SPICE models for Precision DACs

By Rahul Prakash
Electrical Design Engineer

The challenge – complete system verification

Predicting the performance of a design before it is implemented is a challenge faced by every design engineer. IC designers have myriads of tools and models at their disposal to simulate their designs even before fabrication. However, when considering the full system design, there are very few components for which accurate models exist.

This means that a full system-level verification has to be done manually by the designer via budgeting, spot checks, modeling, visual inspection and modifications based on previous experience. Unfortunately, this leaves a potential for errors and bugs in the design. In some cases, several board revisions are required to achieve the intended functionality and performance.

The building blocks – Precision DAC models

The latest TINA-TI™ software models for precision DACs, such as the DAC8411 family from Texas Instruments, enable full system-level verification. The DAC8411 family consists of 8- to 16-bit single-channel, voltage-output digital-to-analog converters (DACs). The SPICE models for this family are available in two variants. The first is a parallel n-bit wide interface with output buffer, compatible with all TINA versions (Figure 1).

The second is a serial peripheral interface (SPI) with output buffer, compatible with professional TINA-TI software (Figure 2).

Both variants can be useful in simulating the analog signal chain from the DAC output buffer. The SPI model with the output buffer completely models the full DAC functionality. It can be used to simulate the digital signal chain from the DAC's input.

The output buffer model for the DAC includes common DC parameters such as end-point errors with respective temperature coefficients, quiescent current, as well as AC parameters such as capacitive load stability, slew rate, settling time, and power-on glitch, among others. For example, simulation results for DAC8411 gain (Gerr) and offset (Offs) error are shown in Figure 3. Note that the gain error is a percentage of the full-scale range, and the offset error is in microvolts (µV).

Figure 1. DAC parallel interface model

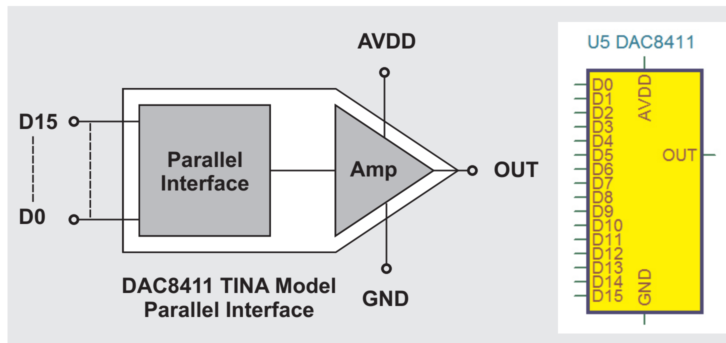


Figure 2. DAC serial interface model

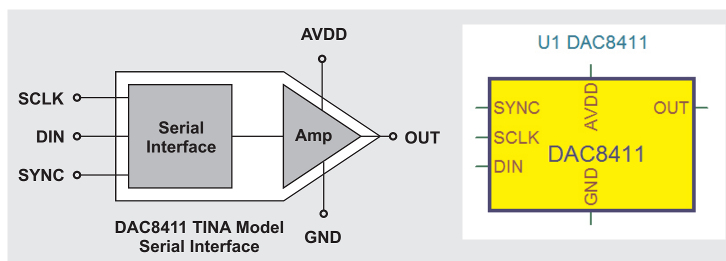


Figure 3. Gain and offset error DC simulations

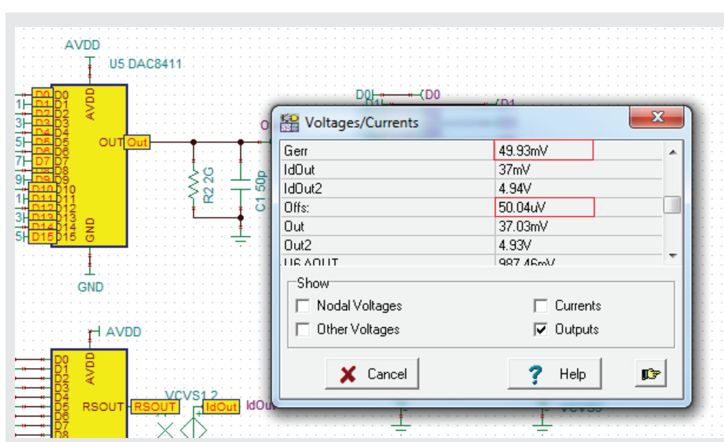


Figure 4 shows a transient simulation that was performed on the DAC with a code step from quarter to three-quarter scale. The plot shows close correlation of the simulated plot to the datasheet plot for this analysis.

The models also allow the designer to enter specific values for some parameters such as the DAC gain and offset errors. This is particularly useful in running what-if simulations for estimating system performance.

Bringing it together – complete system models

Case Study: 0- to 20-mA DAC

One of the most common DAC applications is to create a 0- to 20-mA signal in an industrial automation system, also known as a three-wire system. There are multiple ways to implement this system that range from a fully discrete implementation using a DAC, operations amplifiers, and passive components, to fully-integrated implementations using devices such as the DAC8760.

For this exercise, let's design a basic 0- to 20-mA system using a fully discrete implementation with TINA models for the DAC8411 and OPA192 (Figure 5).

Theory of operation

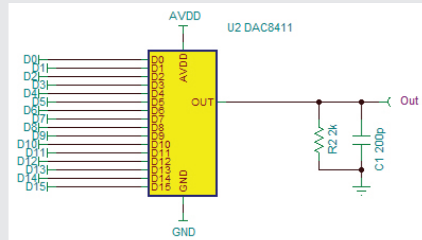
This implementation uses models for the DAC8411, two OPA192 operational amplifiers (OP1 and OP2), two MOS transistors (T1 and T2), and four resistors (R1, R2, R4, and RLOAD). This system generates an output load current into RLOAD that is proportional to a 16-bit input digital code. For this design, OP1 and OP2 are required to handle rail-to-rail inputs.

In order to understand this basic system, we will assume that OP1 and OP2 are ideal. However, subsequent sections use the OPA192 TINA models to simulate the complete system. The DAC8411 model converts the 16-bit DAC code into a proportional analog output voltage (VDAC) in the 0- to 5-V range. This voltage is then applied to the positive input of the operational amplifier (OP2). The negative input of OP2 is also driven to the DAC output voltage (VDAC), thus forcing a current through resistor R4 (VDAC/R4). The operational amplifier (OP2) ensures this current by controlling the gate voltage of MOSFET (T2). This current is drawn from the supply (V2) via resistor R1. This completes the first stage of this design in which a code proportional current is generated.

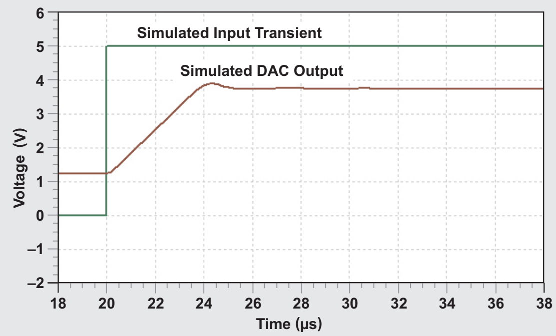
The operational amplifier (OP1) maintains equal voltage drops across R1 and R2. Since the value of R2 in this design is a 100 times less than R1, for an equal voltage drop, the current flowing through R2 must be a 100 times greater than the current flowing through R1. This current can be expressed by the formula (VDAC/R4) × (R1/R2).

The operational amplifier (OP1) ensures this current by controlling

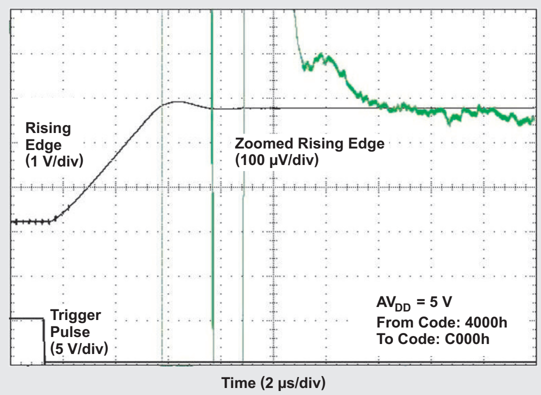
Figure 4. Transient simulation showing half-scale settling time



(a) Simulation model



(b) Settling-time simulation



(c) Settling time from datasheet

Figure 5. DAC 0- to 20-mA system model

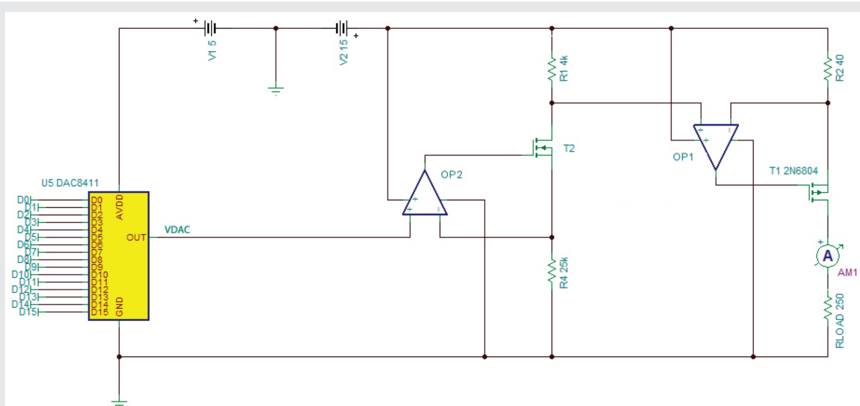


Figure 6. Input interface test bench for 0- to 20-mA DAC system

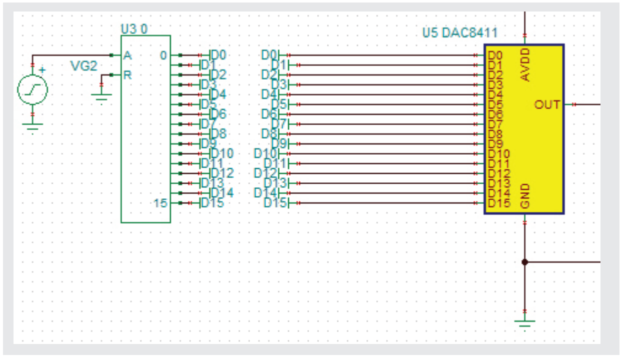
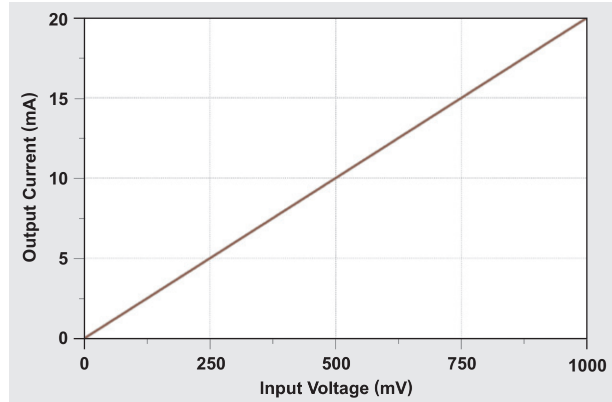


Figure 7. DAC system simulation of output current DC sweep



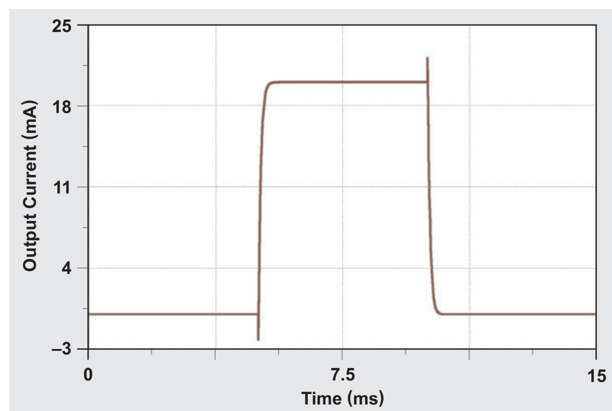
the gate of MOSFET T1. The drain of the T1 is connected to the 250-Ω load resistor (RLOAD) via an ammeter (AM1).

Simulation setup and results

The test-bench configuration shown in Figure 6 uses an ideal 16-bit analog-to-digital converter (ADC) to convert a 0- to 1-V analog signal (VG2) into the 16-bit code for the system. A DC sweep of VG2 generates full 16-bit code for the system. The resulting output current is shown in Figure 7.

Figure 8 shows a transient analysis for the same circuit. The DAC code is toggled from zero scale to full scale and the resulting output current is plotted.

Figure 8. DAC system simulation of output current transient



Real system non-idealities

Previously, the 0- to 20-mA system was simulated with DAC8411 and OPA192 parameters modeled as typical. As with any integrated chip, the parameters listed in the datasheet have a typical value, and for some, a max/min value. The intent of placing these boundaries is to guarantee a level of performance on these parameters over a specified temperature range, supply voltages, and process variations. Thus, it is useful to have the system simulated for these variations in the specifications.

The latest TINA-TI software models for the DAC allow designers to modify some critical parameters and run what-if simulations. To illustrate this feature, an example simulation was chosen in which the DAC offset voltage is varied from a typical to the maximum value. This spec is captured in the models by the OFFS parameter shown in Figure 9.

Figure 9. DAC model, user-adjustable DAC offset voltage

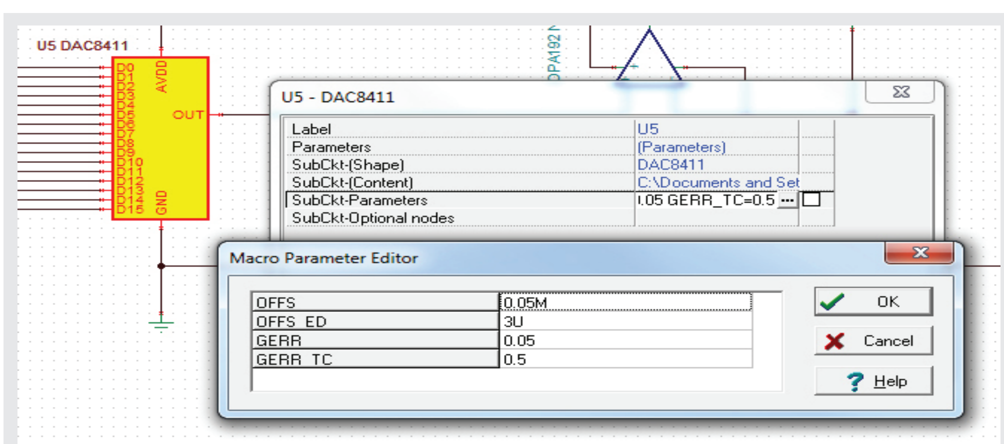
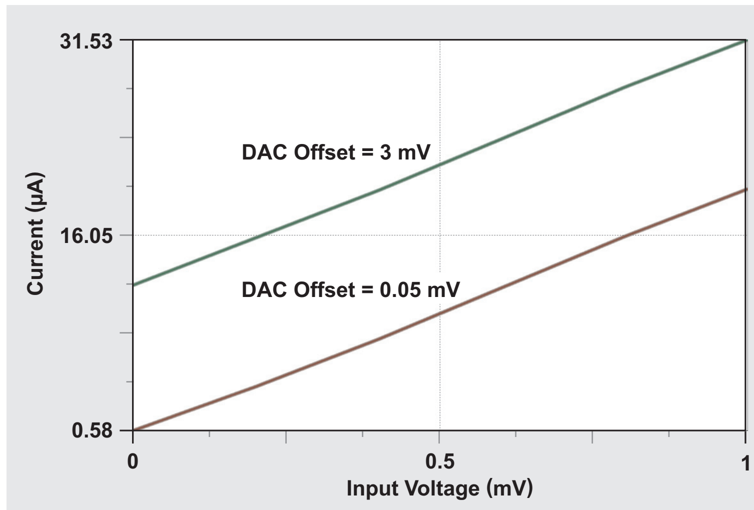


Figure 10 shows the system's DC performance (system output current of model in Figure 5) for two values of DAC offset voltage.

Note that the green curve is the simulation result with the worst-case offset voltage (3 mV), and the red curve is with offset voltage set to typical value of 0.05 mV. For simplicity, the displayed output current in Figure 10 is zoomed in to show the offset in the output. This particular simulation is useful to predict the response of the system for the worst-case DAC offset voltage.

Figure 10. DAC system simulation for output-current DC sweep with user-adjusted offset error



Conclusion

The DAC models described allow full system verification. However, the level of accuracy and system parameters that can be verified depend on the accuracy of the models as well as the capability of the simulation tool. Using the system shown in Figure 5 as an example, the level of verification depends on the DAC models, operational amplifiers, MOSFETs, and discrete components along with the capability of the TINA simulator. The simulator capability can be improved by using the professional version of the simulation software. This leaves the accuracy of the component models to be the limiting factor for comprehensiveness of the system verification.

References

1. SPICE-Based Analog Simulation Program by Texas Instruments. Available: **www.ti.com/tool/tina-ti**
2. DAC8411 models. Available: **www.ti.com/product/DAC8411/toolssoftware**
3. OPA192 models. Available: **www.ti.com/product/OPA192/toolssoftware**

Related Web sites

www.ti.com/4q14-DAC8411

www.ti.com/4q14-DAC8760

www.ti.com/4q14-OPA192

Subscribe to the AAJ:
www.ti.com/subscribe-aaj

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI E2E™ Community Home Page
e2e.ti.com

Product Information Centers

Americas	Phone	+1(512) 434-1560
Brazil	Phone	0800-891-2616
Mexico	Phone	0800-670-7544
	Fax	+1(972) 927-6377
	Internet/Email	support.ti.com/sc/pic/americas.htm

Europe, Middle East, and Africa

Phone

European Free Call	00800-ASK-TEXAS (00800 275 83927)
International	+49 (0) 8161 80 2121
Russian Support	+7 (4) 95 98 10 701

Note: The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

Fax	+(49) (0) 8161 80 2045
Internet	www.ti.com/asktexas
Direct Email	asktexas@ti.com

Japan

Fax	International	+81-3-3344-5317
	Domestic	0120-81-0036
Internet/Email	International	support.ti.com/sc/pic/japan.htm
	Domestic	www.tij.co.jp/pic

Asia

Phone	Toll-Free Number

Note: Toll-free numbers may not support mobile and IP phones.

Australia	1-800-999-084
China	800-820-8682
Hong Kong	800-96-5941
India	000-800-100-8888
Indonesia	001-803-8861-1006
Korea	080-551-2804
Malaysia	1-800-80-3973
New Zealand	0800-446-934
Philippines	1-800-765-7404
Singapore	800-886-1028
Taiwan	0800-006800
Thailand	001-800-886-0010

International	+86-21-23073444
Fax	+86-21-23073686
Email	tiasia@ti.com or ti-china@ti.com
Internet	support.ti.com/sc/pic/asia.htm

Important Notice: The products and services of Texas Instruments Incorporated and its subsidiaries described herein are sold subject to TI's standard terms and conditions of sale. Customers are advised to obtain the most current and complete information about TI products and services before placing orders. TI assumes no liability for applications assistance, customer's applications or product designs, software performance, or infringement of patents. The publication of information regarding any other company's products or services does not constitute TI's approval, warranty or endorsement thereof.

A021014

© 2014 Texas Instruments Incorporated. All rights reserved.

E2E and TINA-TI are trademarks of Texas Instruments. All other trademarks are the property of their respective owners.

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2014, Texas Instruments Incorporated