Load Sharing Concepts: Implementation for Large-Signal Applications

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ABSTRACT

Selecting a suitable large-signal swing operational amplifier driver for instrumentation or test and measurement applications can be challenging. In addition to developing the necessary theoretical background for load sharing, this report provides bench results to demonstrate the implementation and benefits of load sharing and output paralleling.

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1 What Constitutes a Large Signal?

Most operational amplifier data sheets define *large signal* as any output signal that swings greater than 2 V_{PP} for ±5-V amplifiers and 5 V_{PP} for ±15-V amplifiers. However, the performance that is specified as *large signal* depends on the intended application as well as the internal architecture of the specific device. For example, a low-voltage, +5-V, fully-differential, voltage-feedback architecture analog-to-digital converter (ADC) driver amplifier such as the THS4521 specifies a 2-V_{PP} large-signal bandwidth because 2 V_{PP} is a common ADC analog input range. On the other hand, a high-voltage ,+28-V, current-feedback architecture, high output power line driver device such as the THS6204 specifies large-signal performance for 4-V_{PP} to 20-V_{PP} output.

In fact, the output voltage swing of an amplifier can affect the bandwidth by more than 50% at 20-V_{PP} output compared to a small-signal (200 mV_{PP}) bandwidth as a direct result of slew rate limitation or loading. For a detailed discussion on the parameters affected by the output voltage swing, refer to the application note *Large-Signal Specifications for High-Voltage Line Drivers* (SBOA126), available for download from the TI website. As a first-order rule, distortion performance is also degraded by 6 dB for second-harmonic distortion and 12 dB for third-harmonic distortion every time the signal doubles. This behavior is shown in Figure 1 for a 1-kHz signal using the THS6182.

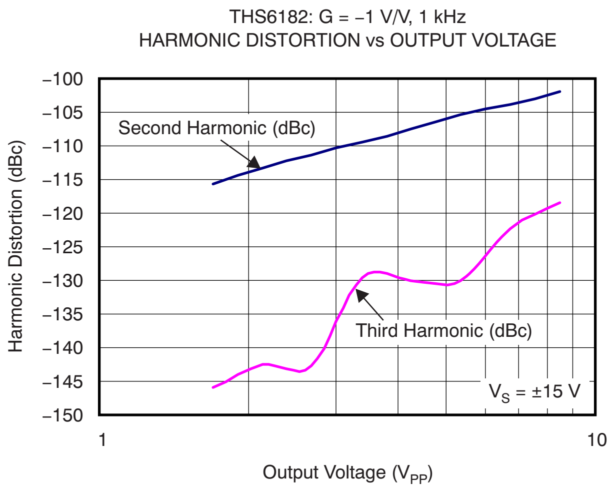

Figure 1. 1-kHz Harmonic Distortion vs. Output Voltage (THS6182)

Slew rate, output voltage swing, and output current are key operational amplifier parameters to consider for large signals applications, in particular when targeting low distortion as key design parameter. As a reminder, here is a brief summary of these three specific parameters and the respective relationships to bandwidth, distortion, and amplifier architecture.

1. Slew rate is directly related to the large-signal bandwidth of an operational amplifier. Slew rate limitation may also be a factor in the distortion of the amplifier. As a rule of thumb, to be able to support 80 dBc for a given frequency, the amplifier achievable slew rate must be 20x the slew rate requirement to support the signal at that frequency.
2. The amplifier output current sourcing and sinking ability into the load determine the output voltage swing range of the device. As the load current increases, distortion suffers. Additionally, high-speed large signal swings into a capacitive load require the amplifier to quickly charge and discharge the load. Depending on the load capacitance, the limited amplifier current sourcing and sinking ability may lead to a lower effective slew rate into the capacitive load.
3. The amplifier output is distorted as it approaches the output voltage swing range as a result of compression because the transistor swing is getting too close to the voltage rail.

In high voltage swing applications, where an operational amplifier is pushed to drive close to its supply rail, it is possible to drive several identical operational amplifiers in parallel and combine the outputs to achieve higher bandwidth and lower distortion. The remainder of this application report develops this concept of load sharing, and demonstrates how this technique can be used to reduce current sourcing and sinking requirements in the amplifier.

2 Load Sharing Amplifiers

2.1 Concepts

The fundamental concept of load sharing is to drive a load using two or more of the same operational amplifiers. Each amplifier is driven by the same source. Figure 2 shows three THS3091 amplifiers sharing the same load.

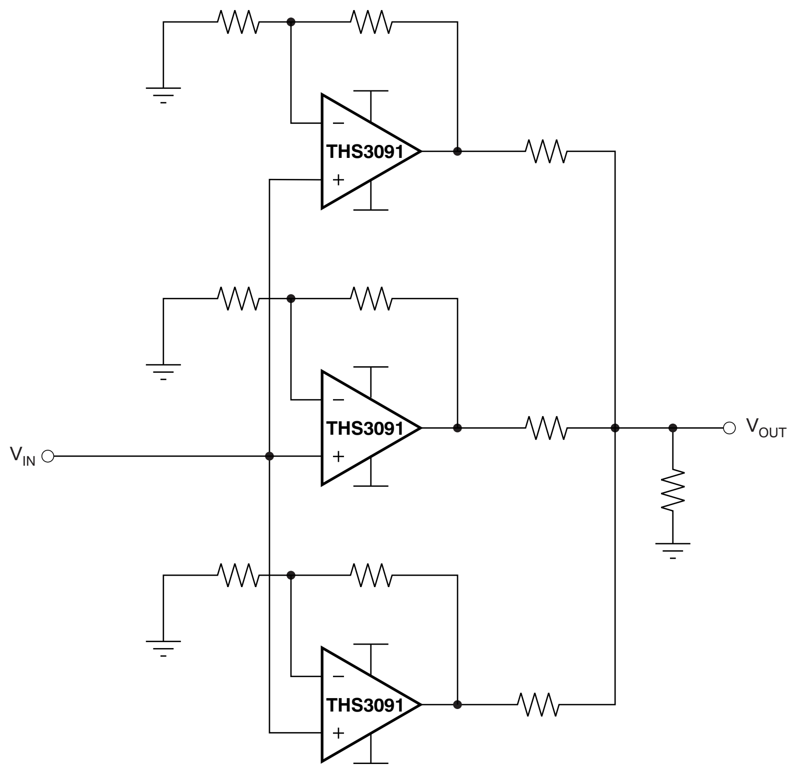

Figure 2. Load Sharing Conceptual Block Diagram

This concept effectively reduces the current load of each amplifier by 1/N, where *N* is the number of amplifiers.

The balance of this report focuses on selection of component values and demonstrated performance improvements.

Figure 3 shows two THS3091 devices configured in a typical load sharing configuration.

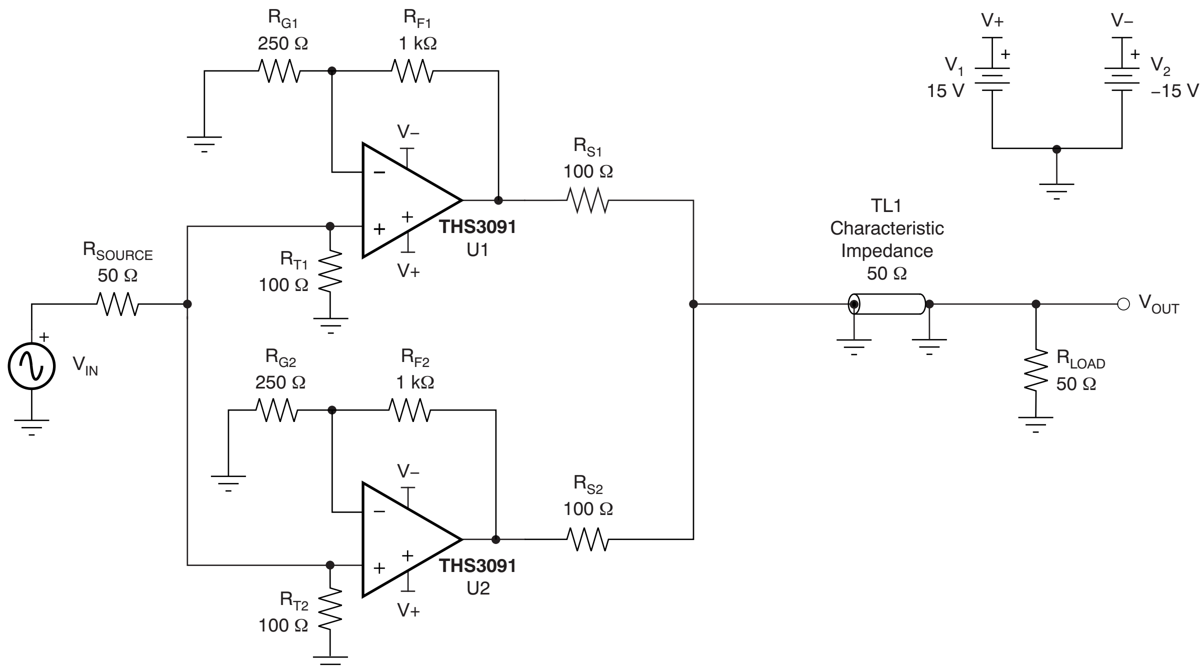

Figure 3. Two THS3091 Amplifiers in Load Sharing Configuration

In this example, each THS3091 is configured in a noninverting gain of +5 V/V with the two noninverting inputs tied to a common input signal, V_{IN}. Several items are worth noting:

- Each output has 100-Ω resistors in series. This configuration provides matching to the 50-Ω load. Looking from the load, then, both resistors appear to be in parallel, presenting a 50-Ω matched impedance to the 50-Ω load through the transmission line.
- The matched load 50-Ω impedance minimizes reflections at the load end of the transmission line. This reduced reflection, however, comes at the expense of 6-dB attenuation of the signal that reaches the load.
- The matched input impedance is realized with two 100-Ω resistance that appear to be in parallel with the 50-Ω source.

For applications where back or double termination is not required or desired, a non-zero resistor on each amplifier output is highly recommended; the resistors help to balance the current load so that each amplifier provides the same current. Because both amplifiers are low-impedance, this configuration also minimizes the tendency of one amplifier driving the other amplifier, as could be the case if the output offset voltages were different.

The next section focuses on the dc offset contribution that results in unequal load current distribution. Differences in gain from one amplifier to the next because of mismatched resistors also leads to imbalanced output voltages and load currents.

Note that the topic of gain mismatch is not developed in this report, but may need to be considered, depending on the final application.

2.2 Output DC Offset

One guideline for selecting the value of the series output resistors can be determined by analyzing the circuit of Figure 3. The goal of load sharing amplifiers is for the current load of each amplifier to be reduced by sharing the load current requirement. This method requires that neither amplifier supplies the majority of the load current and that neither amplifier sources current into or sinks current from the output of the other amplifier. If these conditions were to occur, the circuit would not work at all, and the purpose of the load sharing approach is defeated entirely.

Note that on one hand, the current requirement for a given amplifier has been reduced, but the amplifier must support the full voltage swing. This approach only relaxes the driving capability requirement of the driver and increases the pool of amplifiers to select from. This increased selection pool further allows the design to achieve higher bandwidth than would otherwise have been possible with monolithic amplifiers.

Unequal load currents can result when load sharing amplifier outputs are mismatched in voltage. One source of mismatch is output-referred offset voltage. The worst-case, output-referred offset voltage can be calculated using Equation 1.

$$V_{OS\_RTO} = |V_{OS}| \bullet \left(1 + \frac{R_F}{R_G}\right) + |I_{B+}| \bullet R_{NE} \bullet \left(1 + \frac{R_F}{R_G}\right) + |I_{B-}| \bullet R_F \tag{1}$$

Where V_{OS} is the input offset voltage, I_{B+} is the noninverting input bias current, I_{B-} is the inverting bias current, and R_{NE} is the equivalent resistance looking out of the noninverting terminal.

For the THS3091, the maximum input offset voltage is 4 mV; the maximum noninverting and inverting input bias currents are both 20 µA. Looking out of the noninverting terminal of either amplifier, the equivalent resistance is $R_{T1} \| R_{T2} \| R_{SOURCE}$ = 25 Ω. Using these values in Equation 1, the output-referred offset voltage is calculated as Equation 2 shows.

$$V_{OS\_RTO} = 4\text{ mV} \bullet \left(1 + \frac{1\text{ k}\Omega}{250\ \Omega}\right) + 20\ \mu\text{A} \bullet 25\ \Omega \bullet \left(1 + \frac{1\text{ k}\Omega}{250\ \Omega}\right) + 20\ \mu\text{A} \bullet 1000\ \Omega = 42.5\text{ mV} \tag{2}$$

For a worst-case analysis, it is typical to presume that the offset can either be positive or negative; consequently, the final output-referred offset voltage is ±42.5 mV. For two amplifiers in a load sharing configuration, an offset of ±42.5 mV for each amplifier indicates that a voltage as high as 85 mV can be developed between the two outputs at dc, assuming perfectly-matched gain-setting resistors.

Although dual amplifiers should have better matching than single operation amplifier, a dual operational amplifier in a single package approach is not recommended because of limited power-supply rejection (PSR) isolation in the standard dual footprint package. In a dual standard footprint package, the power-supply pins are shared; this configuration could lead to positive feedback on the other amplifier, and result in oscillations. The other issue to consider if looking into a dual operational amplifier in a single package is thermal power dissipation, especially where heavy loads are concerned.

The circuit shown in Figure 3 can be simplified for further analysis as shown in Figure 4. Consider a case where the input to the load sharing amplifiers is at 0 V. Because of the non-ideal offset and bias currents of the amplifiers, the outputs are not 0 V. In the worst-case situation, the output of Amplifier U1 is the positive worst-case, output-referred offset voltage and the output of Amplifier U2 is the negative worst-case offset.

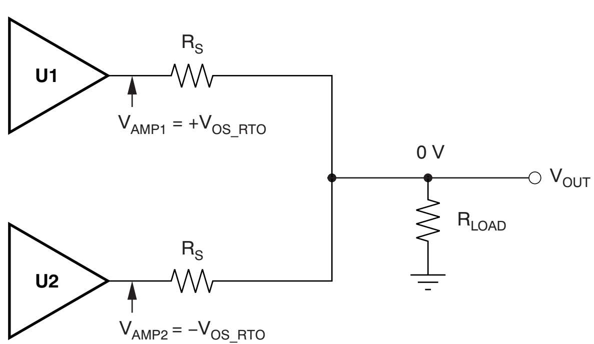

Figure 4. Simplified Load Sharing Circuit

With matched series output resistors (R_S), the voltage at the load (V_{OUT}) is 0 V. The current from Amplifier 1 is simply $+V_{OS\_RTO}/R_S$ and the current from Amplifier 2 is $–V_{OS\_RTO}/R_S$.

Amplifier U1 is sourcing current into the output of Amplifier U2 without generating any signal on the load. This event is not a desired behavior; at best, this configuration would dissipate power, and at worst, it could damage the amplifiers. R_S is therefore necessary in order to limit the current that one amplifier attempts to drive into the other in this worst-case condition.

The difference in the two currents is given by Equation 3.

$$I_{DIFF} = \frac{V_{OS\_RTO}}{R_S} - \left(-\frac{V_{OS\_RTO}}{R_S}\right) = 2 \bullet \frac{V_{OS\_RTO}}{R_S} \tag{3}$$

The effect of this difference in current is best illustrated with an example. If R_S is chosen to be 5 Ω for a configuration with two THS3091 amplifiers in a load sharing configuration, the worst-case difference in the two amplifier output currents is 17 mA (= 2 ● 42.5 mV / 5 Ω). During normal operation, if the nominal output of each amplifier in Figure 5 is 5 V, the worst case is that the output of Amplifier U1 is 5.0425 V and the output of Amplifier 2 is 4.9575 V (or the other way around) because of the mismatched offset voltages. Figure 5 shows the resulting currents. As expected, Amplifier U1 supplies 17 mA more current to the load than does Amplifier U2. The total current to the load is the same, but one amplifier always appears to be hotter than the other, and will be more susceptible to failure. In this example, Amplifier U1 also shows harmonic distortion that is worse than expected.

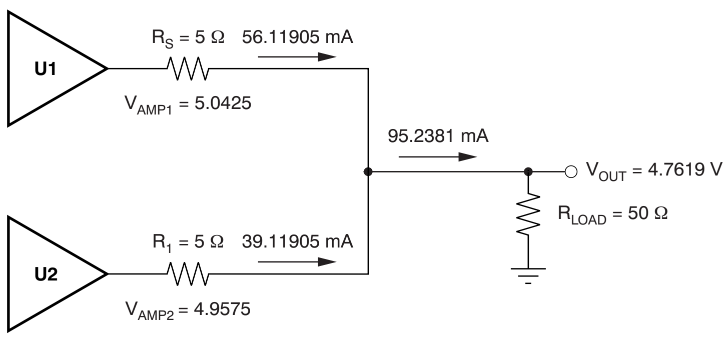

Figure 5. Example of Mismatched Amplifier Output Voltages Producing Unbalanced Amplifier Currents

The difference in amplifier currents can be plotted against the series resistor, R_S. Figure 6 shows the difference in amplifier currents for two load sharing THS3091 amplifiers versus the series resistor, R_S. With an R_S of 10 Ω, the difference in amplifier currents is reduced to 4.25 mA.

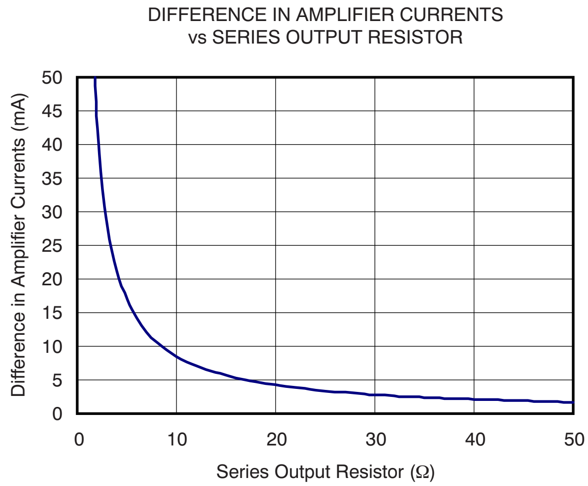

Figure 6. Difference in Amplifier Currents for Two Load Sharing THS3091 Amplifiers vs Series Output Resistor

3 Load Sharing Amplifiers and Distortion Performance

In addition to providing higher output current drive to the load, the load sharing configuration can also provide improved distortion performance. In many cases, an operational amplifier shows better distortion performance as the load current decreases (that is, for higher resistive loads) until the feedback resistor starts to dominate the current load. In a load sharing configuration of *N* amplifiers in parallel, the equivalent current load that each amplifier drives is 1/N times the total load current. For example, in a two-amplifier load sharing configuration with matching resistance (refer to Figure 3) driving a resistive load, R_L, each series resistance is 2 ● R_L and each amplifier drives 2 ● R_L.

A convenient indicator of whether an op amp will function well in a load sharing configuration is the characteristic performance graph of harmonic distortion versus load resistance. Such graphs can be found in most of TI's high-speed amplifier data sheets. These graphs can be used to obtain a general sense of whether or not an amplifier will show improved distortion performance in load sharing configurations.

For example, Figure 7 (from the OPA695 product data sheet) provides a figure of 10-MHz harmonic distortion versus load resistance. This graph shows 9-dB improvement in second-order harmonic performance with a load of 200 Ω compared to a 100-Ω load. Third-order harmonic performance also shows an improvement of about 6 dB. Consequently, the OPA695 may be a good candidate for a load sharing configuration of two OPA695 amplifiers driving a 100-Ω load. The apparent load to each OPA695 will be double the shared resistor load, or 200 Ω.

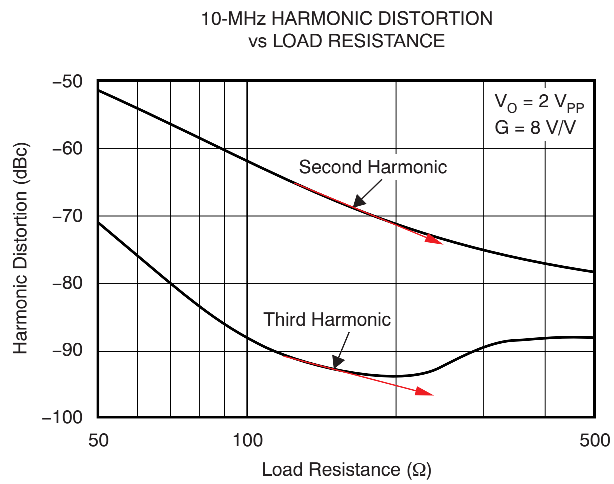

Figure 7. Harmonic Distortion vs. Load Resistance Graph from OPA695 Data Sheet

It is important to note, however, that harmonic distortion does not always improve monotonically as the load resistance increases. Figure 7 shows that for the OPA695, for example, third-harmonic distortion reaches a minimum at a 200-Ω load. With a 500-Ω load, third-harmonic distortion is virtually the same as that observed with a 100-Ω load, while second-harmonic distortion continues to improve. Distortion performance also varies with the output signal swing, typically degrading as the output swing increases, though not always monotonically.

Product data sheets that do not include harmonic distortion versus load resistance graphs usually include distortion versus frequency graphs for different load resistances. The typical distortion performance at a specific frequency for two different loads may also be included in the Electrical Specifications table. For example, the THS3091 data sheet includes typical distortion performance graphs for 100-Ω and 1-kΩ loads. The distortion performance at 10 MHz for a 2-V/V gain configuration and 2-V_{PP} output are also included in the Electrical Characteristics table for this device, and are given in Table 1. The data show that second-harmonic distortion performance is better with a 1-kΩ load than with a 100-Ω load; however, third-harmonic distortion is better with a 100-Ω load than with a 1-kΩ load.

Suppose the THS3091 is chosen to drive a 20-V_{PP} signal into a 100-Ω load (in other words, a double-terminated, 50-Ω cable) and load sharing is being considered. No definitive conclusion can be reached from the available 100-Ω and 1-kΩ performance data and additional characterization would be required.

Table 1. Harmonic Distortion for 100-Ω and 1-kΩ Loads (from THS3091 Product Data Sheet)

			THS3091				
			TYP	MIN/MAX OVER TEMPERATURE			
PARAMETER	CONDITIONS		+25°C	+25°C	0°C to 70°C	–40°C to +85°C	UNIT
Second Harmonic Distortion	G = 2, R_F = 1.21 kΩ, V_O = 2 V_{PP}, f = 10 MHz	R_L = 100 Ω	66				dBc
		R_L = 1 kΩ	77				dBc
Third Harmonic Distortion	G = 2, R_F = 1.21 kΩ, V_O = 2 V_{PP}, f = 10 MHz	R_L = 100 Ω	74				dBc
		R_L = 1 kΩ	69				dBc

4 THS3091 Test Circuits and Load Sharing Performance

As is the case in every design, lab evaluation is the best gauge of performance. Two test circuits are shown in Figure 8, one for a single THS3091 amplifier driving a double-terminated, 50-Ω cable and one with two THS3091 amplifiers in a load sharing configuration. In the load sharing configuration, the two 100-Ω series output resistors act in parallel to provide 50-Ω back-matching to the 50-Ω cable.

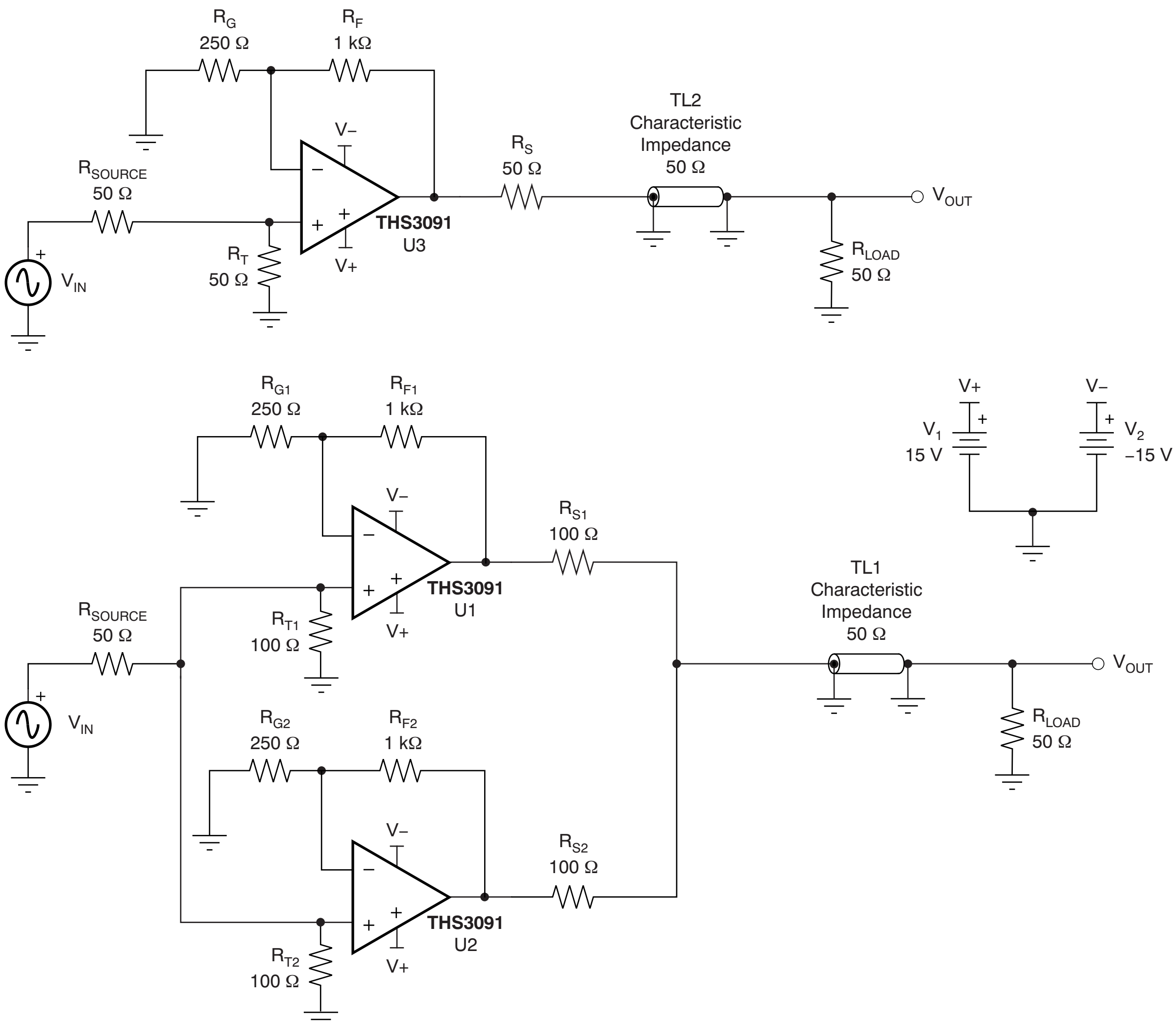

Figure 8. Reference THS3091 and THS3091 Load Sharing Test Configurations

Figure 9 and Figure 10 show the 32-MHz, 18-V_{PP} sine wave output amplitudes for the single THS3091 configuration and the load sharing configuration, respectively, measured using an oscilloscope. An ideal sine wave is also included as a visual reference (the dashed red line).

Figure 9 shows visible distortion in the single THS3091 output. In the load sharing configuration of Figure 10, however, no obvious degradation is visible.

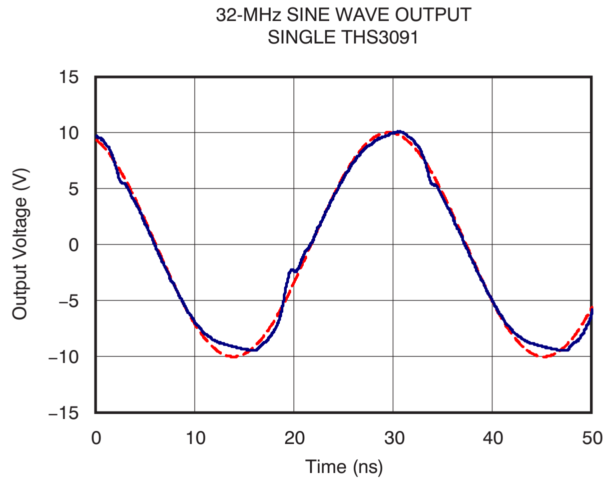

Figure 9. 32-MHz Sine Wave Output (Gain = 5 V/V, Signal Amplitude Referred to Amplifier Output), Single THS3091 Circuit Configuration

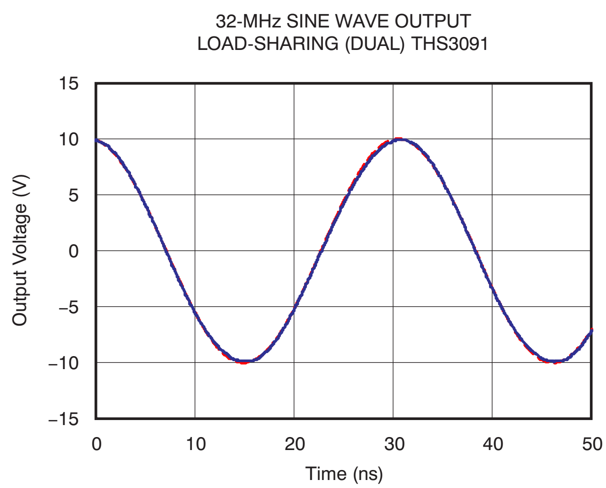

Figure 10. 32-MHz Sine Wave Output (Gain = 5 V/V, Signal Amplitude Referred to Amplifier Output), Two THS3091 Amplifiers in Load Sharing Configuration

Figure 11 and Figure 12 show the 64-MHz sine wave outputs of the two configurations from Figure 8. While the single THS3091 output is clearly distorted in Figure 11, the output of the load sharing configuration in Figure 12 shows only minor deviations from the ideal sine wave.

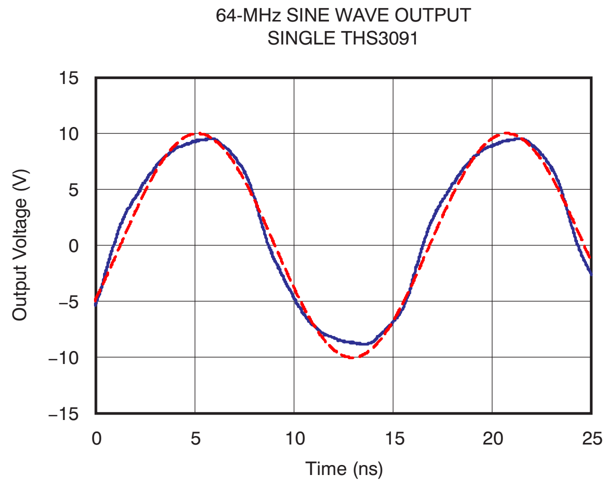

Figure 11. 64-MHz Sine Wave Output (Gain = 5 V/V, Signal Amplitude Referred to Amplifier Output), Single THS3091 Circuit Configuration

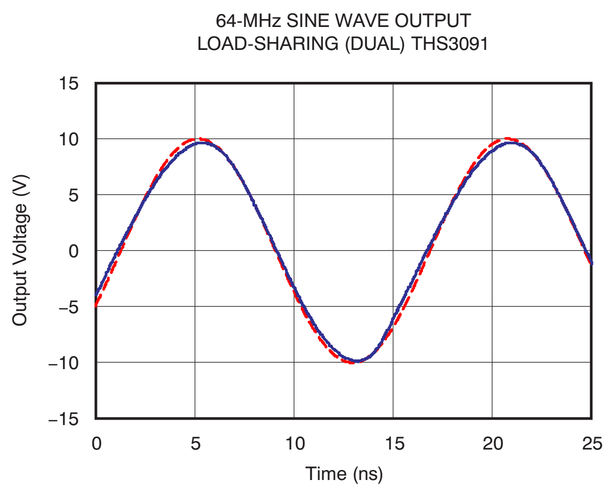

Figure 12. 64-MHz Sine Wave Output (Gain = 5 V/V, Signal Amplitude Referred to Amplifier Output), Two THS3091 Amplifiers in Load Sharing Configuration

The improved output waveform as a result of load sharing is quantified in the harmonic distortion versus frequency graphs shown in Figure 13 and Figure 14 for the single amplifier and load sharing configurations, respectively. While second-harmonic distortion remains largely the same between the single and load sharing cases, third-harmonic distortion is improved by approximately 8 dB in the frequency range between 20 MHz to 64 MHz.

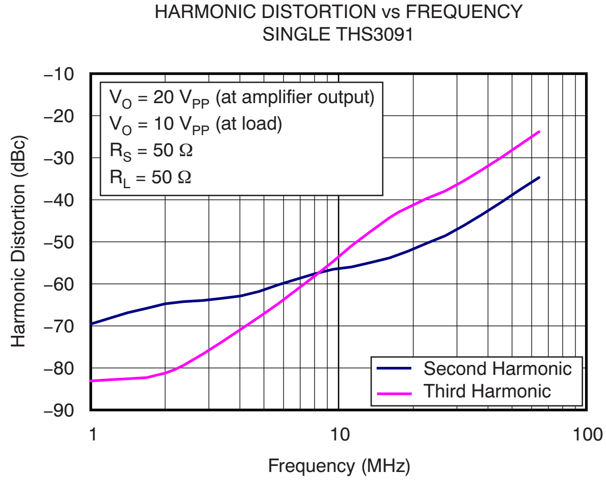

Figure 13. Harmonic Distortion vs Frequency, Single THS3091 Circuit Configuration

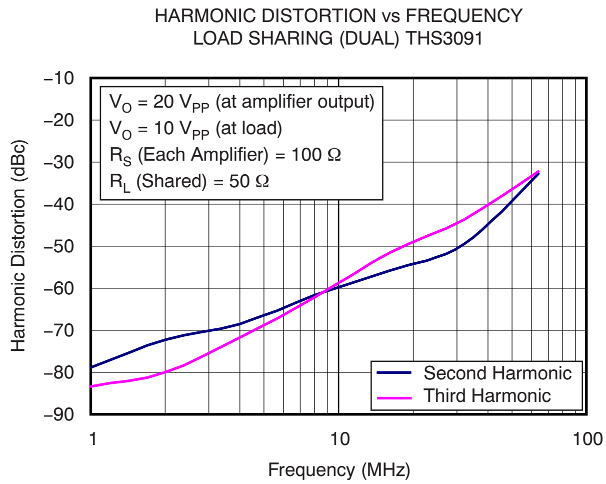

Figure 14. Harmonic Distortion vs Frequency, Two THS3091 Amplifiers in Load Sharing Configuration

5 Conclusion

The operational amplifier limitations imposed by slew rate and output current must be considered when an application requires large output signal swings. Output current is an especially important factor. This application note reviewed and explained a load sharing method to increase the output current ability of an amplifier and potentially improve distortion performance.