1.0 SINGLE SUPPLY OPERATION INTRODUCTION

Single supply operation of power op amps is most often done out of necessity. Examples of such applications are battery powered applications or circuits operating from vehicular power systems.

Single supply operation improves the efficiency of power supply usage. In split supply applications, current is drawn from only one supply at a time, with the opposite supply sitting idle unless bridge circuits are used.

This application note deals exclusively with applications operating off of positive supplies as this occurs 95% of the time. Negative supply principles are identical except for the reversal of polarity.

2.0 RESTRICTIONS OF SINGLE SUPPLY OPERATION

2.1 COMMON-MODE RESTRICTIONS

Keeping op amp inputs biased to within their linear common-mode voltage range is the most important requirement in single supply circuits. The actual value required varies for each amplifier model, and is described in individual model data sheets under SPECIFICATIONS, COMMON MODE VOLTAGE RANGE. DO NOT USE the specification given in the ABSOLUTE MAXIMUM RATINGS block of the data sheet.

2.2 LOAD CONNECTION TO GROUND

There will be several options available for load connection, as shown in Fig. 1. The first option shown in Fig. 1A, is a load connected to ground. Obviously only positive going outputs are possible. Note that when the output voltage the load “sees” is near zero, the amplifier considers its output to be swung to its negative rail.

Note also that amplifiers have limits as to how close they can swing to either rail. So the output for the grounded load can never actually go to zero. It has been observed that substantial current is available under these non-zero conditions, and that the amplifier has full source and sink capability. As an example, a PA12 in a single positive supply will swing as low as 2.5 volts on the output. If a load is connected from output to ground, even with the amplifier overdriven in a negative direction, it will supply substantial positive current, on the order of amps, and up to the current limit, into the load.

2.3 BRIDGE LOAD CONNECTION

The bridge load connection using two amplifiers, as shown in Fig. 1B, permits bipolar swings across the load. For DC coupled loads this is the only practical way to obtain bipolar swings. Note that the bridge effectively doubles the gain of the circuit.

2.4 LOAD TO HALF SUPPLY

Bipolar drive is possible if the load can be referred to a point at half supply, as in Fig. 1C. This is usually not practical, nor efficient, as the half supply point must have the current capacity to support the load requirements. It might be possible to use a second power op amp as a high current source and sink regulator for this point, but this second op amp would be much more efficiently utilized as the second half of a bridge.

2.5 CAPACITIVE COUPLED LOAD

In applications such as audio, it is possible and often desirable to AC couple the load with a capacitor. A simple series capacitor allows driving a ground connected load, as in Fig. 1D. An alternative is to connect the ground side of the load to two large electrolytics, as in Fig. 1E. The only possible advantage of Fig. 1E is the possible reduction of turn-on “pop” in circuits where this may be a problem.

FIGURE 1. LOAD CONNECTION OPTIONS
3.0 CIRCUIT TOPOLOGIES

3.1 UNSYMMETRICAL SUPPLY

Oddly enough, the first option that should be considered is not to use a single supply. Many applications such as those using high voltage amplifiers require a single large high voltage supply and unipolar output swings. This is to allow incorporation into systems which already have lower bipolar supplies such as ±15 or ±12 volts present. Should this be the case, then use the –15 or –12 volt supply on the negative rail of the op amp (more than a few high voltage applications have large negative supplies along with 12 or 15 volt bipolar supplies).

As shown in Fig. 2, as long as the small supply is large enough to accommodate the common-mode requirements of the amplifier over the range of normal inputs, then no other additional components are required.

![Figure 2. Unsymmetrical Supplies](image)

**3.2 DIFFERENTIAL CONFIGURATION**

The most universally useful single supply circuit is the differential configuration shown in Fig. 3. This topology makes it possible to set the gain simply as the ratio of $R_i/R_o$ where each $R_i$ pair and $R_o$ pair are matched to each other. It is feasible to use the circuit either non-inverting or inverting, but keep in mind that noninverting will accommodate inputs which go positive only with respect to ground, and non-inverting negative only with respect to ground. Also note that the $R_o$ pair must be closely matched to each other.

![Figure 3. Single Supply Non-Inverting Configuration](image)

For $V_{IN} = 0$:  
$V_{CM} = V_s (R_i || R_f) / (R_o || R_f)$  
$V_{CM} = \frac{V_s (R_i || R_f)}{R_o || R_f}$

For $V_{IN} > 0$:  
$V_{CM} = V_{CM} @ V_{IN} = 0 + V_{CM}$

$V_{CM}$ is the desired common mode voltage. Once a value is settled on for $R_o$ and the common mode bias point, it should be rechecked over the expected range of input signal values to verify common mode restrictions are met dynamically and readjusted if necessary. Also consider that part of the $R_o$ current flows in $R_i$ and through the source driving the input. The source must be able to accommodate this current.

The differential configuration is so useful that in section 7.0, several design examples will be explored. Appendix A outlines a procedure for the design of this circuit.

4.0 EXPANDED TECHNIQUES

4.1 BRIDGE CONNECTION

The bridge connection shown in Fig. 4 (next page) uses the differential configuration for the master, A1 amplifier, and a unity gain inverter for the slave, A2 amplifier. The slave non-inverting input is referred to a point on a divider at half supply voltage. Since this divider is referred to the supply, there will be susceptibility to power supply variation. Note that the zero output point is defined as the point where both amplifier outputs are equal, and this point is set by the non-inverting input of the slave.
The preferred way of improving the bridge circuit tolerance to power supply variations would be to regulate the half supply point. In the event this is not possible or desirable, Fig. 5 (next page) shows a bridge topology that reduces sensitivity to supply variations. The ratio of \( R_2/R_1 \) should be ratio matched to the ratio of \( R_3/R_4 \). Note that gain of \( A_1 \) will be:

\[
A_V = ((R_f/R_i)+1) \cdot (R_2/(R_2+R_1))
\]

Or, consider that while \( R_1/R_2 \) attenuate the input signal by half, and the bridge circuit effectively doubles circuit gain with respect to the load, then \( A_V \) is equal to the non-inverting gain of \( A_1 \), or \( R_f/R_i+1 \).

FIGURE 5. MODIFIED SINGLE-SUPPLY BRIDGE FOR IMPROVED SUPPLY REJECTION

The AC coupled bridge is a special case of the single supply bridge amplifier circuit, and is especially useful for audio where a stable DC operating point is desirable. Fig. 6 depicts such a circuit. Note that both non-inverting inputs use the half supply point as a bias reference. \( C_1 \) AC couples the input signal. \( C_2 \) blocks the DC ground path in the feedback loop insuring a unity gain for \( A_1 \) at DC.

4.2 CURRENT OUTPUT CONFIGURATION

Any voltage to current configuration is possible in the single supply environment, as long as common mode restrictions are met. The floating load current source will be restricted to unipolar outputs although the output cannot swing to zero current. Of course a bridge topology has many benefits including bipolar output, the ability to deliver zero current, and more voltage available to the load. In magnetic deflection applications, the higher voltages make for faster current transitions.

Since the Improved Howland Current Pump resembles a differential amplifier, it easily lends itself to single supply applications. The only modification will be the addition of the \( R_o \) common mode biasing resistors. The Howland is subject to wide dynamic range variations on both input and amplifier output with an infinite number of possibilities when various gains are factored in. Suffice to say the designer must analyze input common mode values at the four extremes of dynamic range:

1. Most positive input, most positive output
2. Most positive input, most negative output
3. Most negative input, most negative output
4. Most negative input, most positive output.

5.0 SPECIAL OP AMP CASES

5.1 PA02 SINGLE SUPPLY BEHAVIOR

A PA02 presents a special problem in single supply application. Like all BiFET input op amps, a negative common mode violation on either or both inputs causes the output to go full positive. Common mode violations are inherent in power up conditions in all op amp circuits since common mode is measured with respect to the supply rail.

In the case of a PA02, when the inputs are closer than 6 volts to either supply rail there is a common mode violation. It is implicit in this requirement that until total rail-to-rail supply voltage has reached at least 12 volts, the amplifier will not be linear. With a PA02 in particular, until the negative supply rail is at least 5 to 6 volts more negative than BOTH inputs, the output will be hard positive. This causes PA02 output to go full positive during power up in single supply applications. When used as an audio amplifier, this results in a loud “pop” from the speaker during power up.

There is no elegant solution to this problem. If the speaker is AC coupled and returned to positive supply rather than ground, this may help some. But most applications have shown the only dependable solution would be a relay that closes the circuit to the speaker once full supply voltage has been reached.

5.2 PA74 SINGLE SUPPLY CONSIDERATIONS

A PA74 is without a doubt the easiest power op amp to use on single supplies since the input common mode range can actually go more negative than the negative rail. Inputs can be applied to a PA74 in single supply applications without the need for additional biasing circuitry. The circuit shown on the front of the PA74 data sheet illustrates just how easy it is to apply for unipolar inputs in a DC motor drive application.
5.3 COMMON MODE BEHAVIOR IN GENERAL

It is helpful if the designer has some idea of which amplifiers are subject to unusual behavior during common mode violations. Like the BIFET PA02 described above, any FET input power op amp can exhibit polarity reversals during common mode violations. The polarity of most FET input stages, such as a PA07, all high voltage op amps, and Burr-Brown’s OPA541, are such that a positive common mode violation will cause a reversal of output polarity. This occurs since gate to drain of input FETs becomes forward biased under these conditions and the signal effectively bypasses the FET and its normal inversion.

5.4 AMPLIFIERS WHERE SINGLE SUPPLY OPERATION IS NOT RECOMMENDED

The use of a PA89 in single supply circuits is discouraged. The input common mode voltage range dictates the inputs must always operate at least 50 volts inside of either supply rail, an impractical value to establish bias in the differential configuration. Unsymmetrical supply techniques are more applicable for getting large unipolar swings out of PA89 circuits. In the case of a PA89, the smaller supply needs to be at least 50 volts.

The power boosters PB50 and PB58 also present unique problems. For example, the ground pin of these parts must “see” a clean analog ground with low impedance over a wide bandwidth. This can be difficult to insure in a single supply environment. A PB50 must operate with its ground pin 30 volts more positive than the negative rail, while a PB58 must operate at least 15 volts, and preferably 20 volts more positive than the negative rail. While it is possible to use these parts in a single supply environment, it is far preferable to use them with split or unsymmetrical supplies.

6.0 TURN ON “POPS”

Regardless of amplifier choice, audio applications where the load is AC coupled and connected to ground will always be susceptible to turn on “pops.” The two main reasons this occurs are: the amplifier is not linear until supply voltage is high enough; and the amplifier output inherently must go from zero to about half supply.

A bridge configuration will often improve (reduce) the likelihood of pops. Or as mentioned above, a relay which closes the circuit to the load once full supply voltage has been reached can help; although, with an AC coupled grounded load the output capacitor must still be charged.

Controlling power supply rise time to be sufficiently slow can also alleviate this problem. It may require slowing it such that it even takes seconds. Even this technique will add a relay or some type of solid state switch. The easiest way to implement a slow rise supply is with a sufficiently large resistor in series with a filter capacitor.

7.0 DESIGN EXAMPLES

7.1 DESIGN SPECIFICATIONS:

Supply voltage = 28 volts. Input signal range = 0 to 5 volts. Unipolar output, single ended.

A PA12 has been selected for a unipolar voltage output motor drive. Differential configuration is selected, see Fig. 7. (Note that many details will not be discussed here, but are covered in other app notes, such as current limit resistors, flyback diodes, and power supply bypassing.)

\[ \frac{R_F}{R_I} = \frac{dV_{OUT}}{dV_{IN}} \]

Now \( R_F \) must be selected to respect PA12 common mode requirements which dictate that the inputs must be kept 5 volts inside of either supply rail. So the inputs could be set anywhere from 5 to 23 volts. An ideal value would be 14 volts. Let’s try an \( R_F \) value based on that and see if currents through the input resistors and input terminals remains reasonable. From the equation in 3.2 above, this would result in an \( R_F \) value of approximately 8.48K ohms, nearest standard value 8.2K ohms.

This would result in 1.65mA flowing to the input terminals and no inordinate power dissipation in any of the input circuit resistors.

Since the process used to select \( R_F \) is based on worst case negative voltage input/output relationships, the common mode should be re-checked for full positive inputs and outputs. Assuming +5 volts at the input and a theoretical +28 volts at the amplifier output, the circuit simplifies to \( R_F \) and \( R_I \) being in parallel to +28 volts and forming a voltage divider with \( R_I \) as the ground leg. This results in a voltage at the amplifier input of 16.32V, that is within the maximum positive common mode restriction of 23 volts.

7.2 DESIGN SPECIFICATIONS:

Supply voltage = 28 volts. Input voltage -2.5 to +2.5 volts. Voltage in, current output (will require Improved Howland Current Pump). Output range ±2A.

A PA02 is selected for this application along with a bridge circuit. Referring to Fig. 8, the R1, R2 and R4, R3 ratios were selected to provide the required transfer function based on a 0.301 ohm current sense resistor, \( R_s \). Note that over the expected normal range of input signals and output voltages that common mode requirements are met. While true for this application, each one should be checked to verify the voltages are within acceptable limits. Note that even on this circuit that exceeding the ±2.5 volt dynamic range on the inputs will cause common mode violations to occur.
7.3 DESIGN SPECIFICATIONS:
Supply voltage = 450 volts. Input voltage 0 to 10 volts.
A PA88 is selected to meet low consumption requirements, the circuit is shown in Fig. 9. 
\[ R_F \text{ and } R_I \text{ must provide a gain on the master amplifier of 45.} \]
In the process of minimizing power consumption and maintaining a reasonable physical size for components, 
consider there can be as much as 450 volts across \( R_F \). In order to use a half watt resistor, \( R_F \) would need to be 510K ohms. 
For a gain of 45, \( R_I \) would then be 11K ohms.

In this high voltage application, it is wise to design for the minimum acceptable common mode voltage which is 12 volts for a PA88. 
15 volts will be used to provide a little margin. 300K ohms will be required for \( R_O \), 510K ohms will also be required for both gain setting resistors on the slave.

The half supply reference point resistors will each have 225 volts across them. The minimum acceptable value for half watt resistors would be 101K ohms each, but to minimize consumption, 200K ohms each is used. These must be bypassed.

With the large value feedback components around the slave, amplifier problems can result from feedback poles being created by amplifier input capacitance and stray capacitance. This may require a small compensation capacitor from 2 to 20 pF across the feedback resistor.

7.4 DESIGN SPECIFICATIONS:
Supply voltage = 450 volts. Input voltage 0 to 10 volts. Wide band high voltage driver. Single ended.
The circuit in Fig. 10 contrasts with the previous example in that it is a wideband circuit and requires the lowest possible impedances at all modes. The standard differential configuration will be used. This is an example where minimum common mode bias will have to be set to avoid excessive current and dissipation problems in resistors.
Gain for this circuit will be 45. In order to use the lowest possible value for \( R_F \) to insure good bandwidth, a 5 watt resistor will be used. Assuming worst case voltage stress across \( R_F \) to be 450 volts, the lowest permissible standard value is 43K ohms. For a gain of 45, \( R_I \) must be (nearest standard value) 910 ohms.
Because of such low impedances, a minimum common mode bias (from the PA85 data sheet) of 12 volts must be set.
Solving for \( R_O \), assuming 12 volts of common mode bias, with an input of 0 volts and theoretical 0 volt output, the value is (nearest next lowest standard value) 30K ohms. This resistor will have 438 volts across it and will dissipate 6.4 watts. In addition, 15mA will flow through the input terminal. These values will be difficult, if not impossible, to work with. It may be possible to scale up by a factor of two and have sufficient bandwidth.
Re-calculating using 91K ohms \( R_F \) and 2K ohms \( R_I \), \( R_O \) solves to 68K ohms, the nearest standard value. Dissipation in \( R_O \) is now 2.8 watts and 6.3mA flows to the input resistor. While these numbers are better, they could still be a problem. Further scaling up of impedances will aggravate bandwidth problems as the effects of parasitic and amplifier input capacitance become significant.

This design example has been shown to be feasible in the design of a single supply circuit. But use of a –15 volt supply for the negative rail will eliminate the impedance constraints and permit the circuit to be designed for maximum possible bandwidth with a conventional circuit.
APPENDIX A: PROCEDURE FOR DESIGN OF DIFFERENTIAL CONFIGURATION

1. Select $R_F$ and $R_i$:

   \[ \text{GAIN} = \frac{R_F}{R_i} = \frac{dV_o}{dV_i} \]

   In general, $R_i$ should be the resistor value on which all others "pivot." This is because $R_i$ essentially represents the load presented to the input signal. Most small signal op amps work best if $R_i$ is 10K ohms or larger, but many would permit $R_i$ to drop as low as 1K or 2K ohms if necessary.

2. Select $R_O$:

   \[ R_O = \frac{V_S - V_{CM}}{\left( \frac{V_{CM}}{R_i || R_F} \right)} \text{ (MIN, from amplifier data sheet)} \]

3. Check dissipation in $R_O$. If too high, all resistor values need to be re-scaled upward.

4. Re-check $V_{CM}$ at all four possible extremes of both input signal and amplifier output voltage. Although some of these operating conditions may not actually occur, it is wise to have a circuit that has linear common mode bias under all conditions if for no other reason than it is the only hope the op amp has to recover from the following conditions:
   a. Full negative input (usually 0), full negative output (theoretical 0). This condition is accounted for in the equation to select $R_O$.
   b. Full negative input, full positive output (assume theoretical maximum equal to supply voltage).
   c. Full positive input (don't forget that most small signal op amps could swing beyond their 10 volt linear limit, often up to a full 15 volts), full negative output.
   d. Full positive input, full positive output.

5. If being used in a bridge, it is recommended that the slave amplifier noninverting half supply bias point be regulated, either with a zener diode or derived from some regulated voltage.

If any of these four conditions do not meet common mode restrictions, adjust $R_o$ accordingly. For instance, if a violation is more negative than minimum allowable common mode bias, reduce $R_i$ (most common likely problem). If the violation is positive, which is unlikely with most realistic bias levels, then $R_o$ should be increased.

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