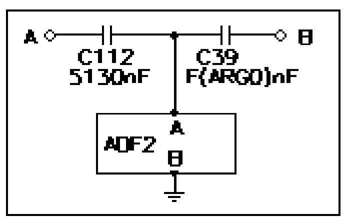




BEST CIRCUIT OF GENERATION 158



• **ADF3** supplies one <u>PARAMETERIZED</u> capacitor **C39** whose value is determined by **ADF3**'s dummy variable, **ARG0**.



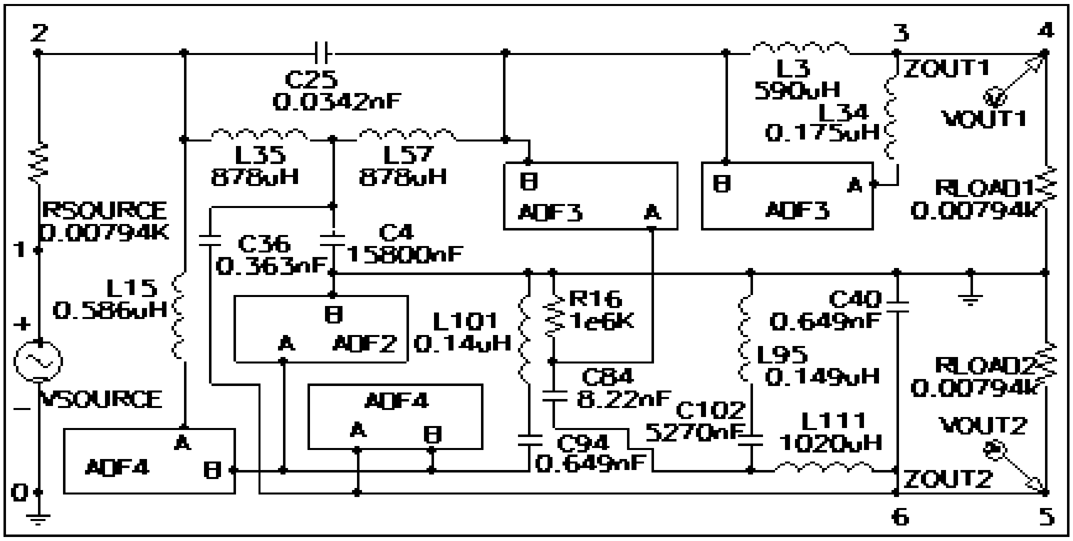
• **ADF3** supplies one unparameterized 5,130 uF capacitor **C112**.

• **ADF3** has one hierarchical reference to **ADF2** (which, in turn, supplies one unparameterized 259 μH inductor).

BEST CIRCUIT OF GENERATION 158 — CONTINUED

- **The combined effect of `ADF3` is to supply two capacitors (one of which is parameterized) and one inductor.**
- **`ADF3` has three ports and is called is called once by `RPB0` and `RPB1`.**

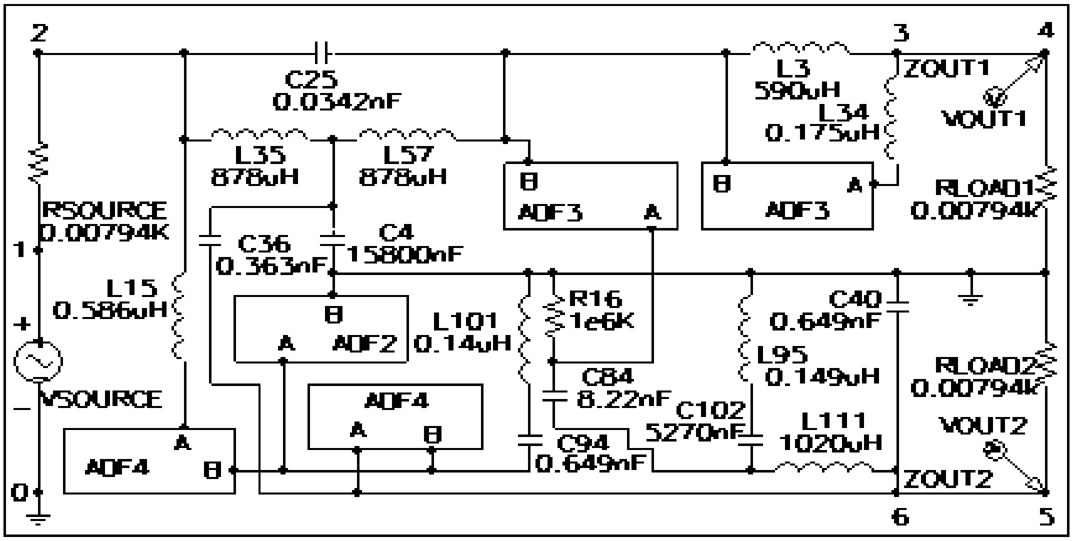
BEST CIRCUIT OF GENERATION 158 – CONTINUED



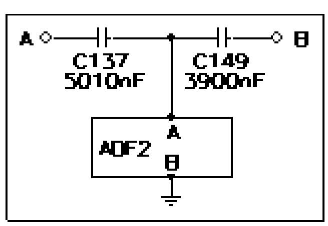
- **ADF0 and ADF1 are not called at all.**

- **ADF2 has two ports and supplies one unparameterized 259 μH inductor L147. ADF2 is called a total of five times – one time by RPB2 directly, twice hierarchically by ADF3 (which is called once by RPB0 and RPB1), and twice hierarchically by ADF4 (called by RFP2). Its ARG0 plays no role.**

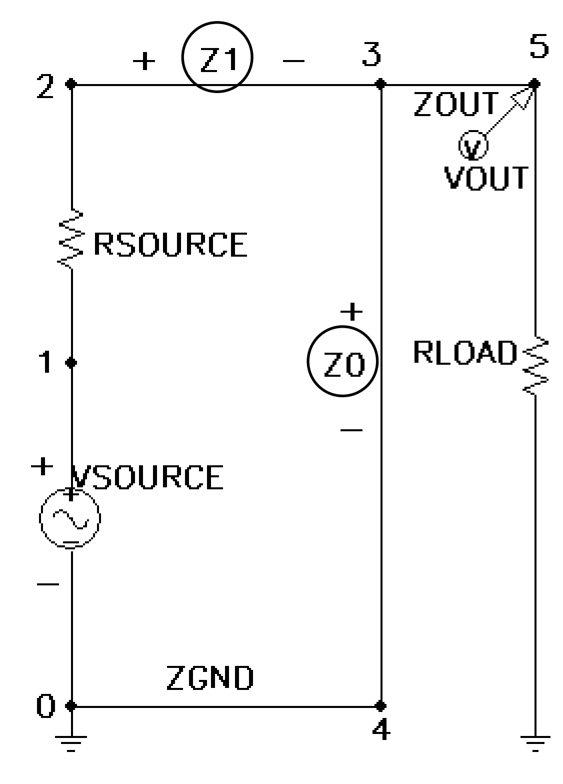
BEST CIRCUIT OF GENERATION 158 – CONTINUED



- **ADF4 has three ports and supplies one unparameterized 3,900 uF capacitor C137 and one unparameterized 5,010 uF capacitor C149. ADF4 has one hierarchical reference to ADF2 (which, in turn, supplies one unparameterized 259 μH inductor). Thus, the combined effect of ADF4 is to supply two capacitors and one inductor.**



ONE-INPUT, ONE-OUTPUT EMBRYONIC ELECTRICAL CIRCUIT FOR LOWPASS FILTER



ARCHITECTURE OF CIRCUIT-CONSTRUCTING PROGRAM TREE FOR LOWPASS FILTER

- **Two result-producing branches (`RPB0` and `RPB1`) joined by a connective `LIST` function**

- **Four automatically defined functions (`ADF0`, `ADF1`, `ADF2`, and `ADF3`)**

- **The circuit-constructing program tree has six branches joined by a connective `LIST` function**

FUNCTION AND TERMINAL SETS FOR LOWPASS FILTER

- **For RPBs, function set for construction-continuing subtree**

$F_{ccs\text{-}rpb}$ = {**ADF0**, **ADF1**, **ADF2**, **ADF3**, C, L, SERIES, PARALLEL0, FLIP, NOP, THGND, CUT, THVIA0, THVIA1, THVIA2, THVIA3, THVIA4, THVIA5, THVIA6, THVIA7}

- **For RPBs, terminal set for construction-continuing subtree**

$T_{ccs\text{-}rpb}$ = {END, CUT}

- **For ADFs, function set for construction-continuing subtree**

F_{ccs} = {C, L, SERIES, PARALLEL0, FLIP, NOP, THGND, CUT, THVIA0, THVIA1, THVIA2, THVIA3, THVIA4, THVIA5, THVIA6, THVIA7}

- **For ADFs, the terminal set for construction-continuing subtree**

$T_{ccs\text{--}adf}$ = {END, CUT}

FITNESS MEASURE FOR LOWPASS FILTER

- **Our modified version of SPICE (217,000 lines of C source code) gives output values at probe point VOUT**
- **101 frequency values chosen over five decades (from 1 to 100,000 Hz) with each decade divided into 20 parts (using a logarithmic scale).**
  - do not penalize ideal values
  - slightly penalize acceptable deviations
  - heavily penalize unacceptable deviations
- **Fitness is**

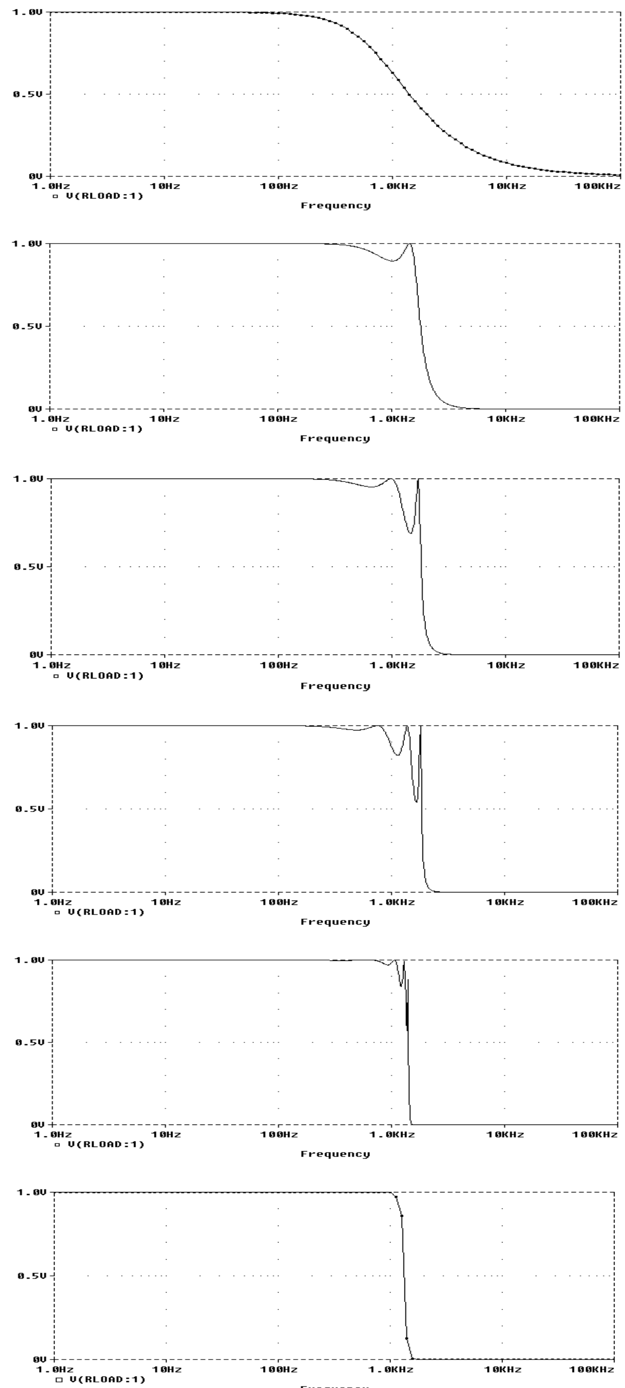
$$F(t) = \sum_{i=0}^{100} [W(f_i)d(f_i)]$$

  - $f(i)$ is the frequency (in Hertz) of fitness case i
  - $d(x)$ is the difference between the target and observed values at frequency (in Hertz) of fitness case i
  - $W(y,x)$ is the weighting at frequency x

FITNESS – CONTINUED

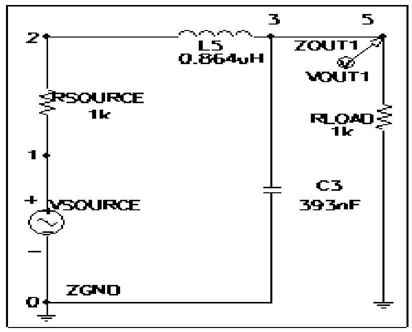
- **61 points in the 3-decade interval from 1 Hz to 1,000 Hz**
  - For voltage equaling the ideal value of 1.0 volts, the deviation is **0.0**
  - For voltage between 970 and 1,000 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by **1.0**
  - For voltage less than 970 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by a factor of **10.0**
- **35 points from 2,000 Hz to 100,000 Hz**
  - For voltage equaling the ideal value of 0.0 volts, the deviation is **0.0**
  - For voltage between 0 millivolts and 1 millivolt, the absolute value of the deviation from 0 millivolts is weighted by **1.0**
  - For voltage above 1 millvolt, the absolute value of the deviation from 0 millivolts is weighted by factor of **10.0**
- **5 "don't care" points between 1,000 Hz and 2,000 Hz**

GENERATIONS 0, 9, 16, 20, 31, AND 35

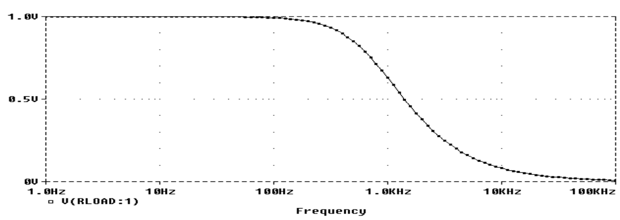


LOWPASS FILTER USING ADFS - RUN B

GENERATION 0 – ONE-RUNG LADDER

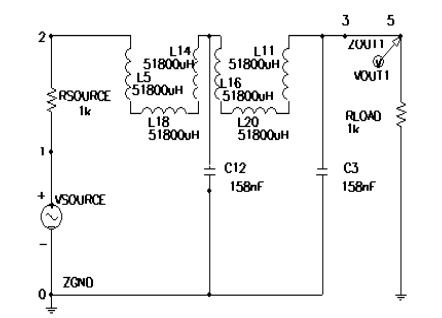


BEHAVIOR IN FREQUENCY DOMAIN

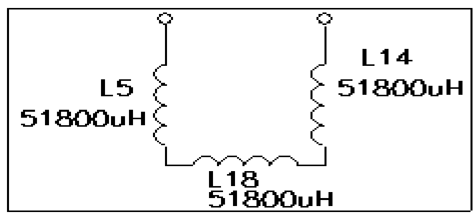


LOWPASS FILTER USING ADFS - RUN B

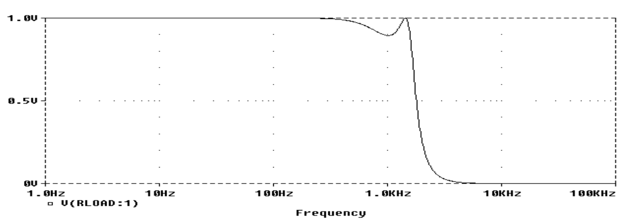
GENERATION 9 - TWO-RUNG LADDER



TWICE-CALLED TWO-PORTED ADF0

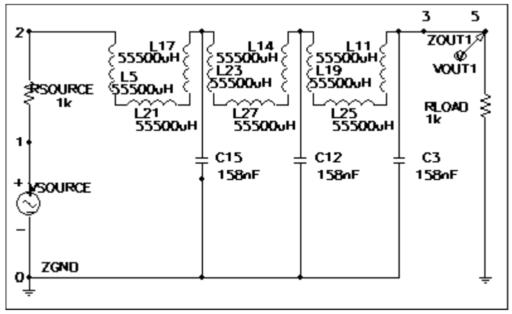


BEHAVIOR IN FREQUENCY DOMAIN

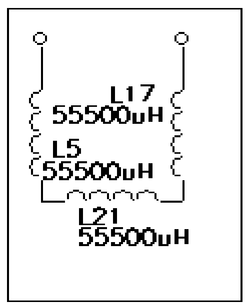


LOWPASS FILTER USING ADFS - RUN B

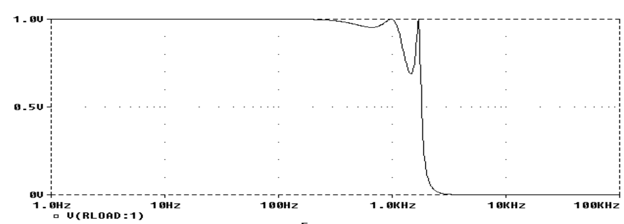
GEN 16 – THREE-RUNG LADDER



THRICE-CALLED TWO-PORTED ADF0

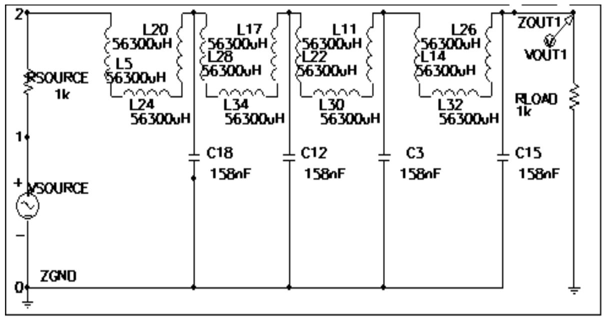


BEHAVIOR IN FREQUENCY DOMAIN

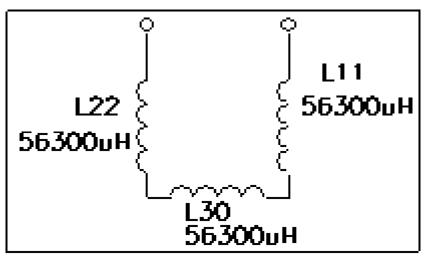


LOWPASS FILTER USING ADFS - RUN B

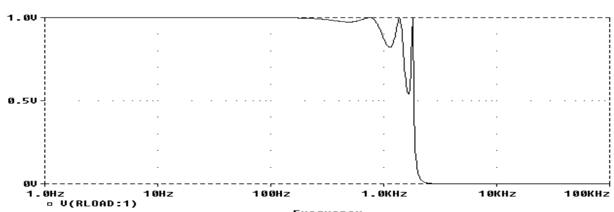
GEN 20 – FOUR-RUNG LADDER



QUADRUPLY-CALLED TWO-PORTED ADF0

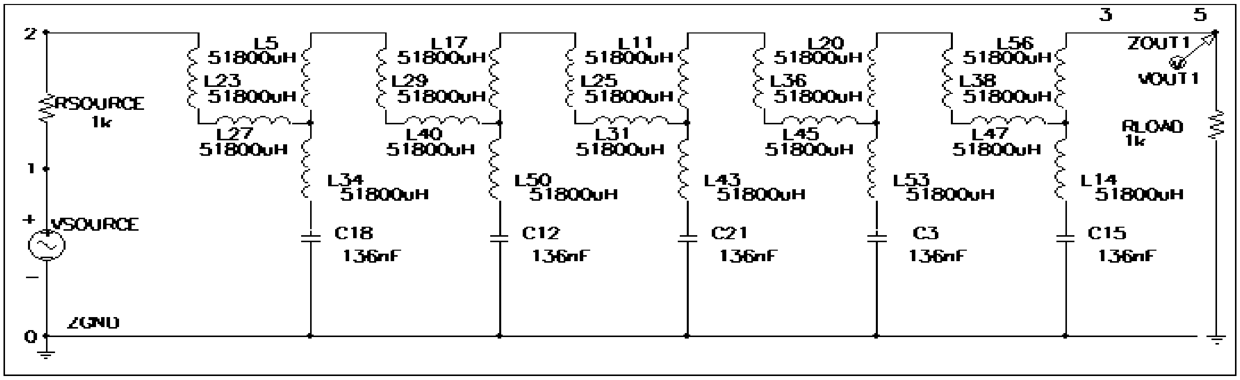


BEHAVIOR IN FREQUENCY DOMAIN

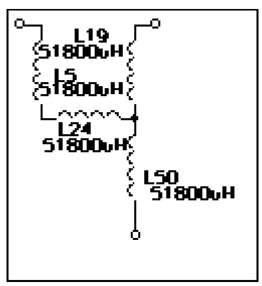


LOWPASS FILTER USING ADFS - RUN B

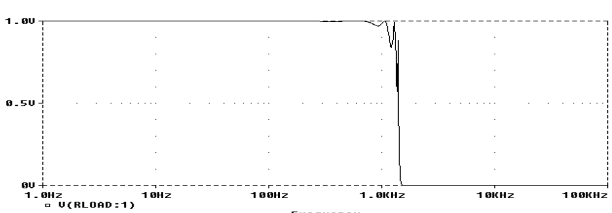
GENERATION 31 — TOPOLOGY OF CAUER (ELLIPTIC) FILTER



QUINTUPLY-CALLED THREE-PORTED ADF0



BEHAVIOR IN FREQUENCY DOMAIN

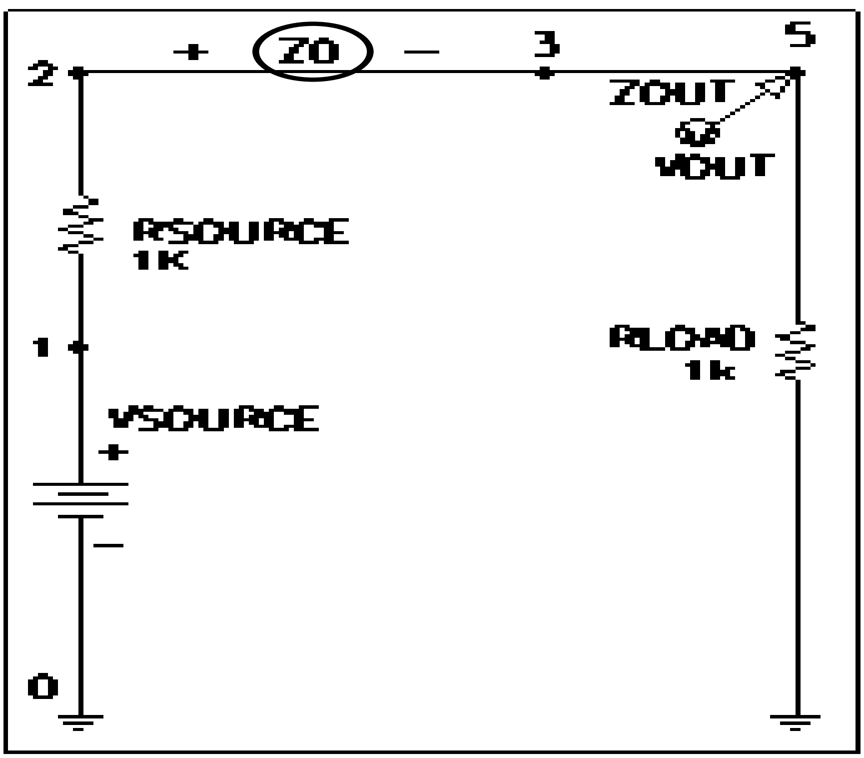


CAUER (ELLIPTIC) FILTERS

"Cauer first used his new theory in solving a filter problem for the German telephone industry. His new design achieved specifications with one less inductor than had ever been done before. The world first learned of the Cauer method not through scholarly publication but through a patent disclosure, which eventually reached the Bell Laboratories. Legend has it that the entire Mathematics Department of Bell Laboratories spent the next two weeks at the New York Public library studying elliptic functions. Cauer had studied mathematics under Hilbert at Goettingen, and so elliptic functions and their applications were familiar to him."

– from Van Valkenburg *Analog Filter Design* (1982, page 379)

ONE-INPUT, ONE-OUTPUT EMBRYO WITH ONE WRITING HEAD (ONE MODIFIABLE WIRE) FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM



ARCHITECTURE OF CIRCUIT-CONSTRUCTING PROGRAM TREE FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM

- **The circuit-constructing program tree has one result-producing branch (`RPB0`).**

- **The circuit-constructing program tree has no automatically defined functions.**

FUNCTION AND TERMINAL SETS OF RESULT PRODUCING BRANCH FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM

- **For the result-producing branch, the function set, $F_{ccs\text{-}rpb}$, for each construction-continuing subtree is**

$F_{ccs\text{-}rpb}$ = {R, L, C, SERIES, PARALLEL0, PARALLEL1, FLIP, NOP, T_PAIR_CONNECT_0, T_PAIR_CONNECT_1}

- **For the result-producing branch, the function set, $F_{ccs\text{-}rpb}$, for each construction-continuing subtree is**

$T_{ccs\text{-}rpb}$ = {END}.

FUNCTION AND TERMINAL SETS FOR ARITHMETIC-PERFORMING SUBTREES (USED IN BOTH RBPs AND ADFs) FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM

- **The function set, F_{aps}, for each arithmetic-performing subtree is,**

$F_{aps} = \{+, -\}$.

- **The terminal set, T_{aps}, for each arithmetic-performing subtree consists of**

$T_{aps} = \{\Re\}$,

where $\Re$ represents floating-point random constants from –1.0 to +1.0.

FITNESS MEASURE FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM

- **Voltage VOUT is probed at node 5 and the circuit is simulated in the frequency domain.**

- **SPICE is requested to perform an AC small signal analysis and to report the circuit's behavior for each of 101 frequency values chosen over four decades of frequency (between 1 and 10,000 Hz). Each decade is divided into 25 parts (using a logarithmic scale).**

- **Fitness is measured in terms of the sum, over these 101 fitness cases, of the absolute weighted deviation between the actual value of the output voltage at the probe point VOUT and the target value for voltage.**

FITNESS MEASURE FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM – 3 POINTS NEAR 256 HZ

- **The three points that are closest to the band located within 10% of 256 Hz are 229.1 Hz, 251.2 Hz, and 275.4 Hz.**
  - If the voltage equals the ideal value of 1/2 volts in this interval, the deviation is 0.0.
  - If the voltage is within 240 millivolts of 1/2 volts, the absolute value of the deviation from 1/2 volts is weighted by a factor of 20.
  - If the voltage is more than 240 millivolts from 1/2 volts, the absolute value of the deviation from 1/2 volts is weighted by a factor of 200.
- **This arrangement reflects the fact that the ideal output voltage for this range of frequencies is 1/2 volts, that a 240 millivolts discrepancy is acceptable, and that a larger discrepancy is not acceptable.**

FITNESS MEASURE – 3 POINTS NEAR 2,560 HZ

- **The three points that are closest to the band located within 10% of 2,560 Hz are 2,291 Hz, 2,512 Hz, and 2,754 Hz.**
  - If the voltage equals the ideal value of 1 volt in this interval, the deviation is 0.0.
  - If the voltage is within 240 millivolts of 1 volt, the absolute value of the deviation from 1 volt is weighted by a factor of 20.
  - If the voltage is more than 240 millivolts from 1 volt, the absolute value of the deviation from 1 volt is weighted by a factor of 200.

FITNESS MEASURE FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM – REMAINING 95 POINTS IN THE FREQUENCY DOMAIN

- **The procedure for each of the remaining 95 points is as follows:**
  - If the voltage equals the ideal value of 0 volts, the deviation is 0.0.
  - If the voltage is within 240 millivolts of 0 volts, the absolute value of the deviation from 0 volts is weighted by a factor of 1.0.
  - If the voltage is more than 240 millivolts from 0 volts, the absolute value of the deviation from 0 volt is weighted by a factor of 10.