AUTOMATIC SYNTHESIS OF ELECTRICAL CIRCUITS USING DEVELOPMENTAL GENETIC PROGRAMMING

PART 5 — ADDITIONAL PASSIVE CIRCUIT EXAMPLES

FUNCTION AND TERMINAL SETS

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

$F_{\text{ccs-rpb}}$ = {**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**

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

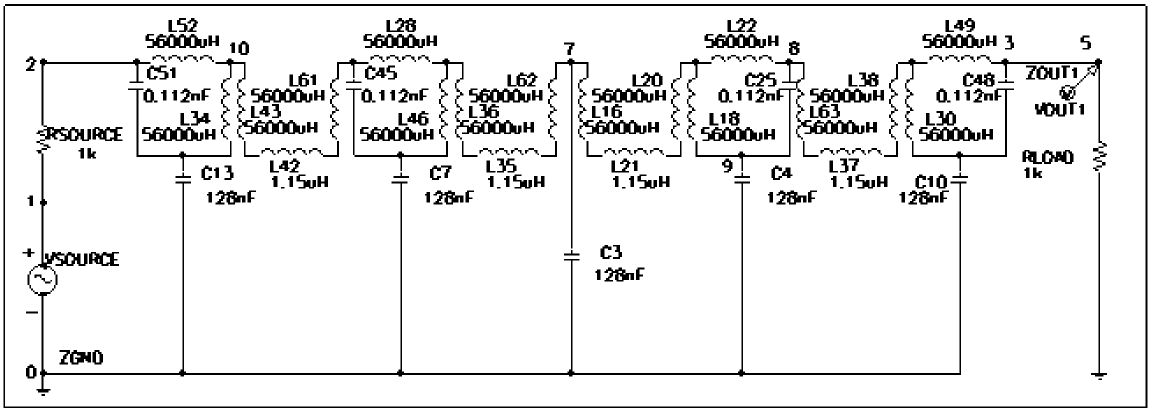
- **For ADFs, function set for construction-continuing subtree**

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**

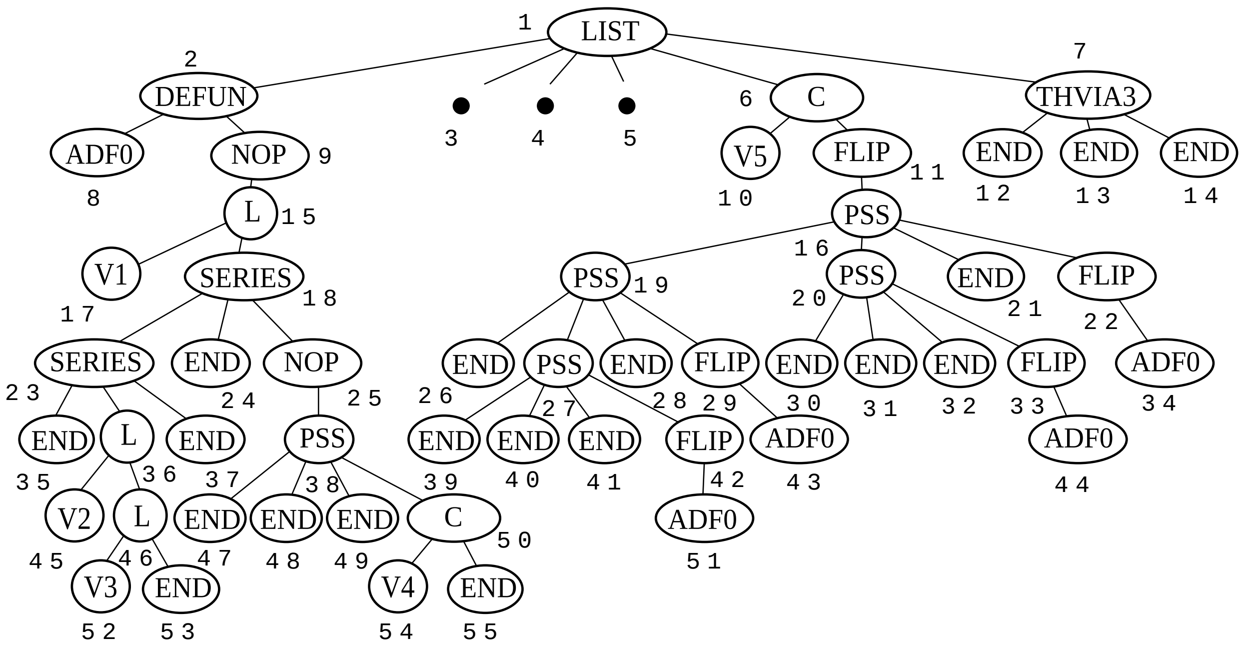
$T_{\text{ccs--adf}}$ = {END, CUT}

BEST-OF-RUN CIRCUIT FROM GENERATION 35 USING ADFs

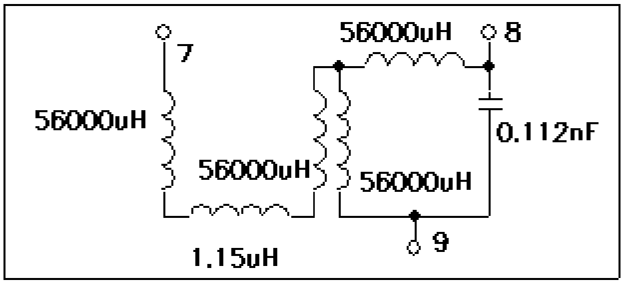


NOTE SYMMETRY

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`}

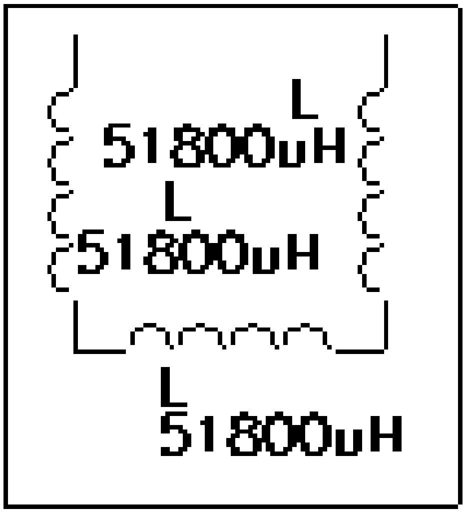
- **For RPBs, terminal set for construction-continuing subtree**

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

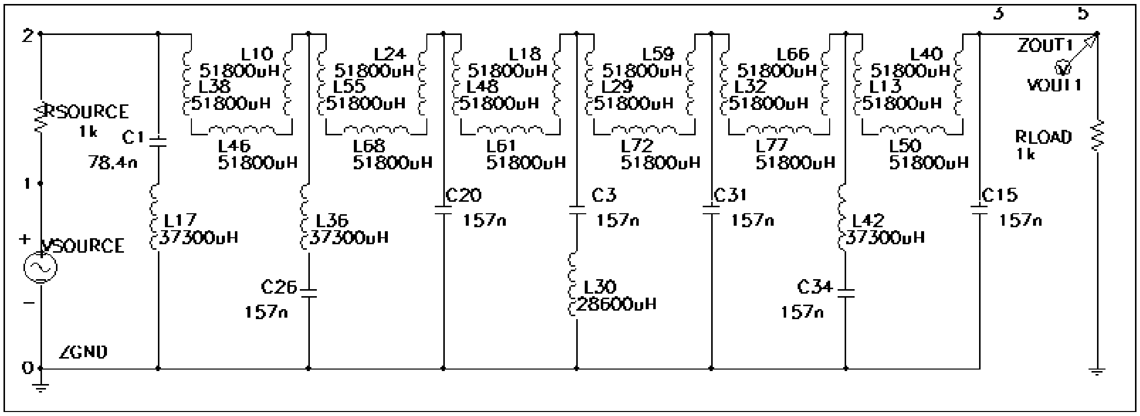
- **For the new ADFs, the set of potential new functions, $F_{ccs\text{-}pot}$, is**

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

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

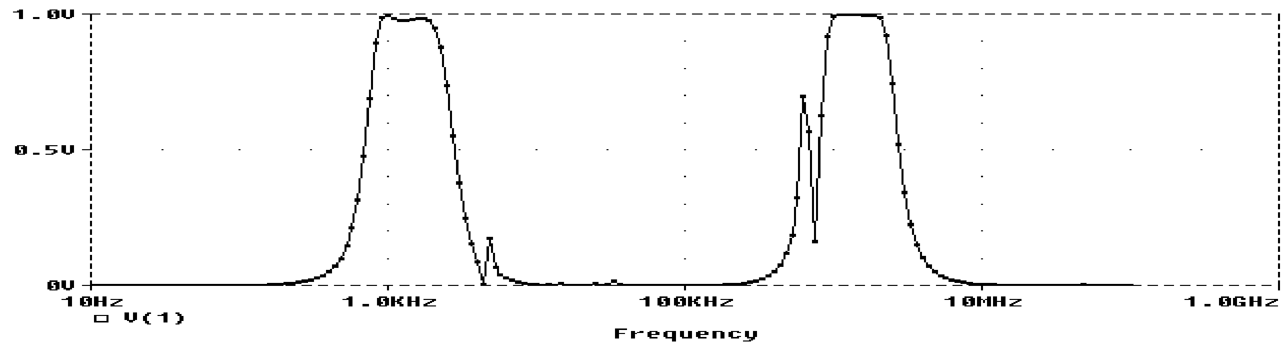


BEST-OF-RUN CIRCUIT FROM GENERATION 77 USING ARCHITECTURE-ALTERING OPERATIONS

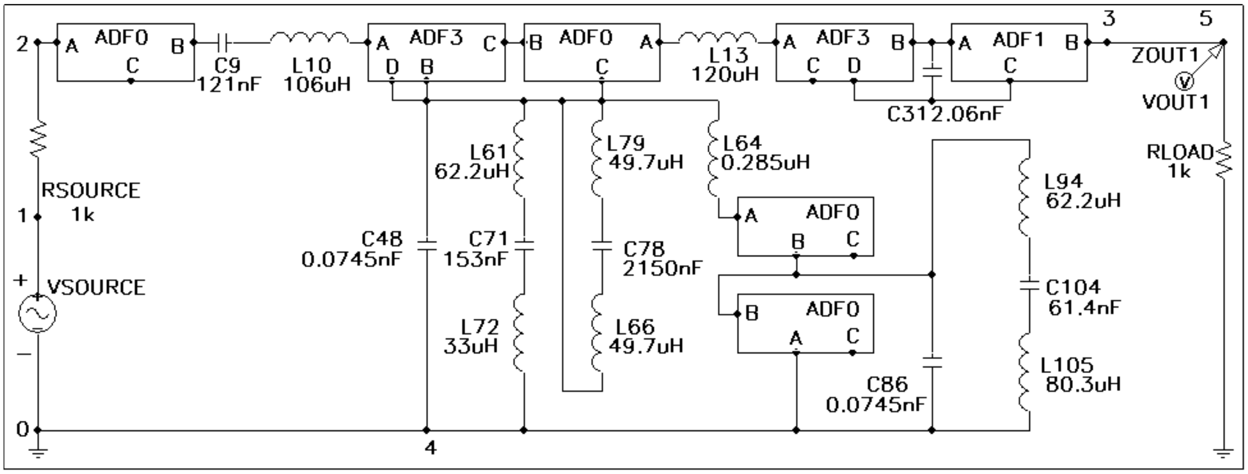


EVOLVING A DOUBLE-BANDPASS FILTER USING ARCHITECTURE-ALTERING OPERATIONS

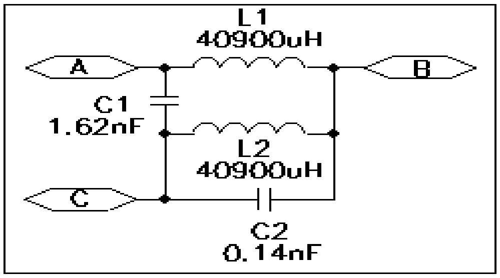
GENERATION 89 – FREQUENCY DOMAIN BEHAVIOR OF THE BEST-OF-RUN CIRCUIT



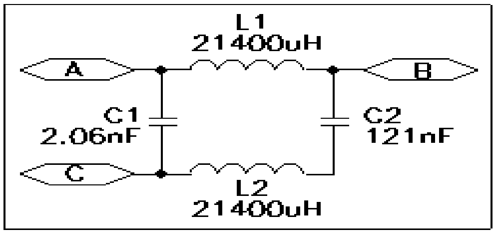
GENERATION 89 – BEST-OF-RUN CIRCUIT



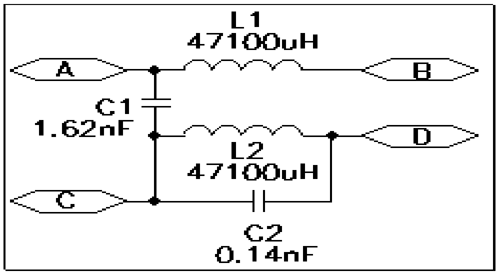
THREE-PORTED QUADRUPLY-CALLED **ADF0**



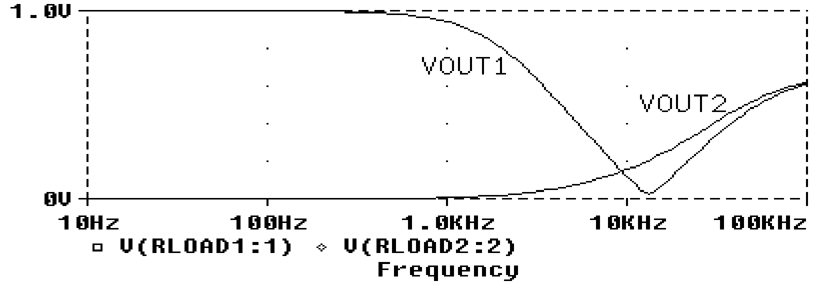
THREE-PORTED **ADF1**

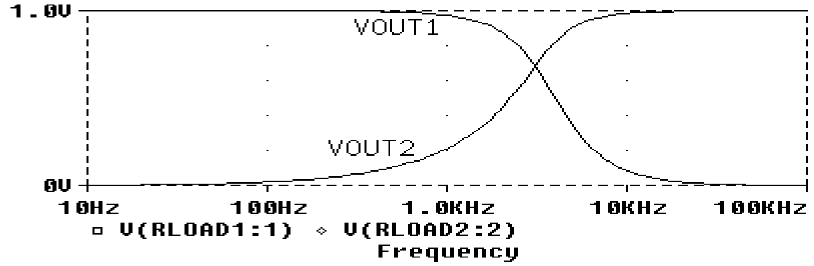


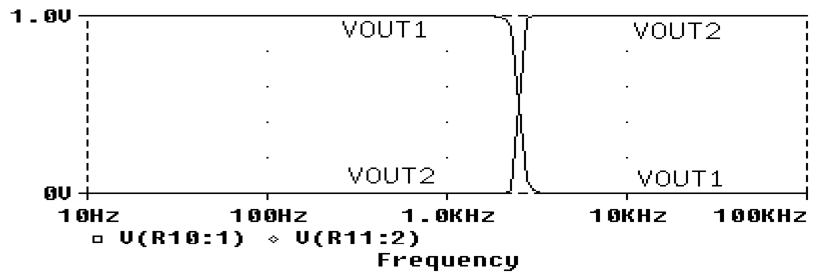
FOUR-PORTED TWICE-CALLED **ADF3**



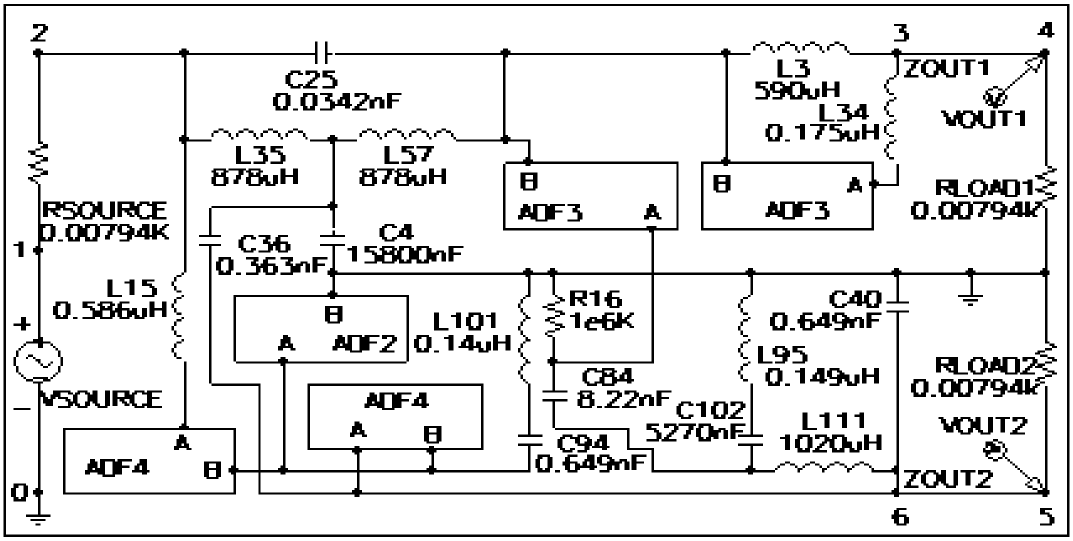
FREQUENCY DOMAIN BEHAVIOR OF BEST CIRCUIT OF GENERATIONS 0, 8, AND 158 FOR A TWO-BAND CROSSOVER FILTER



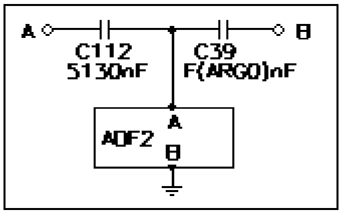




BEST CIRCUIT OF GENERATION 158



- **ADF3 supplies one PARAMETERIZED capacitor C39 whose value is determined by ADF3's dummy variable, ARG0.**

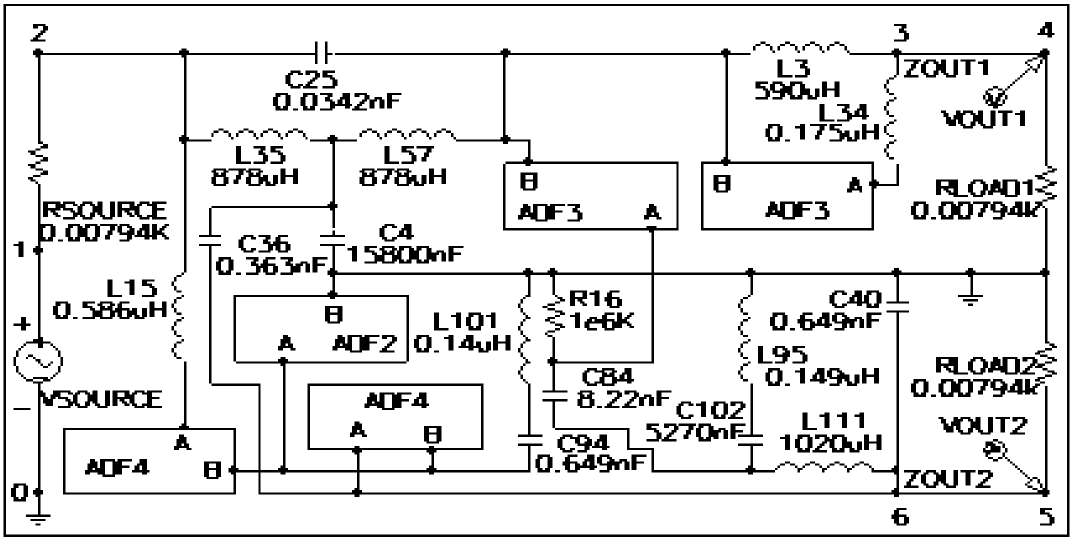


- **ADF3 supplies one unparameterized 5,130 uF capacitor C112.**
- **ADF3 has one hierarchical reference to ADF2 (which, in turn, supplies one unparameterized 259 µH inductor).**

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`.**

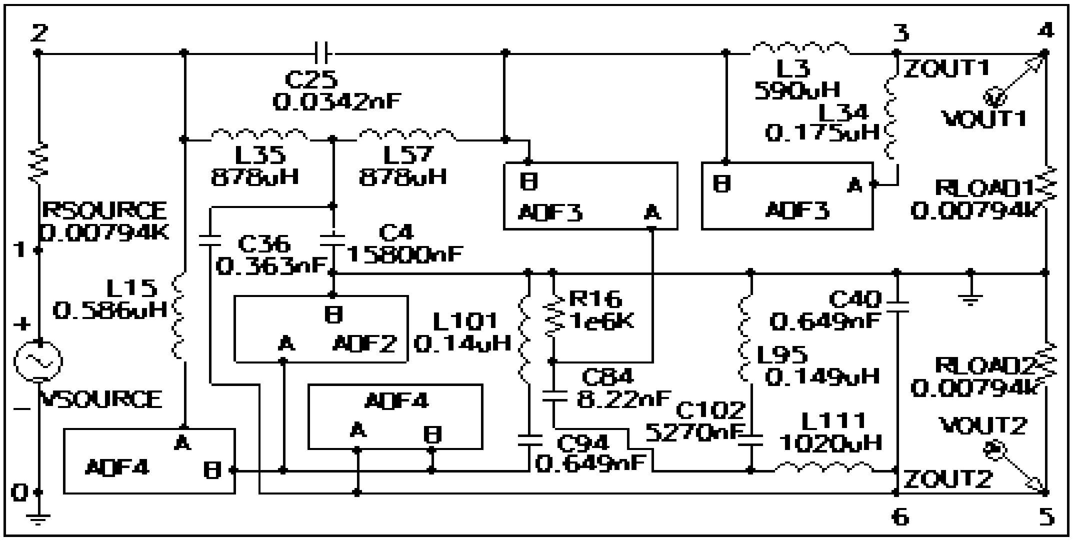
BEST CIRCUIT OF GENERATION 158 – CONTINUED



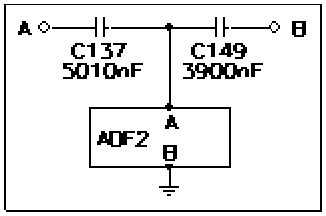
- **`ADF0` and `ADF1` are not called at all.**

- **`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.**

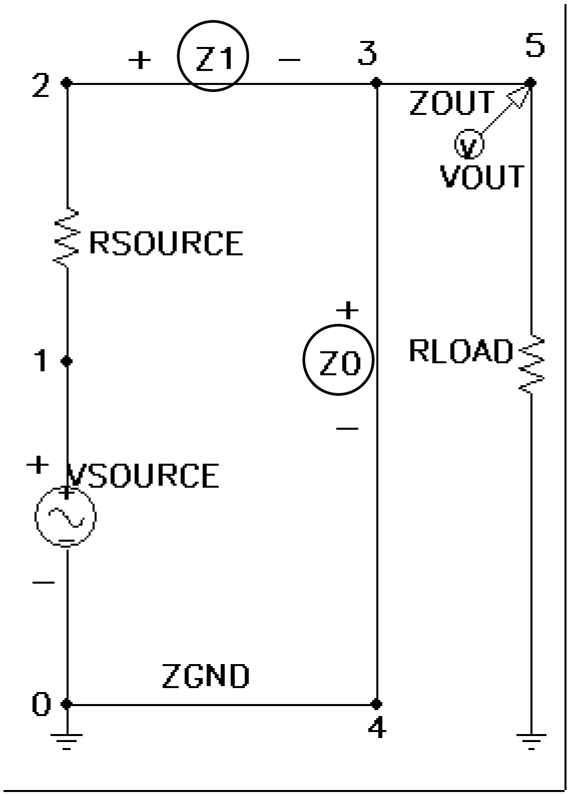
BEST CIRCUIT OF GENERATION 158 – CONTINUED



- **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**

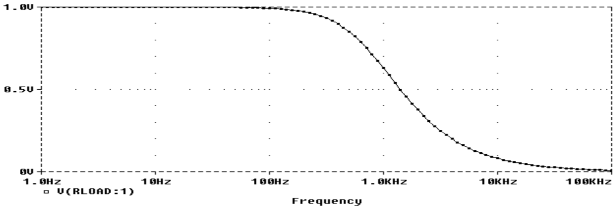
$$F(t) = \sum_{i=0}^{100} [W(f_i) d(f_i)]$$

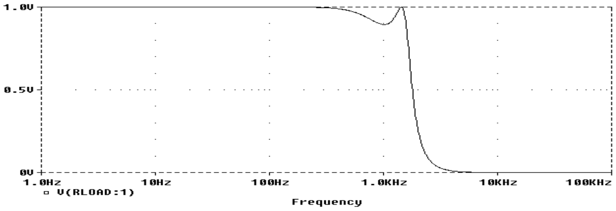
  - $f(i)$ is the frequency (in Hertz) of fitness case i
  - $d(x)$ is the difference between the target and observed values at frequency (in Hertz) of fitness case i
  - $W(y,x)$ is the weighting at frequency x

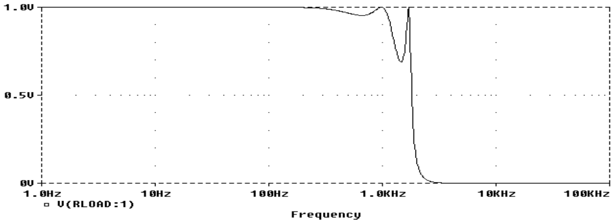
FITNESS – CONTINUED

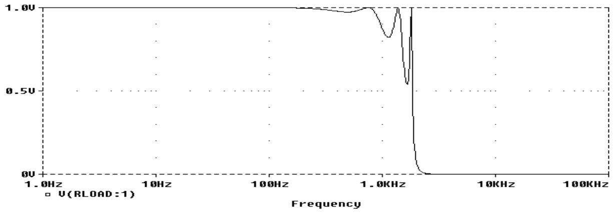
- **61 points in the 3-decade interval from 1 Hz to 1,000 Hz**
  - For voltage equaling the ideal value of 1.0 volts, the deviation is **0.0**
  - For voltage between 970 and 1,000 millivolts, the absolute value of the deviation from 1,000 millivolts is weighted by **1.0**
  - For voltage less than 970 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**

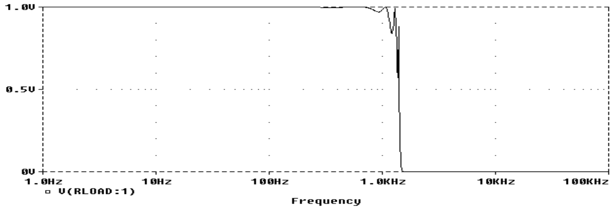
GENERATIONS 0, 9, 16, 20, 31, AND 35

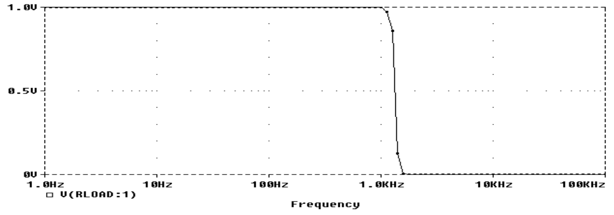






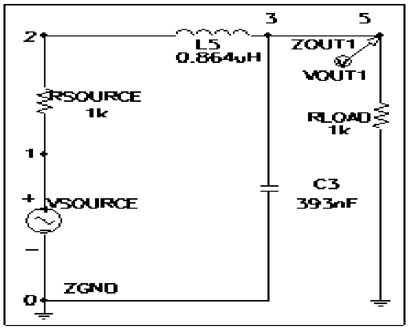




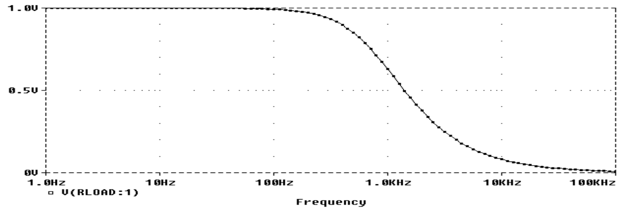


LOWPASS FILTER USING ADFs - RUN B

GENERATION 0 – ONE-RUNG LADDER

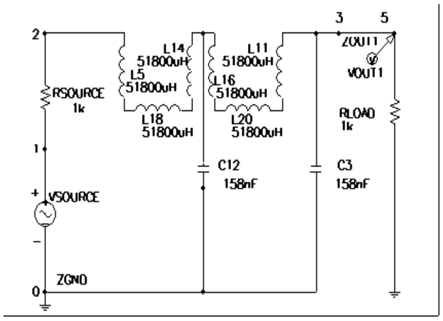


BEHAVIOR IN FREQUENCY DOMAIN

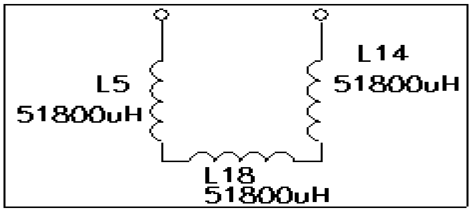


LOWPASS FILTER USING ADFs - RUN B

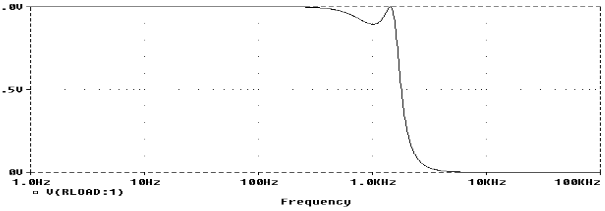
GENERATION 9 - TWO-RUNG LADDER



TWICE-CALLED TWO-PORTED `ADF0`

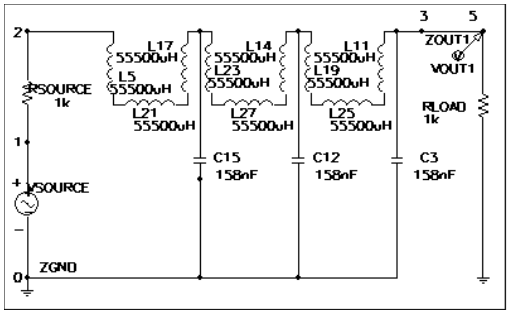


BEHAVIOR IN FREQUENCY DOMAIN

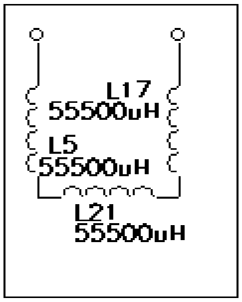


LOWPASS FILTER USING ADFS - RUN B

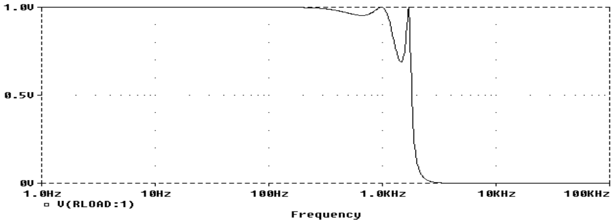
GEN 16 – THREE-RUNG LADDER



THRICE-CALLED TWO-PORTED ADF0

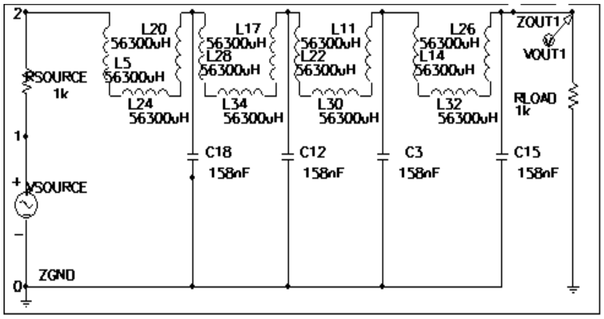


BEHAVIOR IN FREQUENCY DOMAIN

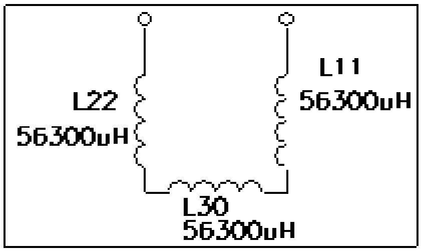


LOWPASS FILTER USING ADFs - RUN B

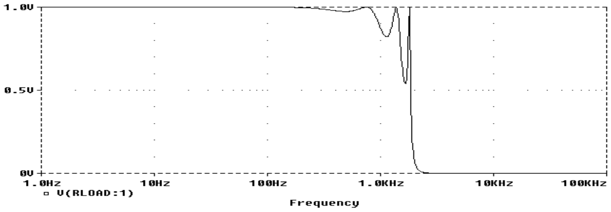
GEN 20 – FOUR-RUNG LADDER



QUADRUPLY-CALLED TWO-PORTED ADF0

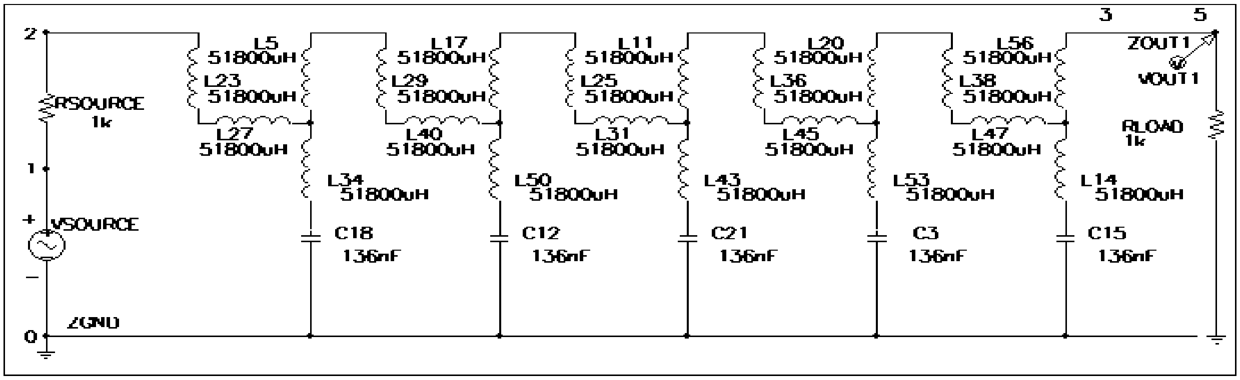


BEHAVIOR IN FREQUENCY DOMAIN

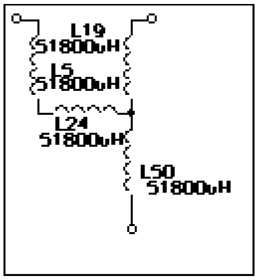


LOWPASS FILTER USING ADFs - RUN B

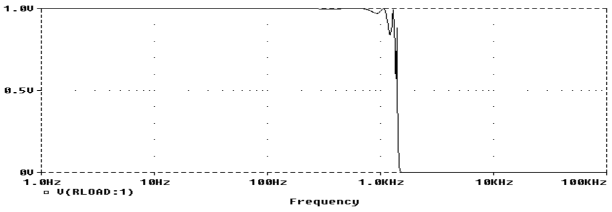
GENERATION 31 — TOPOLOGY OF CAUER (ELLIPTIC) FILTER



QUINTUPLY-CALLED THREE-PORTED `ADF0`



BEHAVIOR IN FREQUENCY DOMAIN

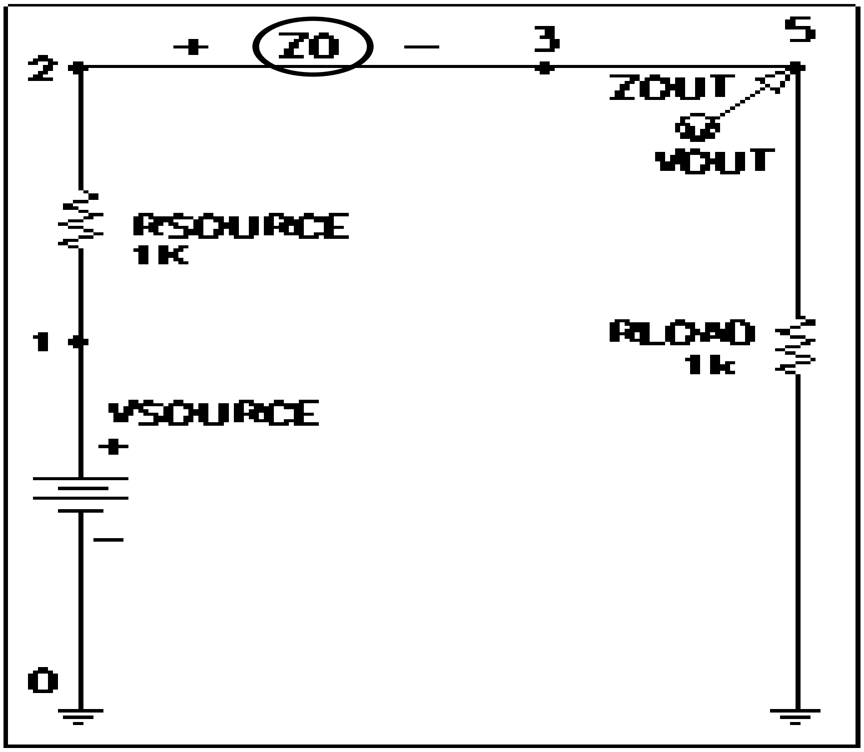


CAUER (ELLIPTIC) FILTERS

> **"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, Faps, for each arithmetic-performing subtree is,**

Faps = {+, -}.

- **The terminal set, Taps, for each arithmetic-performing subtree consists of**

Taps = {$\Re$},

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.
- **Greater weights (20 and 200) were used in the two passbands because they contain only 6 of the 101 points.**

FITNESS MEASURE FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM – CONTINUED

- **Many of the circuits that are created in the initial random population and many that are created by the crossover and mutation operations cannot be simulated by SPICE. Such circuits are assigned a high penalty value of fitness (10^8).**

- **The number of hits is defined as the number of fitness cases (0 to 101) for which the voltage is acceptable or ideal.**

CONTROL PARAMETERS FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM

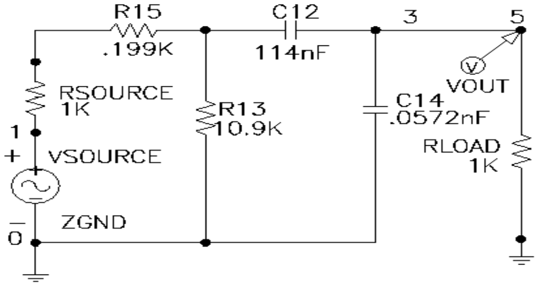
- **Population size, *M*, of 640,000**
- **Maximum number of generations, *G*, is set to be meaninglessly large**
- **Maximum of H_{rpb} = 600 points (functions and terminals) for the result-producing branch**
- **For each generation**
  - 10% reproductions
  - 1% mutations
  - 89% crossovers
  - No architecture-altering operations
- **Secondary parameters are default values in Koza 1994 (appendix D)**

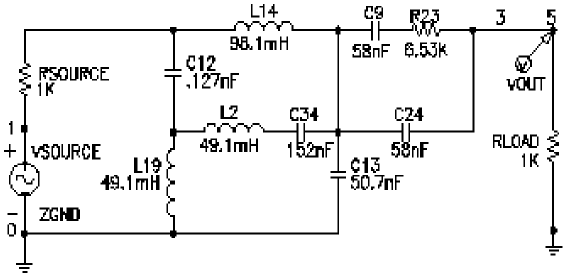
TERMINATION CRITERION AND RESULTS DESIGNATION FOR THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM

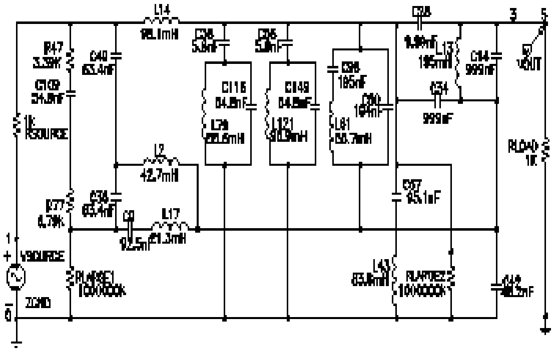
- **Manual intervention in lieu of pre-established termination criterion**

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

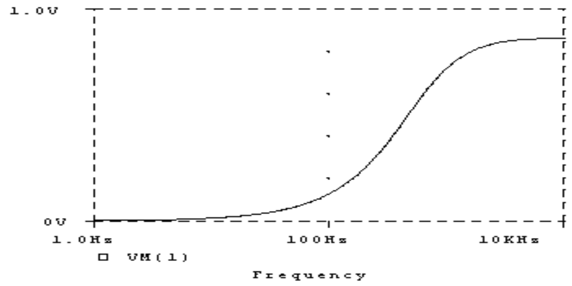
RESULTS FOR THE THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM – GENERATIONS 0, 20, 106

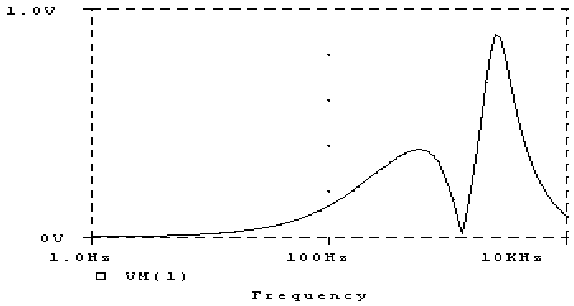


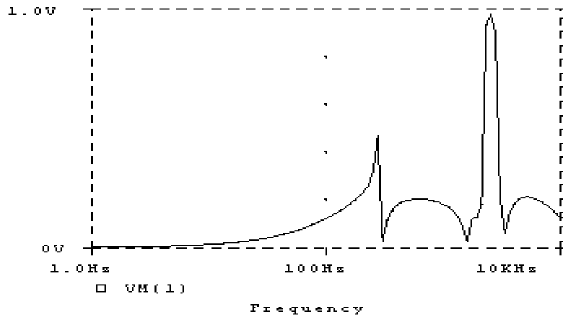




RESULTS FOR THE THREE-WAY ANALOG SOURCE IDENTIFICATION PROBLEM – GENERATIONS 0, 20, 106







THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

- The goal is to evolve the design for a circuit that changes its structure as the number of different sources increases.
  - Initially the circuit classifies the incoming signals into **three** categories
  - Later the circuit undergoes modification so that is can successfully classify them into **four** categories.

THE CHANGING ENVIRONMENT PROBLEM (WITH ADFS AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 1 (3-WAY)

- **During phase 1, the requirements for the desired circuit are similar to those for the tri-state frequency discriminator except that one of the desired outputs is 1/3 volt (instead of 1/2 volt).**
  - The desired circuit is to produce an output of 1/3 volts (plus or minus 166 millivolts) if the frequency of the incoming signal is within 10% of 256 Hz
  - produce an output of 1 volt (plus or minus 166 millivolts) if the frequency of the incoming signal is within 10% of 2,560 Hz, and
  - otherwise produce an output of 0 volts (plus or minus 166 millivolts).

THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 2 (4-WAY)

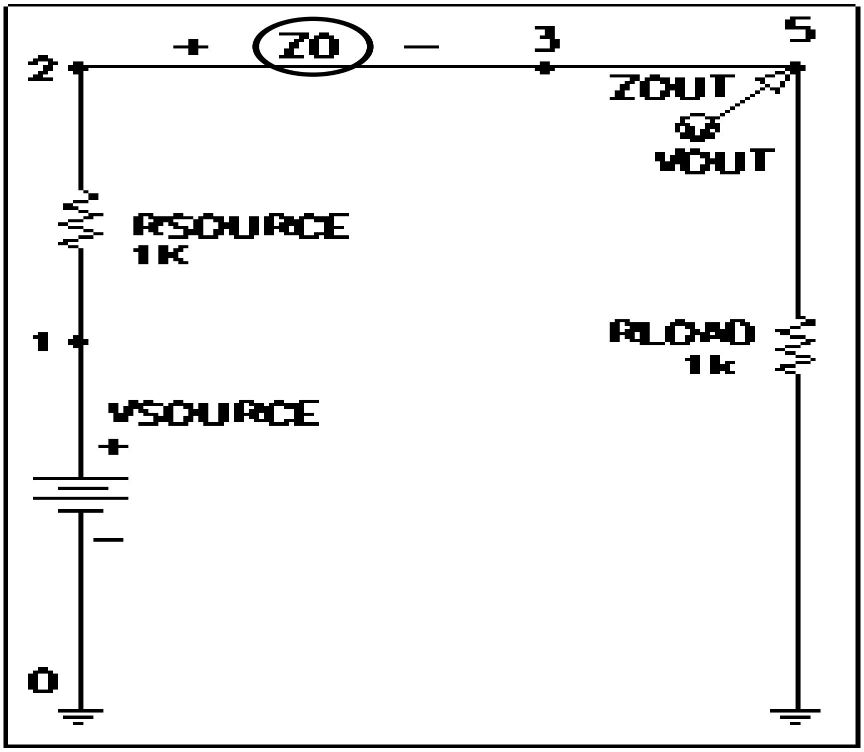
- **After a circuit is evolved that performs the tri-state source identification task, the requirements of the problem are changed to include an additional frequency band.**

- **The run is continued with the existing population until a new circuit is evolved that performs the source identification task for all three frequency bands.**
  - During phase 2, the circuit is to produce an output of 2/3 volts (plus or minus 166 millivolts) if the frequency of the incoming signal is within 10% of 750 Hz
  - While still producing an output of 1/3, 1, and 0 volts (plus or minus 166 millivolts) for the original three signals.

PREPARATORY STEPS FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

ONE-INPUT, ONE-OUTPUT EMBRYO WITH ONE WRITING HEAD (ONE MODIFIABLE WIRE)

SAME AS BEFORE



ARCHITECTURE OF CIRCUIT-CONSTRUCTING PROGRAM TREE FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

- **Since the initial circuit has one modifiable wire (and hence one writing head), there is one result-producing branch in each circuit-constructing program tree.**

- **Each program in the initial population of programs has a uniform architecture with no automatically defined functions. The number of automatically defined functions, if any, will emerge as a consequence of the evolutionary process using the architecture-altering operations.**

FUNCTION AND TERMINAL SETS OF RESULT PRODUCING BRANCH FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFS AND ARCHITECTURE-ALTERING OPERATIONS)

- **The initial function set, Fccs-initial, 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`}

- **The initial terminal set, Tccs-initial, for each construction-continuing subtree is**

Tccs-initial = {`END`, `SAFE_CUT`}.

- **The set of potential new functions, Fpotential, is**

Fpotential = {`ADF0`, `ADF1`, `ADF2`}.

- **The set of potential new terminals, Tpotential, is**

Tpotential = {`ARG0`}.

FUNCTION AND TERMINAL SETS OF RESULT PRODUCING BRANCH FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS) – CONTINUED

- **The architecture-altering operations change the function set, F_{ccs} for each construction-continuing subtree of both the result-producing branches and the function-defining branches, so**

$F_{ccs} = F_{ccs\text{-initial}} \approx F_{potential}$.

- **The architecture-altering operations change the terminal set, $T_{aps\text{-}adf}$, for each arithmetic-performing subtree, so**

$T_{aps\text{-}adf} = T_{aps\text{-}initial} \approx T_{potential}$.

FUNCTION AND TERMINAL SETS FOR ARITHMETIC-PERFORMING SUBTREES (USED IN BOTH RBP AND ADFs)

SAME AS BEFORE

- **The function set, Faps, for each arithmetic-performing subtree is,**

Faps = {+, -}.

- **The terminal set, Taps, for each arithmetic-performing subtree consists of**

Taps = {$\Re$},

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

FITNESS MEASURE FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFS AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 1 (3-WAY)

- **During the first phase, there are only two frequencies of interest (256 Hz and 2,560 Hz); however, in the second phase, there are three frequencies of interest (750 Hz in addition the two just mentioned).**

FITNESS MEASURE FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFS AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 1 (3-WAY) – 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 1/3 volts in this interval, the deviation is 0.0.

  - If the voltage is more than 166 millivolts from 1/3 volts, the absolute value of the deviation from 1/3 volts is weighted by a factor of 20.
  - If the voltage is more than 166 millivolts of 1/3 volts, the absolute value of the deviation from 1/3 volts is weighted by a factor of 200.
- **This arrangement reflects the fact that the ideal output voltage for this range of frequencies is 1/3 volts, that a 166 millivolts discrepancy is acceptable, and that a larger discrepancy is not acceptable.**

FITNESS MEASURE – PHASE 1 (3-WAY) – 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 166 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 166 millivolts from 1 volt, the absolute value of the deviation from 1 volt is weighted by a factor of 200.

FITNESS MEASURE – PHASE 1 (3-WAY) – REMAINING 95 POINTS

- **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 166 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 166 millivolts from 0 volts, the absolute value of the deviation from 0 volt is weighted by a factor of 10.
- **Greater weights (20 and 200) were used in the two passbands because they contain only 6 of the 101 points.**

FITNESS MEASURE FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 2 (4-WAY) – POINTS NEAR 750 HZ

- **In phase 2, frequencies around 750 Hz come into play.**

- **The three points that are closest to the band located within 10% of 750 Hz are 791.8 Hz, 758.6 Hz, and 831.8 Hz.**
  - If the voltage equals the ideal value of 2/3 volts in this interval, the deviation is 0.0.
  - If the voltage is more than 166 millivolts from 2/3 volts, the absolute value of the deviation from 2/3 volts is weighted by a factor of 15.
  - If the voltage is more than 166 mV of 2/3 volts, the absolute value of the deviation from 2/3 volts is weighted by 150.

FITNESS MEASURE FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 2 (4-WAY) – POINTS NEAR 256 HZ AND 2,560 HZ

- **In phase 2, the procedure for the six points nearest 256 Hz and 2,560 Hz are the same as before, except that**
  - the weight is 15 and 150 (instead of 20 and 200), respectively for the complaint and non-complaint points.
  - Lesser weights (15 and 150) were used in the three passbands because 9 of the 101 points lie in the passbands.

FITNESS MEASURE FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS) – PHASE 2 (4-WAY) – REMAINING 92 POINTS

- **In phase 1, the procedure for each of the remaining 92 points is as follows:**
  - If the voltage equals the ideal value of 0 volts, the deviation is 0.0.
  - If the voltage is within 166 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 166 mV from 0 volts, the absolute value of the deviation from 0 is weighted by a factor of 10.
- **As before, for each phase, the number of hits is defined as the number of fitness cases for which the voltage is acceptable or ideal.**

CONTROL PARAMETERS FOR THE CHANGING ENVIRONMENT PROBLEM

- **The percentage of operations on each generation after generation 5 was**
  - 86.5% one-offspring crossovers;
  - 10% reproductions;
  - 1% mutations;
  - 1% branch duplications;
  - 0.5% branch deletions;
  - 1% branch creations; and
  - 0% argument creations.
- **The percentage of operations on each generation before generation 6 was**
  - 78.0% one-offspring crossovers;
  - 10% reproductions;
  - 1% mutations;
  - 5.0% branch duplications;
  - 1% branch deletions;
  - 5.0% branch creations; and
  - 0% argument creations.

CONTROL PARAMETERS FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS) – CONTINUED

- **The maximum size, H_{rpb}, for the result-producing branch is 600 points.**

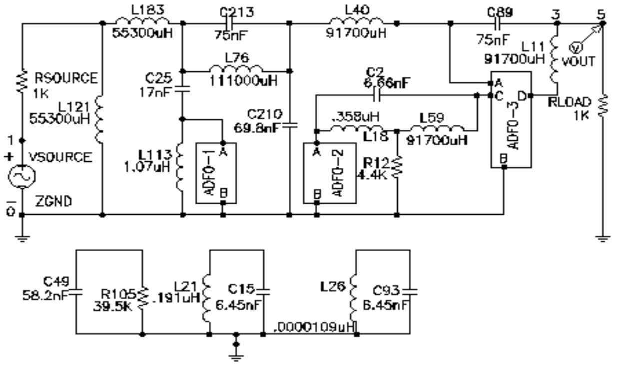
- **The maximum number of automatically defined functions is 2.**

- **The number of arguments for each automatically defined function is 1.**

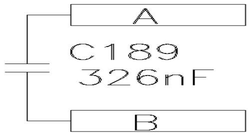
- **The maximum size, H_{adf}, for each of the automatically defined functions, if any, is 300 points.**

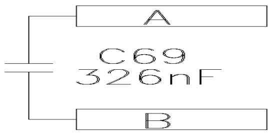
RESULTS FOR THE CHANGING ENVIRONMENT PROBLEM

BEST CIRCUIT FROM GENERATION 41 BEFORE EXPANSION OF THE THREE OCCURRENCES OF `ADF0`

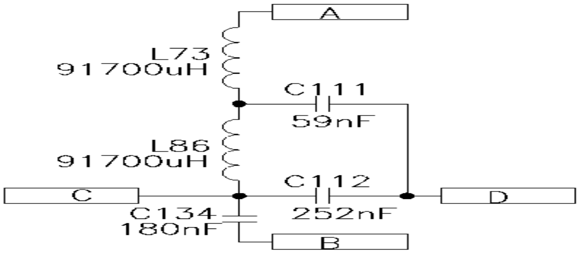


RESULT OF DEVELOPING `ADF0-1` AND `ADF0-1` FOR BEST CIRCUIT FROM GENERATION 41



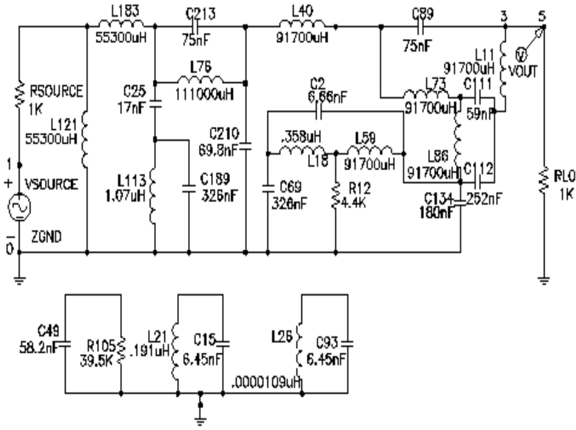


RESULT OF DEVELOPING `ADF0` FOR BEST CIRCUIT FROM GENERATION 41



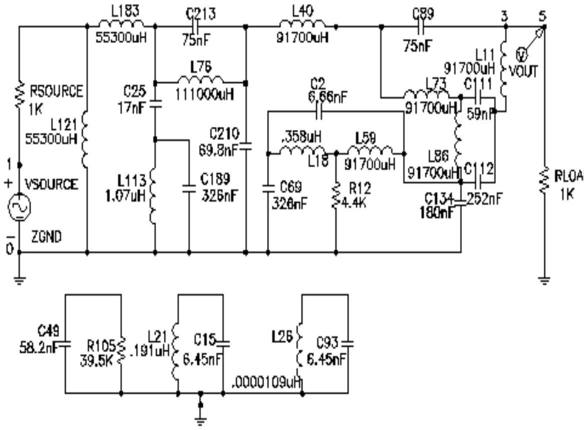
RESULTS FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

BEST CIRCUIT FROM GENERATION 41 AFTER EXPANSION OF THE THREE OCCURRENCES OF `ADF0`



RESULTS FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

BEST CIRCUIT FROM GENERATION 85 AFTER EXPANSION OF ITS AUTOMATICALLY DEFINED FUNCTIONS



RESULTS FOR THE CHANGING ENVIRONMENT PROBLEM (WITH ADFs AND ARCHITECTURE-ALTERING OPERATIONS)

FREQUENCY DOMAIN BEHAVIOR OF THE BEST CIRCUIT OF GENERATION 0, 41, AND 85