EDITED BY BRAD THOMPSON
AND FRAN GRANVILLE

designideas

READERS SOLVE DESIGN PROBLEMS

DIs Inside

80 Enhanced, three-phase VCO features ground-referenced outputs

84 Improved current monitor delivers proportional-voltage output

▶ What are your design problems and solutions? Publish them here and receive $150! Send your Design Ideas to edndesignideas@reedbusiness.com.

Programmable analog circuits yield single-chip sinusoidal oscillators

Stefano Salvatori and Paolo Lorenzi, University of Rome, Rome, Italy

Programmable-logic devices provide a popular method of implementing complex functions in digital designs. Although manufacturers don't yet offer analog circuits whose complexity compares to VLSI digital circuits, field-programmable analog circuits are enjoying extensive use in signal-conditioning and filtering applications. Based on CMOS-operational-transconductance and switched-capacitor amplifiers, these devices offer a convenient approach to relatively complex design problems. Lattice Semiconductor's (www.latticesemi.com) ispPAC10 in-system-programmable analog circuit and its accompanying PAC Designer software offer a convenient method of circuit design and verification (**Reference 1**). This Design Idea presents two simple sinusoidal oscillators based on the ispPAC10.

Resistors within the ispPAC10 are fixed at a nominal 250 kΩ, and all capacitors are user-selectable from 1.07 to 61.59 pF. **Figure 1** shows an ispPAC10 with its internal blocks 1, 2, and 4 connected as a cascade of three first-order lowpass filters to form a classic phase-shift RC oscillator. Altering the capacitors' values produces oscillation frequencies over a range of 18 to 130 kHz. Each PAC block's gain is fixed at a factor of two to obtain a loop gain of −8, which Barkhausen's condition for oscillation requires (**Reference 2**). Configured from Block 3, a first-order lowpass filter reduces the THD (total harmonic distortion) on the oscillator's output. The values of capacitors in Block 3 are optimized for filtering performance and thus differ from those of the phase-shift stages.

The circuit in **Figure 2** describes a two-integrator loop that forms a classic quadrature-RC oscillator. The circuit's oscillation frequency spans 12 to 126 kHz and depends on the time con-

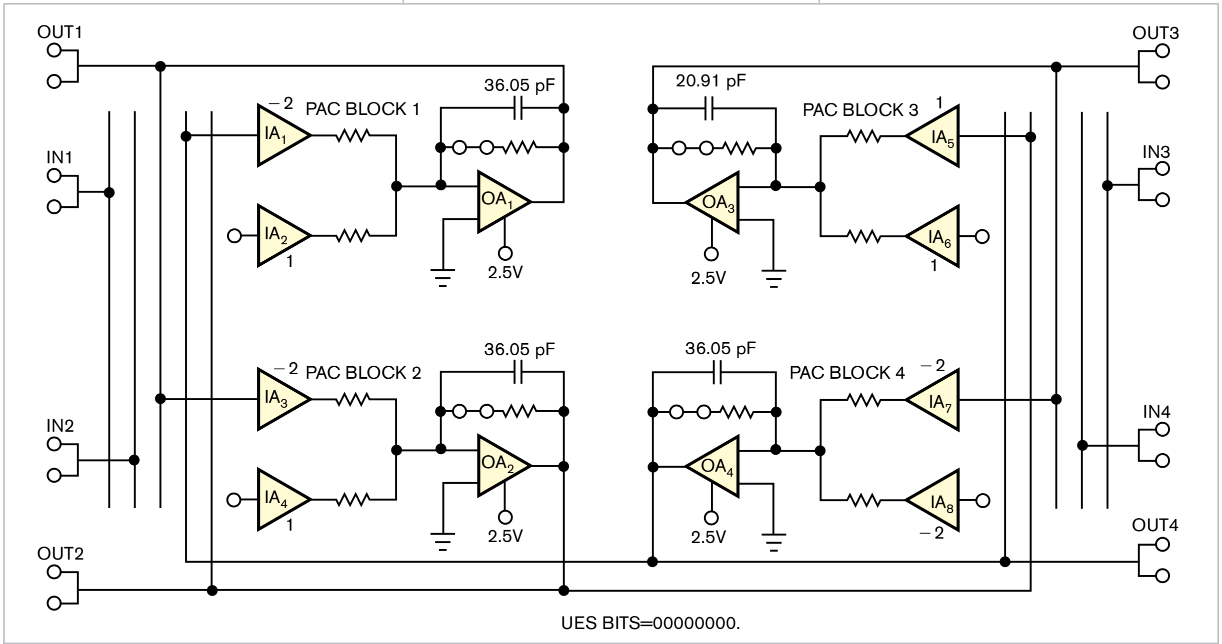


Figure 1 Based on a Lattice Semiconductor ispPAC10 programmable analog circuit, this phase-shift sine-wave oscillator and lowpass filter require no external components. The values are for a 30.4-kHz oscillator.

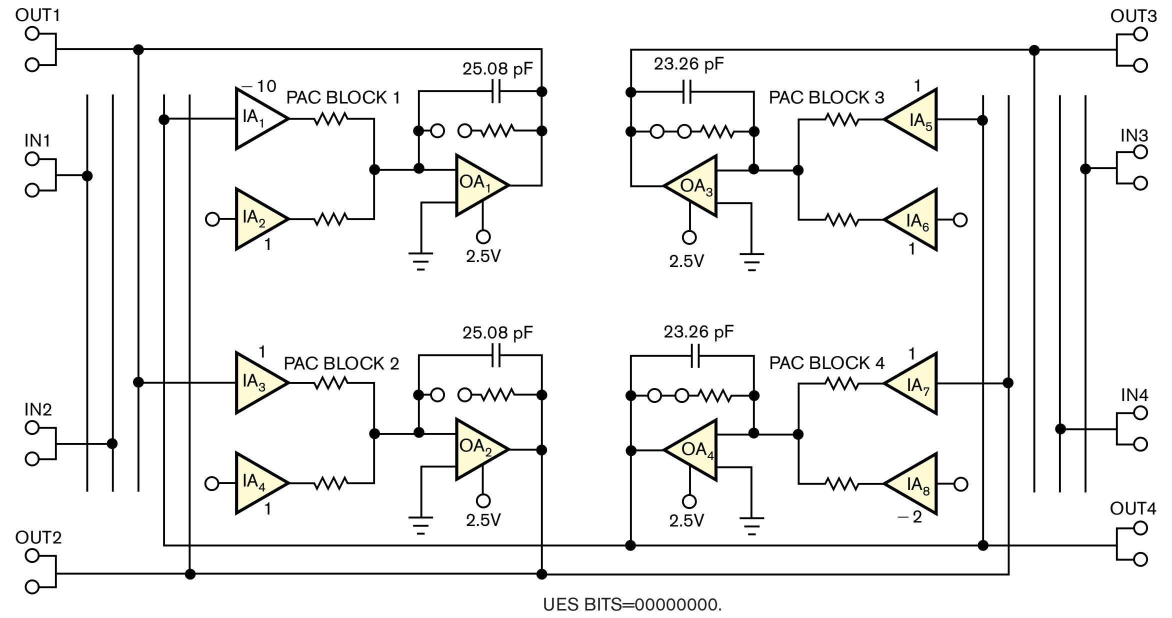


Figure 2 Cascaded dual integrators implement a quadrature sine-wave oscillator, with blocks 3 and 4 forming a lowpass filter. Again, the circuit design uses no external components. The values shown are for a 27.2-kHz oscillator.

stants of the integrators that blocks 1 and 2 form. In theory, each integrator's gain should have an absolute value of unity, but, in practice, ispPAC allows specification only of inverting integrators, and producing a stable sinusoidal signal requires a gain of at least −4 in Block 1. The circuit uses a gain of −10. Two additional blocks of the ispPAC10 device form a second-order lowpass filter that decreases the output's THD. In both oscillator circuits, you can alter the lowpass filters' gain so that the circuit's outputs deliver specific voltages, such as 1V p-p, at all frequencies.

Tables 1 and **2**, respectively, contain summaries of the phase-shift and quadrature oscillators' components and output characteristics. C_N refers to the value of the capacitor used in the

TABLE 1 PHASE-SHIFT OSCILLATOR

C_1 (pF)	C_2 (pF)	C_3 (pF)	C_4 (pF)	f_0 (kHz)	Δf (kHz) at −20 dB	THD (dB)
5.46	5.46	5.06	5.46	130.1	6	−25
6.92	6.92	5.92	6.92	115.4	6	−30
7.77	7.77	6.92	7.77	109.9	6	−30
9.19	9.19	6.92	9.19	97.8	2.5	−32
14.62	14.62	9.19	14.62	67.9	2.5	−39
20.91	20.91	12.78	20.91	50.1	2.5	−40
36.05	36.05	20.91	36.05	30.4	1.2	−40
61.59	61.59	35.25	61.59	17.7	0.6	−41

TABLE 2 QUADRATURE OSCILLATOR

C_1 (pF)	C_2 (pF)	C_3 (pF)	C_4 (pF)	f_0 (kHz)	Δf (kHz) at −20 dB	THD (dB)
1.07	1.07	5.06	5.06	125.9	6	−27
3.56	3.56	5.92	5.92	105.1	6	−25
5.92	5.92	7.77	7.77	80.4	2.5	−30
7.77	7.77	9.62	9.62	66.3	2.5	−34
14.22	14.22	15.45	15.45	41.7	2.5	−40
25.08	25.08	23.26	23.26	27.2	1.2	−40
40.08	40.08	26.29	26.29	18.6	1.2	−42
50.01	50.01	35.25	35.25	15	0.6	−42
61.59	61.59	40.98	40.98	12.3	0.6	−41

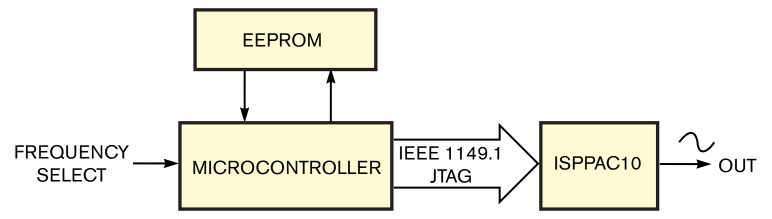


Figure 3 Either ispPAC10 circuit's implementation can serve as a foundation for a programmable oscillator by adding a microcontroller and nonvolatile storage.

nth PAC block for oscillation at frequency f_0. The design uses a Tektronix TDS1002 digital oscilloscope's FFT function to measure THD and the spectral line width of each output frequency at a level of −20 dB with respect to the central frequency, f_0.

Figure 3 illustrates the application of a microcontroller to dynamically reconfigure an ispPAC-based oscillator for specific frequencies. The nonvolatile memory stores frequency-specific capacitance and gain values for each of the ispPAC10's circuit blocks. Data transfers occur using the IEEE 1149.1 JTAG-standard protocol through the ispPAC10's serial test-access-port interface. EDN

REFERENCES

1. PAC Designer software, www.latticesemi.com.
2. http://jlnlabs.imars.com/spgen/barkhausen.htm.

Enhanced, three-phase VCO features ground-referenced outputs

Harry Bissell Jr, Welding Technology Corp, Farmington Hills, MI

Three-phase VCOs (voltage-controlled oscillators) see service in many applications, including power inverters and in electronic-music synthesis as control and modulation sources. A previous Design Idea describes a basis for a simple, three-phase VCO (**Reference 1**). However, adding a few components enhances the circuit's performance. The original circuit delivers an output of only 600 mV p-p and cannot tolerate substantial loading, especially at low operating frequencies at which the circuit draws the least operating current. Providing ac coupling for the output signals doesn't work well at low frequencies and worsens the loading problem. Finally, the circuit's dc operating point varies with frequency.

The circuit in **Figure 1** elegantly overcomes these limitations. The original circuit uses three of six of a CD4069UB hex inverter's subcircuits. One of the spares, IC_{1A}, senses the complete circuit's dc operating point. Resistor R_2 provides linear feedback around IC_{1A}, forcing the input voltage at Pin 9 to equal the output transition threshold voltage over a range of operating currents. In other words, the voltage is proportional to the average dc value of the sinusoidal output waveforms.

A voltage follower, IC_{2A}, buffers the averaged voltage at IC_{1A}'s Pin 8. The remaining sections of IC_2 buffer the oscillator's three outputs, equalizing the loading on the oscillator and providing low-impedance drive to three differential amplifiers: IC_{3A}, IC_{3B}, and IC_{3C}. The differential stages subtract the dc offset voltage from IC_{2A} from the buffered three-phase outputs. You can alter the voltage gain of the three differential amplifiers from its nominal factor of five to suit other applications.

Zener diode D_1 limits the voltage to 10V at IC_1's Pin 14. At low frequencies and currents, the oscillator's dc operating point can easily exceed the linear range of IC_2's inputs. You can use rail-to-rail-capable operational amplifiers instead of LM324-family devices. Note that the inputs of IC_1's remaining unused inverters connect to IC_1's Pin 7 and not to circuit ground per normal practice.

Adding an exponential current source eases the task of adjusting the circuit over a wide frequency range. Transistors Q_1 and Q_2 and their associated components form a simple exponential voltage-to-current converter. For best results, the base-emitter voltages of Q_1 and Q_2 should match at the circuit's nominal operating current—100 μA—and you should thermally couple both transistors. If your application requires precise thermal tracking, replace R_6 with a 2-kΩ temperature-compensating resistor with a coefficient of 3500 ppm/°C, such as a Tel Labs Q81, which is available from such companies as Precision Resistor (www.precisionresistor.com). Place this resistor in thermal contact with Q_1 and Q_2. Temperature-compensating resistors are also available from Micro-Ohm (www.micro-ohm.com), Vishay (www.vishay.com), Ultronix (www.ultronix.com), and KRL Bantry (www.krlbantry.com).

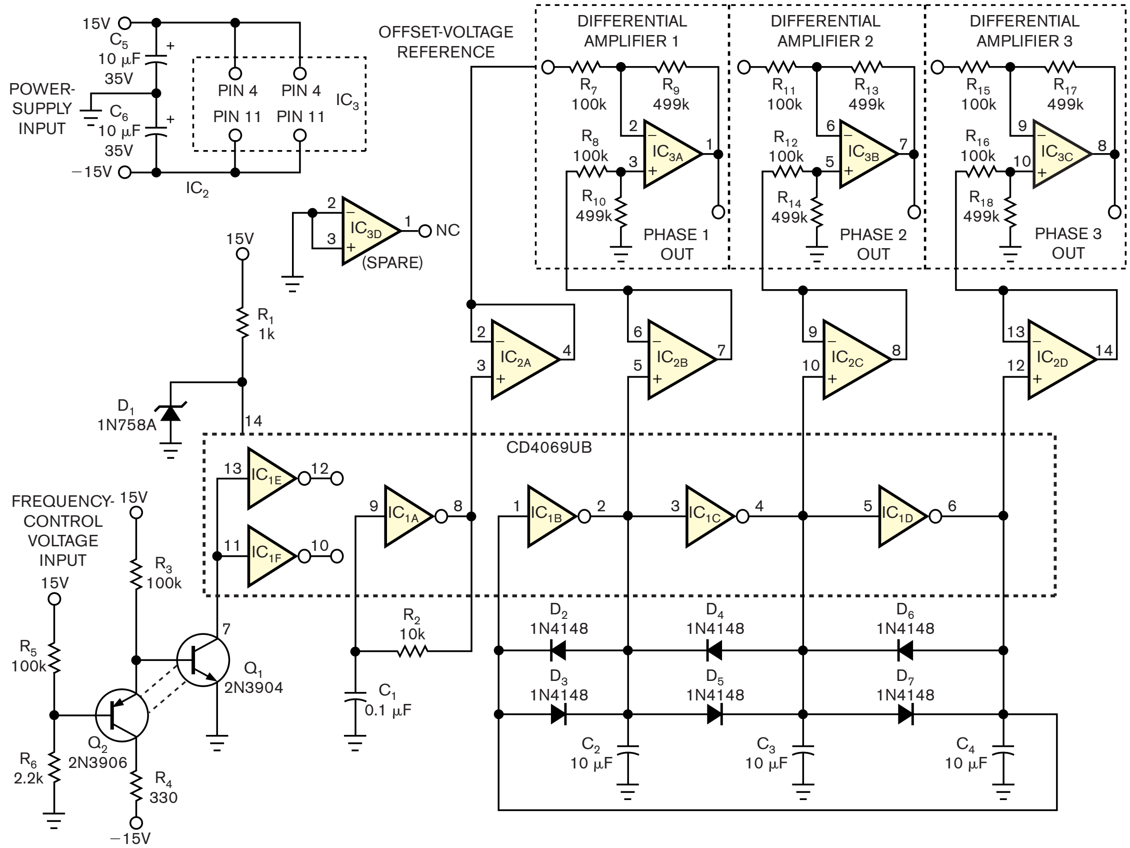
Using the component values in **Figure 1**, the circuit's operating frequency spans 0.1 to 26 Hz. Adding the components in this Design Idea reduces the circuit's dc operating-point shift from 5.5V to less than 25 mV over the frequency range. Most of the frequency

(continued on pg 84)

error occurs at the low end of the frequency range, at which it's the least objectionable.**EDN**

REFERENCE

1 Dutcher, Al, “Inverters form three-phase VCO,” *EDN*, Aug 2, 2001, pg 102, www.edn.com/article/CA149120.



NOTES:
PLACE Q_1 AND Q_2 IN THERMAL CONTACT.
FOR BEST STABILITY, USE NONPOLARIZED CAPACITORS FOR C_2, C_3, AND C_4.
DOTTED LINES BETWEEN Q_1 AND Q_2 INDICATE THERMAL CONTACT.

Figure 1 Adding differential and buffer amplifiers and an exponential voltage-to-current converter enhances the performance of a low-frequency, three-phase voltage-controlled oscillator.

Improved current monitor delivers proportional-voltage output

Susanne Nell, Breitenfurt, Austria

This Design Idea expands the capabilities of a previously published one (**Reference 1**). The original version featured a current transformer whose secondary winding formed part of an oscillator's tank circuit. Under normal conditions, direct current flowing through the current transformer's single-turn primary winding kept the circuit from oscillating until primary current flow ceased. Although the circuit acted as a power-interruption detector, when you add a few components, the operating principle lends itself to measurement applications. This revised circuit delivers an accurate linear-voltage output that's proportional to direct current flow through current-sense transformer T_1's primary winding (**Figure 1**). In addition, the circuit also offers possibilities as an ac current sensor.

To achieve improved performance, the design retains the original oscillat-

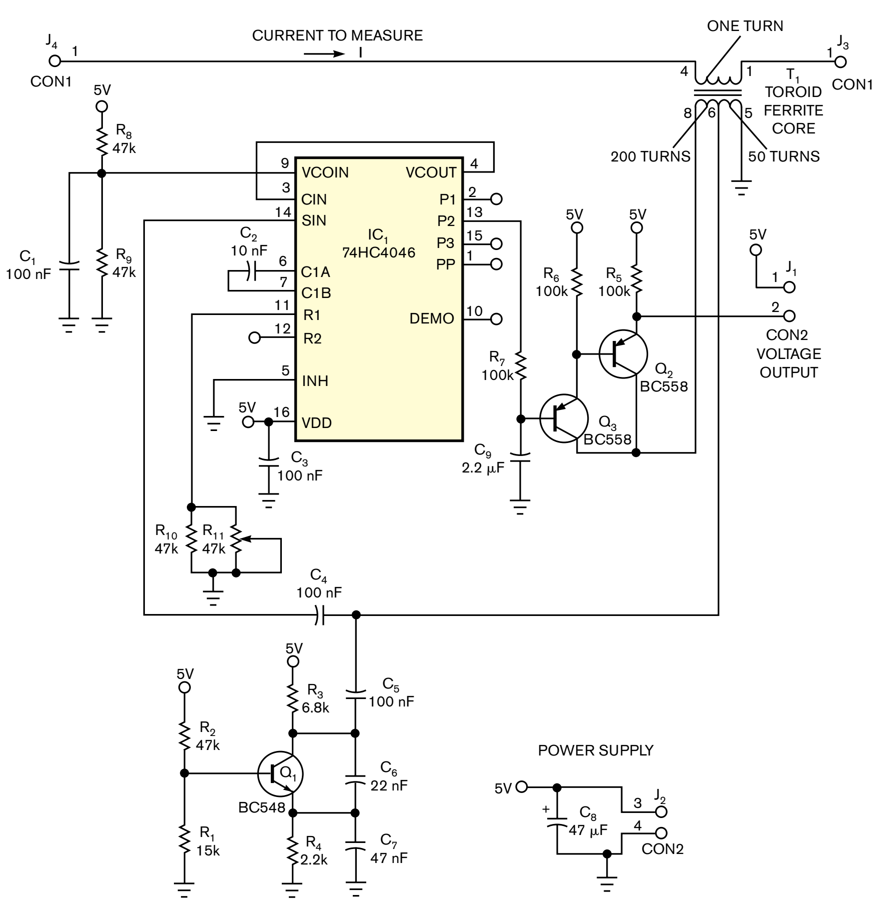


Figure 1 This current sensor uses a variable-frequency oscillator, Q_1, and a PLL, IC_1, to measure current in an isolated circuit.

ing-circuit concept and adds a PLL circuit and one additional winding to the current transformer whose secondary forms an LC oscillator's resonant circuit. Integrating a 74HC4046, IC_1, the PLL measures the frequency of an LC oscillator comprising Q_1 and its associated components and compares it with a fixed-frequency internal VCO (voltage-controlled oscillator). The PLL's phase-comparator output drives a current source comprising Q_2 and Q_3, which in turn feeds current to an additional winding on the current-sense transformer's core.

Sources of T_1's ferrite core include Epcos (www.epcos.com), which offers the B64290L 632×87-toroid 20×10×7 material N87; Pramet (wwwpramet.com), which offers Fonox Type T20 material H60; Vacuumschmelze (www.vacuumschmelze.com), with the VAC T60006L2020-W409-52; and other manufacturers. Depending on the ferrite material you use, the circuit will operate to some degree with virtually any ferrite toroidal core. (It is difficult to simulate this circuit using PSpice or other simulators; for accurate results, you need a complex model that accurately portrays the core's nonlinear behavior at various current levels.)

The added winding induces magnetic flux in the core, decreasing its permeability and inductance and raising the LC oscillator's frequency. When the oscillator's frequency matches the VCO (reference) frequency, the circuit reaches an equilibrium state. An increasing or decreasing current through the compensation coil balances any additional magnetic flux that dc current flowing through the measurement coil produces.

Within the PLL's frequency-tracking range, the current waveform through the compensation coil has the same shape as fluctuations of the measured current. The turns ratio of 1-to-250, which also represents the ratio of currents in transformer T_1, establishes a secondary current of 10 mA for a primary current of 2.5A. If the PLL circuit's gain is sufficient and the ferrite core's region of operation avoids saturation, the circuit's closed-loop configuration maintains the core's magnetic flux at a constant value and thus minimizes the effects of core-material nonlinearities.

Measuring the voltage difference across resistor R_5 shows that the circuit's output voltage is linearly proportional to the compensation current, and R_5's resistance scales the voltage output. For 100Ω at R_5, a 1V output corresponds to a primary-side current of 2.5A. With zero current flowing in the single-turn primary winding, calibrate the circuit's range by adjusting potentiometer R_{11} to a set operating point. A voltage drop of 2V across R_5 sets a measurement range of +5 to −5A. To accommodate other measurement ranges, you can alter T_1's turns ratio or vary the compensation current by using different values for R_5 and R_{11}. Use a well-regulated power supply to provide power for the circuit. You may be able to replace the 74HC4046 with a software PLL-emulation routine that uses a microcontroller's spare processing resources. **EDN**

REFERENCE

1 Ackerley, Kevin, "Impedance transformer flags failed fuse," *EDN*, Dec 17, 2004, pg 67, www.edn.com/article/CA486572.