MICROCHIP

Mindi™
Active Filter Designer
User's Guide

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Preface

NOTICE TO CUSTOMERS

All documentation becomes dated, and this manual is no exception. Microchip tools and documentation are constantly evolving to meet customer needs, so some actual dialogs and/or tool descriptions may differ from those in this document. Please refer to our web site (www.microchip.com) to obtain the latest documentation available.

Documents are identified with a "DS" number. This number is located on the bottom of each page, in front of the page number. The numbering convention for the DS number is "DSXXXXXA", where "XXXXX" is the document number and "A" is the revision level of the document.

For the most up-to-date information on development tools, see the MPLAB® IDE on-line help. Select the Help menu, and then Topics to open a list of available on-line help files.

INTRODUCTION

This chapter contains general information that will be useful to know before using the Mindi™ Active Filter Designer & Simulator. Items discussed in this chapter include:

- Document Layout
- Conventions Used in this Guide
- The Microchip Web Site
- Customer Support
- Document Revision History

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DOCUMENT LAYOUT

This document describes how to use the Mindi™ Active Filter Designer & Simulator as a development tool to emulate and debug firmware on a target board. The manual layout is as follows:

- **Chapter 1. "Overview"** – this chapter provides an overview of the Mindi™ Active Filter Designer & Simulator.
- **Chapter 2. "Filter Design Tutorial"** – this chapter provides a filter design example.
- **Chapter 3. "Filter Requirements"** – this chapter discusses the desired parameters for the filter.
- **Chapter 4. "Advanced Options"** – this chapter discusses the filter topologies and the specifications of components to be used in the filter circuit.
- **Chapter 5. "Op Amp Selection"** – this chapter discusses the selection of op amps to be used in the filter design.
- **Chapter 6. "Analyze"** – this chapter discusses the analysis of the filter and displays the filter response.
- **Appendix A. "Filter Magnitude Templates"** – this chapter gives an introduction of the filter magnitude templates such as low-pass filter template, band-pass filter template and high-pass filter template.
- **Appendix B. "Low-Pass Filter Approximations"** – this chapter discusses the characteristics of the filter approximations supported by the Mindi™ Active Filter Designer & Simulator in greater detail.
- **Appendix C. "Op Amp Selection"** – this chapter discusses how to select the op amps for your filter to avoid problems with non-linear distortion and filter response distortion.
- **Appendix D. "Group Delay"** – this chapter discusses Group Delay and focuses on the relative delay among sine waves of nearly equal frequency.
- **Appendix E. "Selected References"** – this chapter provides a list of reference material on filter textbooks and classic references as well as application notes.

CONVENTIONS USED IN THIS GUIDE

This manual uses the following documentation conventions:

DOCUMENTATION CONVENTIONS

Description	Represents	Examples
Arial font:		
Italic characters	Referenced books	*MPLAB® IDE User's Guide*
	Emphasized text	...is the *only* compiler...
Initial caps	A window	the Output window
	A dialog	the Settings dialog
	A menu selection	select Enable Programmer
Quotes	A field name in a window or dialog	"Save project before build"
Underlined, italic text with right angle bracket	A menu path	*File>Save*
Bold characters	A dialog button	Click **OK**
	A tab	Click the **Power** tab
N'Rnnnn	A number in verilog format, where N is the total number of digits, R is the radix and n is a digit.	4'b0010, 2'hF1
Text in angle brackets < >	A key on the keyboard	Press <Enter>, <F1>
Courier New font:		
Plain Courier New	Sample source code	`#define START`
	Filenames	`autoexec.bat`
	File paths	`c:\mcc18\h`
	Keywords	`_asm, _endasm, static`
	Command-line options	`-Opa+, -Opa-`
	Bit values	`0, 1`
	Constants	`0xFF, 'A'`
Italic Courier New	A variable argument	`file`.o, where `file` can be any valid filename
Square brackets [ ]	Optional arguments	`mcc18 [options] file [options]`
Curly brackets and pipe character: { | }	Choice of mutually exclusive arguments; an OR selection	`errorlevel {0|1}`
Ellipses...	Replaces repeated text	`var_name [, var_name...]`
	Represents code supplied by user	`void main (void) { ... }`

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THE MICROCHIP WEB SITE

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- **Product Support** – Data sheets and errata, application notes and sample programs, design resources, user's guides and hardware support documents, latest software releases and archived software
- **General Technical Support** – Frequently Asked Questions (FAQs), technical support requests, online discussion groups, Microchip consultant program member listing
- **Business of Microchip** – Product selector and ordering guides, latest Microchip press releases, listing of seminars and events, listings of Microchip sales offices, distributors and factory representatives

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- Distributor or Representative
- Local Sales Office
- Field Application Engineer (FAE)
- Technical Support

Customers should contact their distributor, representative or field application engineer (FAE) for support. Local sales offices are also available to help customers. A listing of sales offices and locations is included in the back of this document.

Technical support is available through the web site at: http://support.microchip.com.

DOCUMENT REVISION HISTORY

Revision B (December 2008)

- Updated the tool's name to Mindi™ Active Filter Designer & Simulator.
- Updated the Figures through the User Guide.

Revision A (June 2007)

- Initial Release of this Document.

Chapter 1. Overview

1.1 INTRODUCTION

The Mindi™ Active Filter Designer & Simulator is an Application Circuit within the Mindi™ Circuit Designer & Simulator, which is available on the Microchip home page (http://www.microchip.com) under **"Analog Design & Sim. Tool"** or going directly to the Mindi home page (http://www.microchip.com/mindi). The Mindi™ Circuit Designer & Simulator provides full schematic diagrams of the active filter circuit with recommended component values and displays the signal responses in frequency and time domains.

The Mindi™ Active Filter Designer & Simulator allows the design of low-pass filters up to an 8th order filter with Chebychev, Bessel or Butterworth approximations from frequencies of 0.1 Hz to 1 MHz. It also can be used to design band-pass and high-pass filters with Chebychev and Butterworth approximations. The circuit topologies supported by the tool are the Sallen Key and Multiple Feedback (MFB). The low-pass filters can use either the Sallen Key or MFB, the band-pass filter is available with the MFB and the high-pass filter uses the Sallen Key.

Users can select a flat pass-band or sharp transition from pass-band to stop-band. Other options, such as minimum ripple factor, sharp transition and linear phase delays are available. Once the filter characteristics have been identified, the Mindi™ Active Filter Designer & Simulator can generate and simulate the schematic of filter circuit. For maximum design flexibility, changes in resistor and capacitor values can be implemented to fit the demands of the application. The tool will recalculate all values to meet the desired response, allowing real-world values to be substituted or changed as part of the design process. The tool also generates a Bill of Materials (BOM) of the designed filter. Users can directly order the op amps and evaluation boards from the Microchip web site at www.microchip.com.

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1.2   ACCESSING MINDI™

The Mindi™ Circuit Designer & Simulator can be accessed on Microchip's Home Page (http://www.microchip.com) under **"Analog Design & Sim. Tool"** or by going directly to the Mindi™ Home web page (http://www.microchip.com/mindi).
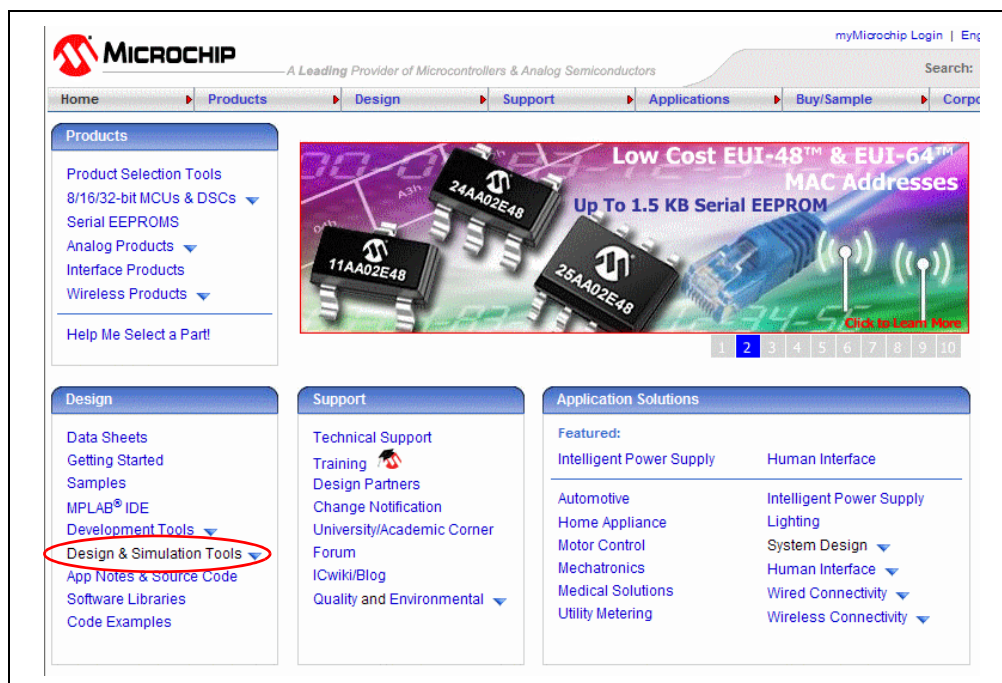

FIGURE 1-1:   *Mindi™ can be accessed on the Microchip Home Page.*

The Mindi™ Home Page is shown in Figure 1-2. To enter the Mindi™ Circuit Designer & Simulator, click the **Click Here to Start** button in the window.
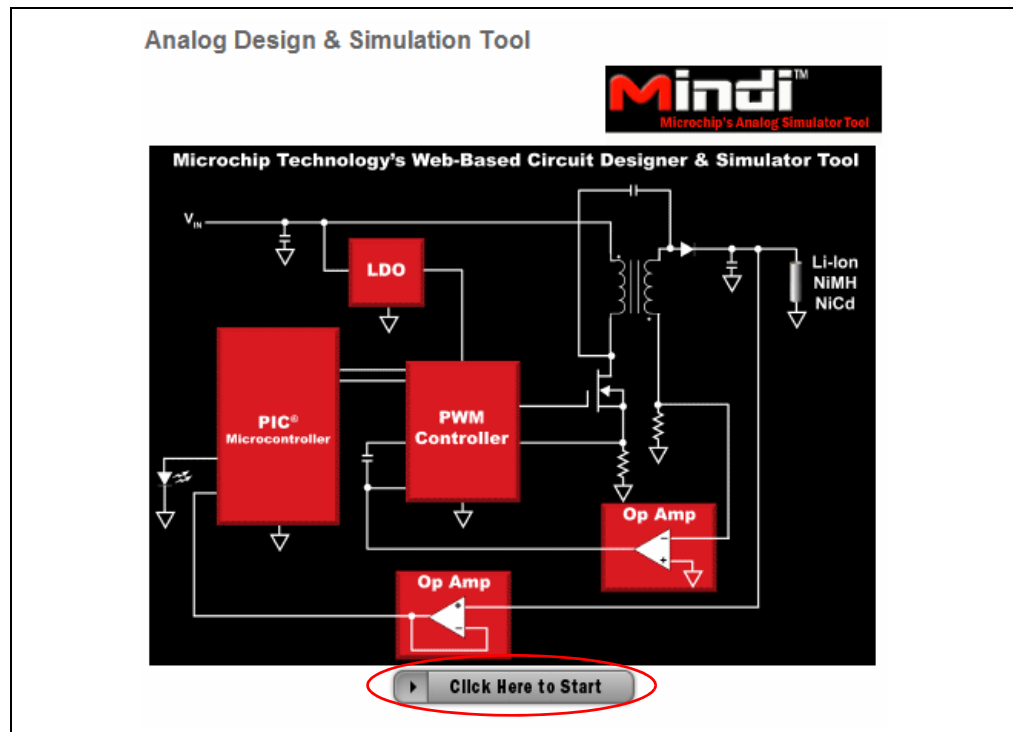
FIGURE 1-2:   *Bring up the Mindi™ Circuit Designer & Simulator on the Mindi™ Home Page.*

Once users log onto Mindi™, the home page is displayed, indicating the application circuits that are available for design and simulation, as shown in Figure 1-3. The **Active Filters** button is indicated in the upper-left corner of the web page. Click on it to enter the active filter online design and simulation test environment.

The first time **Active Filters** accessed, users will be prompted to provide some basic registration informatio, as shown in Figure 1-4. Once registered, an account is created on the Host Server and users will be able to generate and analyze designs on the Mindi™ Circuit Designer & Simulator web page. Custom designs can also be saved to users' PC, where they can be accessed for future reference.

Note: If a Pop-Up Blocker is enabled on the users' browser, there may be a problem with the registration process. Please be sure to disable this feature when registering on Mindi™. On Internet Explorer, this is done by selecting the Pop-Up Blocker window under the **Tools** pull-down menu.
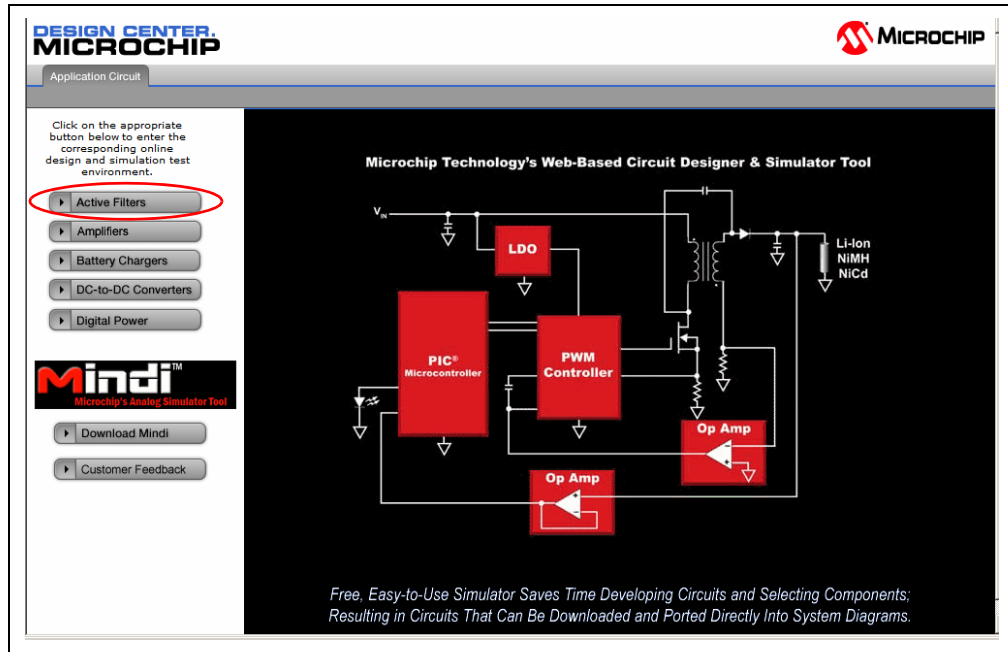

Mindi™ Active Filter Designer User's Guide

FIGURE 1-3: *Application Circuit.*

FIGURE 1-4: *New User Registration.*

1.3   ACTIVE FILTER DESIGN

The Mindi™ Active Filter Designer & Simulator has five filter design tabs which include **Application Circuit, Filter Requirement, Advanced Options, Op Amp Selection, Analyze**, as shown on the Tab bar on the top of the tool page in Figure 1-5. These tabs enable the user to move through the design steps of specifying performance requirements. An overview of the Mindi™ Active Filter Designer & Simulator is given in the following sections.

1.3.1   Application Circuit Tab

The active filter design starts from the **Application Circuit** tab (see Figure 1-3). Select **Active Filters** button to enter the online simulation test environment.

1.3.2   Filter Requirements Tab

Click the **Filter Requirements** tab and set desired parameters for the filter. (This tab is discussed in more detail in **Chapter 3. "Filter Requirements"**.)

FIGURE 1-5:   *Filter Requirements.*

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1.3.3 Advanced Options Tab

Click the **Advanced Options** tab, configure the desired filter topology and set the specifications for the components to be used in the filter circuit. (This tab is discussed in more detail in **Chapter 4. "Advanced Options"**).
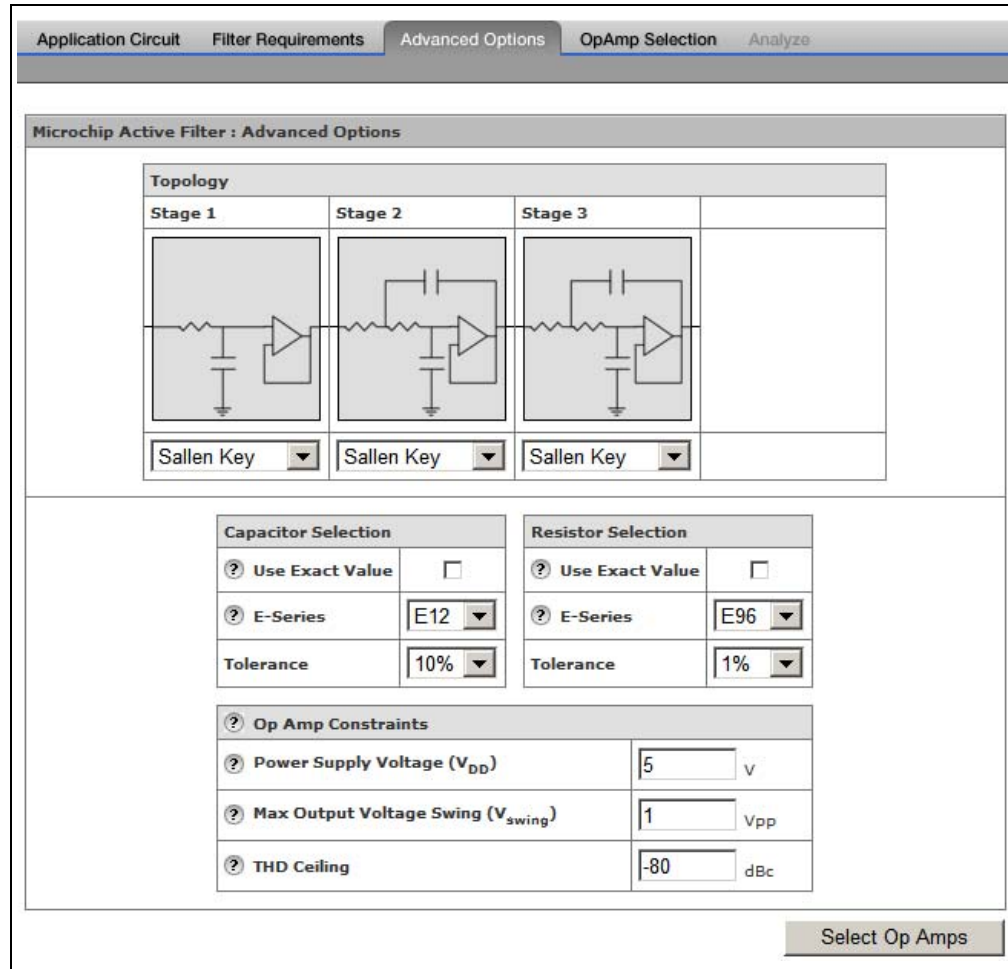

FIGURE 1-6:   *Advanced Options.*

1.3.4 Op Amp Selection Tab

Click the **Op Amp Selection** tab, choose an op amp to be used in the filter and click the corresponding **Analyze** link to start the next phase of the design. (This tab is discussed in more detail in **Chapter 5. "Op Amp Selection"**).

Op Amp Family	Gain Bandwidth Product (kHz)	Slew Rate (V/µs)	Min Stable Gain (V/V)	Vos Max (±µV)	Vdd Min (V)	Vdd Max (V)	Iq Max (µA/amplifier)	Rail-to-Rail Input	Rail-to-Rail Output	
Ideal Op Amp	1.0E30	1.0E30	1.0	0.0	0.0	1.0E30	0.0	Y	Y	Analyze
TC1034	60.0	0.035	1.0	500.0	1.8	5.5	6.0	Y	Y	Analyze
MCP606	155.0	0.08	1.0	250.0	2.5	5.5	18.7	N	Y	Analyze
MCP616	190.0	0.08	1.0	150.0	2.3	5.5	19.0	N	Y	Analyze
MCP6231	300.0	0.15	1.0	5000.0	1.8	5.5	20.0	Y	Y	Analyze
MCP6241	550.0	0.3	1.0	5000.0	1.8	5.5	50.0	Y	Y	Analyze
MCP6001	1000.0	0.6	1.0	4500.0	1.8	5.5	100.0	Y	Y	Analyze
MCP6271	2000.0	0.9	1.0	3000.0	2.0	5.5	170.0	Y	Y	Analyze
MCP601	2800.0	2.3	1.0	2000.0	2.7	5.5	230.0	N	Y	Analyze
MCP6281	5000.0	2.5	1.0	3000.0	2.2	5.5	450.0	Y	Y	Analyze
MCP6021	10000.0	7.0	1.0	250.0	2.5	5.5	1000.0	Y	Y	Analyze
MCP6291	10000.0	7.0	1.0	3000.0	2.4	5.5	1000.0	Y	Y	Analyze

FIGURE 1-7:   *Op Amp Selection.*

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1.3.5   Analyze Tab

There are four buttons associated with the Analyze tab:

- **Interactive Schematic**
- **Reset Design**
- **Design Summary**
- **Downloads, Samples and More**

The Mindi™ Active Filter Designer & Simulator generates the filter circuit schematic on this tab. For maximum design flexibility, changes in resistor and capacitor values can be implemented to fit the demands of the application. To run a simulation, choose a mode from the **Select** drop-down menu and click the **Run** button to simulate the schematic. Once the simulation is complete, waveforms will be available via the **Waveforms** drop-down menu. A single-page design summary can be generated by clicking **Design Summary** button. Moreover, the schematic, BOM, filter SPICE model and Mindi™ offline version can be downloaded. (This tab is discussed in more detail in **Chapter 6. "Analyze"**).
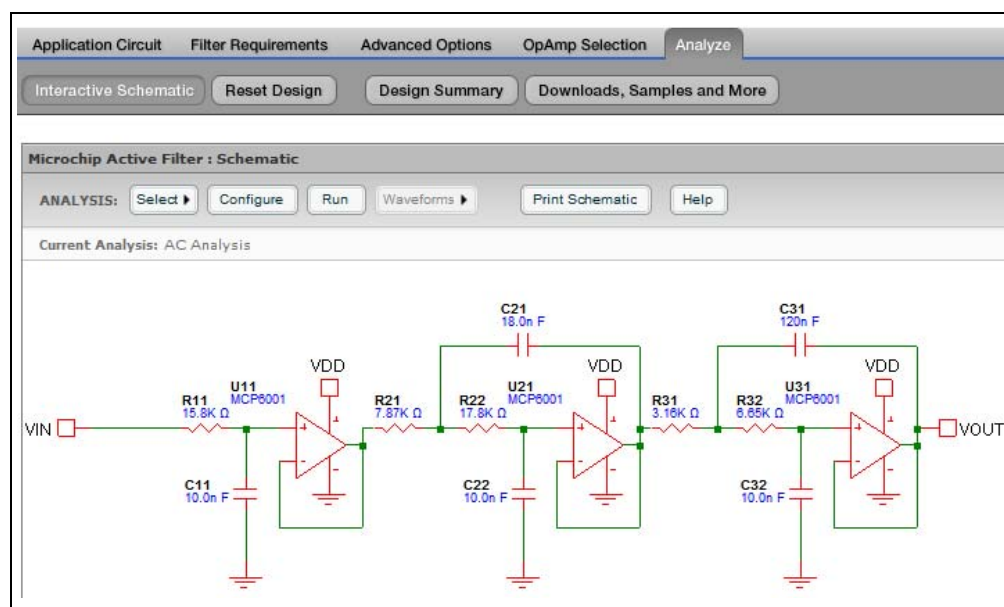
FIGURE 1-8:   *Analyze.*

Chapter 2. Filter Design Tutorial

2.1 INTRODUCTION

This chapter steps users through the design of an example active filter circuit.

2.2 FILTER DESIGN EXAMPLE

Design a Butterworth low-pass filter with overall gain H_M = +1 V/V, pass-band frequency f_P = 1 kHz, stop-band frequency f_S = 10 kHz, pass-band attenuation A_P = 3 dB, stop-band attenuation A_S = 80 dB.

The Butterworth low-pass filter can use the filter response template shown in Figure 2-1. Refer to Figure A-1 for a more complete template.

FIGURE 2-1:   *Filter Response Template for a Butterworth Low-Pass Filter.*

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1. To access the Mindi™ Active Filter Designer & Simulator, refer to
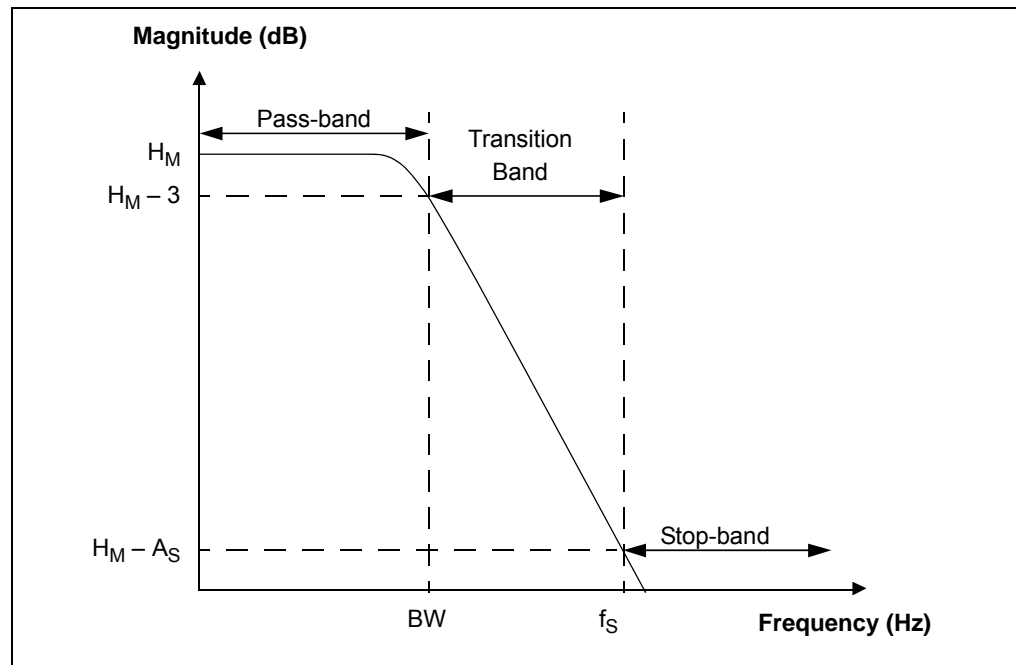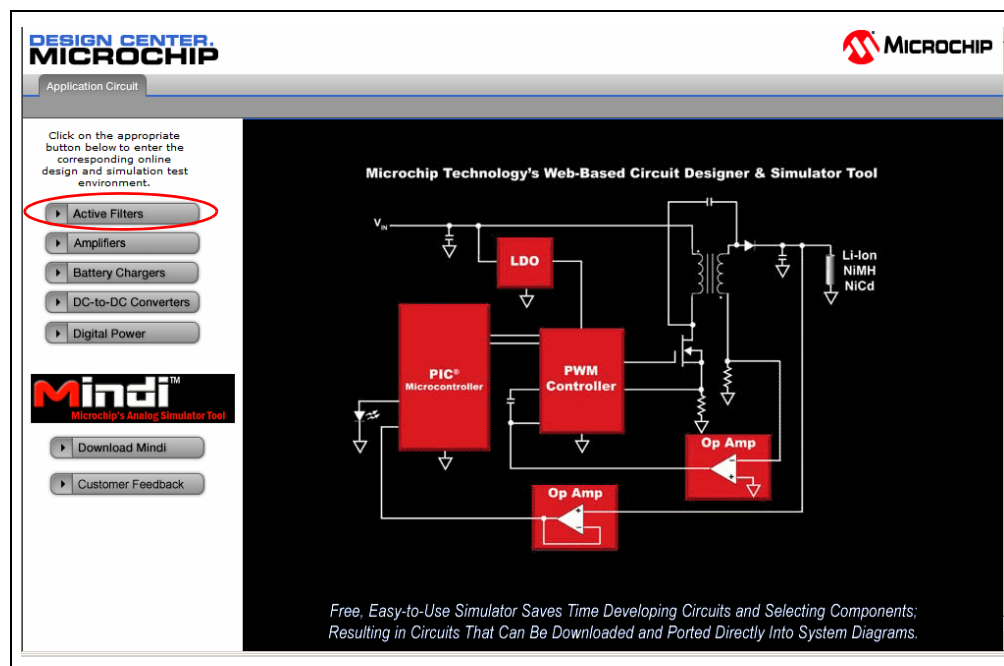   **Section 1.2 "Accessing Mindi™"** for more detail.

FIGURE 2-2: *Active Filters.*

2. Set Desired Parameters

Click the **Selectivity** drop-down menu and specify **low-pass** in the selectivity pull-down menu. The Filter Characteristics dialog enables users to specify the approximation type, pass-band characteristics, stop-band characteristics, etc.

There are three approximation types available: Butterworth, Bessel and Chebychev (For more detail about these three approximation types, see **Appendix B. "Low-Pass Filter Approximations"**). Click the **Approximation** drop-down menu and specify the filter approximation by Butterworth.

For Pass-band Characteristics, enter **-3** in the Attenuation text box and enter **1k** in the Frequency text box. For Stop-band Characteristics, enter **-80** in the "Attenuation" box and enter **10k** in the "Frequency text" box. (For more details about pass-band or stop-band characteristics, see **Appendix A. "Filter Magnitude Templates"**.)

> **Note:** The current version of Mindi requires negative values for the attenuations (e.g., A_P and A_S). For example, A_P = 3 dB is entered as -3 in the Attenuation text box; A_S = 80 dB is entered as -80 in the Attenuation textbox.This will be fixed in future versions.

FIGURE 2-3: *Filter Requirements.*

3. Configure the desired topology and set the specifications for the components to be used in the filter.

The **Topology** drop-down menus include Sallen Key and Multiple Feedback (MFB) topologies for low-pass filter. The choice of circuit topology depends on performance requirements. The MFB has low sensitivity to component variations and better high-frequency behavior. The Sallen Key inherently has the superrior gain accuracy at unity gain because its gain is not dependent on component values.

Here, Sallen Key topology is chosen for all stages. The Constraints text boxes enable users to specify the values of Power Supply Voltage, Maximum Output Voltage Swing and THD ceiling.
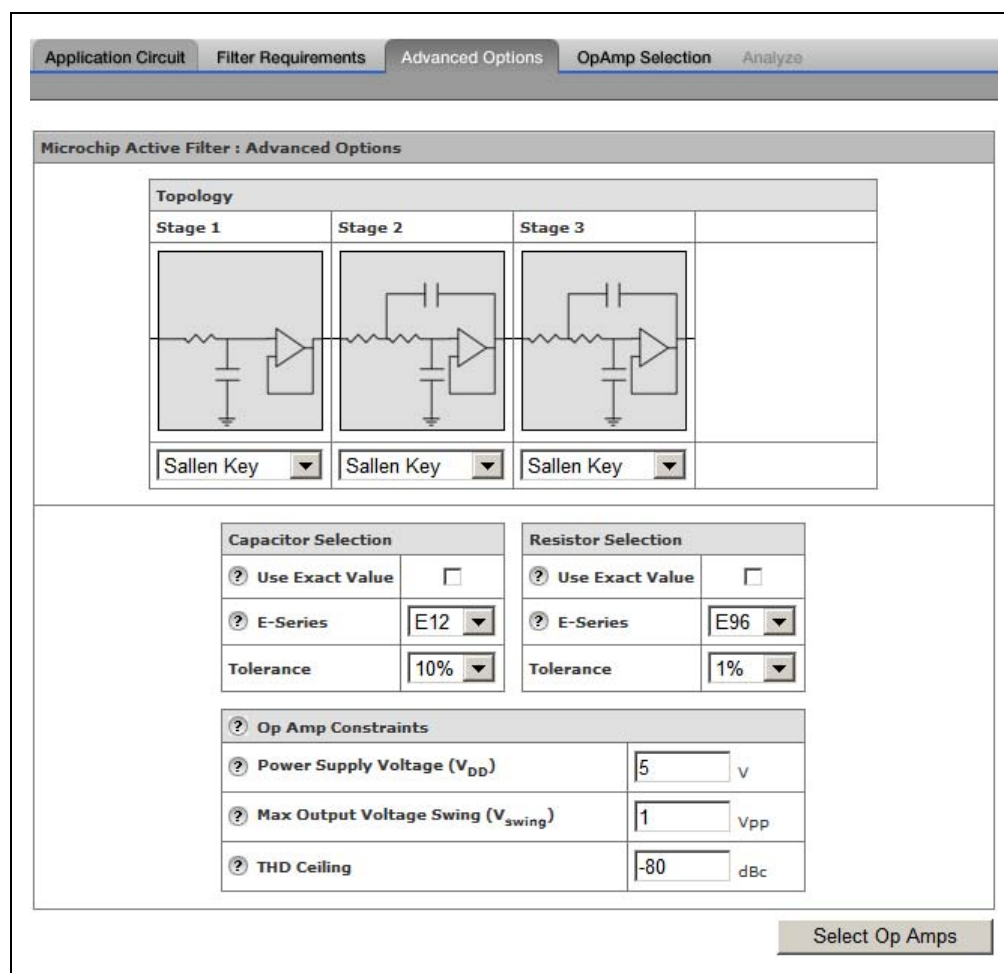

FIGURE 2-4: *Advanced Options.*

4. Select Op Amp

The Filter Characteristics table lists key filter design information as a reminder. The Recommended Op Amp table lists those op amps that come close to the recommended op amp specs. For more detail, see **Appendix C. "Op Amp Selection"**. For this tutorial, select **MCP6001** by clicking the corresponding **Analyze** link.

Application Circuit	Filter Requirements	Advanced Options	OpAmp Selection	Analyze

Microchip Active Filter: Op Amp Selection

Op Amp Design Constraints

Power Supply Voltage (V_{DD})	5 V
Max Output Voltage Swing (V_{swing})	1 Vpp
THD Ceiling	-80 dBc

Recommended Op Amp Parameters

? Gain Bandwidth Product	100.0 kHz
? Slew Rate	0.00631 V/µs

Filter Characteristics

Selectivity	Lowpass
Approximation	Butterworth
Gain (G)	1 V/V
Cutoff Frequency (f_p)	1 kHz
Filter Order	5
Number of Stages	3

Recommended Op Amps

Op Amp Family	Gain Bandwidth Product (kHz)	Slew Rate (V/µs)	Min Stable Gain (V/V)	Vos Max (±µV)	Vdd Min (V)	Vdd Max (V)	Iq Max (µA/amplifier)	Rail-to-Rail Input	Rail-to-Rail Output	
Ideal Op Amp	1.0E30	1.0E30	1.0	0.0	0.0	1.0E30	0.0	Y	Y	Analyze
TC1034	60.0	0.035	1.0	500.0	1.8	5.5	6.0	Y	Y	Analyze
MCP606	155.0	0.08	1.0	250.0	2.5	5.5	18.7	N	Y	Analyze
MCP616	190.0	0.08	1.0	150.0	2.3	5.5	19.0	N	Y	Analyze
MCP6231	300.0	0.15	1.0	5000.0	1.8	5.5	20.0	Y	Y	Analyze
MCP6241	550.0	0.3	1.0	5000.0	1.8	5.5	50.0	Y	Y	Analyze
MCP6001	1000.0	0.6	1.0	4500.0	1.8	5.5	100.0	Y	Y	Analyze
MCP6271	2000.0	0.9	1.0	3000.0	2.0	5.5	170.0	Y	Y	Analyze
MCP601	2800.0	2.3	1.0	2000.0	2.7	5.5	230.0	N	Y	Analyze
MCP6281	5000.0	2.5	1.0	3000.0	2.2	5.5	450.0	Y	Y	Analyze
MCP6021	10000.0	7.0	1.0	250.0	2.5	5.5	1000.0	Y	Y	Analyze
MCP6291	10000.0	7.0	1.0	3000.0	2.4	5.5	1000.0	Y	Y	Analyze

FIGURE 2-5: *Op Amp Selection.*

5. Analyze

The Mindi™ Active Filter Designer & Simulator automatically generates the full schematic diagram of the filter circuit with recommended component values. There are two types of analysis in the **Select** drop-down menu: AC Analysis and Transient Analysis.

First, choose **AC Analysis**. Then, click the **Configure** button to set up the AC simulation condition. This pull-down menu allows the user to set up the start frequency, stop frequency and resolution. Finally, click the **Run** button to simulate the schematic. Once the simulation is completed, the AC response will be available via the **Waveforms** drop-down menu. Similarly, the Transient Analysis can be completed and the Step Response will also be available via the **Waveforms** drop-down menu. Moreover, a design summary can be generated by clicking **Design Summary** button. (See Figures 2-6 to 2-15).
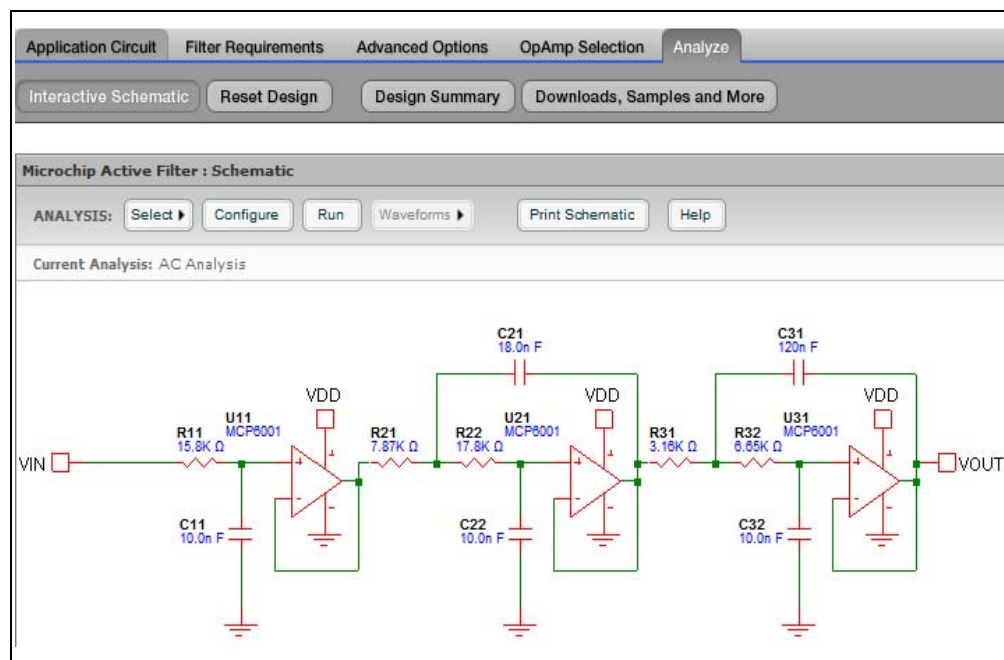
FIGURE 2-6:   *AC Analysis and Transient Analysis.*
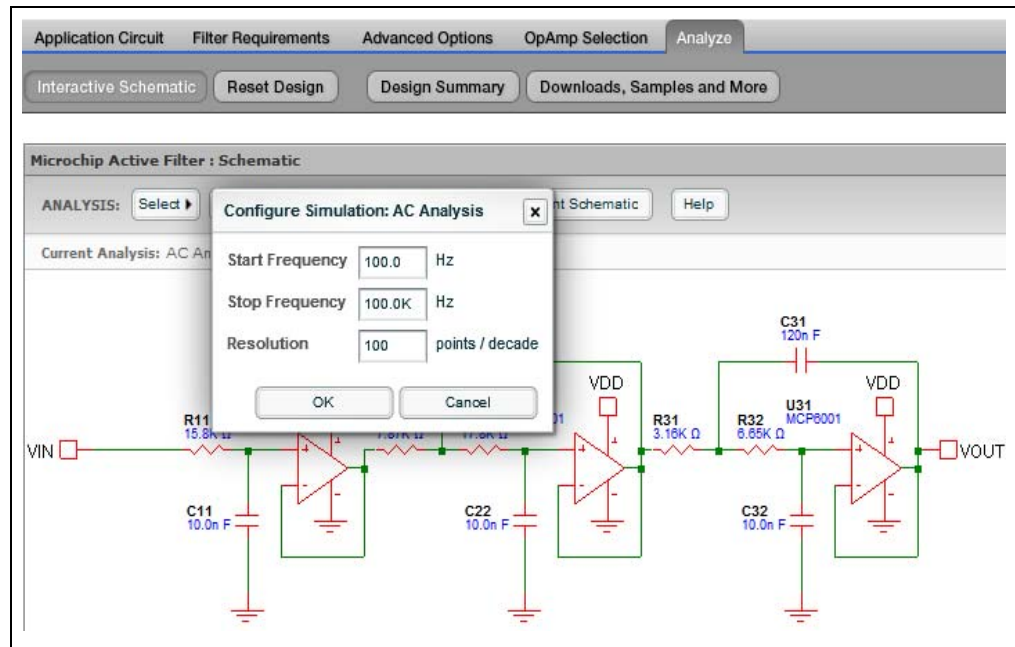
FIGURE 2-7:   *Configure the Simulation.*
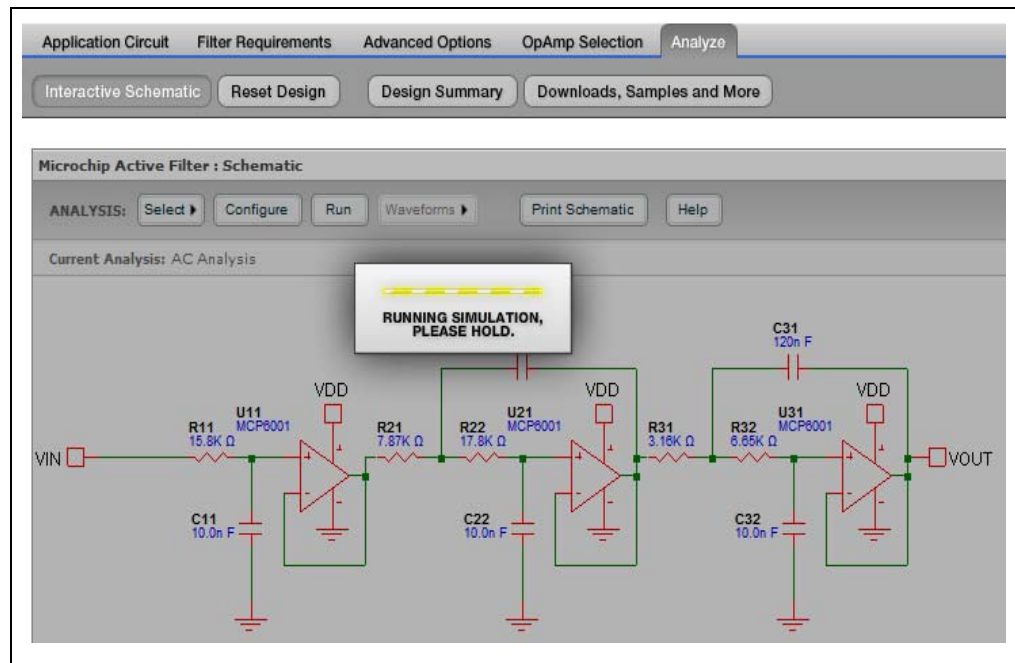
FIGURE 2-8:   *Running the Simulation.*

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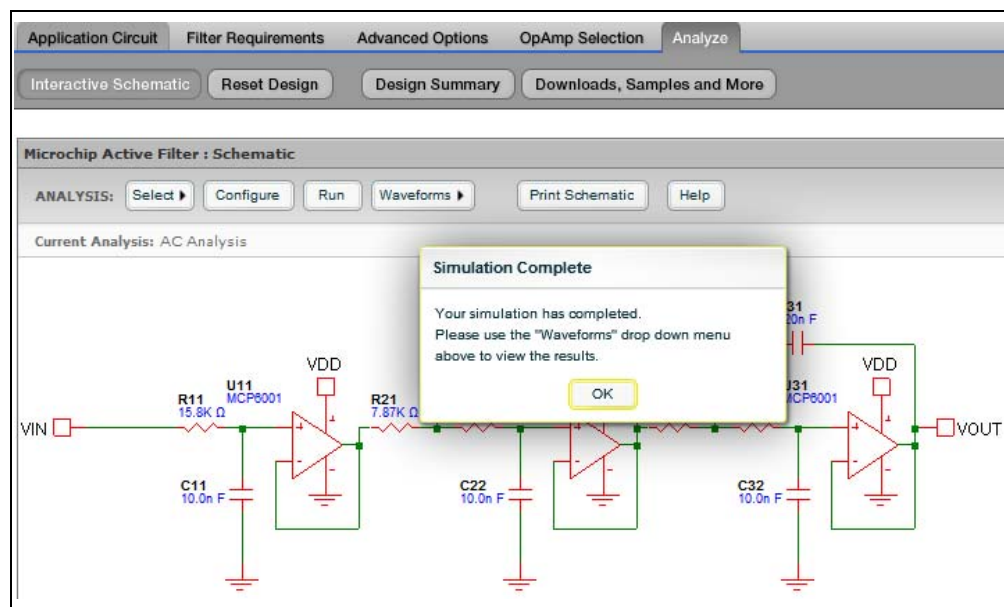
FIGURE 2-9: Simulation Complete.
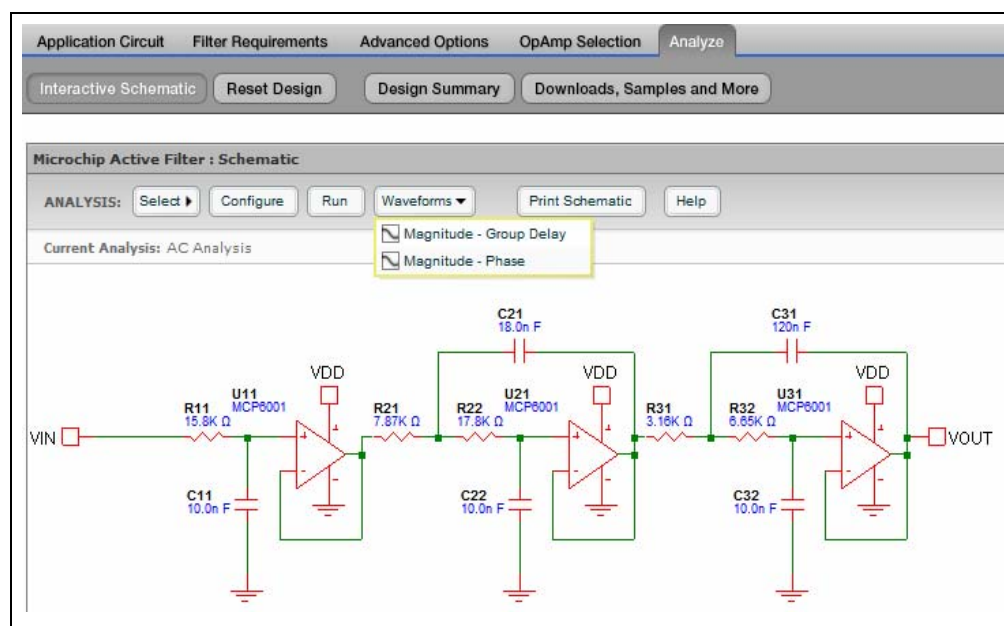
FIGURE 2-10: View the Waveform.
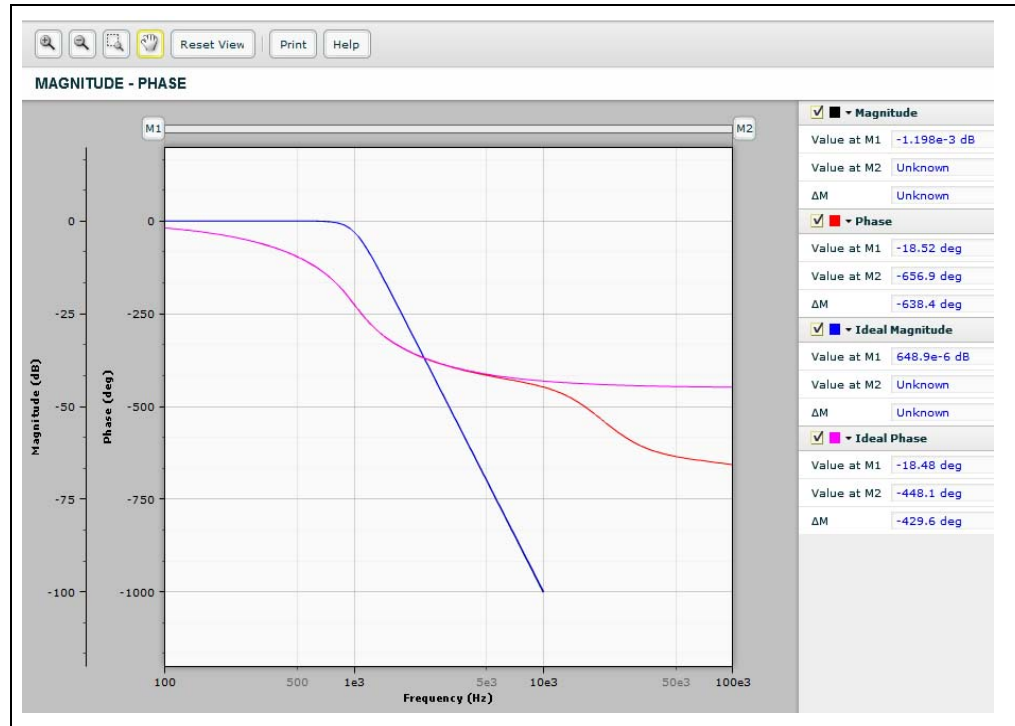
FIGURE 2-11: *AC Response: Magnitude-Phase Delay.*
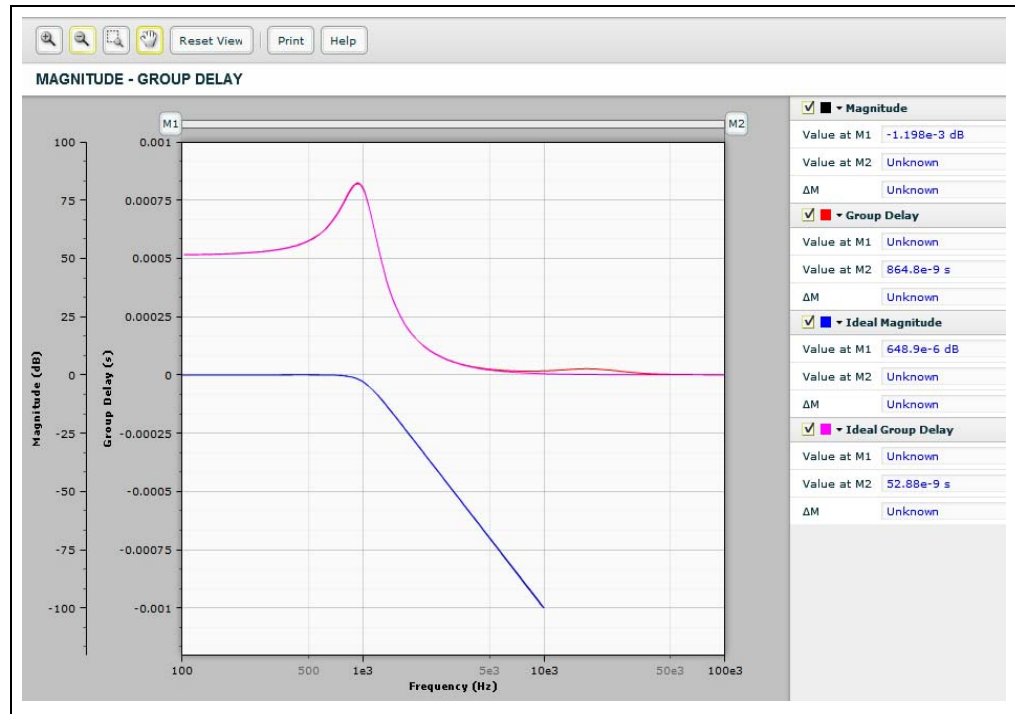
FIGURE 2-12: *AC Response: Magnitude-Group Delay.*
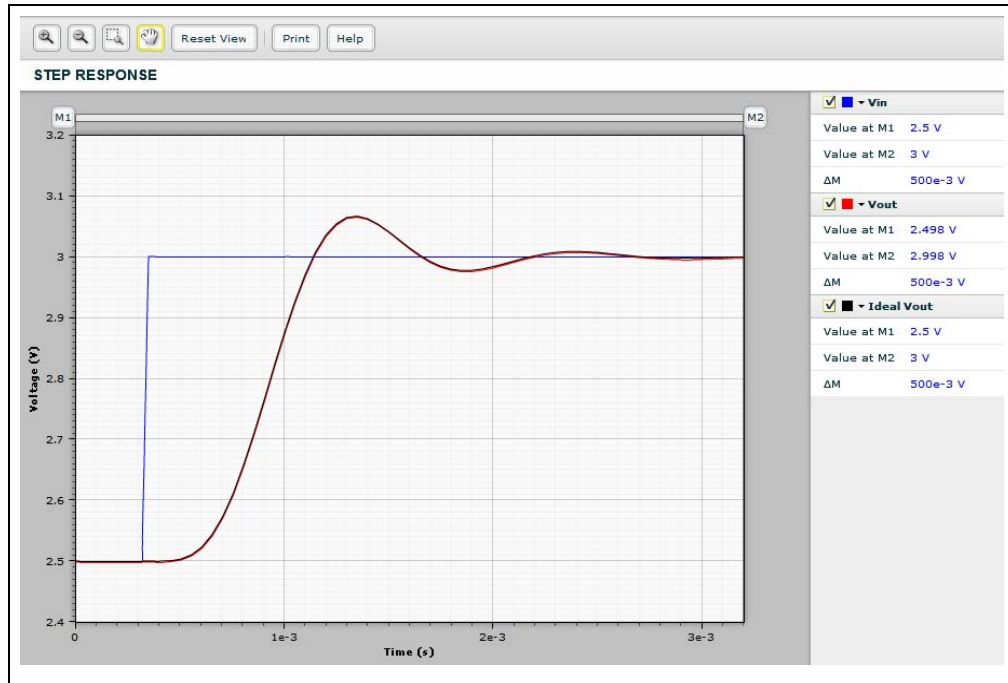
FIGURE 2-13: Step Response.
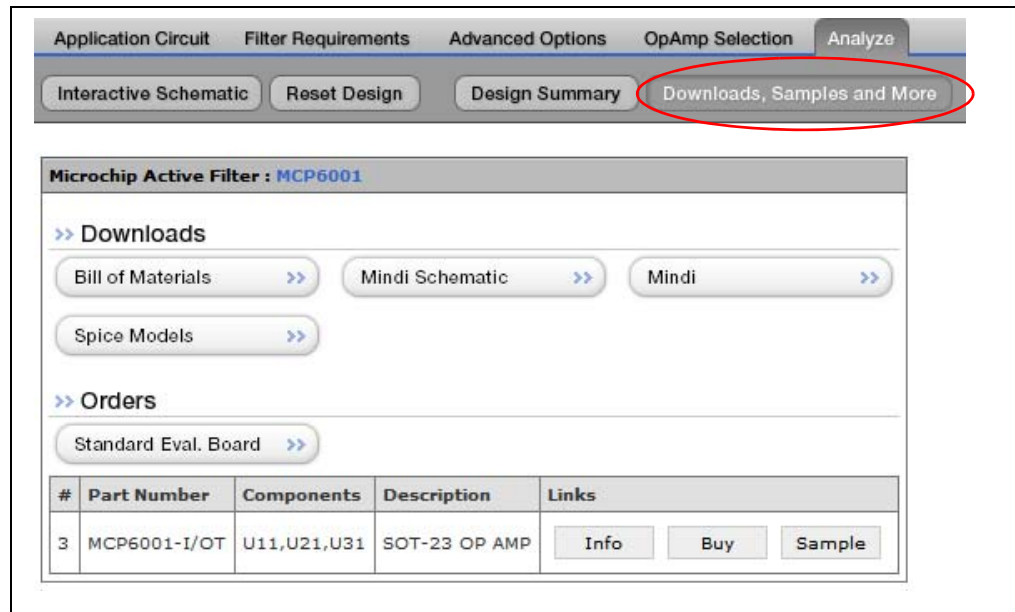
FIGURE 2-14: Design Summary.

FIGURE 2-15: *Downloads, Samples and More.*

NOTES:

Chapter 3. Filter Requirements

3.1 INTRODUCTION

This chapter discusses the Mindi **Filter Requirements** tab in greater detail. The Filter Requirements tab is shown in Figure 1-5 in Section 1.3.2.

3.2 FILTER SELECTIVITY

The **Selectivity** drop-down menu enables the user to specify a filter type as Low-pass, High-pass and Band-pass.
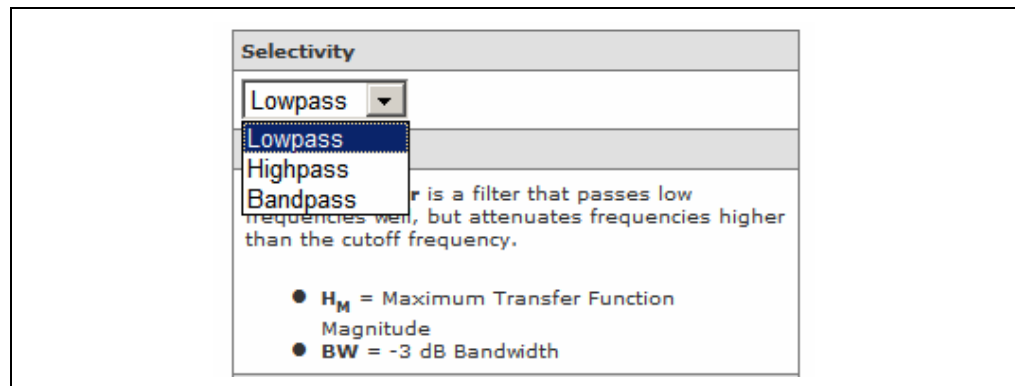
FIGURE 3-1:   Filter Selectivity.

3.3 FILTER DESCRIPTION

The **Description** table below the **Selectivity** pull-down menu describes the specified filter, as indicated in Figures 3-2 thru 3-4.
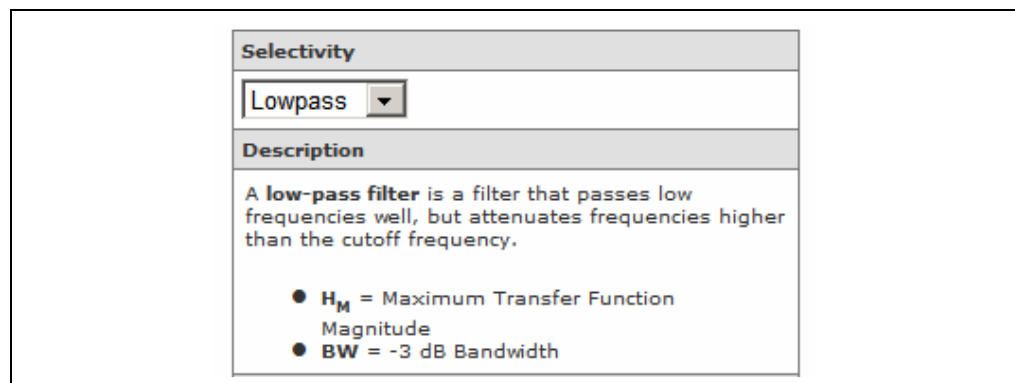
FIGURE 3-2:   Low-Pass Filter Description.
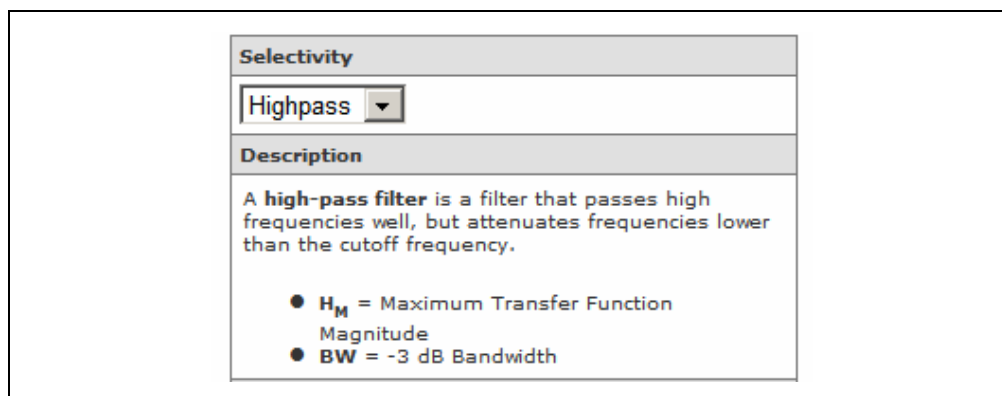
FIGURE 3-3: *High-Pass Filter Description.*
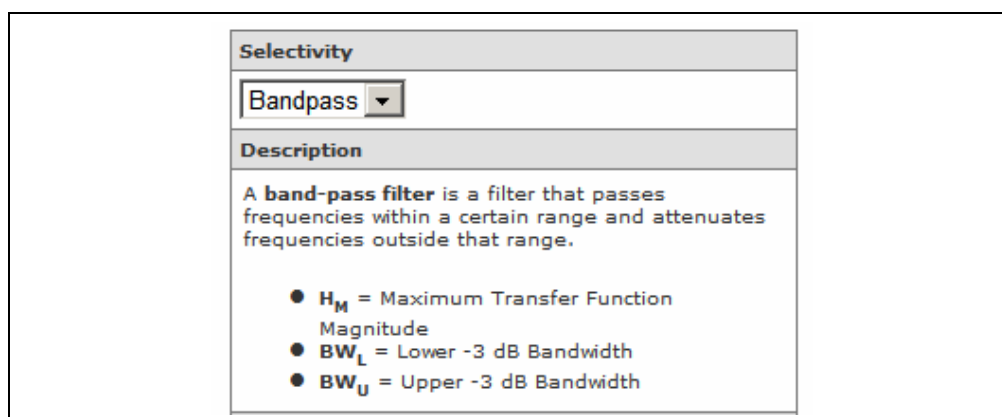
FIGURE 3-4: *Band-Pass Filter Description.*

3.4   FILTER RESPONSE

1.   Move the mouse to the filter response graph and click on it to enlarge.
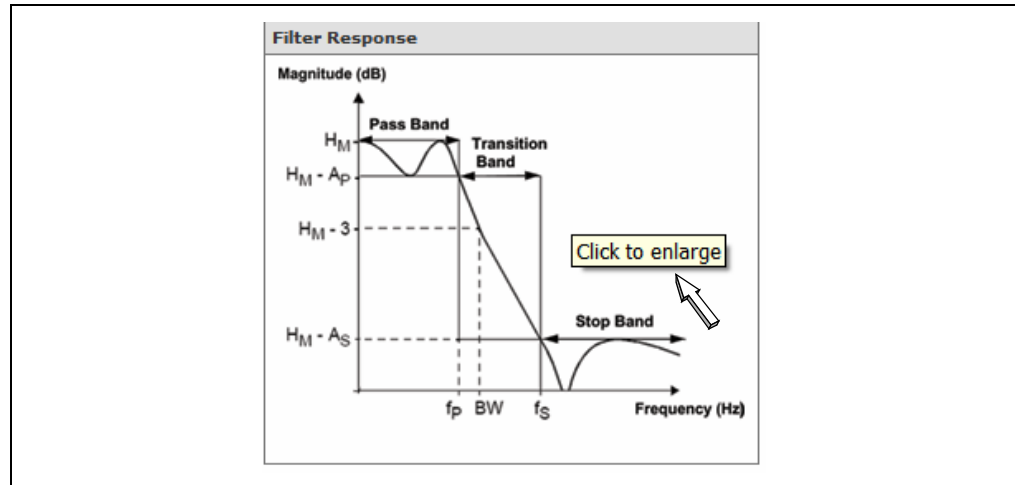
FIGURE 3-5:   *Enlarge the Filter Response Graph.*

Figure 3-6 thru Figure 3-8 provide a simplified representation of the filter responses and specification parameters. For all selectivities, A_P and A_S represent the pass-band and stop-band attenuations. H_M represents the maximum transfer function magnitude. A detailed discussion is provided in **Appendix A. "Filter Magnitude Templates"**.

3.4.1   Low-Pass Filter

• f_P = Pass-band Frequency; f_S = Stop-band Frequency; BW = -3 dB Bandwidth
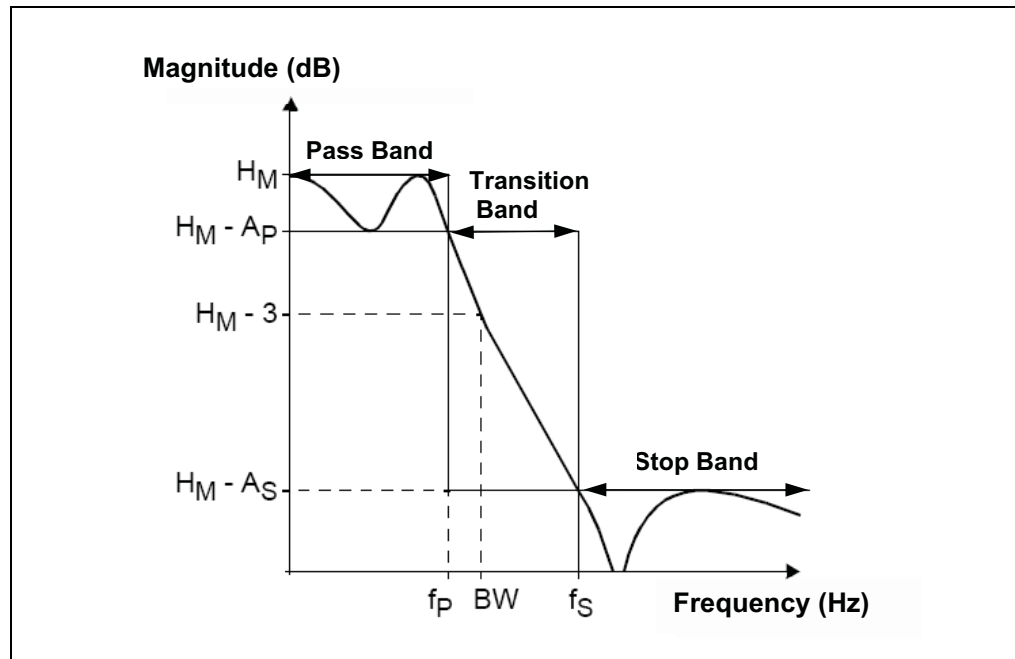
FIGURE 3-6:   *Filter Response and Parameter Definitions for Low-pass Selectivity.*

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3.4.2   High-Pass Filter

- f_P = Pass-band Frequency; f_S = Stop-band Frequency; BW = -3 dB Bandwidth
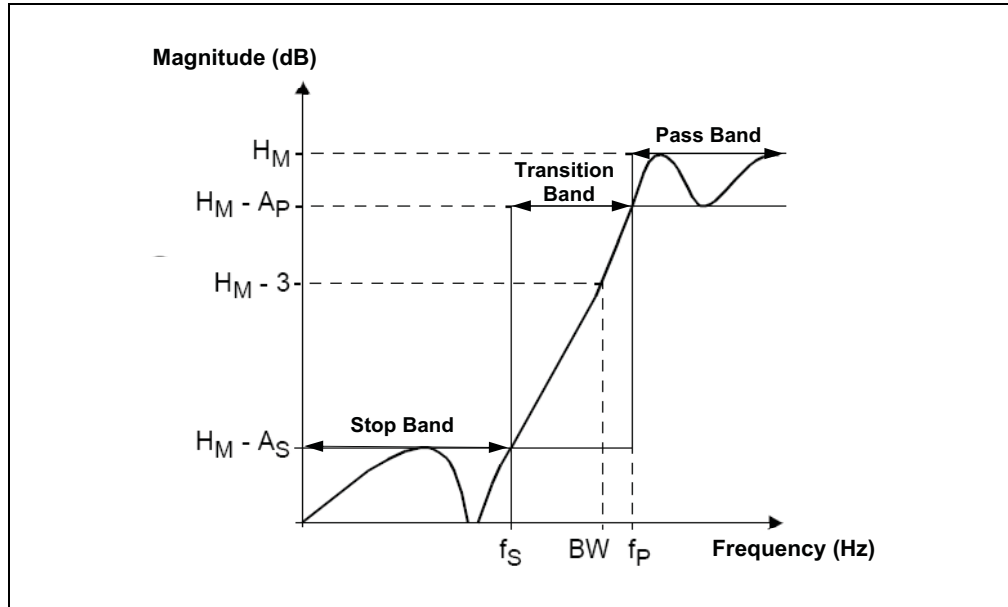
FIGURE 3-7:   *Filter Response and Parameter Definitions for High-pass Selectivity.*

3.4.3   Band-Pass Filter

- f_{PL} = Lower Pass-band Frequency; f_{PU} = Upper Pass-band Frequency
- f_{SL} = Lower Stop-band Frequency; f_{SU} = Upper Stop-band Frequency
- BW_L = Lower -3 dB Bandwidth; BW_U = Upper -3 dB Bandwidth
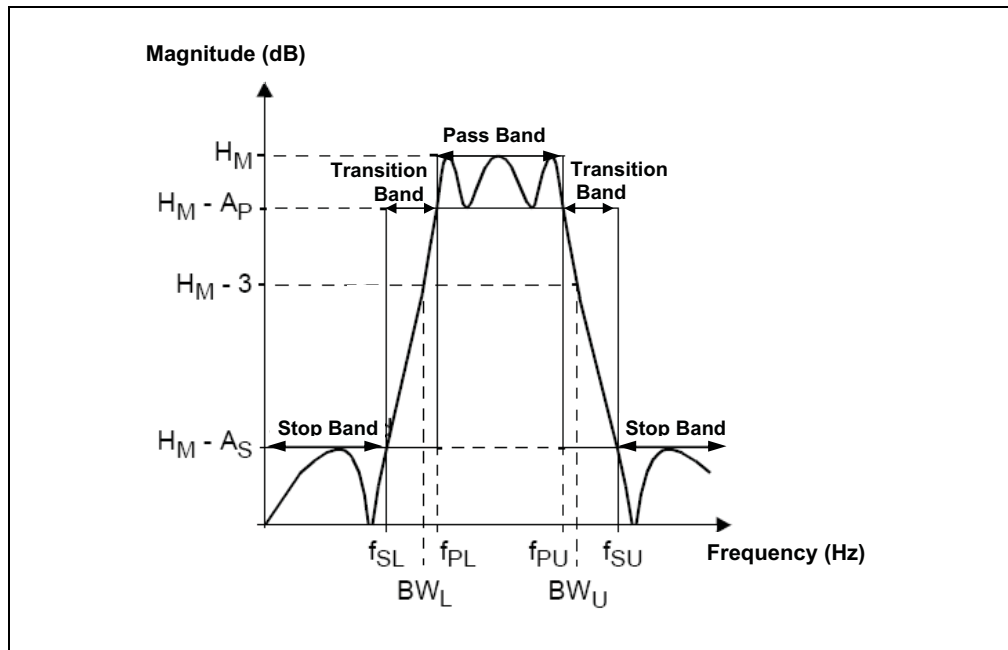
FIGURE 3-8:   *Filter Response and Parameter Definitions for Band-pass Selectivity.*

3.5   FILTER CHARACTERISTICS

The Filter Characteristics dialog enables users to specify the Approximation type, Filter Order, Overall Filter Gain, Pass-band characteristics and Stop-band characteristics.

3.5.1   Approximation

The **Approximation** drop-down menu specifies three most commonly used filter approximations: Butterworth, Bessel and Chebyshev. A detailed discussion about the differences between these approximations is provided in **Appendix B. "Low-Pass Filter Approximations".**

Note: *Bessel is available only when Low-pass is selected.*

FIGURE 3-9:   Filter Approximation.

3.5.2   Overall Filter Gain

- For a Butterworth, Bessel and some Chebyshev approximations, the overall filter gain (G) is set as H_M as shown in Figure 3-6 through Figure 3-8. This setting is reflected in Figure 3-10 and Figure 3-11.
- For other Chebychev Approximation: Low-pass of even order, High-pass of even order and Band-pass of orders 4 and 8, the overall filter gain (G) is set as H_M - A_P as shown in Figure 3-6 through Figure 3-8. This setting is reflected in Figure 3-12 and Figure 3-13.

The allowable range of overall filter gain is 1 V/V to 10 V/V.

FIGURE 3-10:   Overall Filter Gain For Butterworth.

FIGURE 3-11:   Overall Filter Gain For Bessel.

Filter Characteristics	
Approximation	Chebychev ▼
Filter Order (n)	4 Force ☐
Overall Filter Gain (G) $G = H_M - A_P$	1 V/V

FIGURE 3-12: *Overall Filter Gain For Chebychev.*

Chebychev Filter Notes

Certain chebychev filters are computed using $G = H_M - A_P$ instead of $G = H_M$. This occurs for the following configurations:

Selectivity	Filter Order
Lowpass	[2,4,6,8]
Highpass	[2,4,6,8]
Bandpass	[4,8]

FIGURE 3-13: *Chebychev Filter Notes.*

3.5.3 Filter Order

The **Filter Order** drop-down menu allows users to specify the filter order, if desired.

By default, the **Force** checkbox is unselected, and users only need to specify the characteristics of Pass-band and Stop-band. The Mindi™ Active Filter Designer will automatically calculate the best filter order according to the characteristics of pass-band and stop-band specified by users. The calculated filter order will be the minimum order that meets or exceeds the required stop-band attenuation.

When the **Force** checkbox is selected, the Stop-band characteristics text boxes will be disabled. In this case, users only need to specify the filter order and Pass-band characteristics.

Band-pass selectivity only permits an even filter order. Therefore, the order will increment by two when the Band-pass selectivity is selected.

FIGURE 3-14: Filter Order.

FIGURE 3-15: Filter Characteristics with Force Filter Order Selected.

FIGURE 3-16: *Filter Characteristics with Bessel Approximation Selected.*

Note: Bessel approximations only support forced filter orders. When the Bessel approximation is selected, the **Force** checkbox will be selected and disabled.

3.5.4   Pass-band and Stop-band Characteristics

The Pass-band and Stop-band characteristics text boxes allow users to modify the filter circuit parameters. For all selectivities, A_P represents the Pass-band attenuations and A_S represents the Stop-band attenuations. For Low-pass selectivities, f_P represents the Pass-band frequencies and High-pass selectivities, f_S represent the Stop-band frequencies.

> **Note:** The current version of Mindi requires negative values for the attenuations (e.g., A_P and A_S). For example, A_P = 3 dB is entered as **-3** in the "Attenuation text" boxes; A_S = 80 dB is entered as **-80** in the "Attenuation" text box.

Passband Characteristics		
Attenuation (A_p)	-3	dB
Frequency (f_p)	1k	Hz
Stopband Characteristics		
Attenuation (A_S)	-80	dB
Frequency (f_S)	10k	Hz

FIGURE 3-17:   *Pass-band and Stop-band Characteristics for Low-pass and High-pass Filters.*

For Band-pass selectivity, f_{PU} and f_{PL} represent the Pass-band upper and lower frequencies, while f_{SU} and f_{SL} represent the Stop-band upper and lower frequencies.

Passband Characteristics		
Attenuation (A_p)	-3	dB
Frequency Lower (f_{PL})	1k	Hz
Frequency Upper (f_{PU})	5k	Hz
Stopband Characteristics		
Attenuation (A_S)	-80	dB
Frequency Lower (f_{SL})	100	Hz
Frequency Upper (f_{SU})	50k	Hz

FIGURE 3-18:   *Pass-band and Stop-band Characteristics for Band-pass Filter.*

3.5.4.1 PASS-BAND ATTENUATION

The Pass-band Attenuation is the change in magnitude of the frequencies in the Pass-band. The Pass-band attenuation for each selectivity (Low-pass, High-pass, Band-pass) is shown in Figure 3-6 thru Figure 3-8. The allowable range is -0.01 dB to -3 dB.

> **Note:** When the Bessel approximation is selected, the Pass-band Attenuation is forced to -3 dB.

3.5.4.2 STOP-BAND ATTENUATION

The Stop-band attenuation is the minimum reduction in magnitude of the frequencies in the Stop-band relative to the pass-band. The Stop-band attenuation for each selectivity is shown in Figure 3-6 thru Figure 3-8. The allowable range is -10 dB to -100 dB.

3.5.4.3 PASS-BAND FREQUENCY

The Pass-band frequency is the starting point of the Pass-band, as shown in Figure 3-6 thru Figure 3-8. The allowable range is 0.1 Hz to 1 MHz.

- For a Low-pass filter, the Pass-band frequency must be lower than the Stop-band frequency for Low-pass selectivity.
- For a High-pass filter, the Pass-band frequency must be greater than the Stop-band frequency for High-pass selectivity.
- For a Band-pass filter, the lower Pass-band frequency must be lower than the upper Pass-band frequency and both Stop-band frequencies for Band-pass selectivity.

3.5.4.4 STOP-BAND FREQUENCY

The Stop-band frequency is the starting point of the Stop-band, as shown from Figure 3-6 thru Figure 3-8. The allowable range is 0.1 Hz to 1 MHz.

- For a Low-pass filter, the Stop-band frequency must be greater than the Pass-band frequency for Low-pass selectivity.
- For a High-pass filter, the Pass-band frequency must be greater than the Stop-band frequency for High-pass selectivity.
- For a Band-pass filter, the lower Pass-band frequency must be lower than the upper Pass-band frequency and both Stop-band frequencies for Band-pass selectivity.

3.5.5 Reset

The **Reset** button on the lower left of the window allows the user to reset any changes made to the Filter Characteristics text boxes to their initial settings.

3.5.6 Advanced Options

After setting the desired parameters for the filter, click on the **Advanced Options** button to configure the topologies, specify component tolerances, and set the Op Amp constraints.

Chapter 4. Advanced Options

4.1 INTRODUCTION

This chapter discusses the Mindi **Advanced Options** tab in greater detail. The **Advanced Options** tab is shown in Figure 1-6 in **Section 1.3.3**. This tab allows users to specify the circuit topology for each filter stage and set the rules for component selection.

4.2 TOPOLOGY SELECTION

The circuit topologies supported are the Sallen Key and Multiple Feedback (MFB). The Low-pass filters can use either the Sallen Key or MFB, the Band-pass filter is available with the MFB and the High-pass filter uses the Sallen Key. The choice of circuit topology for Low-pass filter depends on performance requirements. The MFB has low sensitivity to component variations and superior high-frequency behavior. The Sallen Key inherently has the superior gain accuracy at unity gain because its gain is not dependent on component values. For more information, refer to the filter textbooks listed in **Appendix E. "Selected References"**.

> **Note:** For Low-pass filters, changing the topology only affects the selected stage.
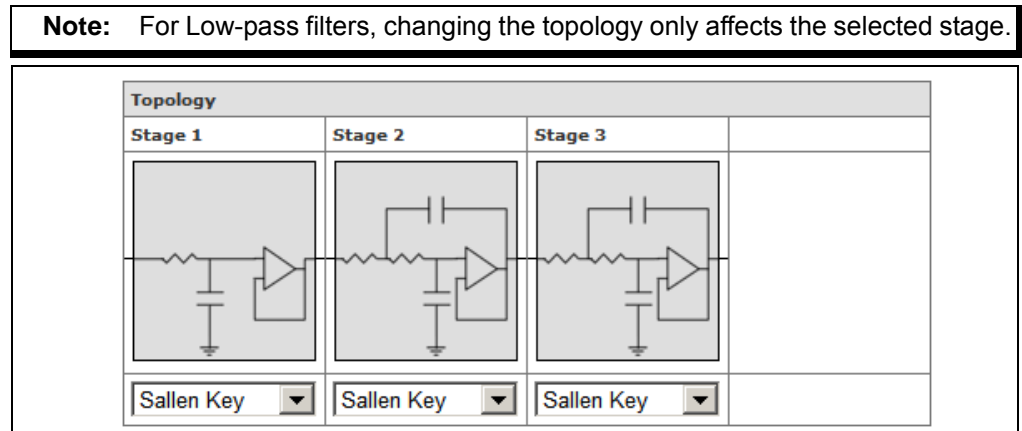
FIGURE 4-1:   *Topologies Selection.*

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4.3 RESISTOR SELECTION

The **Resistor Selection** allows users to select the tolerance of the resistors used in the filter circuit or use the exact calculated value. Changing the **Resistor Selection** affects all stages of the filter circuit. The resistor selection defaults to **E96** allowing off-the-shelf components to be specified in the filter circuit solution.

> **Note:** "E96" is a preferred number series specified in IEC 60063. The number following the "E" indicates how many standardized (commercially) available values exist in each decade (e.g., between 10 and 100, or between 100 and 1000). So, resistors conforming to "E96" have 96 distinct values between 10 and 100.

FIGURE 4-2: *Resistors Selection with Tolerance.*

4.4 CAPACITOR SELECTION

The **Capacitor Selection** allows users to select the tolerance of the capacitors used in the filter circuit or use the exact calculated value. Changing the **Capacitor Selection** affects all stages of the filter circuit. The capacitor selection defaults to **E12** allowing off-the-shelf components to be specified in the filter circuit solution.

> **Note:** "E12" is a preferred number series specified in IEC 60063. The number following the "E" indicates how many standardized (commercially) available values exist in each decade (e.g., between 10 and 100, or between 100 and 1000). So, capacitors conforming to "E12" have 12 distinct values between 10 and 100.

FIGURE 4-3: *Capacitors Selection with Tolerance.*

4.5   OP AMP CONSTRAINTS

The **Op Amp Constraints** text boxes allow users to specify the values for:

• **Power Supply Voltage (V_{DD})**

V_{DD} is the filter's nominal single supply voltage with a range of 1.4V to 5.5V and dual supply voltages need to be converted to an equivalent single supply value.

• **Maximum Output Voltage Swing (V_{swing})**

V_{swing} is the maximum expected voltage swing at any filter op amp's output with a range of 0 V to V_{DD}.

• **THD Ceiling**

THD Ceiling is the maximum harmonic (non-linear) distortion allowed in the application with a range of -100 dBc to -40 dBc.

FIGURE 4-4:   *Op Amp Constraints.*

After configuring the desired topology and setting the specifications for the components, click the **Op Amp Selection** tab to select the op amp to be used in this filter.

NOTES:

Chapter 5. Op Amp Selection

5.1 INTRODUCTION

This chapter discusses the Mindi **Op Amp Selection** tab in greater detail. The **Op Amp Selection** tab is shown in Figure 1-7 in Section 1.3.4. This tab allows the user to specify which Microchip op amp is used in the active filter circuit.

5.2 RECOMMENDED OP AMPS

Five tables are provided in this tab as indicated in Figure 5-1:

1. The **Filter Characteristics** table lists the key filter design information as a reference.
2. The **Op Amp Design Constraints** and **Recommended Op Amp Parameters** tables show the recommended op amp specifications for the filter design.
3. The **Recommended Op Amps** table lists those op amps that come close to the recommended op amp specifications. The ideal op amp list at the top is included for comparing simulation results to textbook filter responses.
4. The **Other Op Amps** table lists other op amps that are not as close to the recommended op amp specifications. The specifications that do not meet recommendations are indicated in red.

Once the op amp has been selected, click the corresponding **Analyze** link, the Mindi™ Active Filter Designer & Simulator can generate and simulate the schematic of the filter circuit.

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Microchip Active Filter: Op Amp Selection

Op Amp Design Constraints

Power Supply Voltage (V$_{DD}$)	5 V
Max Output Voltage Swing (V$_{swing}$)	1 Vpp
THD Ceiling	-80 dBc

Recommended Op Amp Parameters

(?) Gain Bandwidth Product	100.0 kHz
(?) Slew Rate	0.00631 V/µs

Filter Characteristics

Selectivity	Lowpass
Approximation	Butterworth
Gain (G)	1 V/V
Cutoff Frequency (f$_p$)	1 kHz
Filter Order	5
Number of Stages	3

Recommended Op Amps

Op Amp Family	Gain Bandwidth Product (kHz)	Slew Rate (V/µs)	Min Stable Gain (V/V)	Vos Max (±µV)	Vdd Min (V)	Vdd Max (V)	Iq Max (µA/amplifier)	Rail-to-Rail Input	Rail-to-Rail Output	
Ideal Op Amp	1.0E30	1.0E30	1.0	0.0	0.0	1.0E30	0.0	Y	Y	Analyze
TC1034	60.0	0.035	1.0	500.0	1.8	5.5	6.0	Y	Y	Analyze
MCP606	155.0	0.08	1.0	250.0	2.5	5.5	18.7	N	Y	Analyze
MCP616	190.0	0.08	1.0	150.0	2.3	5.5	19.0	N	Y	Analyze
MCP6231	300.0	0.15	1.0	5000.0	1.8	5.5	20.0	Y	Y	Analyze
MCP6241	550.0	0.3	1.0	5000.0	1.8	5.5	50.0	Y	Y	Analyze
MCP6001	1000.0	0.6	1.0	4500.0	1.8	5.5	100.0	Y	Y	Analyze
MCP6271	2000.0	0.9	1.0	3000.0	2.0	5.5	170.0	Y	Y	Analyze
MCP601	2800.0	2.3	1.0	2000.0	2.7	5.5	230.0	N	Y	Analyze
MCP6281	5000.0	2.5	1.0	3000.0	2.2	5.5	450.0	Y	Y	Analyze
MCP6021	10000.0	7.0	1.0	250.0	2.5	5.5	1000.0	Y	Y	Analyze
MCP6291	10000.0	7.0	1.0	3000.0	2.4	5.5	1000.0	Y	Y	Analyze

(?) Other Op Amps [Hide]

Op Amp Family	Gain Bandwidth Product (kHz)	Slew Rate (V/µs)	Min Stable Gain (V/V)	Vos Max (±µV)	Vdd Min (V)	Vdd Max (V)	Iq Max (µA/amplifier)	Rail-to-Rail Input	Rail-to-Rail Output	
MCP6141	100.0	0.024	10.0	3000.0	1.4	5.5	0.6	Y	Y	Analyze
MCP6041	14.0	0.0030	1.0	3000.0	1.4	5.5	0.6	Y	Y	Analyze

FIGURE 5-1: *Op Amp Selection.*

5.3 OP AMP SPECIFICATIONS

The following specificitions are shown to help the designer choose the right op amp.

1. **Gain Bandwidth Product:**

   The product of op amp open-loop gain times the frequency at any point where the amplifier response is attenuating at a rate of -20 dB/decade of frequency.

2. **Slew Rate:**

   The maximum rate of change at the output of an op amp. Basically, says how fast the output can "follow" the input.

3. **Power Supply Voltage:**

   The acceptable supply voltage which allows the linear operation of an op amp.

4. **Quiescent Current (I$_q$):**

   The amount of current consumed by op amp when it is not performing any work (idle).

5. Rail-to-Rail Input/Output:

The op amp will operate correctly when its input/output is closely driven to either power rail under defined operating conditions. (N means *No* and Y means *Yes*).

A detailed discussion of the op amp selection algorithms and criteria are provided in **Appendix C. "Op Amp Selection"**.

NOTES:

Chapter 6. Analyze

6.1 INTRODUCTION

This chapter discusses the Mindi **Analyze** tab in greater detail. The **Analyze** tab is shown in Figure 1-8 in **Section 1.3.5**. This tab includes four buttons which are **Interactive Schematic**, **Reset Design**, **Design Summary** and **Downloads, Samples and More**.

6.2 INTERACTIVE SCHEMATIC

6.2.1 Schematic Viewer

The Mindi™ Active Filter Designer & Simulator automatically generates the full schematic view of the filter circuit with recommended component values. The individual components of the schematic can be modified, allowing users to further evaluate the design solution. Various Simulation operations can also be selected in order to analyze and evaluate the performance of the filter circuit. Detailed help on using the Schematic Viewer can be accessed via the **Help** button.
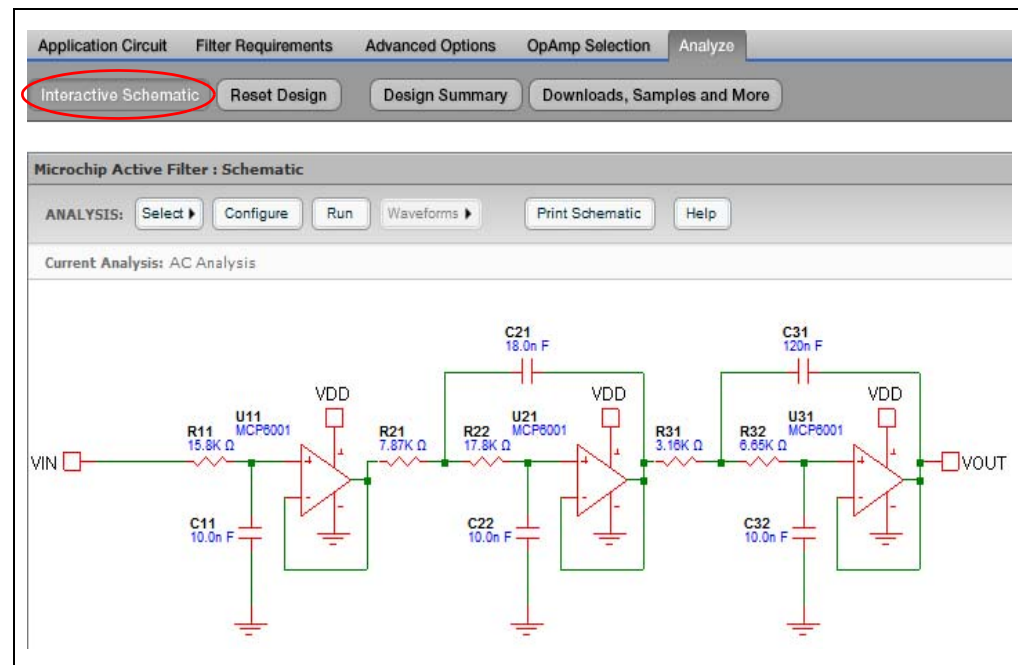

FIGURE 6-1:   *Schematic Viewer.*

6.2.2 Edit Component Value

The value of a component (resistor or capacitor) can be changed from its default value calculated by the Mindi™ Active Filter Designer & Simulator. Changing the component value only affects the component that is selected. To modify a component value, click on the component to access its attributes window, as shown in Figure 6-2 through Figure 6-5.

- Database Tab: Contains recommended parts to use with this circuit. Users can click on the header of any column to sort the database by that column. Columnwidths can also be adjusted by dragging the boundary between columns.
- Custom Tab: Enter custom parameter for this component.

The allowable range of capacitance is from 1.0 pF to 10 µF.

The allowable range of resistance is from 0Ω to 1.0 GΩ.

> **Note 1:** 0Ω , 1.0 GΩ, 1.0 pF, and 10 µF are intended for simulation purposes and is not practical in real applications.
>
> **2:** To remove parts from the schematic for simulation purposes, use 1.0 GΩ for shunt resistors and 0Ω for series resistor, and use 1.0 pF for shunt capacitors and 10 µF for series capacitors.

> **Note:** It is the user's responsibility to ensure the proper filter behavior when component values are changed.
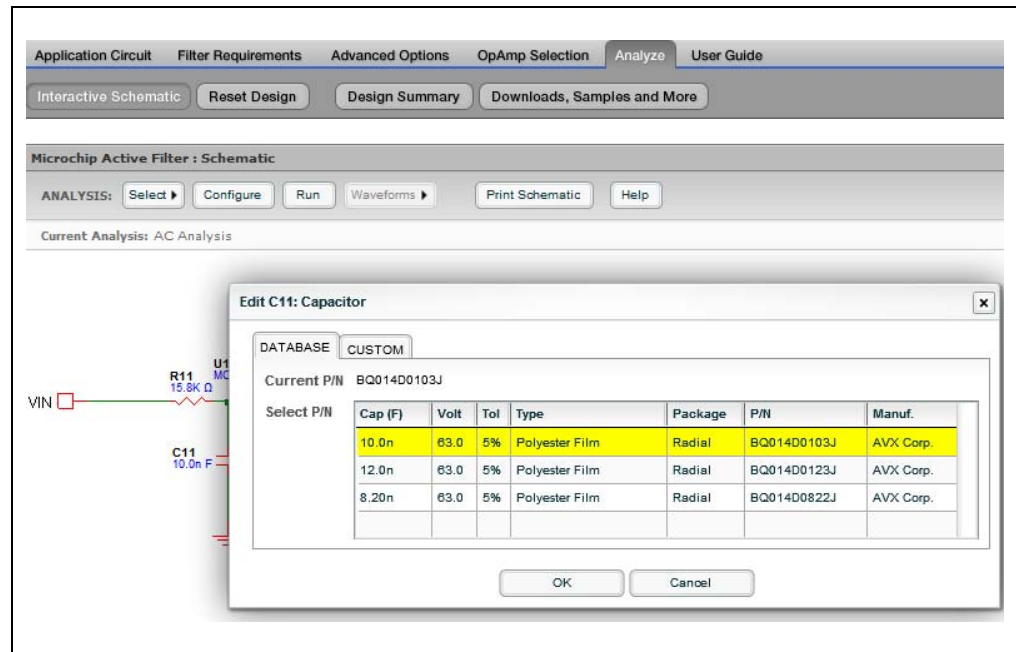
FIGURE 6-2: Edit Capacitor: Database Tab.
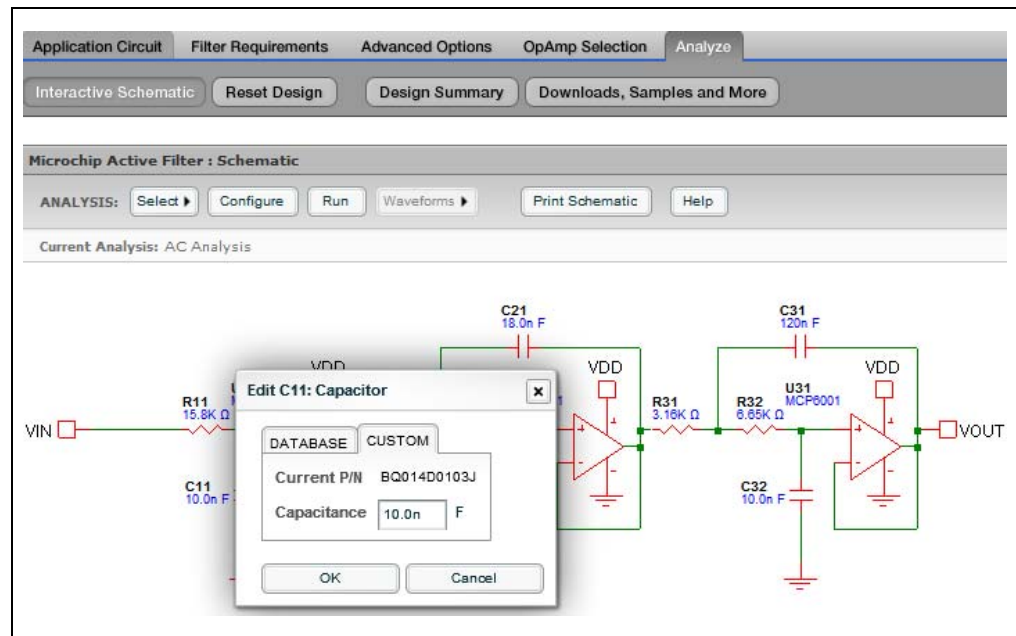
FIGURE 6-3: Edit Capacitor. Custom Tab.

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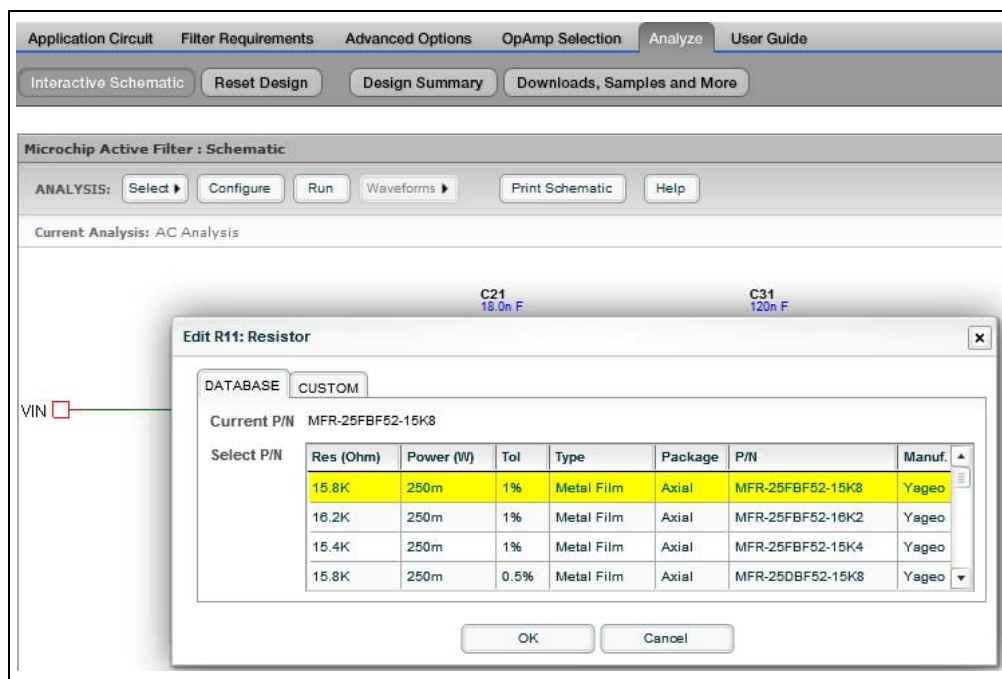
FIGURE 6-4: *Edit Resistor: Database Tab.*
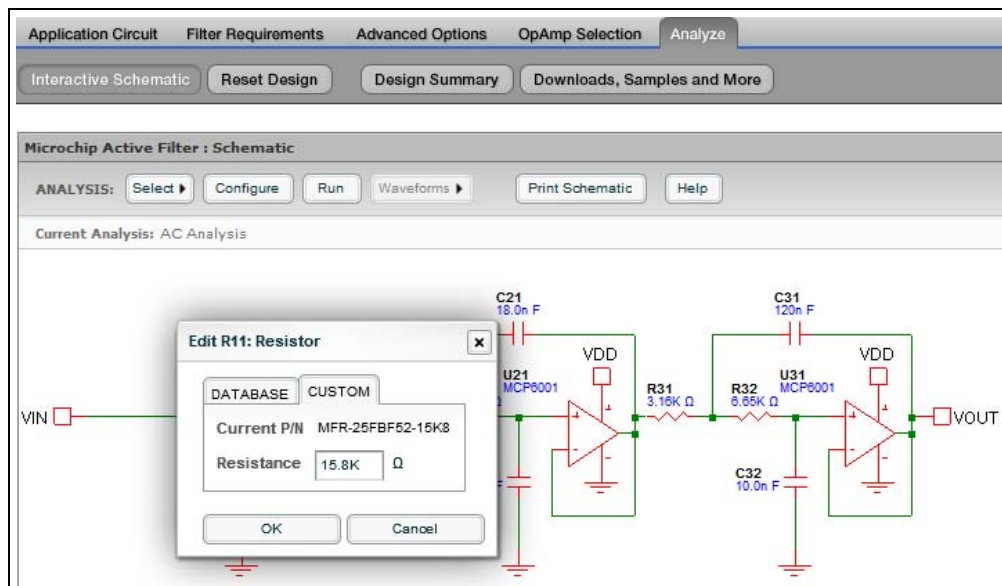
FIGURE 6-5: *Edit Resistor: Custom Tab.*

6.2.3   Edit Op Amp

The type of op amp can also be changed. Changing the type of op amp only affects the op amp that is selected as shown in Figure 6-6. To change the op amp, move the mouse the appropriate op amp, then left-click the mouse. A dialog box will appear and the user can select the type of op amp and click **OK**.

> **Note:**   It is user's responsibility to ensure the proper filter behavior when the op amp is changed.

FIGURE 6-6:   *Edit Op Amp.*

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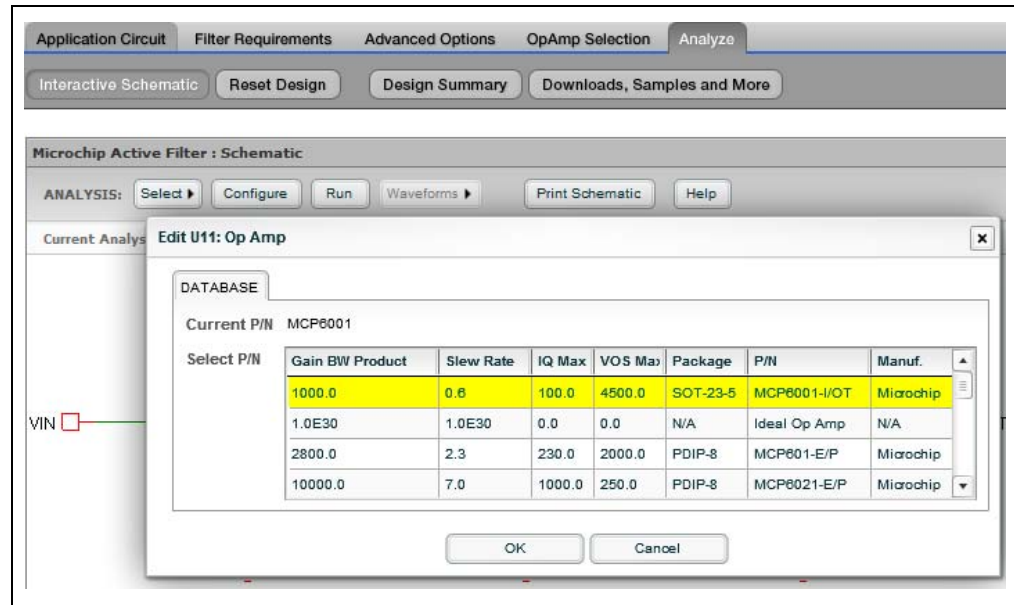
6.2.4 Select Analysis

Two types of analysis can be selected in the **Select** drop-down menu: **AC Analysis** and **Transient Analysis**.

- **AC Analysis** or frequency-domain analysis is used mainly in connection with amplifiers and filters, where the frequency response is of interest. The AC simulation is usually based on a sweep over a range of frequencies. In the real world, this kind of measurement would be made with a network analyzer
- **Transient Analysis** or time-domain analysis most closely simulates the phenomena seen in the real circuit by means of an oscilloscope. A simulation consists usually of a time sweep starting at t = 0

6.2.4.1 AC ANALYSIS

AC Analysis can be chosen from the **Select** drop-down menu.
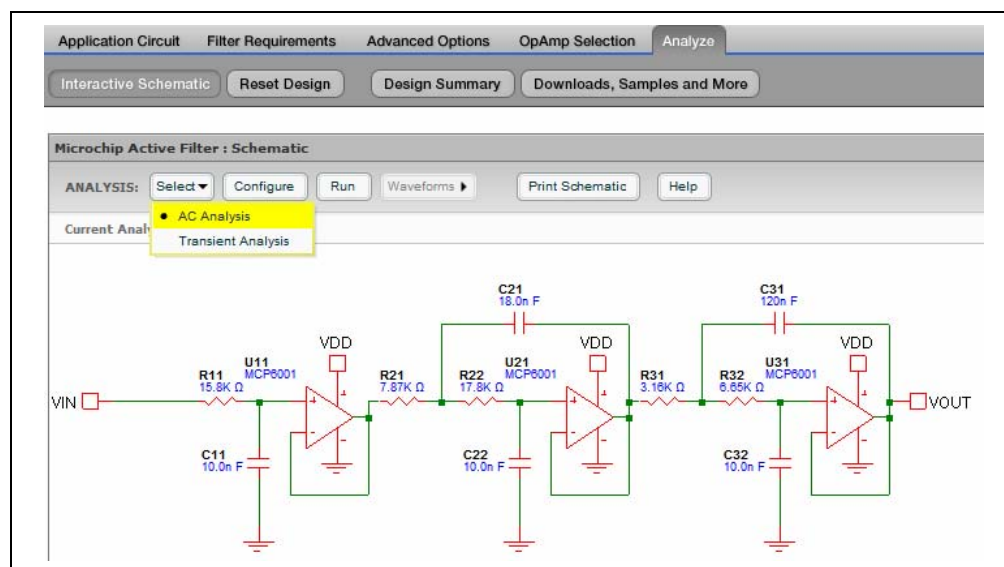
FIGURE 6-7:   *Select AC Analysis.*

6.2.4.1.1 Configure Simulation

The Configure Simulation text box allows users to set up the start frequency, stop frequency and resolution for AC Analysis.

- The allowable range of start and stop frequencies: 0.001 Hz to 100 MHz
- The allowable range of resolution: 1 point/decade to 10000 points/decade
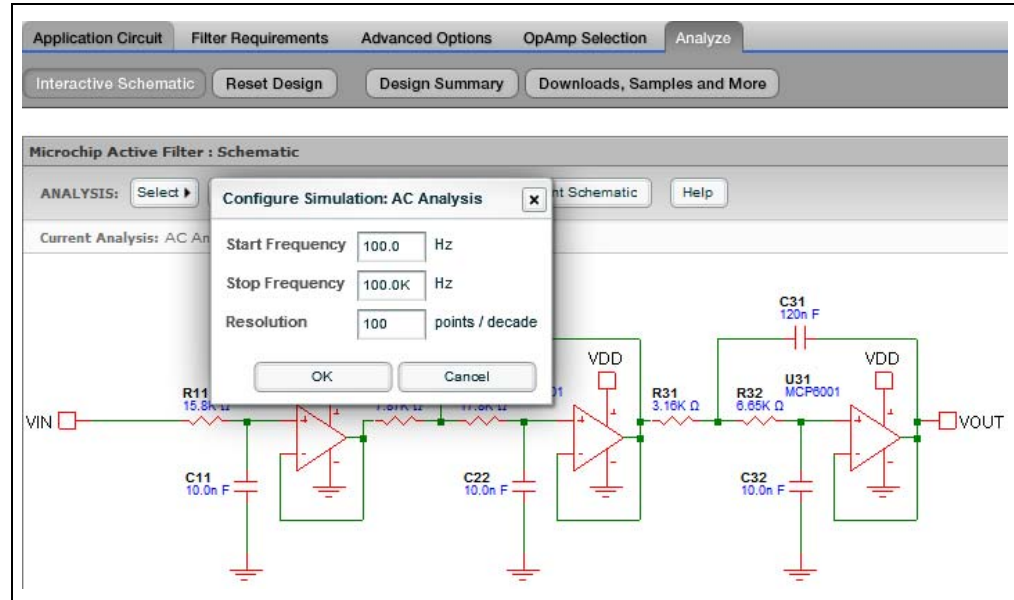
FIGURE 6-8: Configure Simulation: AC Analysis.

6.2.4.2 RUN SIMULATION

Click the **Run** button to start the simulation. A Simulation Complete dialog box pops up when the simulation is complete. Click the **OK** button to view the waveforms. (See Figure 6-9 and Figure 6-10).
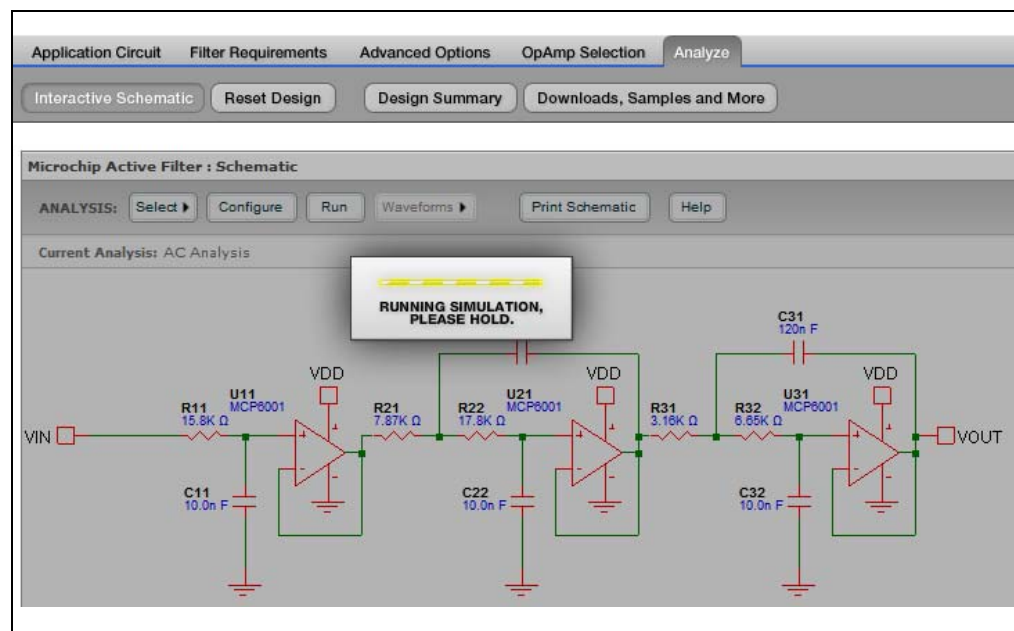
FIGURE 6-9: Run Simulation.
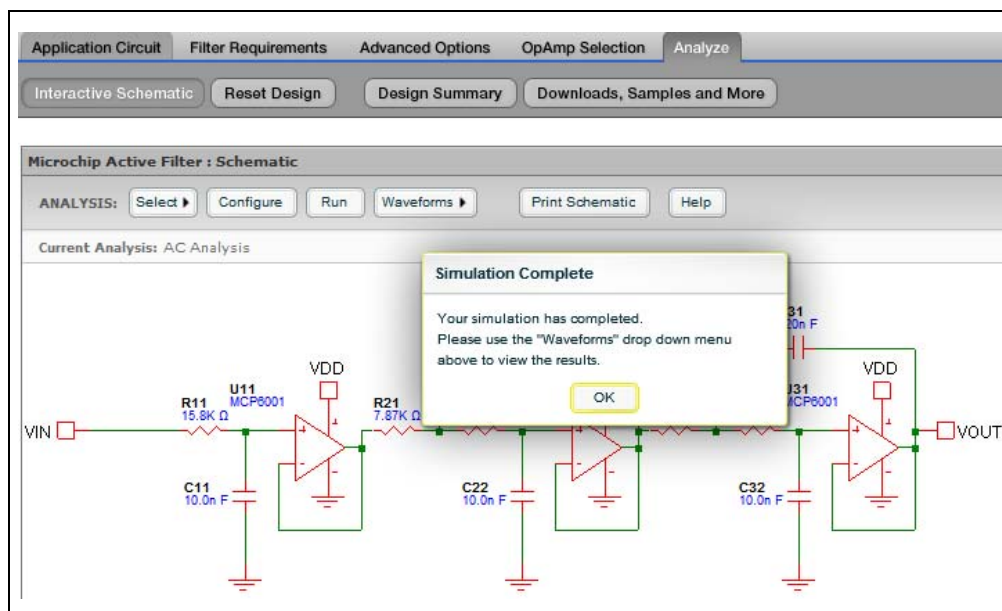
FIGURE 6-10: *Simulation Complete.*

6.2.4.3   VIEW WAVEFORMS

The **Waveforms** drop-down menu includes two kinds of waveforms:

• Magnitude - Group Delay
• Magnitude - Phase

> **Note 1:** Group Delay is a measure of frequency domain response of the active filter. It focuses on the relative time delay among sine waves of nearly equal frequency.
>
> **2:** Magnitude means the magnitude response of the filter transfer function, which is the overall filter gain.
>
> **3:** Phase means the phase response of the filter transfer function, which is the overall filter phase shift.
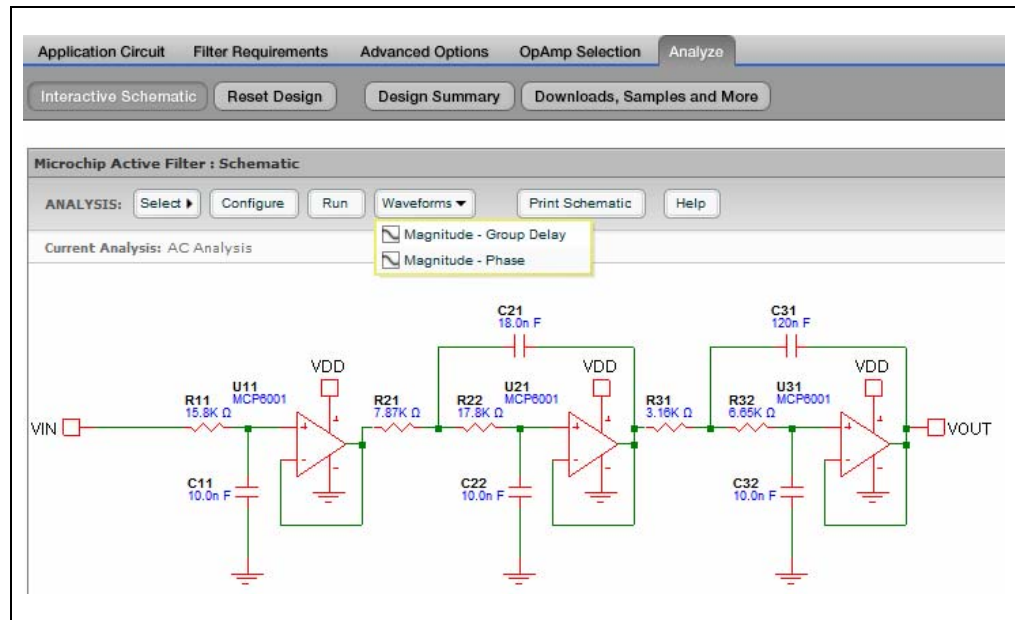
FIGURE 6-11:   *View Waveforms.*

6.2.4.3.1   Magnitude - Group Delay

Magnitude - Group Delay can be chosen in the **View Waveforms** drop-down menu. The y-axes display the magnitude of the overall filter gain function and the group delay of the filter. The x-axis displays the frequency.

Two sets of simulation data are shown: the response using an ideal op amp model, and the response using the selected op amp's model.
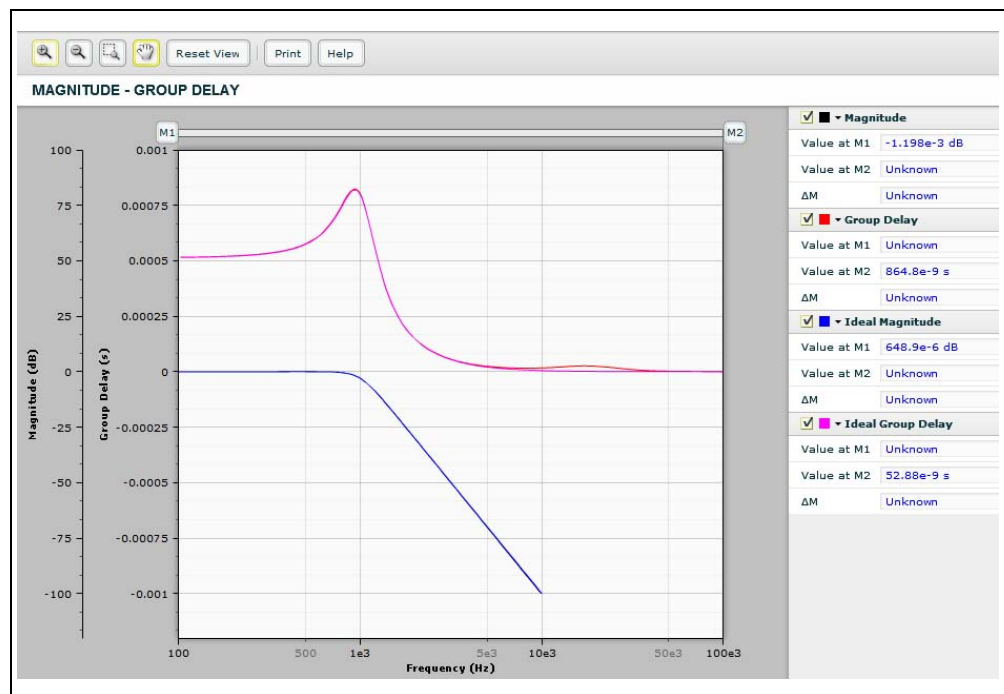
FIGURE 6-12:   *Magnitude - Group Delay Waveform.*

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M1 or M2 can be moved horizontally to a desired frequency value. Or, double click M1 or M2 and a dialog box will appear and the user can input a frequency value to force the marker to that value. (See Figure 6-13).

After the frequency value is set for M1 and M2, the values of magnitude, group delay, ideal magnitude and ideal group delay will be updated. When the checkbox is not selected, the filter response will not display the related waveforms.

Also worth noting are the buttons in the upper left hand corner of the window (zoom in, zoom out, magnifier, hand tool, reset view and print) that allow the waveform view to be changed or printed. Detailed help can be accessed via the **Help** button.
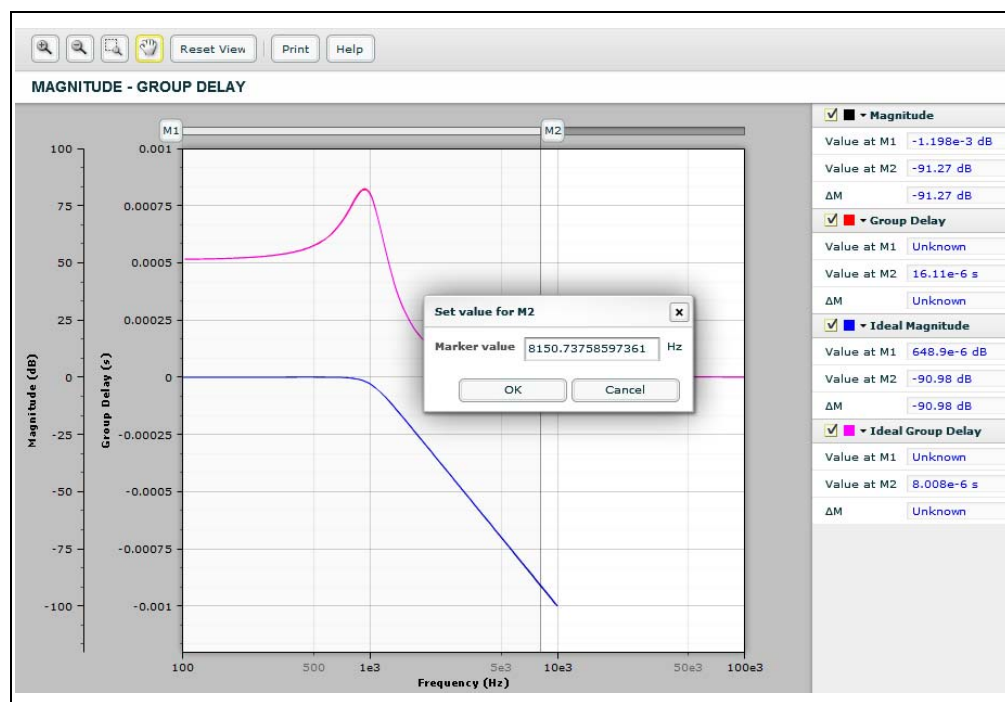
FIGURE 6-13: Set Value for Markers.

6.2.4.3.2 Magnitude - Phase

Magnitude - Phase can be chosen in the **Waveforms** drop-down menu. The y-axes displays the magnitude of overall filter gain and the phase shift between V_{OUT} and V_{IN}. The x-axis displays the frequency.

Two sets of simulation data are shown: the response using an ideal op amp model, and the response using the selected op amp's model.
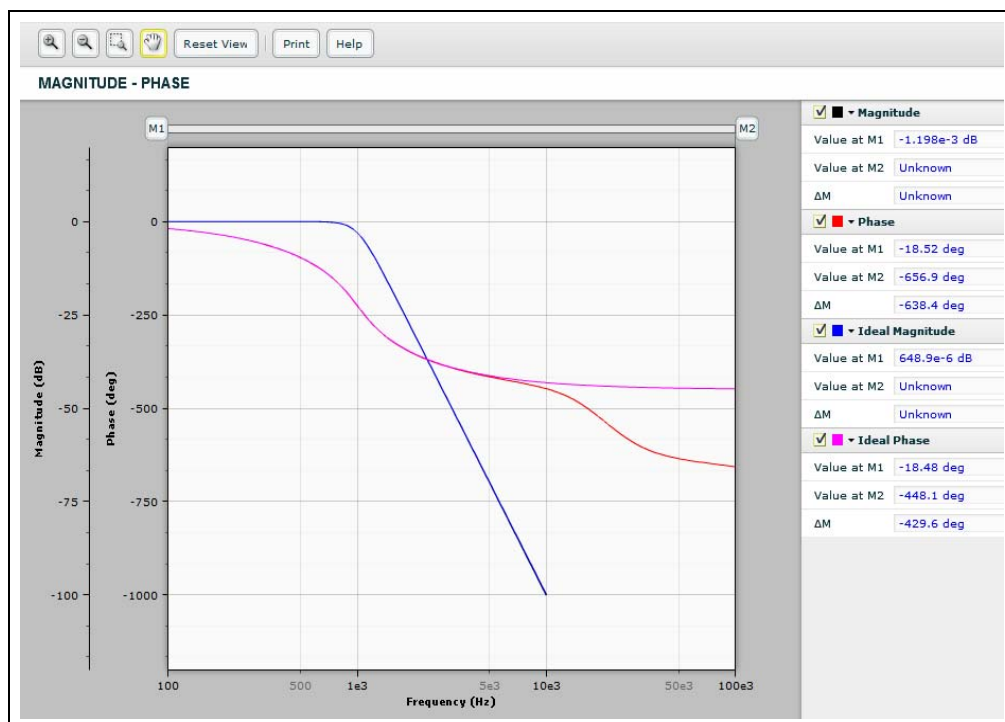
FIGURE 6-14: *Magnitude - Phase Waveform.*

Magnitude - Phase waveform has the same user interface as Magnitude - Group Delay waveform. (**Section 6.2.4.3.1**)

6.2.4.4   TRANSIENT ANALYSIS

Transient Analysis can be chosen from the **Select** drop-down menu.
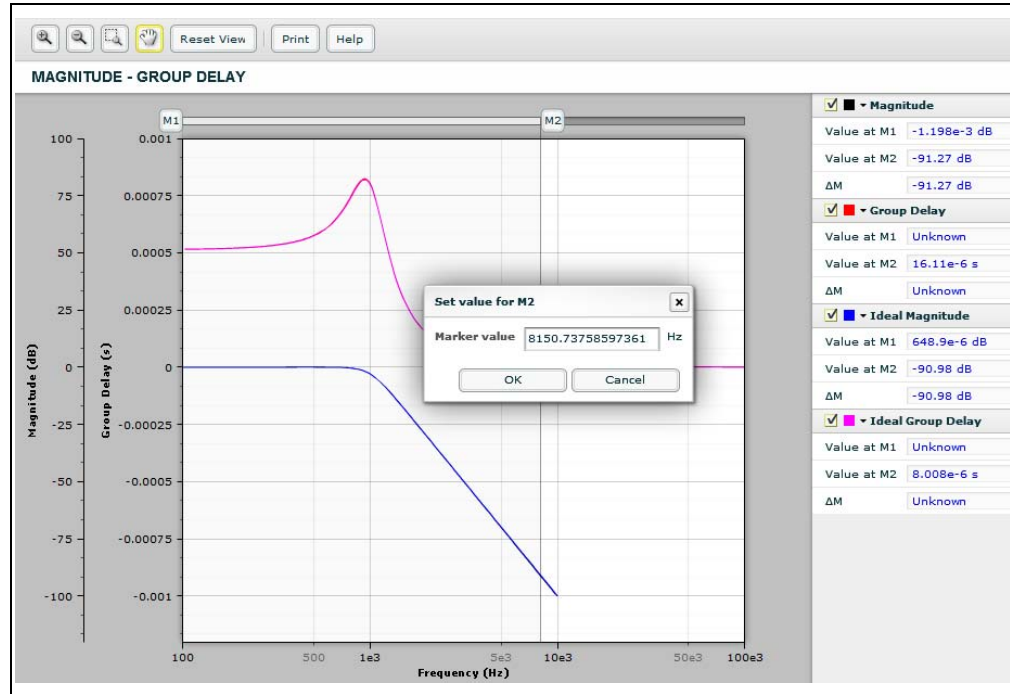
FIGURE 6-15:   *Transient Analysis.*

6.2.4.5   CONFIGURE SIMULATION

The Configure Simulation text boxes allows the user to set up the start time and stop time for the Transient Analysis. The allowable range of Stop Time: 1 us to 100s.
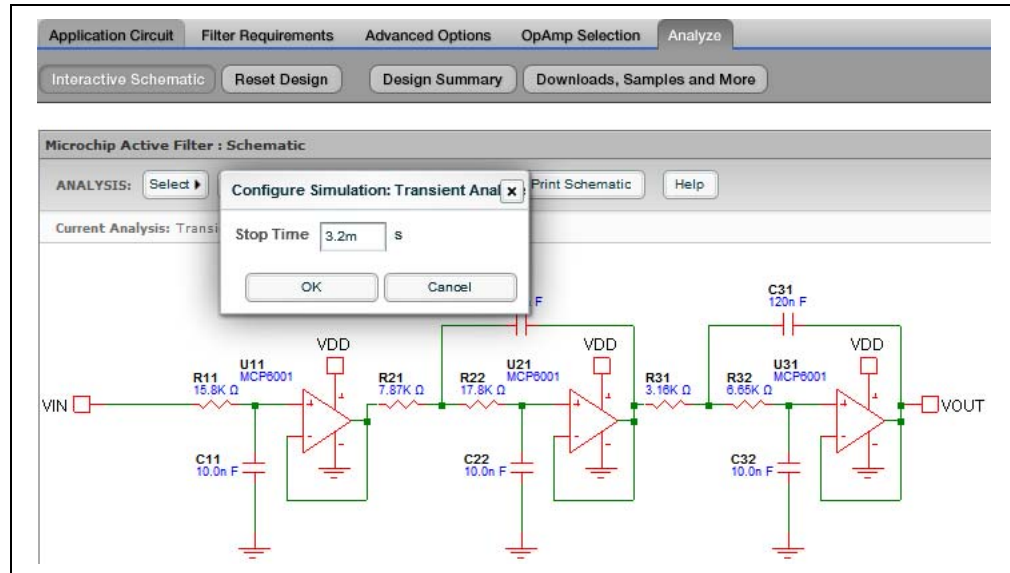
FIGURE 6-16:   *Configure Simulation: Transient Analysis.*

6.2.4.6   RUN SIMULATION

Click the **Run** button to start the simulation. A Simulation Complete dialog pops up when the simulation is complete. Click the **OK** button to view the waveforms.
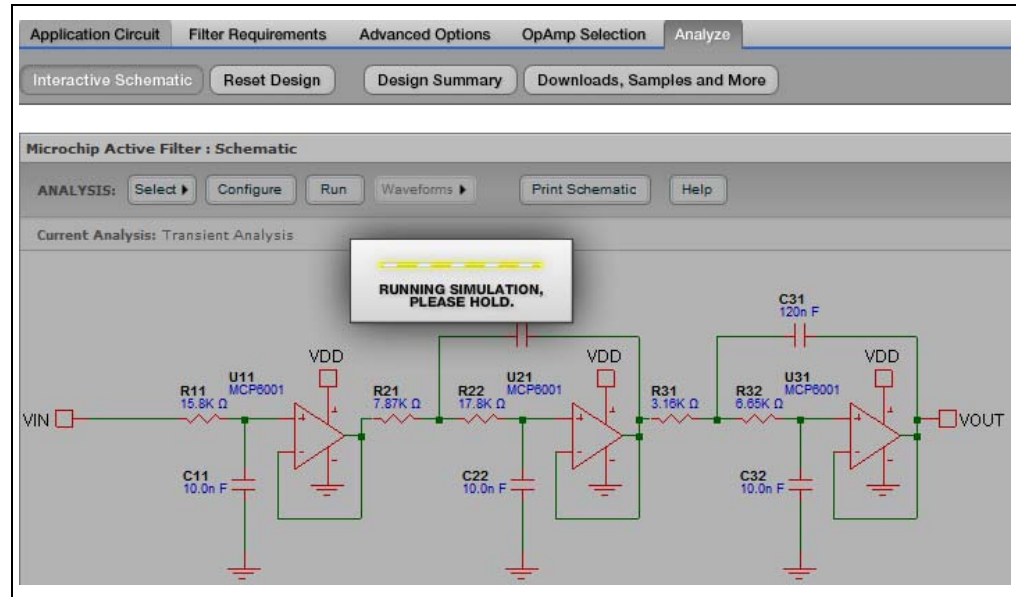
FIGURE 6-17:   Run imulation.
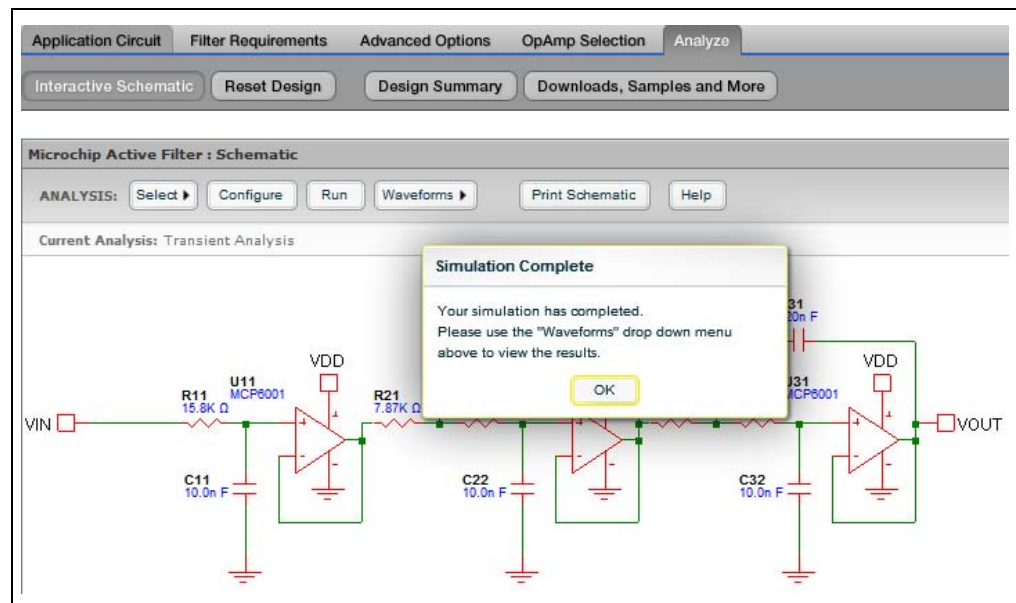
FIGURE 6-18:   Simulation Complete.

6.2.4.7   VIEW WAVEFORMS

Click the **Waveform** drop-down menu and select **Step Response**.
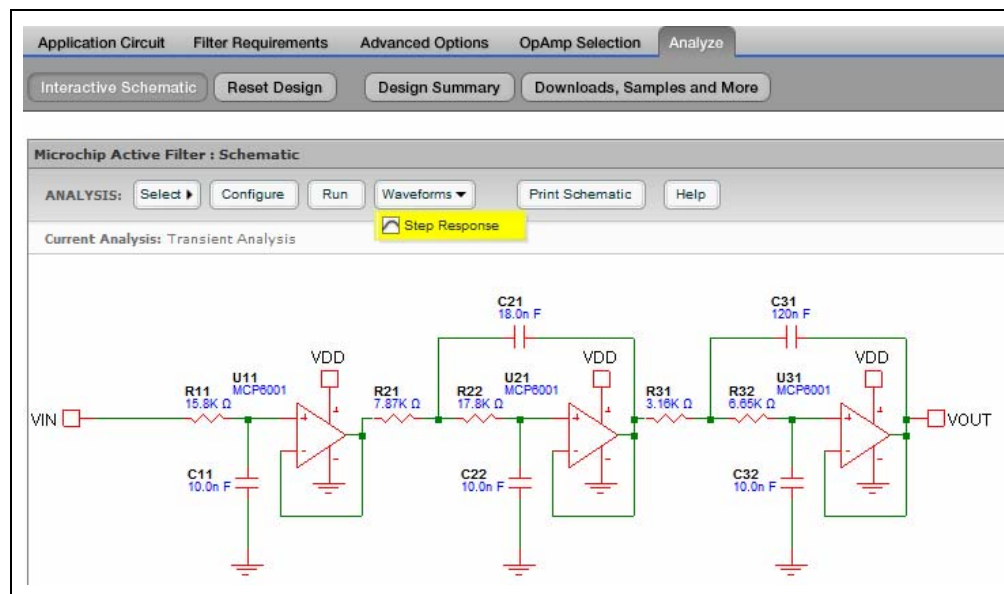
FIGURE 6-19: *Waveforms.*

6.2.4.7.1   Step Response

The y-axis displays the voltage of the step response. The x-axis displays the time.
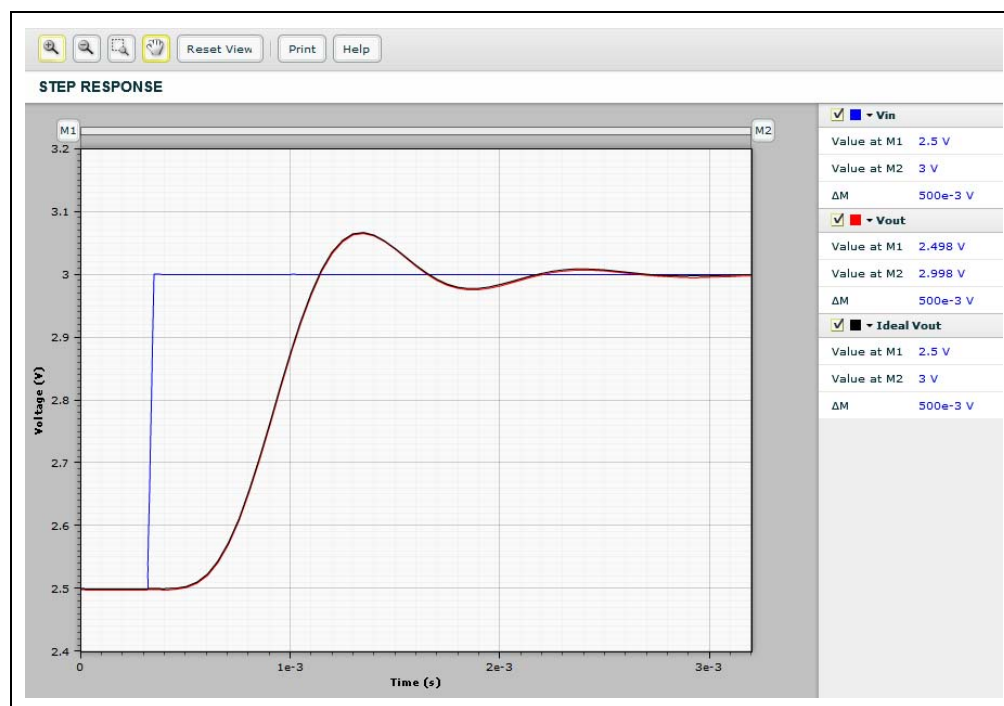
FIGURE 6-20: *Step Response.*

Step Response waveform has the same user interface as Magnitude-Group Delay waveform. For more information, refer to **Section 6.2.4.3.1**.

6.3 RESET DESIGN

Click the **Reset Design** button to restore schematic to the original application circuit that was generated from the user's inputs on the Input Requirements page. This action will reset all component values back to their default values.
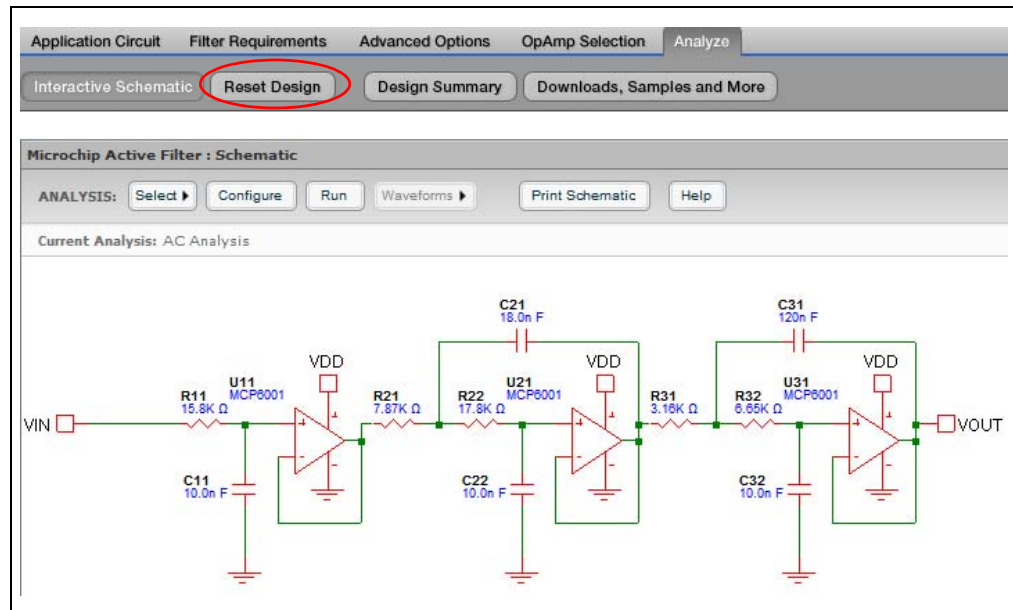
FIGURE 6-21: Reset Design.

6.4 DESIGN SUMMARY

Click the **Design Summary** button to display or print a single page summary of the application circuit solution, including Input Requirements, Schematic, Simulation Waveforms and Bill of materials (BOM).
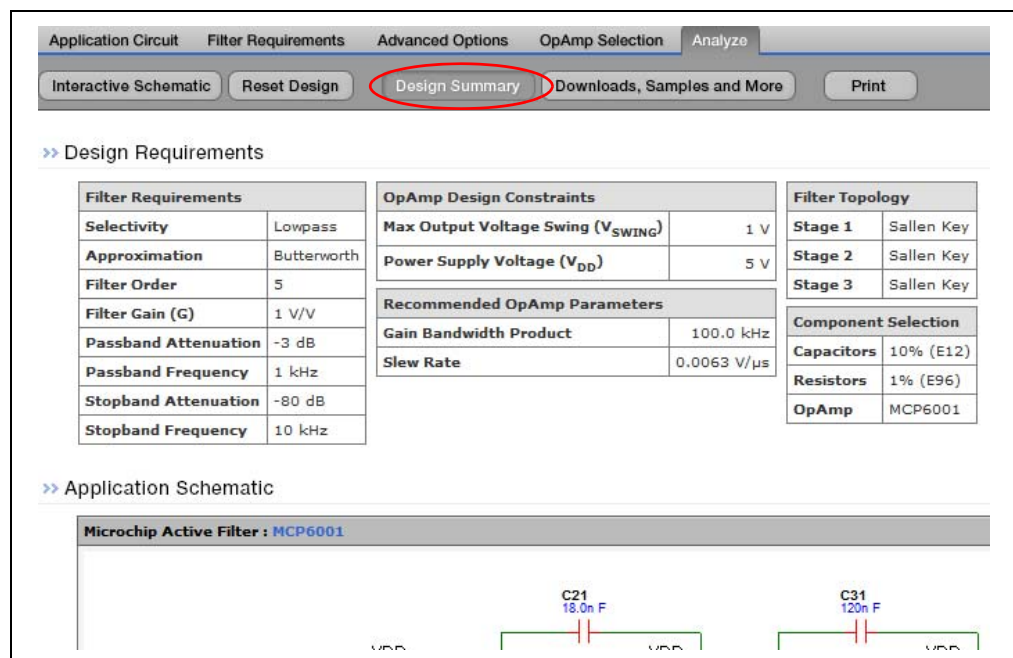
FIGURE 6-22: Design Summary.

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6.5   DOWNLOADS, SAMPLES AND MORE

Click the **Downloads, Sample and More** button to download tools and materials which includ the schematic, BOM, filter SPICE model and Mindi™ offline version. Users also can directly link to Microchip's device web pages, sample/order a device, order an evaluation board.
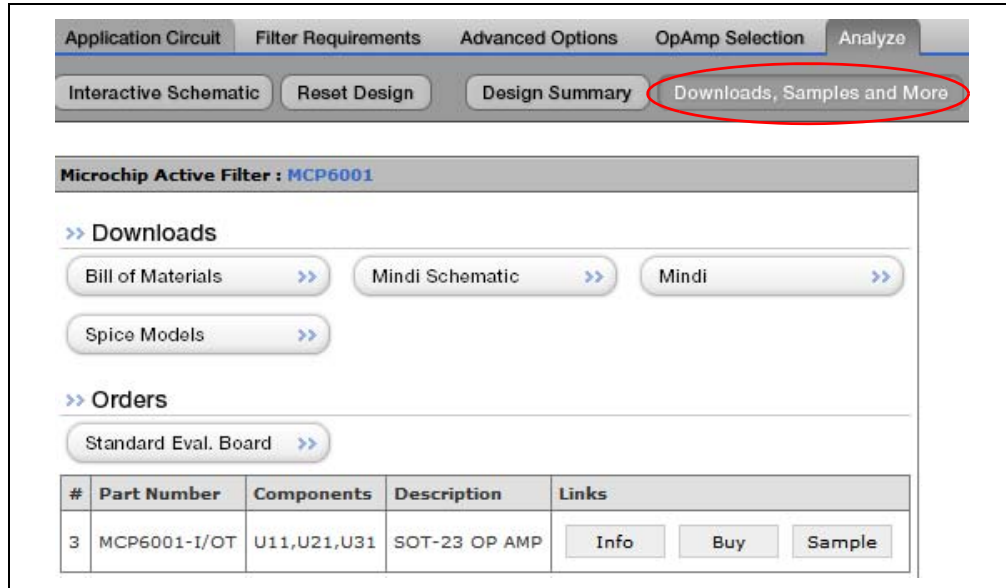
FIGURE 6-23:   *Downloads, Samples and More.*

Appendix A. Filter Magnitude Templates

A.1   INTRODUCTION

This chapter provides additional information on the Low-pass, Band-pass, and High-pass filter templates used in the Mindi™ Active Filter Designer & Simulator.

A.2   FILTER MAGNITUDE RESPONSES

A.2.1   LOW-PASS FILTER MAGNITUDE RESPONSE

The magnitude response of Low-pass filters is shown in Figure A-1.

FIGURE A-1:   *Low-pass Filter Template.*

The nominal filter response is required to stay within the three regions: Pass-band, Transition band and Stop-band. The relevant parameters for the three regions and the controlling inequalities are:

• Pass-band

   $0 \leq f \leq f_P$

   $0 \leq A \leq A_P$

   Where:

   H_M =   Maximum Transfer Function Magnitude (dB)

   A   =   Attenuation (relative to H_M) (dB)

   A_P *   =   Pass-band Ripple/Max. Attenuation (dB)

   f_P *   =   Pass-band Frequency (Hz)

   BW   =   -3 dB Bandwidth

   * sometimes referred to as cut-off

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- Transition Band

  $f_P \leq f \leq f_S$

  $A_P \leq A \leq A_S$

  Where:

f_P	=	Pass-band Frequency (Hz)
f_S	=	Stop-band Edge Frequency (Hz)
A_P	=	Pass-band Ripple/Max. Attenuation (dB)
A	=	Attenuation (relative to HM) (dB)
A_S	=	Minimum Stop-band Attenuation (dB)

- Stop-band

  $f_S \leq f$

  $A_S \leq A$

  Where:

f_S	=	Stop-band Edge Frequency (Hz)
A_S	=	Minimum Stop-band Attenuation (dB)
A	=	Attenuation (relative to H_M) (dB)

The gain parameter (G) in the Mindi™ Active Filter Designer & Simulator corresponds to the DC gain (for good sensitivity performance). Thus:

G	=	HM;	Bessel, Butterworth and Chebychev (n = 1, 3, 5, 7)
G	=	HM - AP;	Chebychev (n = 2, 4, 6, 8)

The limits that Mindi™ Active Filter Designer & Simulator enforces on these Low-pass parameters are:

$0.1 \text{ Hz} \leq f_P < f_S \leq 1.0 \text{ MHz}$

$A_P = 3.0 \text{ dB}$, Bessel Filters

$0.01 \text{ dB} \leq A_P \leq 3.0 \text{ dB}$, Butterworth and Chebychev

$10 \text{ dB} \leq A_S \leq 100 \text{ dB}$

$1 \text{ V/V} \leq G \leq 10 \text{ V/V}$, (0 dB to 20 dB)

Note: The current version of Mindi requires negative values for the attenuations (e.g., A_P and A_S). For example, A_P = 3 dB is entered as **-3** in the Attenuation text box. A_S = 80 dB is entered as **-80** in the Attenuation text box.

A.2.2   BAND-PASS FILTER MAGNITUDE RESPONSE

The magnitude response of Band-pass filters is shown in Figure A-2.
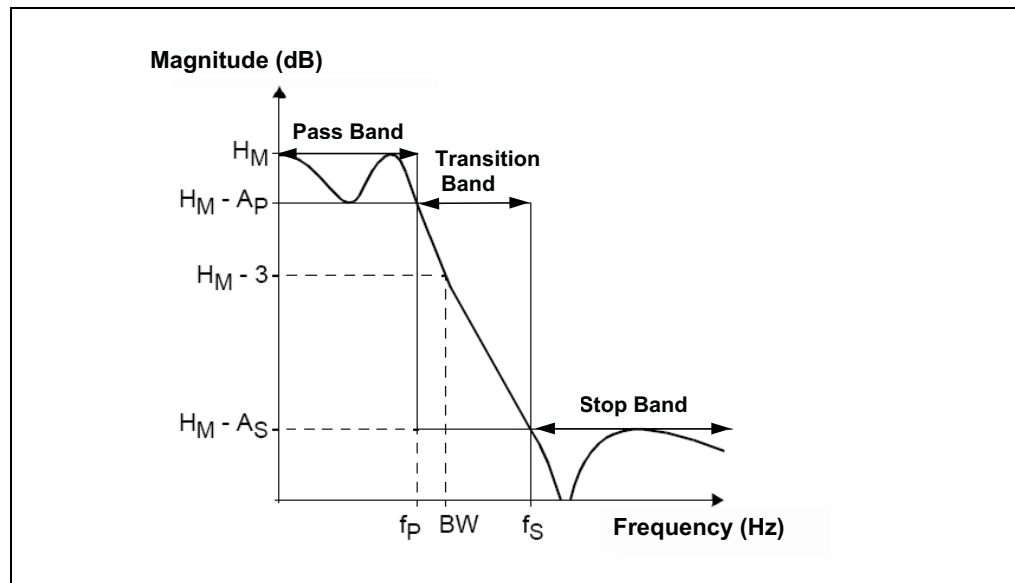

FIGURE A-2:   *Band-pass Filter Template.*

The nominal filter response is required to stay within the five regions shown
(Pass-band, two transition bands and two Stop-bands). The relevant parameters for the
three regions and the controlling inequalities are:

* Lower Stop-band

    $f \le f_{SL}$

    $A_S \le A$

    Where:

f_{SL}	=	Lower Stop-band Edge Frequency (Hz)
A_S	=	Minimum Stop-band Attenuation (dB)
A	=	Attenuation (relative to H_M) (dB)
H_M	=	Maximum Transfer Function Magnitude (dB)

* Lower Transition Band

    $f_{SL} < f < f_{PL}$

    $A_P < A < A_S$

    Where:

f_{SL}	=	Lower Stop-band Edge Frequency (Hz)
f_{PL} *	=	Lower Pass-band Frequency (Hz)
A_P	=	Pass-band Ripple/Max. Attenuation (dB)
A	=	Attenuation (relative to H_M) (dB)
A_S	=	Minimum Stop-band Attenuation (dB)

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- Pass-band

  $f_{PL} \leq f \leq f_{PU}$

  $0 \leq A \leq A_P$

  Where:

f_{PL} *	=	Lower Pass-band Frequency (Hz)
f_{PU} *		Upper Pass-band Frequency (Hz)
A	=	Attenuation (relative to H_M) (dB)
A_P *	=	Pass-band Ripple/Max. Attenuation (dB)

  * sometimes referred to as cut-off

- Upper Transition Band

  $f_{PU} < f < f_{SU}$

  $A_P < A < A_S$

  Where:

f_{PU} *	=	Upper Pass-band Frequency (Hz)
f_{SU}	=	Upper Stop-band Edge Frequency (Hz)
A_P *	=	Pass-band Ripple/Max. Attenuation (dB)
A_S	=	Min. Stop-band Attenuation (dB)

  * sometimes referred to as cut-off

- Upper Stop-Band

  $f_{SU} \leq f$

  $A_S \leq A$

  Where:

f_{SU}	=	Upper Stop-band Edge Frequency (Hz)
A_S	=	Min. Stop-band Attenuation (dB)

The gain parameter (G) in the Mindi™ Active Filter Designer & Simulator corresponds to the mid-band gain (for ease of implementation), where:

f_0	=	Mid-band Frequency
	=	$(f_{PL} f_{PU})1/2$

Thus,

G	=	H_M;	Bessel, Butterworth and Chebychev (n = 2, 6)
G	=	$H_M - A_P$;	Chebychev (n = 4, 8)

The limits that Mindi™ Active Filter Designer & Simulator enforces on these band-pass parameters are:

$0.1\ Hz \leq f_{SL} < f_{PL} < f_{PU} < f_{SU} \leq 1.0\ MHz$

$1.2210 \leq f_{PU}/f_{PL} \leq 5.8284$

$0.01\ dB \leq A_P \leq 3.0\ dB$

$10\ dB \leq A_S \leq 100\ dB$

$1\ V/V \leq G \leq 10\ V/V,\ (0\ dB\ to\ 20\ dB)$

The current version of Mindi requires negative values for the attenuations (e.g., A_P and A_S). For example, A_P = 3 dB is entered as **-3** in the Attenuation text box. A_S = 80 dB is entered as **-80** in the Attenuation text box.

A.2.3   HIGH-PASS FILTER MAGNITUDE RESPONSE

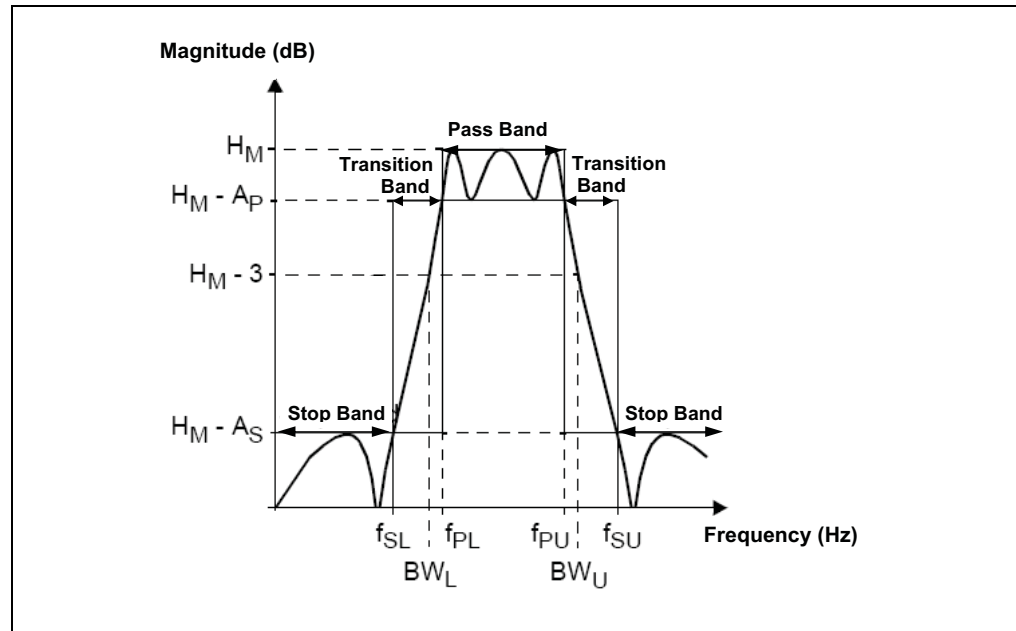The magnitude response of High-pass filters is shown in Figure A-3.
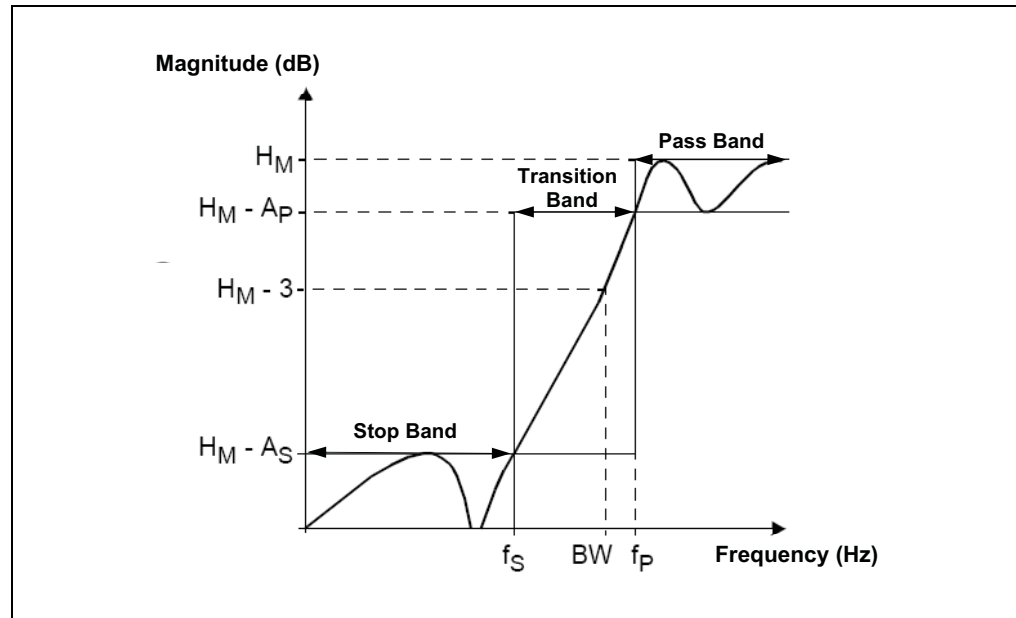
FIGURE A-3:   *High-pass Filter Template.*

The nominal filter response is required to stay within the three regions shown (Pass-band, Transition Band and Stop-band). The relevant parameters for the three regions and the controlling inequalities are:

- Pass-band

    $f_P \leq f$

    $0 \leq A \leq A_P$

    Where:

f_P *	=	Pass-band Frequency (Hz)
BW	=	-3 dB Bandwidth
H_M	=	Maximum Transfer Function Magnitude (dB)
A	=	Attenuation (relative to H_M) (dB)
A_P *	=	Pass-band Ripple/Max. Attenuation (dB)

    * sometimes referred to as cutoff

- Transition Band

    $f_S < f < f_P$

    $A_P < A < A_S$

    Where:

f_S	=	Stop-band Edge Frequency (Hz)
f_P *	=	Pass-band Frequency (Hz)
A_P *	=	Pass-band Ripple/Max. Attenuation (dB)
A	=	Attenuation (relative to H_M) (dB)
A_S	=	Minimum Stop-band Attenuation (dB)

    * sometimes referred to as cutoff

- Stop-band

    $f \leq f_S$

    $A_S \leq A$

    Where

f_S	=	Stop-band Edge Frequency (Hz)
A_S	=	Minimum Stop-band Attenuation (dB)
A	=	Attenuation (relative to H_M) (dB)

The gain parameter (G) in the Mindi™ Active Filter Designer & Simulator corresponds to the high frequency gain (at "infinity" for good sensitivity performance). Thus:

G	= H_M;	Bessel, Butterworth and Chebychev (n = 1, 3, 5, 7)
G	= $H_M - A_P$;	Chebychev (n = 2, 4, 6, 8)

The limits that the Mindi™ Active Filter Designer & Simulator enforces on these High-pass parameters are:

$0.1 \text{ Hz } \leq f_S < f_P \leq 1.0 \text{ MHz}$

$0.01 \text{ dB } \leq A_P \leq 3.0 \text{ dB}$

$10 \text{ dB } \leq A_S \leq 100 \text{ dB}$

$1 \text{ V/V } \leq G \leq 10 \text{ V/V, (0 dB to 20 dB)}$

> **Note:** The current version of Mindi requires negative values for the attenuations (e.g., A_P and A_S). For example, A_P = 3 dB is entered as **-3** in the Attenuation text box. A_S = 80 dB is entered as **-80** in the Attenuation text box.

Appendix B. Low-Pass Filter Approximations

B.1   INTRODUCTION

The Mindi™ Active Filter Designer & Simulator supports three most commonly used filter approximations: Butterworth, Bessel and Chebyshev. The tool allows the design of Low-pass filters with Chebychev, Bessel or Butterworth. It also allows design Band-pass and High-pass filters with Chebychev and Butterworth responses.

Let's choose the Low-pass filter with 6th order as an example and discuss the difference between these approximations.

B.1.1   Butterworth Low-pass Approximation

It has the following characteristics:

- Maximally-flat-magnitude-response filters, optimized for gain flatness in the Pass-band. Above the pass-band frequency the attenuation is -20 dB/decade/order (Figure B-1)
- Moderate group delay response (Figure B-2)
- Moderate overshoot and ringing in the step response (Figure B-3)

The magnitude - phase response of the 6th order Low-pass filters with Butterworth approximation is shown in Figure B-1.
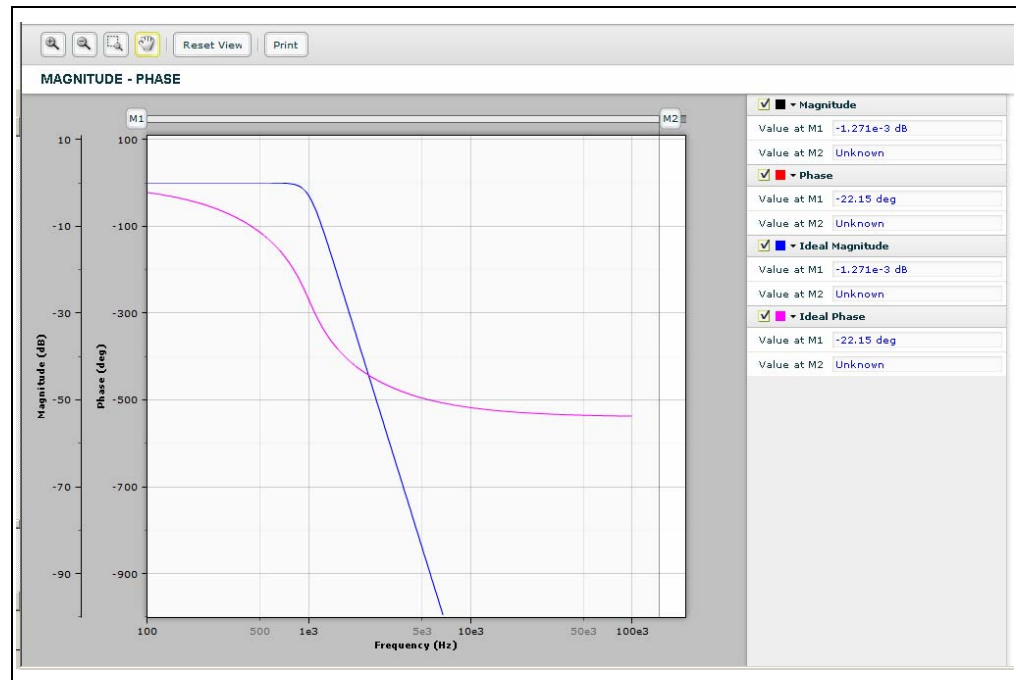

FIGURE B-1:   Magnitude - Phase Response.

The magnitude - group delay response of the 6th order Low-pass filters with Butterworth approximation is shown in Figure B-2.
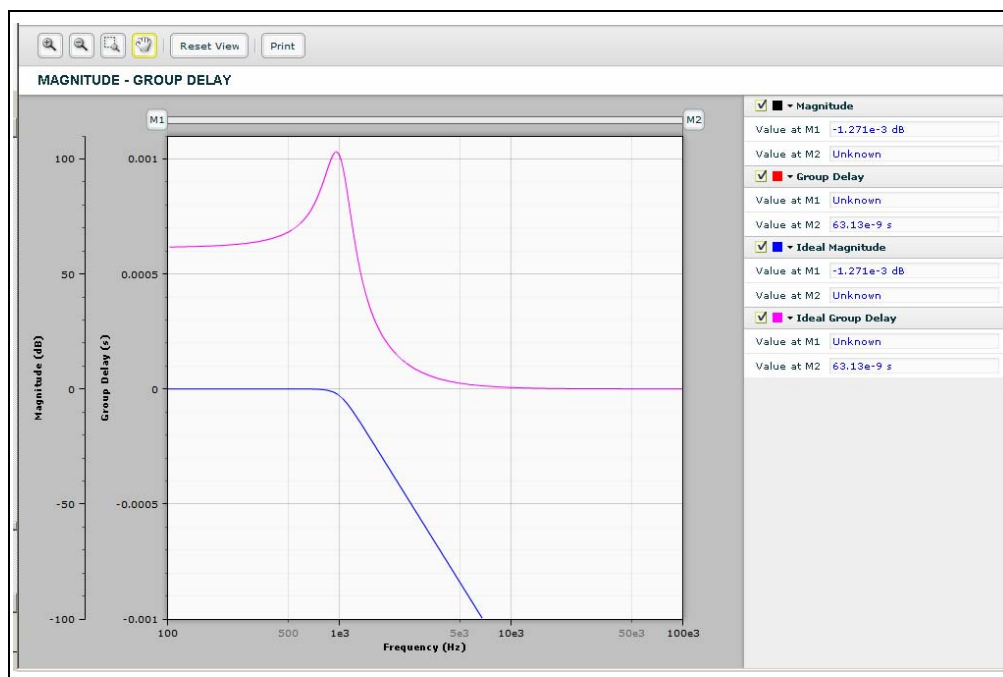
FIGURE B-2: *Magnitude - Group Delay Response*

The step response of the 6th order Low-pass filters with Butterworth approximation is shown in Figure B-3.
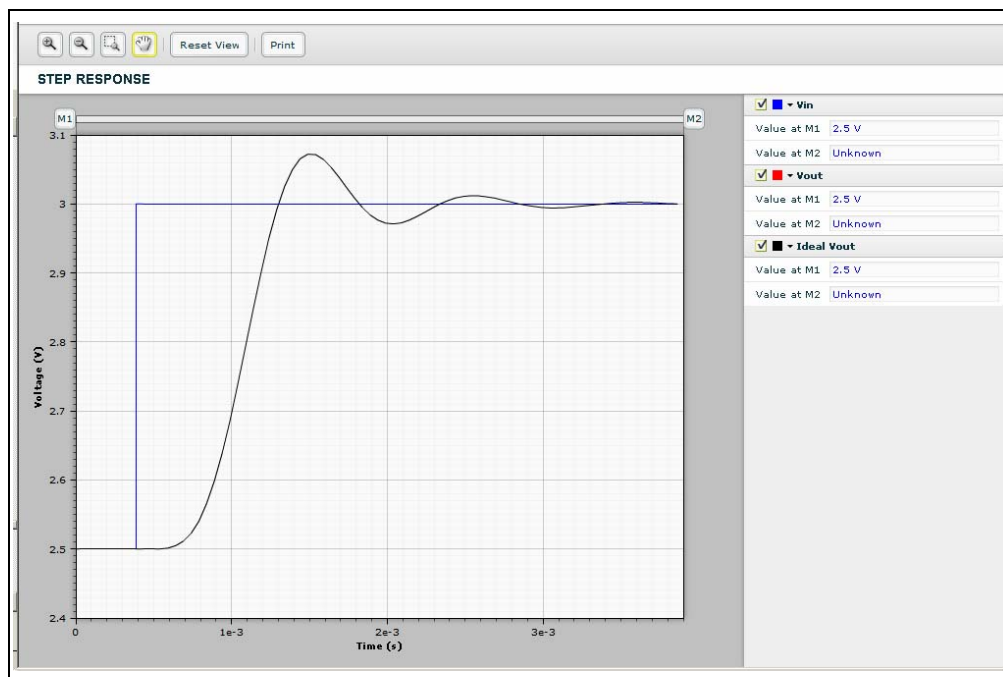
FIGURE B-3: *Step Response.*

B.1.2   Bessel Low-pass Approximation

It has the following Low-pass characteristics:

- Moderate magnitude response and the attenuation above pass-band frequency which is not as steep as a Butterworth response of the same order. (Figure B-4)
- Maximally flat group delay or linear phase response (Figure B-5)
- Minimal overshoot and ringing in the step response (Figure B-6)

The magnitude - phase response of the 6th order Low-pass filters with Bessel approximation is shown in Figure B-4.

FIGURE B-4:   *Magnitude - Phase Response with Bessel Approximation.*

The magnitude - phase response of the 6th order Low-pass filters with Bessel approximation is shown in Figure B-5.
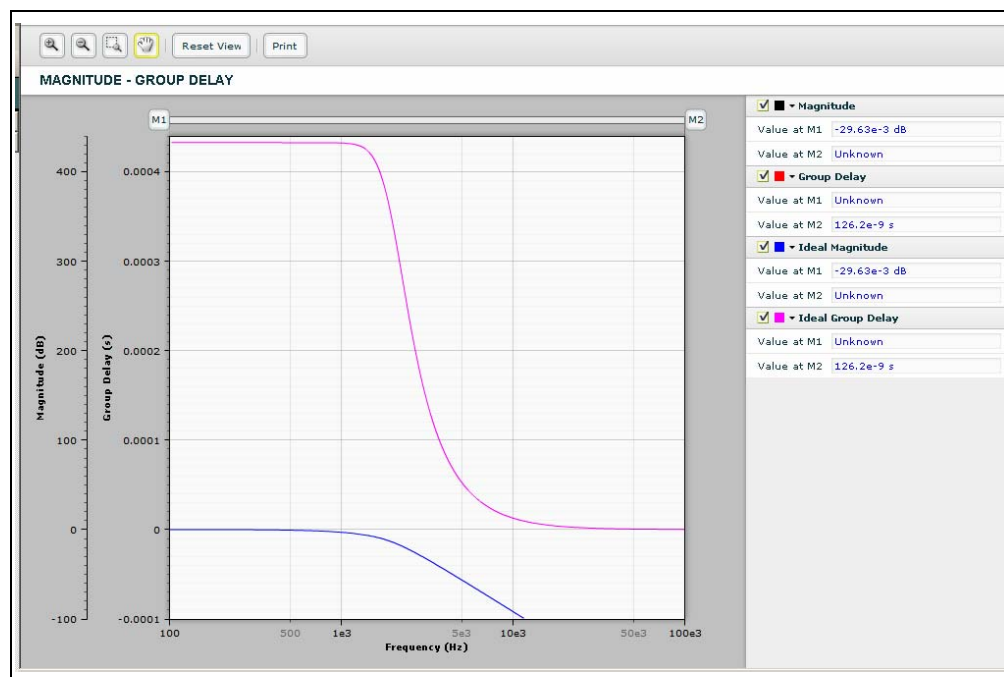
FIGURE B-5: *Magnitude - Group Response with Bessel Approximation.*

The step response of the 6th order Low-pass filters with Bessel approximation is shown in Figure B-6.

FIGURE B-6: *Step Response with Bessel Approximation.*

B.1.3 Chebyshev Low-pass Approximation

It has the following Low-pass characteristics:

• Amplitude variation (ripple) in the Pass-band, but steeper roll-off above the pass-band frequency than Butterworh and Bessel (Figure B-7)
• Poor group delay or phase response (Figure B-8)
• More overshoot and ringing in the step response than Butterworth and Bessel (Figure B-9)

The magnitude - phase response of the 6th order Low-pass filters with Chebyshev approximation is shown in Figure B-7.
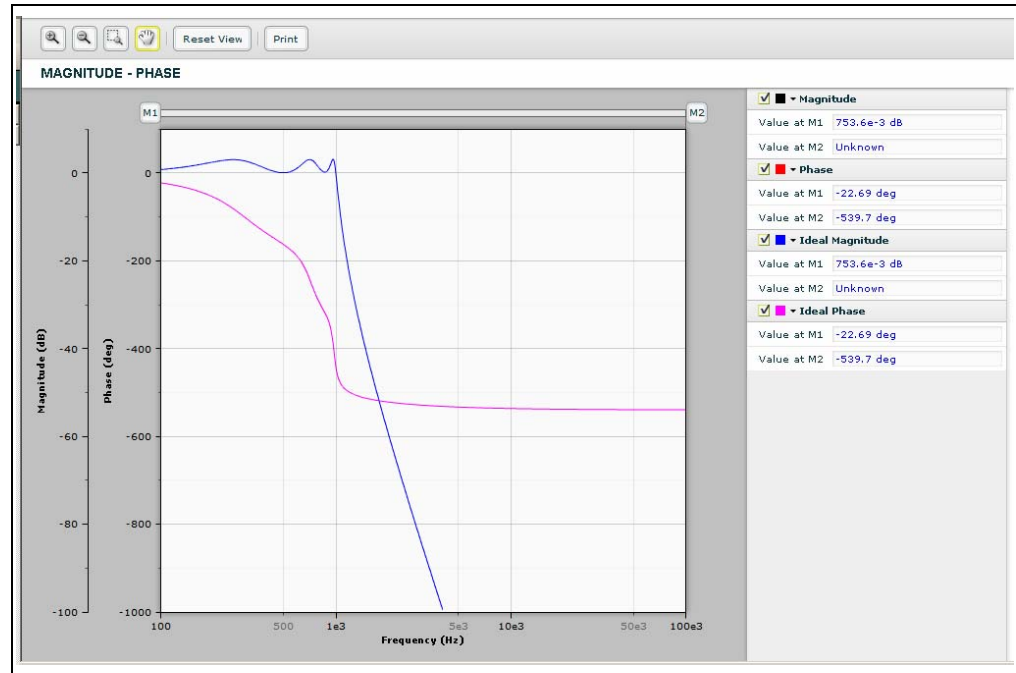
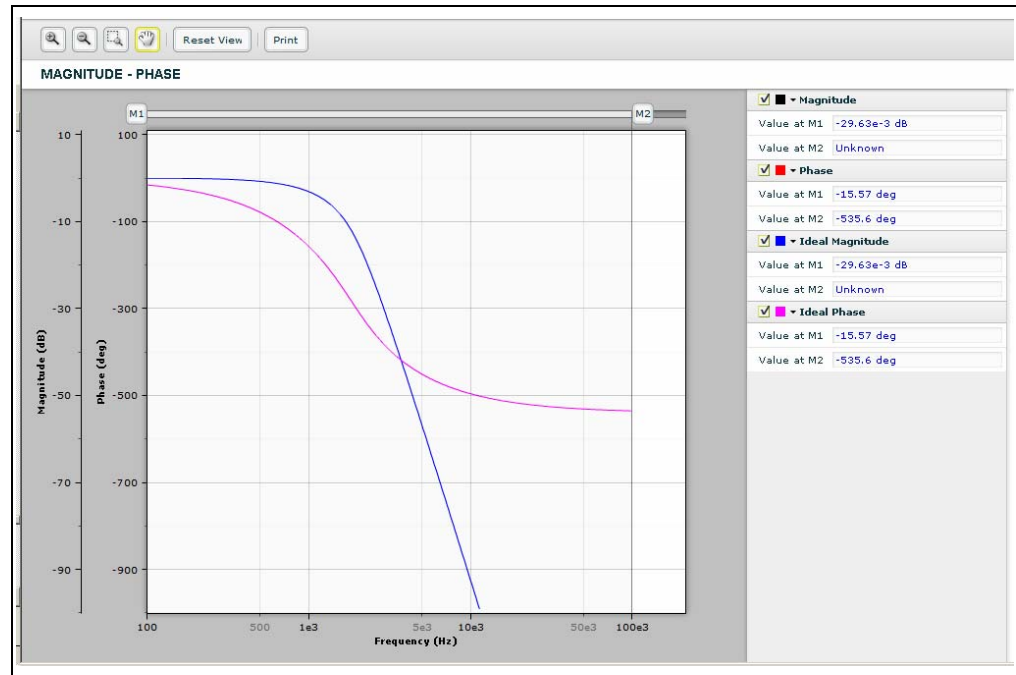*FIGURE B-7:*   *Magnitude - Phase Response with Chebyshev Approximation.*

The magnitude - group response of the 6th order Low-pass filters with Chebyshev approximation is shown in Figure B-8.
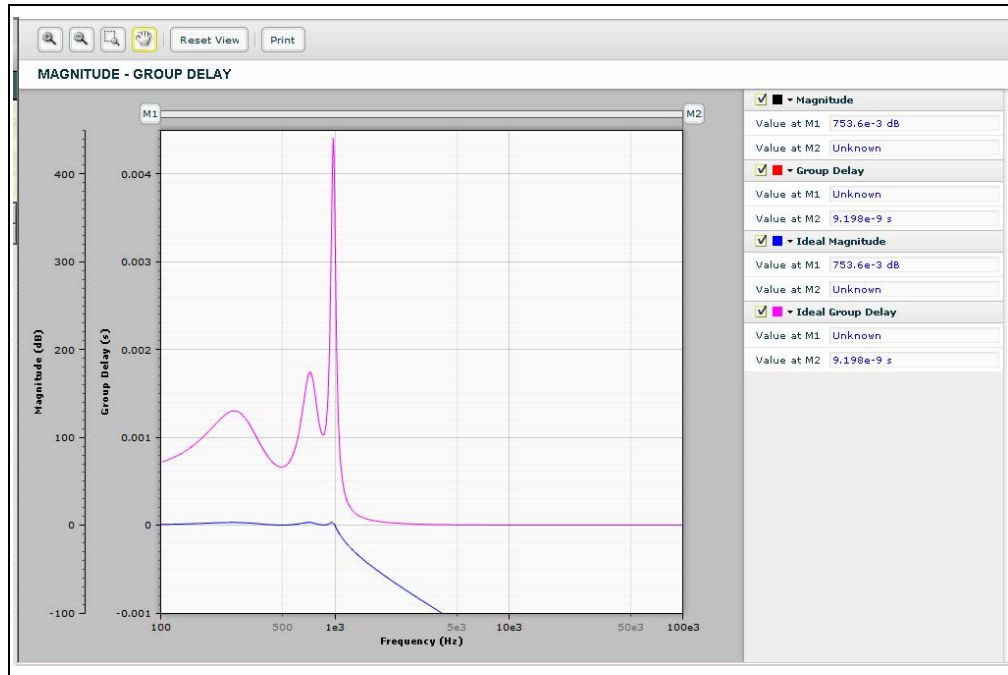
FIGURE B-8: *Magnitude - Group Delay Response with Chebyshev Approximation.*

The step response of the 6th order Low-pass filters with Chebyshev approximation is shown in Figure B-9.

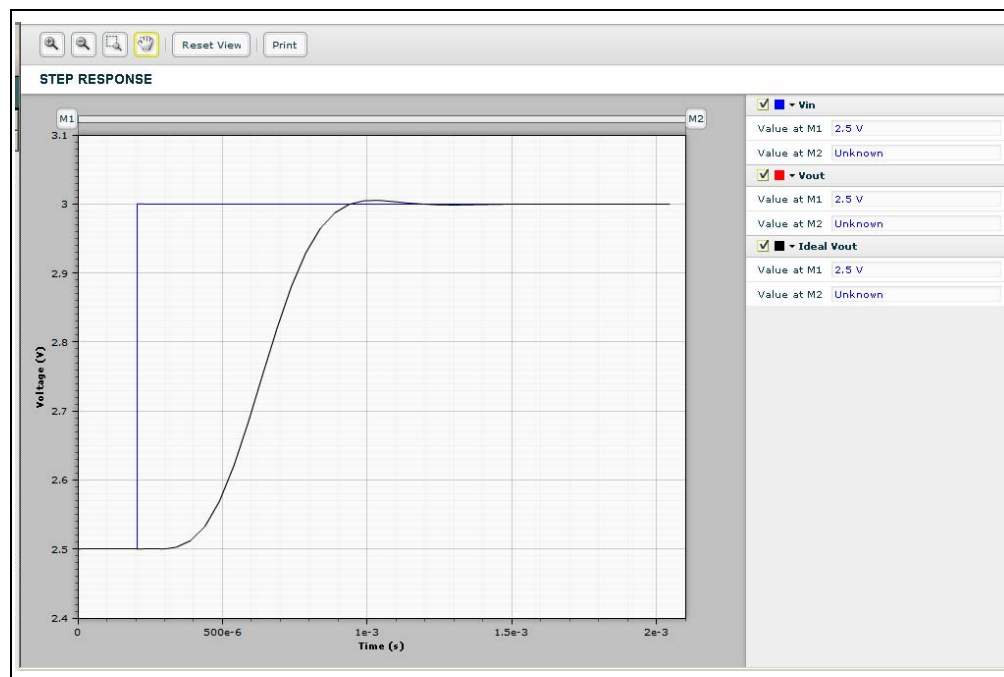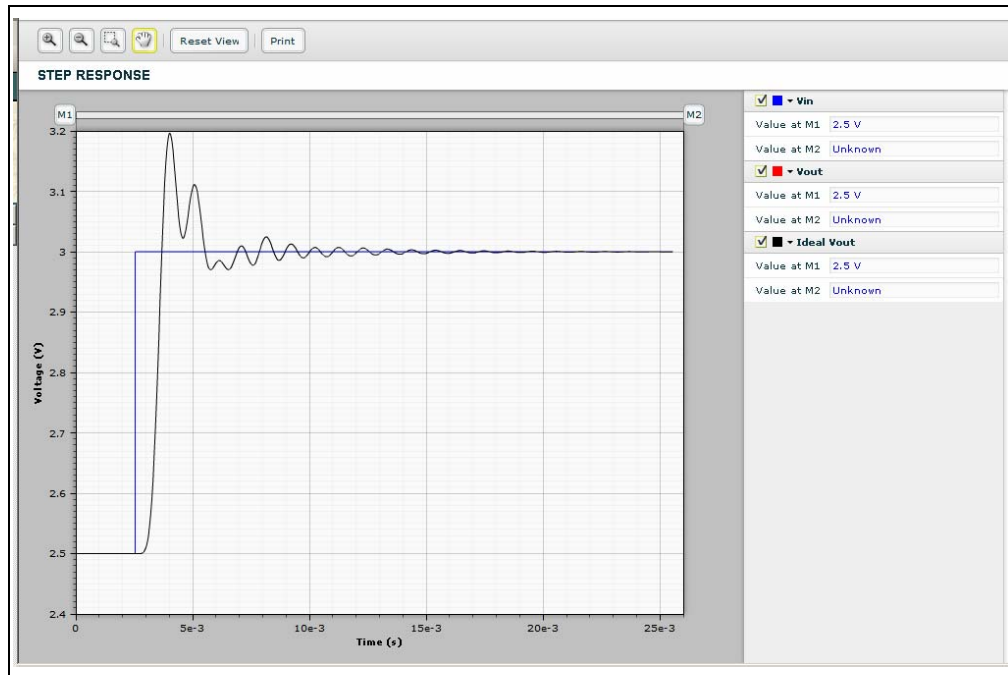**FIGURE B-9:** *Step Response with Chebyshev Approximation.*

B.1.4 Summary of Low-pass Filter Responses

TABLE B-1: FILTER APPROXIMATION SUMMARY (NOTE 1 THRU NOTE 3)

Approximations	Frequency Domain			Time Domain	
	Gain Flatness in Pass-band	Group Delay Flatness in Pass-band	Transition from Pass-band to Stop-band	Overshoot	Ringing
Bessel	Moderate	Good	Poor	Good	Good
Butterworth	Good	Moderate	Moderate	Moderate	Moderate
Chebyshev	Poor	Poor	Good	Poor	Poor

Note 1: Bessel approximation only supports Low-pass filter.

2: Overshoot is the amount which output voltage exceeds its target value.

3: Ringing is an unwanted oscillation of a voltage or current.

NOTES:

Appendix C. Op Amp Selection

C.1 INTRODUCTION

C.1.1 OP AMP SMALL SIGNAL BANDWITH

The op amps selected for your filter need to be fast enough to avoid problems with non-linear distortion and filter response distortion. A crude estimate of the op amp GBWP (Gain Bandwidth Product) that you need for a filter section is:

$$
\begin{aligned}
\text{GBWP} \quad &= \quad H_M \, 100 \, f_P, \text{ Low-pass} \\
&= \quad H_M Q \, 100 \, f_{PU}, \text{ Band-pass} \\
&= \quad H_M \, max \, \{100 \, f_P, \, f_{max}\}, \text{ High-pass}
\end{aligned}
$$

Where:

H_M	=	Filter section's maximum gain (V/V)
f_P	=	Low-pass and High-pass filters' Pass-band frequency (Hz)
f_{PU}	=	Band-pass filter's upper Pass-band frequency (Hz)
Q	=	Band-pass filter's overall Q-factor
	=	1/"fractional bandwidth"
	=	$(f_{PL} \, f_{PU})1/2/(f_{PU} - f_{PL})$
f_{max}	=	Maximum Pass-band/signal frequency for High-pass response $\gg f_P$

Try op amps with different GBWPs to see what you require. Small signal frequency response (typically $V_{OUT} < 100 \, mV_{P-P}$) starts to peak as the GBWP goes too low. Harmonic distortion also grows as the GBWP goes lower.

C.1.2 OP AMP FULL-POWER BANDWIDTH

The op amps also need to handle large signals. The SR (Slew Rate) specified in the op amp data sheets is related to the full-power bandwidth as follows.

f_{FPBW}	=	$SR/(\pi V_{OUT\_P-P})$ (Hz)

Where:

V_{OUT_P-P}	=	Filter section's maximum output voltage swing (V_{P-P}) $< V_{DD} - V_{SS}$
SR	=	Slew rate (V/s); data sheets usually give units of V/µs (1 V/µs = 1,000,000 V/s)
f_{FPBW}	=	op amp full-power bandwidth (Hz)

Sine waves faster than f_{FPBW} will not be faithfully reproduced because their derivative (slew rate) is too high.

In order to keep harmonic (non-linear) distortion to a minimum, the recommended minimum SR for all op amps in the filter is:

$$SR = X_{FF}\, \pi\, V_{OUT\_P\text{-}P}\, f_P, \text{ Low-pass}$$
$$= X_{FF}\, \pi\, V_{OUT\_P\text{-}P}\, f_{PU}, \text{ Band-pass}$$
$$= X_{FF}\, \pi\, V_{OUT\_P\text{-}P}\, f_{max}, \text{ High-pass}$$

Where:

f_P	=	Low-pass and High-pass filters' Pass-band frequency (Hz)
f_{PU}	=	Band-pass filter's upper Pass-band frequency (Hz)
f_{max}		Maximum Pass-band/signal frequency for High-pass response $\gg f_P$
X_{FF}	=	rough fudge factor for distortion performance (relative to fundamental)
	$\approx$	2, THD_{SR} = -60 dBc
	$\approx$	4, THD_{SR} = -72 dBc
	$\approx$	8, THD_{SR} = -84 dBc
	$\approx$	16, THD_{SR} = -96 dBc
THD_{SR}	=	Slew Rate induced distortion level (dBc)

Note that non-linear distortion may include a DC offset term.

C.1.3   OP AMP OUTPUT LOADING

Choose the resistance values in your filter so that the op amp is not overloaded. A compromise among loading, noise and parasitic RC time constants needs to be made. To scale the resistor values, change the capacitor values in the **Filter Circuit Schematic** within the Mindi.

C.1.4   MINIMUM GAIN

Most op amps are unity gain stable (G ≥ +1 V/V). A few op amps need to be set at higher gains to remain stable (e.g., G ≥ +10 V/V for the MCP6141). If you need gain in your filter, this kind of part can give you the bandwidth and the gain you need with less quiescent current. Note that inverting gains, used in Multiple Feedback (MFB) sections, have an equivalent "noise gain" that is used to determine stability. It is calculated as:

1 + |G| (e.g., a signal gain of -1 V/V gives a noise gain of +2 V/V).

Appendix D. Group Delay

D.1   INTRODUCTION

Group Delay is a measure of frequency domain response. It focuses on the relative time delay among sine waves of nearly equal frequency. Its usual definition is:

Ω	=	Radian Frequency (rad/s)
$\varphi(\omega)$	=	Phase Response (rad)
	=	$atan(Im\{G\}/Re\{G\})$
$\tau_{gd}(\omega)$	=	group delay (s)
	=	$-d\varphi(w)/d\omega$

An equivalent definition, when frequency is in Hz and phase is in degrees, is:

f	=	Frequency (Hz = cycles/s)
$\varphi(f)$	=	Phase Response (°)
	=	$atan(Im\{G\}/Re\{G\})$
$\tau_{gd}(f)$	=	group delay (s)
	=	(1 cycle/360°) ($-d\varphi(f) / df$)

Figure D-1 and Figure D-2 illustrate phase and group delay.
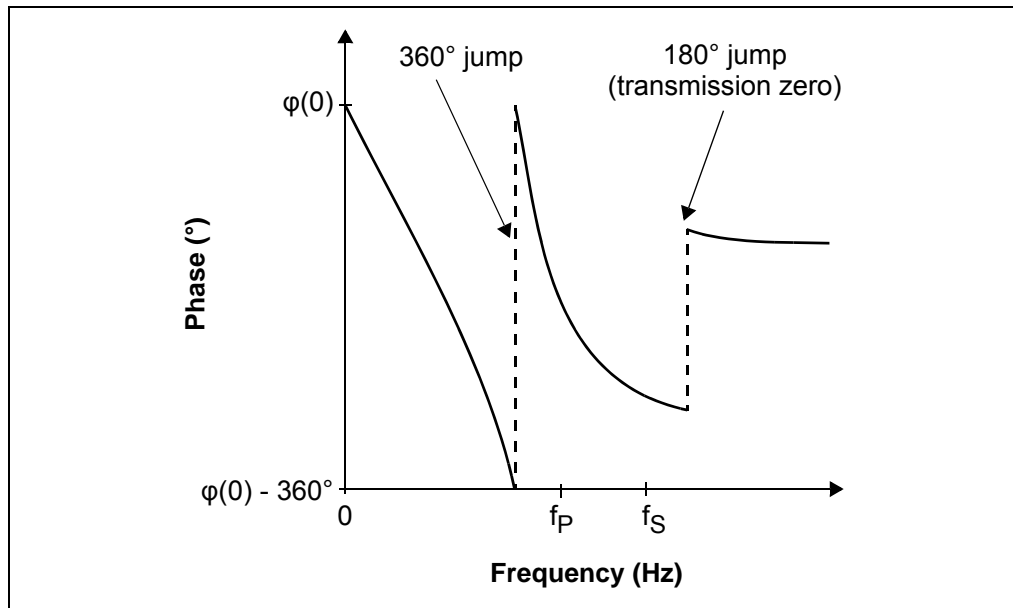

FIGURE D-1:   *Low-pass Phase Response.*
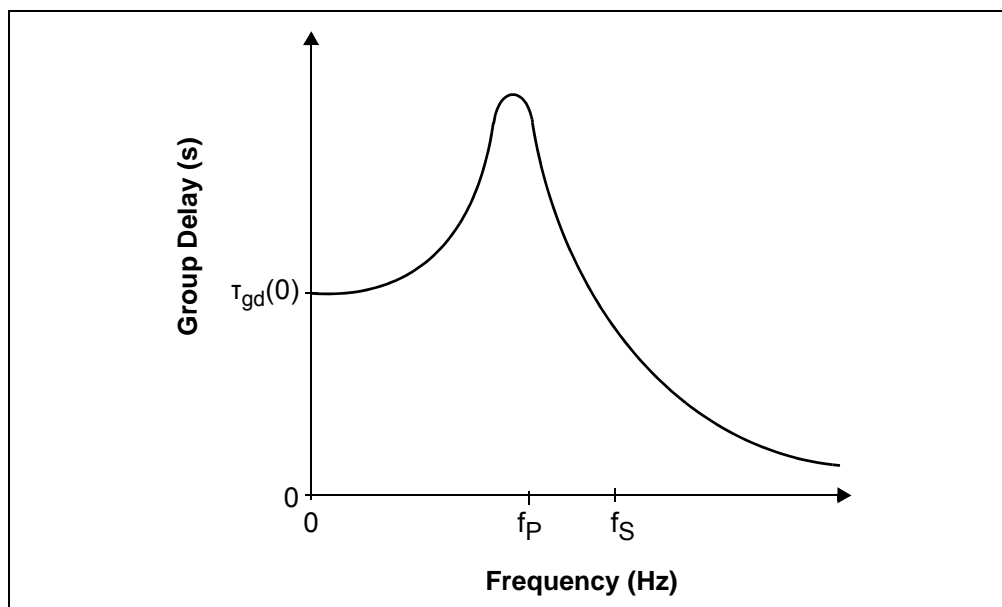
FIGURE D-2:   *Low-pass Group Delay.*

Some reasons that group delay has been traditionally used for filter work are:

- It is easier to manipulate mathematically (no arc-tangent functions)
- Group delay is easier to optimize:
  - Its jump discontinuities are only at transmission zeros on the *jω*-axis (gain is zero)
  - It is a non-negative function for Low-pass filters
- It applies directly to AM modulated signals:
  - The information is delayed by the group delay (also known as envelope delay)
  - It maps directly to group delay at baseband
  - The carrier is delayed by a different time (total phase shift divided by carrier frequency)
- It is a good indicator of Low-pass step response quality:
  - Constant group delay in the pass-band, and well into the Transition band (A < 10 dB to 20 dB), indicates a very good step response
  - Group delay with peaking (usually near f_P) indicates overshoot and ringing

Appendix E. Selected References

E.1 INTRODUCTION

E.1.1 FILTER TEXTBOOKS AND CLASSIC REFERENCES

[1] Arthur B. Williams and Fred J. Taylor, *Electronic Filter Design Handbook*, 3rd ed., McGraw-Hill, 1995.

[2] Rolf Schaumann, M.S. Ghausi, and Kenneth R. Laker, *Design of Analog Filters: Passive, Active RC, and Switched Capacitor*, Prentice Hall, 1990.

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E.1.2 APPLICATION NOTES

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