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PSoC® 1 – Approximating an Opamp with a Switched Capacitor Integrator

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Abstract

A switched capacitor integrator can approximate the functionality of an opamp. You do this by exploring the opamp's characteristics and learn how they are similar to an integrator. Next you create an integrator (a faux opamp) using PSoC® 1 switched capacitor blocks. Examples of a voltage follower and a programmable gain amplifier demonstrate the use of a faux opamp in real-world applications.

Introduction

Opamps have simplified circuit design for engineers. They form a basic building block for the analog and mixed-signal design. PSoC 1 analog blocks, both continuous time (CT) and switched capacitor (SC) do not have a native opamp mode. They are wired so that they can create PGAs, insamps, filters, integrators, and so on. However, in some designs you only need a plain opamp. This application note shows you how to configure a SC block so that it approximates the functionality of an opamp.

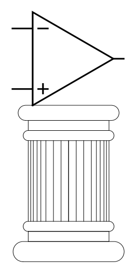
You see:

- A brief explanation of how an opamp works.
- An explanation of how a SC integrator can emulate an opamp (faux opamp).
- Examples of faux opamp circuits.
- This application note does not give in depth information about SC blocks. For more information see AN2041 – Understanding PSoC 1 Switched Capacitor Analog Blocks.

Opamp Primer: The Ideal Opamp

An ideal opamp is shown is Figure 1.

Figure 1. The Ideal Opamp



The ideal opamp has the following characteristics:

- Infinite gain
- Infinite bandwidth
- Infinite input impedance
- Zero output impedance
- Zero input offset error
- Zero phase delay
- Zero noise
- Zero power consumption
- Zero cost
- Available off-the-shelf everywhere
- Free shipping for any size order

They are fabricated from Utopian Nitrate and are packaged in Impossibilium. The Ideal opamp is only a model to help with the design and analysis of opamp circuits.

Opamp Golden Rules

From the ideal opamp characteristics two golden rules are obtained that simplify the analysis of opamp circuits.

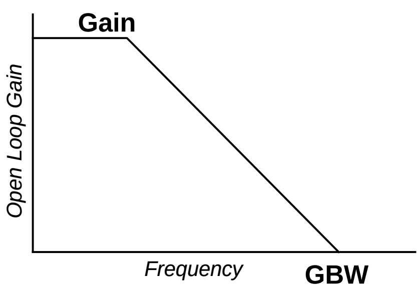
If there is a negative feedback:

- The output attempts to do whatever is necessary to make the voltage difference between its inputs zero.
- The inputs draw no current.

Real World Compensated Opamp

In the real world opamps are not ideal; they have many non-idealities such as finite gain and phase delay. Phase delay can introduce instability into opamp circuits. To reduce the possibility of instability (oscillations), most widely used commercial opamps have frequency compensation. This reduces the chance of oscillation when the opamp is connected in a feedback network. A Bode plot of a generic compensated opamp is shown in Figure 2.

Figure 2. Typical Opamp Bode Plot



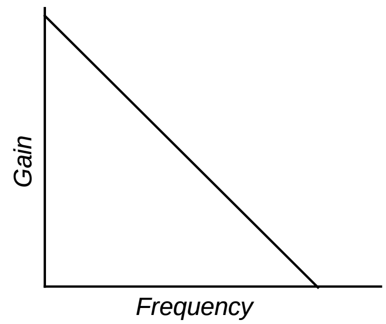
The compensated opamp has an open loop DC Gain and rolls off to unity gain at a frequency known as the gain bandwidth (GBW). A compensation pole is located at GBW/Gain. The transfer function is shown in Equation 1.

$$H(s) = \frac{Gain}{1 + \frac{s}{2\pi\left(\frac{GBW}{Gain}\right)}}$$ **Equation 1**

Equation 1 and Figure 2 show that the compensated opamp is actually a high gain low pass filter (LPF). Due to this an opamp can also be considered as an integrator with saturated gain at lower frequencies. Equation 2 shows the simplified transfer function; Figure 3 shows the typical integrator Bode plot.

$$H(s) \approx \frac{2\pi GBW}{s}$$ **Equation 2**

Figure 3. Typical Integrator Bode Plot

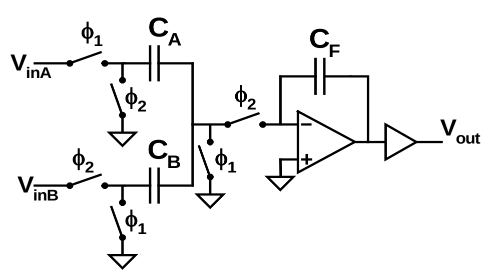


For frequencies greater than the roll off point, the transfer function and bode plot of an opamp approximate an integrator. For closed-loop control circuits, an integrator can be used in place of an opamp.

Differential Switched Capacitor Integrator

An integrator can be created in PSoC 1 SC blocks; its implementation is shown in Figure 4.

Figure 4. Differential Input SC Integrator



The transfer function is shown in Equation 3.

$$H(s) \approx \frac{\left(\frac{f_s C_i}{C_F}\right)}{s}: \quad C_A = C_B = C_i$$ **Equation 3**

Since SC integrators can function as opamps but actually are not opamps, we refer to them as faux opamps. For more information on SC blocks see AN2041 - Understanding PSoC® 1 Switched Capacitor Analog Blocks.

As stated earlier, the opamp embedded in the SC block cannot natively be used as a standalone opamp. Thus the need for an SC integrator that approximates the functionality of an opamp in closed-loop systems is a must.

Programmable GBW

Combining equations 2 and 3 produces the GBW value for a SC integrator, shown in Equation 4.

$$GBW = \frac{f_s}{2\pi}\frac{C_i}{C_F}$$ **Equation 4**

Changing the values of C_i (C_A C_B), C_F, or f_S alters the GBW. Flexible control of GBW enables you to design a stable closed-loop feedback system.

The SC block power settings and bias levels determine the maximum sample frequency (f_S). Table 1 shows the maximum sample frequency for all six power and bias settings. These settings are configured in the global resources window of PSoC Designer. Power is set by changing the analog power setting; bias is changed by changing the opamp bias setting.

Table 1. Power Settings

Power Setting	Max f_s
High Power High Bias	4 MHz
High Power Low Bias	2 MHz
Medium Power High Bias	1 MHz
Medium Power Low Bias	500 kHz
Low Power High Bias	250 kHz
Low Power Low Bias	125 kHz

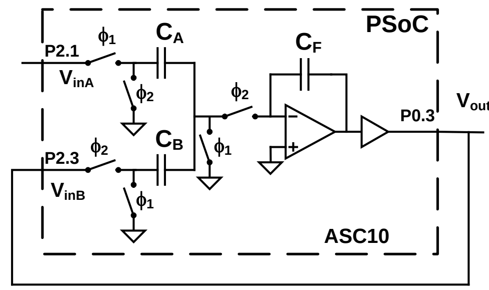
Examples

Now that we have covered how a SC integrator can act as an opamp, we are going to go through a few examples of how this faux opamp can be used in real world applications. Included with this application note is a basic example project that the reader can use to implement the examples discussed as following.

Example I (Voltage Follower)

In this example the faux opamp acts as a voltage follower or buffer. V_{inA} is the Non-Inverting input and V_{inB} is the Inverting Input. To create the voltage follower/buffer the output needs to be fed back to V_{inB}. The schematic for the follower is shown in Figure 5.

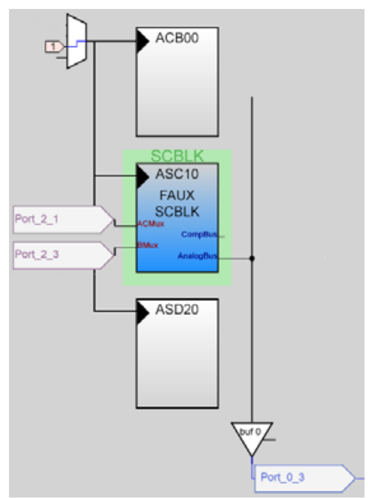
Figure 5. Voltage Follower Schematic



With negative feedback established, the output must become equal to the V_{inA} for the input difference to be zero; remember the golden opamp rules discussed earlier.

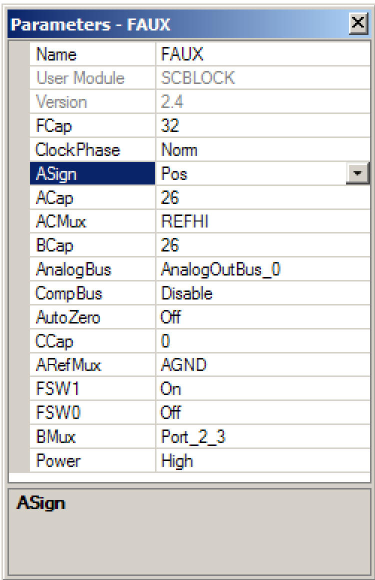
To create a faux opamp an SCBLOCK needs to be placed in a PSoC Designer project. The SCBLOCK is located in the generic folder of the user module catalog. Figure 6 is an example of the user module placement.

Figure 6. Faux Opamp User Module Placement



The SCBLK user module should be configured as shown in Figure 7.

Figure 7. Parameter Selections for FAUX SCBlock



Parameters - FAUX

Name	FAUX
User Module	SCBLOCK
Version	2.4
FCap	32
ClockPhase	Norm
ASign	Pos
ACap	26
ACMux	REFHI
BCap	26
AnalogBus	AnalogOutBus_0
CompBus	Disable
AutoZero	Off
CCap	0
ARefMux	AGND
FSW1	On
FSW0	Off
BMux	Port_2_3
Power	High

ASign

For more information on these configuration settings refer to AN2041 – Understanding PSoC 1 Switched Capacitor Analog Blocks

The following system parameters must be set:

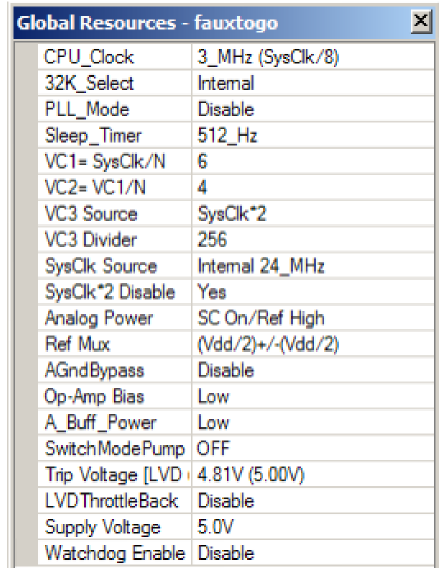
1. Ref Mux to (V_{dd}/2) +/- (V_{dd}/2). This sets AGND to Vdd/2**.** For more information on the Ref Mux and the meaning of the different settings see: AN2219 - PSoC® 1 Selecting Analog Ground and Reference.

2. Set VC1 to 4 MHz. This value is selected as the column clock frequency.

$$f_s = \frac{f_{cc}}{4} = \frac{4.0MHz}{4} = 1MHz$$ **Equation 5**

The global resource parameters are shown in Figure 8.

Figure 8. Global Resources



Global Resources - fauxtogo

CPU_Clock	3_MHz (SysClk/8)
32K_Select	Internal
PLL_Mode	Disable
Sleep_Timer	512_Hz
VC1= SysClk/N	6
VC2= VC1/N	4
VC3 Source	SysClk*2
VC3 Divider	256
SysClk Source	Internal 24_MHz
SysClk*2 Disable	Yes
Analog Power	SC On/Ref High
Ref Mux	(Vdd/2)+/-(Vdd/2)
AGndBypass	Disable
Op-Amp Bias	Low
A_Buff_Power	Low
SwitchModePump	OFF
Trip Voltage [LVD (	4.81V (5.00V)
LVDThrottleBack	Disable
Supply Voltage	5.0V
Watchdog Enable	Disable

Using Equation 4 as a template, the parameters are plugged in to determine **GBW**. The calculation is shown in Equation 5.

$$GBW = \frac{f_s}{2\pi}\frac{C_i}{C_F} = \frac{1MHz}{2\pi}\frac{26}{32} = 129kHz$$ **Equation 6**

When this project is actively running, the output voltage can be measured at V_{out} (P0[3]). The output voltage follows the input voltage (P2[1]).

The faux opamp is useful in a classical voltage follower just as the typical opamp is. However, the faux opamp has other advantages, such as programmable bandwidth and programmable gain. The following examples highlight some other features of the faux opamp that go beyond the traditional opamp.

Differential Input Capacitors

All the analysis until now has been done with the input capacitors (C_A, C_B) equally weighted. Doing so causes the opamp golden rules to apply. However, if the inputs have different weights, then the output attempts to make the differential input capacitor charge transfer zero. This is expressed in Equation 6.

$$V_{inA}C_A - V_{inB}C_B = 0$$ **Equation 7**

Example II (Programmable Gain)

In the previous example the output voltage followed the input. For this example we want the output voltage to be double the input voltage. Remember that the output is relative to AGND (Vdda/2). Equation 7 shows how to calculate the output voltage.

$$V_{out} = AGND + (V_{in} - AGND)\frac{C_A}{C_B}$$ **Equation 8**

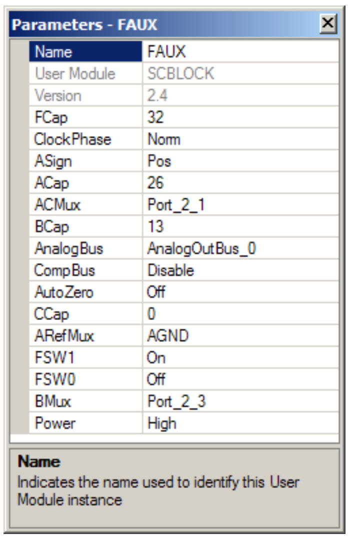
To get 2x gains, the input capacitors need to be sized correctly

$C_A = 26$

$C_B = 13$

These two parameters are changed as shown in Figure 9.

Figure 9. Parameter Selection Voltage Doubler Out


Parameters - FAUX

Name	FAUX
User Module	SCBLOCK
Version	2.4
FCap	32
ClockPhase	Norm
ASign	Pos
ACap	26
ACMux	Port_2_1
BCap	13
AnalogBus	AnalogOutBus_0
CompBus	Disable
AutoZero	Off
CCap	0
ARefMux	AGND
FSW1	On
FSW0	Off
BMux	Port_2_3
Power	High

Name
Indicates the name used to identify this User Module instance

When this project is actively running, the output follows equation 7 with the parameters set in Figure 9.

The GBW is determined by the value of the capacitor connected to the feedback path. It is calculated in Equation 8.

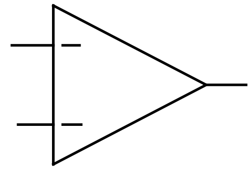
$$GBW = \frac{f_s}{2\pi}\frac{C_B}{C_F} = \frac{1MHz}{2\pi}\frac{13}{32} = 64.7kHz$$ **Equation 9**

You can change the input capacitors to create a wide variety of input-to-output voltage ratios; creating a programmable gain amplifier out of SC blocks.

Changing Input Polarity

An opamp cannot have two negative inputs. However, a faux opamp can. The SC blocks allow for switching the polarity of V_{inA}. This results in the component shown in Figure 10.

Figure 10. Switched Polarity Component



The new faux opamp golden rule must be expanded to reflect this change. It is shown in Equation 9.

$$A_{sign}V_{inA}C_A - V_{inB}C_B = 0$$ **Equation 10**

Example III (Programmable Gain with Polarity)

With the new opamp shown in Figure 10, you can create negative gain. For this example, a gain of –2 needs to be applied to the input. For this configuration the output follows Equation 10.

$$V_{out} = AGND + A_{Sign}(V_{in} - AGND)\frac{C_A}{C_B}$$ **Equation 11**

Looking at the previous example it is known how to get a gain of 2. All you need to do is switch the polarity of the A input.

One solution is:

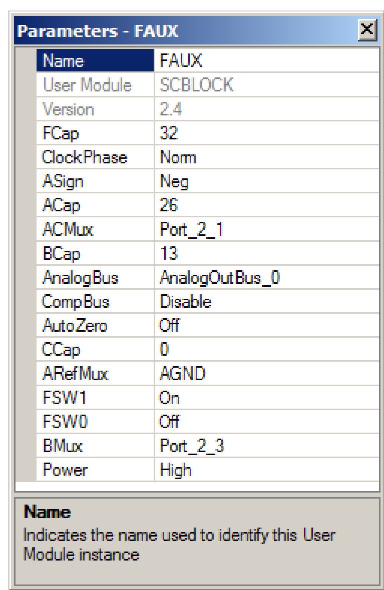
$C_A = 26$

$C_B = 13$

$A_{sign} = neg$

These three parameters are changed as shown in Figure 11.

Figure 11. Parameter Selection –2 gain


Parameters - FAUX

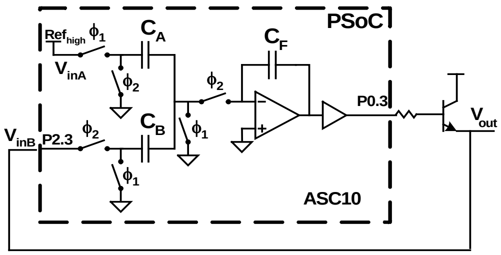
Name	FAUX
User Module	SCBLOCK
Version	2.4
FCap	32
ClockPhase	Norm
ASign	Neg
ACap	26
ACMux	Port_2_1
BCap	13
AnalogBus	AnalogOutBus_0
CompBus	Disable
AutoZero	Off
CCap	0
ARefMux	AGND
FSW1	On
FSW0	Off
BMux	Port_2_3
Power	High

Name
Indicates the name used to identify this User Module instance

When this project is actively running, the output voltage follows Equation 10, using the parameters from Figure 11. Now you can create a programmable gain and polarity amplifier with the faux opamp.

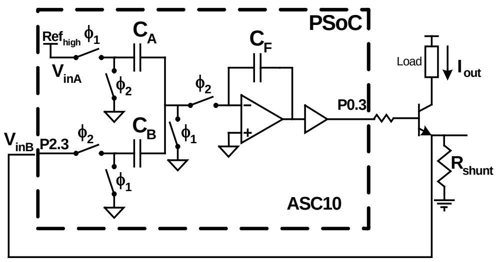
A transistor can be added to the output as shown in Figure 12 to increase the current capacity of the output, thus creating a programmable power supply.

Figure 12. Programmable Power Supply



You can create a programmable current source by adding a shunt resistor to the emitter of the transistor as shown in Figure 13.

Figure 13. Programmable Current Source



The shunt resistor causes the output voltage to be converted into current. This current is available at the collector of the transistor. The output current is determined by the parameters in Equation 11.

$$I_{out} = \frac{AGND + A_{sign}(Vin - AGND)\frac{C_A}{C_B}}{R_{shunt}}$$ **Equation 12**

Note that the V_{inA} input does not have to come from an external source. It can be tied to an internal voltage like RefHi, or the output of a VDAC.

Summary

SC blocks are easily configured as integrators. The integrator then functions as an opamp. Parameterization of the capacitor values and sample frequency enables precise control of GBW. Intentional misbalancing of the input capacitor and adjusting the polarity of the V_{inA} input enables some unique PSoC applications.

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**	1499983	MAXK	10/04/2007	New application note.
*A	2678525	TDU	03/25/2009	Updated software version and associated PSoC project
*B	3253271	TDU	05/13/2011	Updated Project to 5.1, Fixed Grammar and Structure of AN, Updated Title and Abstract to better reflect contents of AN, and Updated Template.
*C	3441042	TDU	11/21/2011	Template update Updated Project files
*D	4382168	MQY	05/16/2014	Sunset review. Minor copy editing. Removed link on Pg. 8 to Optical Navigation Sensors.

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