Application Report

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Large-Signal Specifications for High-Voltage Line Drivers

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ABSTRACT

Output voltage swing, output current, and slew rate interact with many other specifications in operational amplifiers. This application note develops the definitions for each parameter and the relationship between important ac parameters such as large-signal bandwidth and distortion.

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1 Introduction

Bandwidth and distortion performance of an operational amplifier do not remain constant over the entire output voltage swing range of the amp. Some of the device parameters that affect both bandwidth and distortion are what is normally considered ***dc parameters*** (such as output current and output voltage), or parameters defined when the amplifier is saturating (such as slew rate). This application note defines each of these parameters and provides guidelines for designers to follow during the selection process in order to achieve maximum performance.

In the high-speed amplifier market, there are two primary competing architectures. Each approach offers its own set of advantages. It is appropriate to begin, then, by understanding how to identify a good standalone op amp for a high-speed, high voltage swing application.

1.1 Voltage-Feedback or Current-Feedback Op Amps

In applications where a high voltage swing output is required, the output signal conditioning stage (or stages) typically requires gain. The signal may originate from a 3.3-V or 5-V digital-to-analog converter (DAC) with a 1-V_{PP} output voltage range, while the required signal is a single-ended 10 V_{PP} or higher. Depending on the bandwidth and slew rate requirements, the gain and output swing requirements generally determine the use of either a current feedback (CFB) amplifier or a voltage feedback (VFB) amplifier.

Voltage Feedback

VFB op amps are typically constrained by the gain-bandwidth product (GBWP) parameter. GBWP theory dictates that if an op amp has a bandwidth of 10 MHz at a gain of 10 V/V, then it has 5-MHz bandwidth at a gain of 20 V/V, 20-MHz bandwidth at a gain of 5 V/V, and so on. The product of the gain times the bandwidth is constant. High-speed VFB amplifiers do not strictly follow this rule at lower gains because of less compensated designs and package parasitics that affect unity-gain bandwidth (see Ref. 1). However, the general inverse relationship between gain and bandwidth is evident in most VFB amplifiers. As an example, consider the OPA820 and the THS4631, two high-speed VFB amplifiers.

The OPA820 is a high-speed, 12-V capable, bipolar voltage feedback op amp. Table 1 shows the small-signal bandwidth specifications from the OPA820 product data sheet.

Table 1. OPA820 Small-Signal Bandwidth and Gain-Bandwidth Product

		OPA820ID, IDBV				
		TYP	MIN/MAX OVER TEMPERATURE			
PARAMETER	CONDITIONS	+25°C	+25°C	0°C to 70°C	–40°C to +85°C	UNIT
AC PERFORMANCE						
Small-Signal Bandwidth	G = +1, V_O = 0.1V_{PP}, R_F = 0Ω	800				MHz
	G = +2, V_O = 0.1V_{PP}	240	170	160	155	MHz
	G = +10, V_O = 0.1V_{PP}	30	23	21	20	MHz
Gain-Bandwidth Product	G ≥ 20	280	220	204	200	MHz

The GBWP is specified as 280 MHz and all small-signal bandwidths adhere closely to the expected results. At a gain of 10 V/V, the small-signal bandwidth is 30 MHz, which is close to the 280-MHz GBWP. At 2-V/V gain, the small-signal bandwidth is 240 MHz, which already exceeds the GBWP. Notice that at low gains, the small-signal bandwidth times the gain is actually much larger than the GBWP.

Table 2 presents the same performance data for the THS4631, a high-voltage, high slew rate, wideband FET op amp. These data (from the THS4631 product data sheet) indicate that the GBWP relationship holds more steady at lower gains than it does with the OPA820. In the same manner for the lowest gain, however, the relationship between gain and bandwidth breaks down.

Table 2. THS4631 Small-Signal Bandwidth and Gain-Bandwidth Product

		THS4631				
		TYP	MIN/MAX OVER TEMPERATURE			
PARAMETER	CONDITIONS	+25°C	+25°C	0°C to 70°C	–40°C to +85°C	UNIT
AC PERFORMANCE						
Small-Signal Bandwidth, –3 dB	G = 1, R_F = 0 Ω, V_O = 200 mV_{PP}	325				MHz
	G = 2, R_F = 499 Ω, V_O = 200 mV_{PP}	105				MHz
	G = 5, R_F = 499 Ω, V_O = 200 mV_{PP}	55				MHz
	G = 10, R_F = 499 Ω, V_O = 200 mV_{PP}	25				MHz
Gain-Bandwidth Product	G > 20	210				MHz

Current Feedback

In contrast with VFB op amps, CFB op amps do not have a gain-bandwidth product. While the feedback factor that determines compensation in VFB op amps involves both gain-setting resistors (that is, the noninverting gain or the noise gain), the feedback factor in CFB op amps only involves the feedback resistor. This architecture ultimately results in a relative independence between the gain and bandwidth in CFB op amps. An in-depth discussion of the VFB versus CFB topology can be found in the application note, Voltage Feedback vs Current Feedback Op Amps (see Ref. 2).

Looking at the relationship between gain and bandwidth for current-feedback amplifiers, the THS3091 high-speed, 30-V current-feedback op amp shows an example of the relative independence between gain and bandwidth. This effect is illustrated in Table 3 (from the THS3091 product data sheet).

Table 3. THS3091 Small-Signal Bandwidths for Different Gains

PARAMETER	CONDITIONS	THS3091 TYP	THS3091 MIN/MAX OVER TEMPERATURE			UNIT
		+25°C	+25°C	0°C to 70°C	–40°C to +85°C	
AC PERFORMANCE						
Small-Signal Bandwidth	G = 1, R_F = 1.78 kΩ, V_O = 200 mV_{PP}	235				MHz
	G = 2, R_F = 1.21 kΩ, V_O = 200 mV_{PP}	210				MHz
	G = 5, R_F = 1 kΩ, V_O = 200 mV_{PP}	190				MHz
	G = 10, R_F = 866 Ω, V_O = 200 mV_{PP}	180				MHz

While the THS3091 at unity-gain has almost 100 MHz lower bandwidth than the THS4631, the THS3091 is able to maintain a much higher bandwidth than the THS4631 as the gain increases. By the time the gain of both amplifiers is set at a 10-V/V configuration, the THS3091 has more than seven times the bandwidth of the THS4631. The bandwidth advantage at higher gain configurations of the THS3091 CFB amplifier compared to the THS4631 VFB amplifier also suggests that the THS3091 has more loop-gain margin available at higher frequencies (translating to better distortion performance at higher frequencies) than the THS4631. This characteristic is a direct consequence of the device architecture: the CFB compensation is the feedback resistance and the inverting input resistance times the noise gain (R_F + $r_{inv.}$ NG), instead of the noise gain (NG) alone for VFB op amps. As the gain increases, the feedback resistance decreases to maintain optimum compensation; in other words, the term (R_F + $r_{inv.}$ NG) remains constant.

Why review the small-signal bandwidth advantage of CFB amplifiers when the signals of concern have large swings? As this report discusses later, slew rate is the major factor that determines large-signal bandwidth. Small-signal bandwidth typically sets the upper limit on large-signal bandwidth, while slew rate determines how much bandwidth can actually be realized with large signals. Furthermore, the CFB architecture that allows for higher bandwidth at higher gains also allows the CFB amplifier to achieve much higher slew rates than do traditional, differential-pair input VFB amplifiers. This CFB architectural advantage has been implemented in slew-boosted VFB architecture, thereby minimizing the slew rate differences. These slew-boosted VFB op amps, however, are still limited by the GBWP characteristic.

2 Slew Rate

Slew rate is the measure of the maximum rate of change that the operational amplifier output can achieve.

This specification can be expressed as:

$$SR = \frac{dV}{dt}$$

Slew rate is a large-signal parameter and should not be confused with rise and fall times, two small-signal parameters.

Slew rate is specified in units of volts per unit of time; typically, volts per microsecond (V/µs). For example, the THS3091 is rated for a typical slew rate of 7300 V/µs at a gain configuration of 5 V/V for a 20-V output step, meaning that the output can swing 20 V in about 2.7 ns (20 V / 7300 V/µs = 2.7 ns). The time it actually takes for the output to swing 20 V is greater than 2.7 ns because of the fact that the slew rate is measured from 25% to 75% (or 10% to 90%, depending on the definition of the specification that is used) of the step voltage, and there is no slewing in the first and last 25% (or 10%) of the voltage step. Figure 1 shows the pulse response of the THS3091 configured at a gain of 5 V/V and driven with a 4-V_{PP} square wave input. Figure 2 shows the same pulse response but is enlarged to illustrate the slew rate at the rising edge.

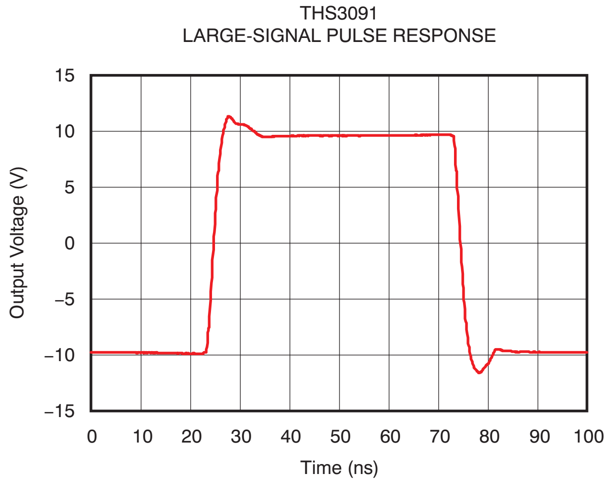

Figure 1. THS3091 10-MHz Pulse Response, Gain of 5-V/V Configuration, 100-Ω Load

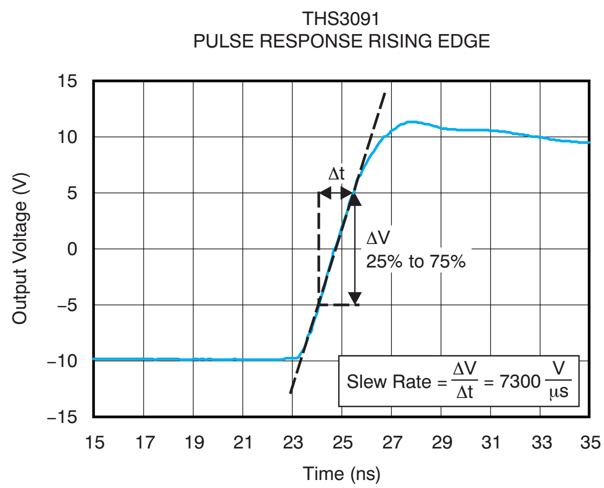

Figure 2. THS3091 Pulse Response Rising Edge, Gain of 5-V/V Configuration, 100-Ω Load

In both VFB and CFB amplifiers, the slew rate is determined by the available current to charge and discharge the internal dominant pole compensation capacitor of the op amp. In a standard VFB amplifier, the current consists of the tail current to the input differential pair. Given a particular device, this tail current is fixed, thus establishing a ceiling to the possible slew rate.

On the other hand, in a CFB amplifier, there is no input differential pair; instead, the noninverting input pin voltage is buffered to the inverting pin, and the resulting error current out of (or into) the inverting input is current-mirrored to charge or discharge the dominant pole compensation capacitor. This error current consists of the current from the op amp output through the feedback resistor and current through the gain setting resistor, which is much greater than the available tail current in a standard VFB amplifier. In this way, a CFB amplifier is capable of having much higher slew rates than a standard VFB amplifier (see Ref. 3).

3 Slew Rate and Large-Signal Bandwidth

For an amplifier with a sine wave input (and ideally, a scaled replica sinewave output centered around 0 V), the maximum slope or rate of change occurs at the zero crossings. For the sine wave signal shown in Figure 3:

$$V(t) = V_P \bullet \sin(2\pi \bullet f \bullet t)$$

The maximum slope magnitudes occur every half-period zero crossing at:

$$T = 0, \frac{T}{2} \ldots n\frac{T}{2}$$

where *n* is any integer and T is the period of the sine wave (or 1/f).

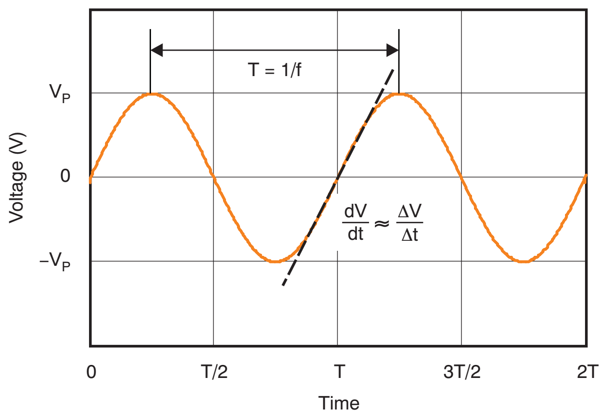

Figure 3. Slew Rate Representation for a Sinewave

The maximum slope can be interpreted as the required slew rate to accurately generate the sine wave. This slew rate can be determined by calculating the first derivative of the waveform with respect to time, and then evaluating the derivative at a zero crossing where the slope is at a maximum.

For the sinusoid V(t), the first time derivative is:

$$\frac{dV(t)}{dt} = 2\pi f \bullet V_P \bullet \cos(2\pi \bullet f \bullet t)$$

Evaluating the derivative at *t* = 0 results in:

$$\frac{dV(0)}{dt} = 2\pi f \bullet V_P$$

Replacing dV/dt in the equation with SR (slew rate) gives a useful relationship that helps determine the required slew rate to pass a sine wave of a desired frequency and amplitude, as shown in Equation 1.

$$SR = 2\pi f \bullet V_P \tag{1}$$

Rearranging Equation 1 yields the inverse equation (Equation 2) that relates an op amp driver with a given slew rate and desired output sine wave amplitude (V_P) to the maximum sine wave frequency, f_{max}, that the driver can successfully pass without being slew-rate limited (see Ref. 4).

$$f_{MAX} = \frac{SR}{2\pi V_P} \tag{2}$$

At frequencies above f_{max}, the output is limited by the slew rate such that the output can no longer track the ideal sine wave output. The op amp enters an open loop when the output becomes slew-limited because the error signal cannot be minimized. For this reason, f_{max} can be considered the non-slew-limited bandwidth of the amplifier.

Figure 4 shows three simulated output waveforms for three drivers with different slew rates versus an ideal 20-V_{PP}, 100-MHz sine wave. Using Equation 1 with a 100-MHz maximum flatband frequency and 10 V for peak amplitude gives a slew rate requirement of 6283 V/µs. In Figure 4, the three drivers are slew-rate limited at 5 kV/µs, 4 kV/µs, and 2.5 kV/µs; thus, the respective outputs are distorted into triangular waves with a slope equal to the slew rate.

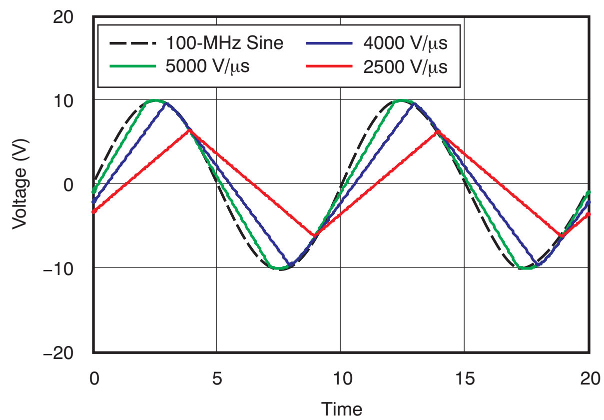

Figure 4. Theoretical Slew-Limited Output for Three Different Slew Rates

As the slew rate decreases to the point where the output reduces to a triangle wave, the peak amplitude of the signal is also reduced, though the fundamental period remains the same. It can be seen from Figure 4 that the peak of a triangular, slew-limited output is the slew rate multiplied by 1/4 of the fundamental period.

It is important to note that the non-slew-limited bandwidth, f_{max}, predicted by Equation 2 is *not* the –3-dB bandwidth. Theoretically, an amplifier with a given slew rate (SR) is able to output a sine wave of amplitude V_P up to a frequency, f_{max}, with no loss in amplitude as a result of slew-limiting. As the signal frequency rises above f_{max}, odd-order harmonic distortion becomes drastically degraded as the output becomes more and more triangular because of slew-limiting. In practice, however, the f_{max} point is not a hard limit, and there is visible distortion (that is, distortion visible on an oscilloscope) well below the non-slew-limited bandwidth.

How well, then, does Equation 2 predict the non-slew-limited bandwidth? In Figure 5 and Figure 6, the measured, non-slew-limited bandwidth for the THS4631 and THS3091 amplifiers are respectively compared against the predicted bandwidths. The calculated non-slew-limited bandwidth using Equation 2 does not correspond to a well-defined frequency response threshold in the same manner that a –3-dB bandwidth does; therefore, Equation 1 can be modified to reflect the loss in signal at the –3-dB point by dividing the amplitude by $\sqrt{2}$ (see Ref. 5), as shown in Equation 3.

$$SR_{-3dB} = 2\pi f \frac{V_P}{\sqrt{2}} \tag{3}$$

The slew rate normally covers only 80% of the signal from 10% to 90%. Consequently, instead of being the derivative of a sine wave, this factor is compensated by multiplying Equation 3 by 0.8, which gives Equation 4:

$$SR_{-3dB,\ 10\% - 90\%} = 0.8 \bullet 2\pi f_{-3dB} \frac{V_P}{\sqrt{2}} \tag{4}$$

The THS4631 product data sheet reports a 10-V step slew rate of 900 V/µs at a gain of 2-V/V configuration. Using Equation 4, the estimated –3-dB bandwidth for a 10-V_{PP} output is 50.6 MHz.

$$f_{-3dB} = \frac{900 \dfrac{V}{\mu s}}{0.8 \bullet 2\pi \dfrac{V_P}{\sqrt{2}}} = 50.6\ \text{MHz}$$

Figure 5 shows the measured large-signal frequency response taken with a network analyzer for the THS4631. As expected, the –3-dB bandwidth is reduced for a 10-V_{PP} output and matches the calculated value.

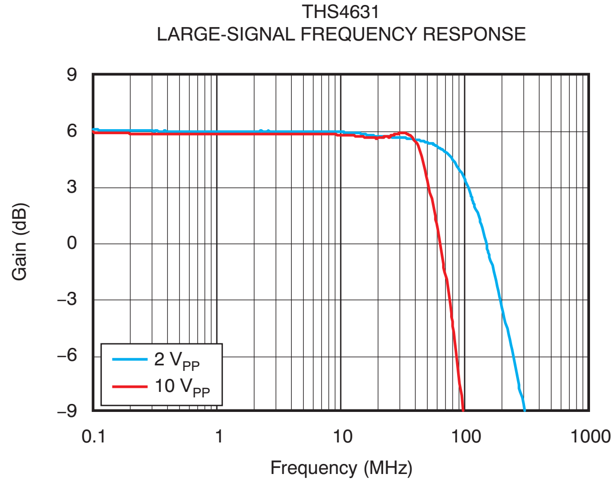

Figure 5. THS4631 Large-Signal Frequency Response, Gain = 2 V/V

Applying Equation 4 to the THS3091 produces a result with some contradiction: 7300 V/µs for a gain of 5 V/V with a 20-V step indicates that the amplifier can support a 200-MHz, 20-V_{PP} large-signal bandwidth, and 5000 V/µs for a gain of 2 V/V with a 10-V step indicates that a 280-MHz large-signal bandwidth is possible. Both of the large-signal bandwidth measurements in Figure 6 show a –3-dB bandwidth in the range of 120 MHz to 150 MHz.

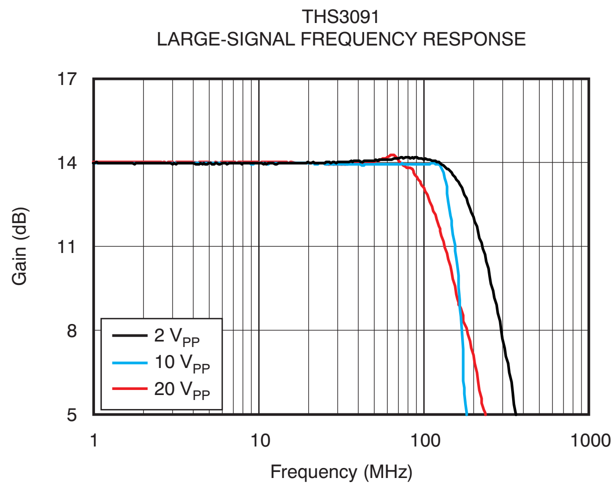

Figure 6. THS3091 Large-Signal Frequency Response, Gain = 5 V/V

This result indicates that the slew rate measurement made is incorrect because the amplifier may not have been slew-limited, or that the 25% to 75% measurement cannot be used when comparing the slew rate to large-signal bandwidth.

Therefore, while Equation 4 can provide a good indicator of the actual slew rate capability of an amplifier, it does not always align with the actual large-signal behavior of a given op amp. As mentioned before, the distortion performance begins to degrade well before the non-slew-limited bandwidth is reached, and choosing an op amp with an excess slew rate (that is, a rate greater than actually required) is recommended. To achieve an 80-dBc distortion level, it is recommended to have the amplifier slew 20 times faster than the maximum signal.

4 A Warning about Spice Simulations

Spice simulation tools are useful to verify the first-order expectation of the behavior and performance of a circuit. To make maximum use of the model, though, it is important to understand the limitations of simulations and device models.

A Spice ac simulation reduces the simulation circuit to an idealized linear model and calculates the circuit frequency response based on infinitely small signals around the operating point. Therefore, an ac sweep is not able to demonstrate any large-signal frequency response of an op amp circuit. A time-domain or transient analysis simulation gives a better indication of large-signal behavior, provided that the op amp slew rate has been modeled in the macromodel. The Spice macro header information for most newer TI high-speed op amp device models specify the device parameters that have been modeled.

5 Output Voltage Swing and Output Current

The last important considerations when selecting an op amp for driving large output signals are output voltage swing and output current drive. The first consideration here is that the output transistors in an op amp output stage require headroom from the supply voltage, thus limiting the output swing. A high-voltage, high output current op amp typically uses a push-pull emitter output stage that requires 1 V to 2 V of headroom from the positive supply and from the negative supply with no output load. This headroom requirement depends on the operating supply voltage of the amplifier as well as the output drive capability. A ±15 V amplifier normally has a higher headroom requirement than a ±5-V supply device. For example, the THS3091 output voltage swing versus load resistance graph shown in Figure 7 illustrates that with a 1-kΩ resistive load, the output voltage swing with ±15-V supplies is approximately ±13.2 V.

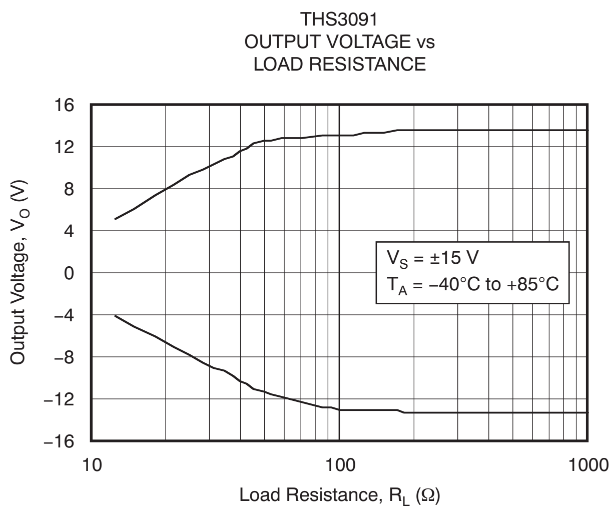

Figure 7. THS3091 Output Voltage Swing versus Load Resistance

The output voltage swing is also affected by the output current ability of the amplifier. Figure 7 shows the significance of an amplifier output current sinking and sourcing capability. As the load resistance decreases below 100 Ω, the output voltage swing range of the THS3091 becomes limited as a result of the finite current output to drive the load (V = IR).

The latest line driver amplifier data sheets also include an output voltage versus output current graph that can be used to quickly evaluate the op amp voltage and current limitations. Figure 8 shows such a graph for the OPA2673 that also provides a useful 2-W internal power dissipation boundary.

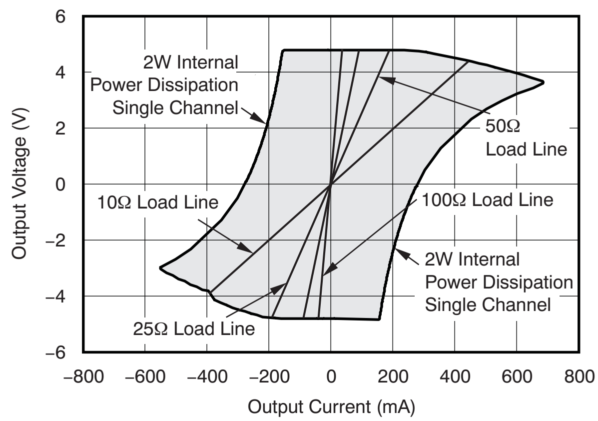

Figure 8. OPA2673 Output Voltage versus Output Current

6 Conclusion

Slew rate, output voltage swing, and output current drive are strongly related to bandwidth and distortion. The parameters and architectural concepts developed in this application note can be used during the selection process to refine component selection.

7 References

Unless otherwise indicated, the following documents are available for download at www.ti.com.

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