Load Sharing with Paralleled Power Supplies

by Bob Mammano

TOPIC 2

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Bob Mammano and Mark Jordan

Introduction

When designing low-voltage power systems to supply large load currents, paralleled lower-current modules are often preferred over a single, large power converter for several reasons. These include the efficiencies of designing and manufacturing standard modular converters which can be combined in whatever number necessary to meet a given load requirement; and the enhanced reliability gained through redundancy. Additional gains are often achieved in mechanical packaging considerations and in distributed heat removal.

While most modern-day power supplies can be paralleled for higher currents, the load current will not share equally between modules without some extra effort in the design process. With unequal load sharing, the stress placed on the individual modules will be unequal, resulting in some units operating with higher temperatures—a recognized contributor to reduced reliability. Therefore, the challenge in paralleling modular supplies is to insure predictable, uniform current sharing—regardless of load levels and the number of modules. Another major goal should be to provide enhanced system reliability through complete redundancy such that the failure of one or more modules could be tolerated as long as the total remaining capacity is equal to or greater than the demands of the load.

Over the years, a variety of schemes have been devised to accomplish load sharing and, as one would expect, these schemes offer a wide range of performance characteristics. A brief description of some of these approaches will, perhaps, be useful in comparing their performance capabilities against the degree of difficulty in their implementation.

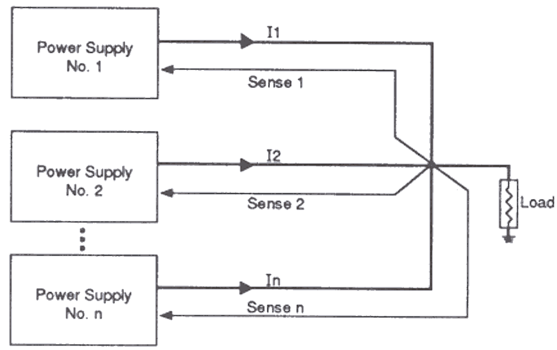

Fig 1. - Current Limit Paralleling

Current Limit Paralleling

The connection diagram for this most basic approach is shown in Figure 1 where it can be seen that each unit is completely independent except for the common load. Each individual module must have inherent current limiting because in practice, the output voltage of all the modules will never be exactly equal. Thus, when several modules are paralleled, the one with the highest output voltage will attempt to supply all the load current, up to the point where its current limit is reached. As this unit goes into current limiting, its output voltage will fall to the level of the next highest module, which then begins to conduct and supply additional load current. When the second module reaches its current limit, number three starts conducting, and so on.

Of course, there is no current sharing at all except for the units which are in current limiting, and it could be expected that the dynamic load regulation, particularly as each current limit threshold is passed, would be less than desirable.

Output Voltage Droop Method

As the name "droop" would imply, this method of paralleling is accomplished by designing the individual power modules with a finite output resistance so that the output voltage falls slightly as the load current is increased. The modules would then be connected together as shown in Figure 2. If the individual units are initially adjusted for equal currents at some load, the action of the output resistances will be to maintain sharing over fairly wide changes in load demand. If one module were to conduct less current, the reduced voltage drop across its output resistance would lower the voltage at the sense point, causing it to increase its conduction and correct for the unbalance. While this approach has seen considerable usage, it also has poorer load regulation, and the problem gets worse as the output resistance is increased to increase the accuracy of sharing. Additional difficulties result from the need for accurate initial balancing and the susceptibility to reference drift in the individual modules.

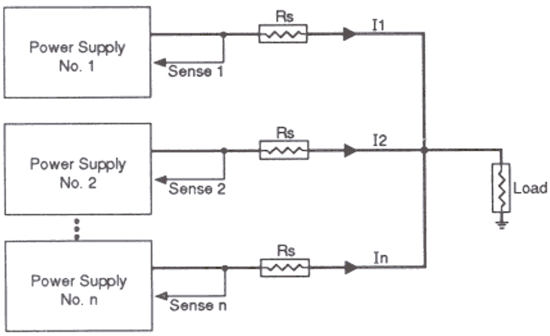

Fig 2. - Output Voltage Droop Sharing

Common Point Voltage-Mode Control

Figure 3 shows a paralleling configuration where the control is achieved by a separate block containing the load voltage sensing, the system reference, and a gain stage. The individual modules then only need to contain the power stage—the ultimate simplicity if low system cost is a primary objective.

While current sharing will not be perfect if power stage variables give different switching waveforms for the same duty cycle command, the fact that most of the gain is in the single control unit minimizes this problem and reasonable sharing can be achieved with excellent line and load regulation over a wide range of operating conditions. With a single control point, output voltage adjustment or margin testing is also easily accomplished.

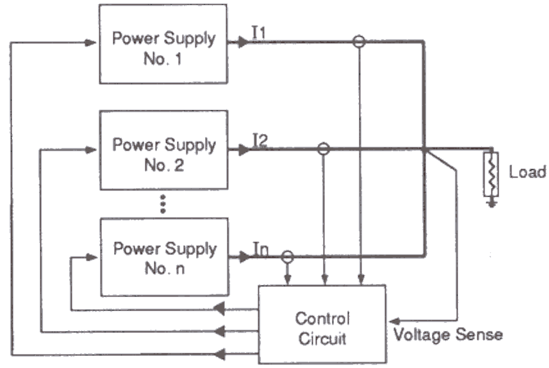

Fig 3. - Sharing with Common Control

The power stages in this configuration can be designed with a blocking diode at the output such that if an individual unit fails, the remaining modules will merely increase conduction to make up for the loss. However, even recognizing the argument that the greatest propensity for failure will be with the high-stress power stages, the fact remains that in this approach, and the one following, a failure in the control stage will cause the entire power system to fail.

Closed Loop Current Mode Control

Current-mode control means that a power supply is controlled by feedback from both inductor current and output voltage. Here, each module's current level is programmed by a voltage control loop and with this capability, current sharing can be very exact. The circuit approach for paralleling can either have a separate controller, as shown above in Figure 3, or the more usual Master / Slave configuration as illustrated in Figure 4. In either case, the transfer function between control input and module current is well defined and a changing control voltage will cause a proportionate change in each module's current.

The module unit configured as a master will

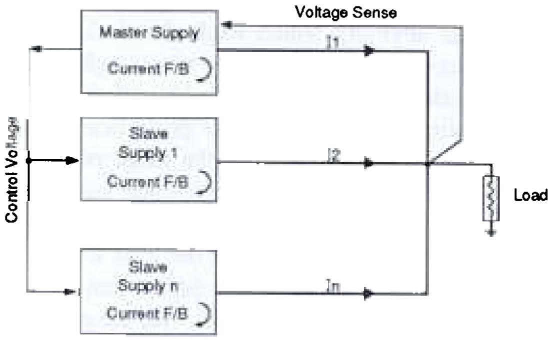

Fig 4. - Master/Slave Current Mode Control

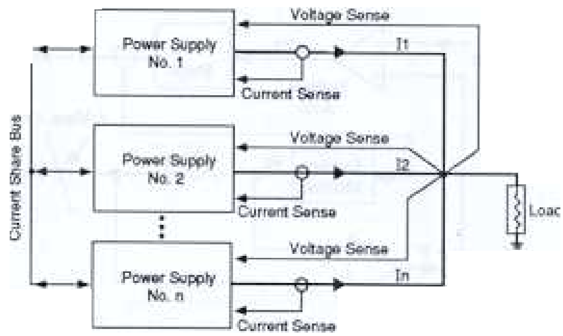

Fig 5. - Independent Current Sharing

work singlely as an independent supply for loads within its rating. However, when higher loads dictate the need for more paralleled modules, slave units may easily be added which will automatically deliver a proportionate share of the total load. The problem, of course, is that redundancy is achieved only with the slave units–not with the master.

Independent Current Sharing

While current-mode techniques can give each module the ability to control its own current, completely independent sharing typically requires more effort. Figure 5 illustrates a more desirable approach for paralleling where each module can act either as a stand-alone supply, or as a proportionate member of a paralleled group. A distinction should be made here between "current-mode control", which uses an internal control loop derived from inductor current, and "current sharing", which adds a current loop based on external module output current. Current sharing can apply equally to either voltage or current-mode designs. In Figure 5, the current sense signal measures the module output current and its function has no bearing on whether or not the modules contain an internal current-mode control loop.

Independent current sharing presents at least two difficulties, however, which must be overcome in order to make a connection as shown in Figure 5 practical. The first is the need for a bidirectional bus for communicating current sharing information between the modules, (more about this later), and the second is that while each module must have its own voltage sensing and reference circuitry, they all must regulate to the same common output voltage level.

Since there will always be differences between the individual references–no matter how slight–the technique used by most implementations is to apply the current sharing control information to adjust the voltage reference in each module. Properly done, this allows each module to achieve a reference value which equalizes the individual currents within each module at exactly the value needed to regulate the load voltage. Since the reference adjustment range need only be large enough to accommodate unit-to-unit tolerances, it is reasonable to include an added feature that allows the module to continue to regulate, losing only the current-share capability, should the current control line open.

The means for generating and distributing current sharing information between the modules is not a trivial task. The signal should be transmitted with a single interconnecting line (the Share Bus). It must be insensitive to noise pickup and parasitic elements. The modules must current share when the control signal is present and must continue to operate when the Bus is either open or shorted. Typically, this involves adding an Adjustment Amplifier within each module. This amplifier's function is to compare a signal derived from that module's current with that received from the Share Bus, and to adjust the reference as needed to drive this difference to zero. At least two techniques have

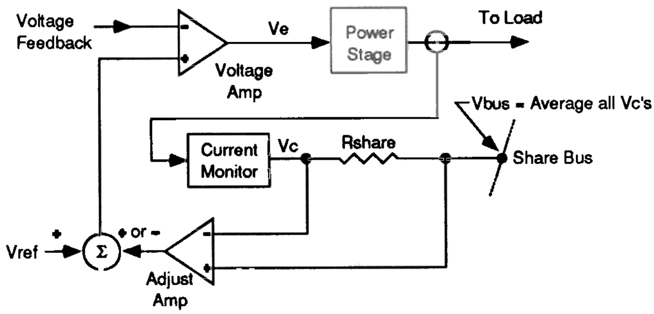

Fig 6. - Sharing the Average Current

been successfully used to accomplish this: Average Current Sharing and Master / Slave Automatic Selection.

Automatic Average Output Current Sharing

This system, which was developed (and patented) by Ken Small at Boschert, is shown in simplified form in Figure 6. The module's power stage is controlled by the Voltage Amplifier in response to a comparison between the sensed output voltage feedback and the adjustable voltage reference. The module's contribution to load current is sensed by the Current Monitor and a voltage proportional to output current is applied to the Share Bus through a series resistor, RSHARE. With the resistors in each module all summed together at the Share Bus, the voltage at this node then always represents the average of all the output currents of all the modules connected together. If the individual currents are not equal, there will be voltage drops—either positive or negative—across the share resistors. The Adjust Amplifiers within each module will then force these signals to zero by changing the value of the individual references for each Voltage Amplifier.

With all modules matching up such that each one delivers a current equal to the average of all, excellent sharing can be achieved. Additionally, since the Share Bus is not a part of the voltage control loop, its bandwidth can be low and the Bus can be decoupled with a large capacitor for good noise rejection. One potential difficulty is that anything which loads down the Share Bus—an external short or a single failed module, for example—could pull down the entire system. A possible protection against this problem is to limit the range of adjustment allowed for the reference but, while this would keep the supplies from collapsing, it would still reduce the load voltage to the value defined by this adjustment limit—a limit which must be lower than the expected reference tolerance.

Master / Slave Automatic Selection

Properly done, a master/slave system with automatic selection would preclude this mode of failure as only the master has control and if it fails, the system would merely select a new master. One such approach is shown in Figure 7. Here, with the series resistor replaced by a diode, the reference is allowed to adjust only in an upward direction. The Share Bus now represents the *highest* current being delivered by any of a paralleled array of power modules. This is because only the module with the highest output current can forward-bias its diode and drive the Share Bus. The differential voltage at the input to this Adjust Amplifier will force its output low, leaving the reference unchanged. This is appropriate because the module initially supplying the highest current already has the highest reference voltage.

Modules initially supplying lower output currents would use the Share Bus voltage as an input command for their Adjust Amplifiers. Their reference

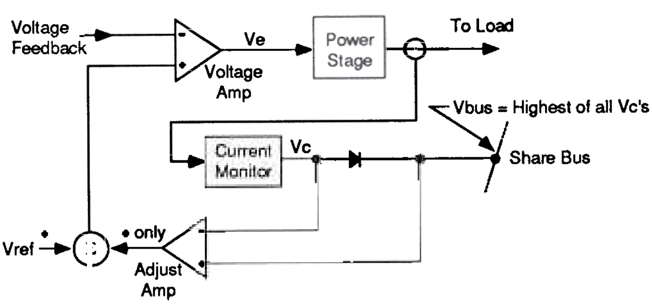

Fig 7. Sharing the Maximum Current

voltages will be adjusted upwards, increasing their output currents until the voltage at the output of the current monitor equals that on the Share Bus.

The forward drop of the master's diode in this system represents an error in current matching between modules. The magnitude of the error is the ratio of the diode voltage drop to the Share Bus voltage and it represents the maximum deviation between the master and any of the slaves. A fault on the Share Bus will now only hold all the Adjust Amplifiers low, leaving all the references unchanged. While forced sharing will be defeated, all the modules will still operate within their tolerances with sharing determined by their individual current limits.

The UC1907 Load Share Regulator

From the above discussion, it would appear that providing good load sharing capability could add a significant degree of complexity to power supply design. To ease this task, an integrated circuit designated the UC1907 has been developed to combine both the voltage regulating and current sharing functions into a single device. The UC1907 would normally be built into each power module and applied as shown in Figure 8 to sense its own module output current and the output voltage directly at the load. For maximum accuracy, differential sensing is used for both measurements. Other than current and voltage sensing, only a single line interconnects the modules for current sharing and each controller communicates with its own power stage, either directly or through an isolating medium.

The overall block diagram of this IC is shown in Figure 9, however, its capability and application can probably be more readily visualized by discussing the functions separately.

Current Sharing with the UC1907

The UC1907 Load Share Regulator takes automatic master / slave selection one step further by replacing the diode described above with a unidirectional Buffer Amplifier as shown in the simplified sketch of Figure 10. In theory, this addition could eliminate the sharing error caused by the diode's voltage drop, and deliver perfect current sharing. In practice, however, this might also result in a constant hunting as modules with coincidently equal references could fight for position as master. The solution chosen for the UC1907, which is more specifically illustrated in Figure 11, is to add a 50mV offset to the Adjust Amplifier (as compared to the 700mV of a diode). This offset acts as hysteresis to insure a positive selection of a master. The amount of output current unbalance can be determined by dividing the 50 mV offset by the gain of the current monitor circuit which in the

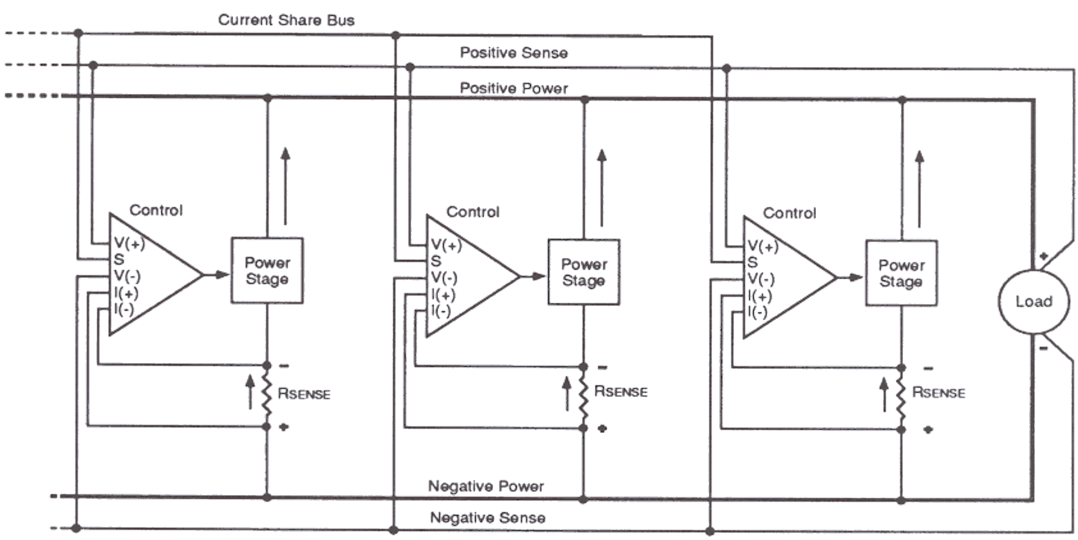

Fig 8. - System Connections for Independent Load Sharing Modules

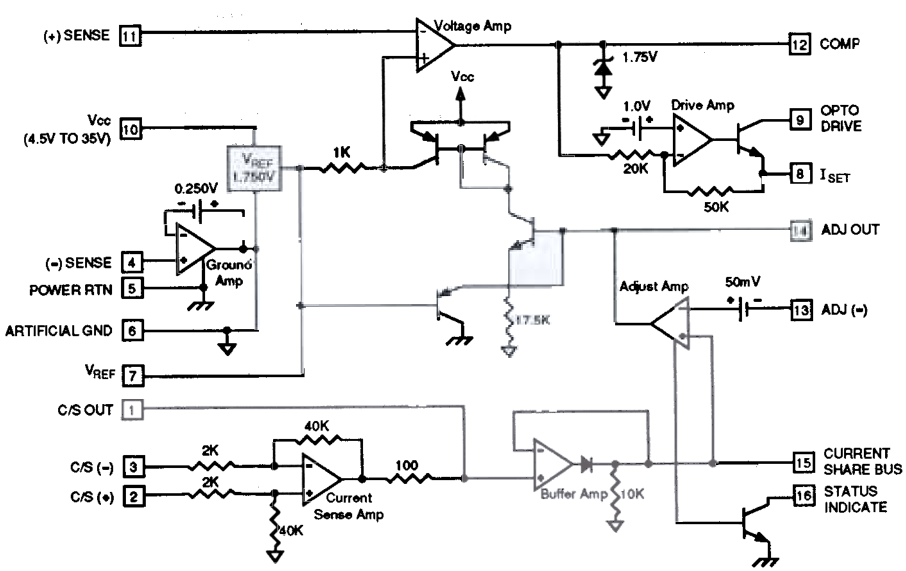

Fig 9. - UC1907 Load Sharing Controller Block Diagram

UC1907 is 20. This means that the module acting as master will have an extra 2.5mV across its current sensing resistor—a fairly low percentage if full scale is in the 100–200mV range.

As can be seen from Figure 11, the current monitor circuit has a fixed gain of 20 with differential inputs for direct sensing across a low-valued shunt. While optimized for sensing in the return line of a power supply, its common-mode range will allow sensing in the high side as long as VCC is at least two volts higher. The output of the Current Amplifier is available through a 100Ω source impedance for interfacing with external current monitoring or limiting functions.

Since the Buffer Amplifier can only source current, only the one in the module with the highest sensed current will be active, serving as a low impedance driver for the Current Share Bus. All others will be inactive with each exhibiting a 10kΩ load impedance to ground at the Bus. While the master module has the only active Buffer Amplifier, its Adjust Amplifier is held inactive at zero. The Adjust Amplifiers in the slave modules are all active, using the Share Bus voltage to increase their references to the appropriate value.

The Adjust Amplifier is a transconductance circuit, allowing its bandwidth to be limited, and noise decoupled from the reference adjust loop, with a single capacitor to ground at its output. The value of the capacitor can be determined from

$$C1 = \frac{g_m}{2\pi f}$$

Where f = desired bandwidth and g_m = 3 mSiemens for the UC1907.

As an added feature, since the master—and only the master—will have its Adjust Amplifier driven into low-side saturation, this can be detected and used to activate a flag output identifying which module is acting as master. This open-collector output has adequate current capabilities for an LED or lamp indicator, as well as serving as a logic output.

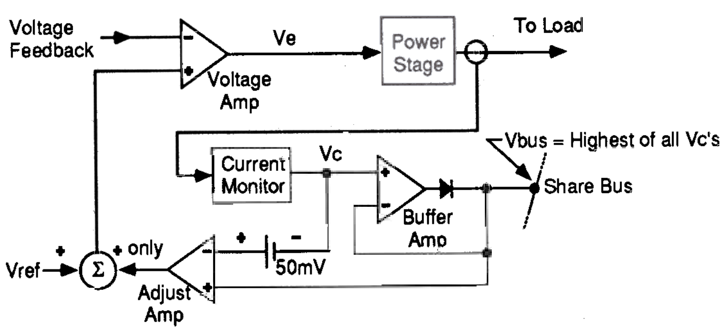

Fig 10. - Automatic Master Selection with the UC1907

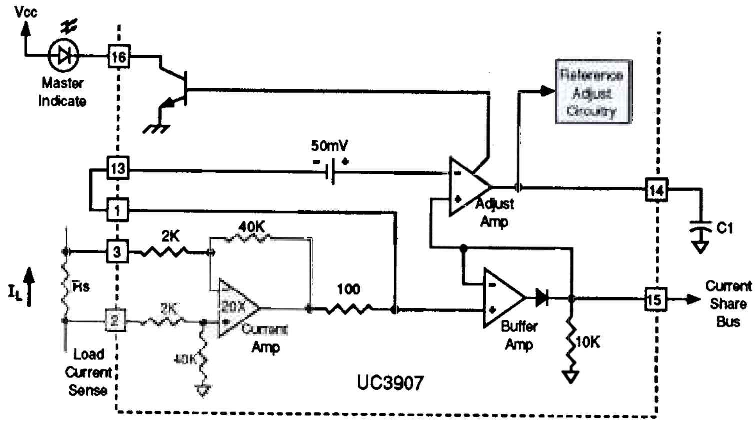

Fig 11. - Current Share Components within the UC1907

Adjusting the reference: Before discussing the reference, there are some aspects of the UC1907 which need to be clarified with respect to grounding. Practical power systems must address the issue of undefined resistance in series with both the feed and return lines between the supply and the load. For accurate load voltage control, high-impedance Kelvin sense inputs are an important part of the voltage control loop. In the UC1907, these are provided by the Voltage and Ground Amplifiers which can measure the load voltage differentially at the point of use. To allow the Ground Amplifier headroom so that it can provide effective system ground sensing, an arbitrary low-impedance reference level is established within the UC1907 which is exactly 250 mV above the load ground. This is called an Artificial Ground and it serves as a return point for all the currents associated with the operation of the UC1907. To accommodate undefined voltage drops in the system power return line, the UC1907 supply return is connected closest to the supply, at the most negative end of the return line. These three different "ground" references within the UC1907 are shown in Figure 12 and differentiated as follows:

Negative Sense (Symbol:) — This is the high-impedance pin intended for remote sensing of the load or system ground, bypassing any voltage drops which might appear in the power return line. It is the input to the Ground Amplifier and should be considered as the "true" ground. Unless otherwise stated, all voltage measurements will be referenced to this point.

Artificial Ground (Symbol:) — This is a low-impedance reference point which is exactly 250 millivolts more positive than the (—) Sense terminal. This offset allows the Ground Amplifier to divert all the control bias and operating currents away from the high impedance at the (—) Sense input. It also serves as a point to return all external resistors and compensating capacitors associated with the operation of the UC1907.

Power Return (Symbol:) — This should be the most negative voltage available and can range from zero to -5V below the (-) Sense terminal. It should be connected as close to the power source as possible so that voltage drops across the return line and the current sensing resistance lie between this terminal and the (-) Sense point.

With this understanding, we can now look at Figure 12 and recognize that while the reference voltage is 1.75V with respect to artificial ground, it is actually 2.00V with respect to the load. The adjustment range for current sharing must be enough to encompass all the tolerances associated with setting

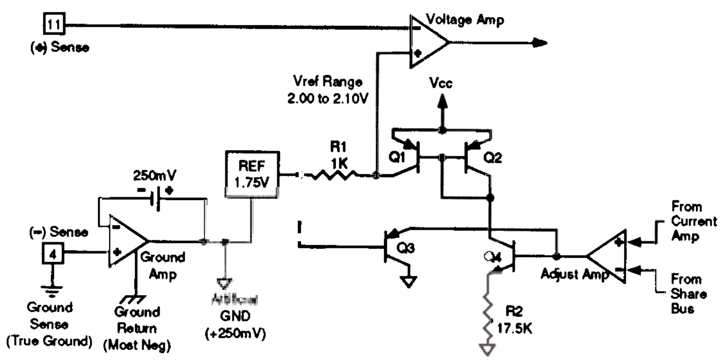

Fig 12. - Reference Adjustment in the UC1907

the output voltage. In the UC1907, reference accuracy is ±1.5% (30mV) and the adjustment range is set at 5% (100mV). The adjustment is accomplished by adding current to R1 to create a voltage drop which is defined by the output of the Adjust Amplifier and resistor R2. Q3 clamps the Adjust Amplifier to limit the voltage across R2 to 1.75 V and therefore, with R1 = 1k, the maximum adjust voltage is limited to 100mV.

Voltage Control with the UC1907

Figure 13 shows the elements within the UC1907 associated with closing an overall feedback loop to regulate the power supply output voltage. In addition to the adjustable Reference and the Ground Amplifier discussed above, this circuit contains a Voltage Amplifier intended to serve as a high-gain error amplifier, and a fixed-gain Drive Amplifier included to ease interfacing with the power stage. With most of the gain in the Voltage Amplifier, this is the place to provide the frequency compensation necessary to stabilize the loop. The Drive Amplifier can be used as either a fixed-gain voltage buffer or a voltage-to-current transconductance stage with the current established externally by RSET. This configuration is particularly appropriate for isolated power supplies where an optocoupler will be used to transmit the feedback control across an isolation boundary. The polarity of this control loop is such that increasing the sense voltage increases the optocoupler current, a requirement for starting an isolated power supply.

Figure 13 also shows the usual method for powering the UC1907, as long as the supply's output voltage is five volts or above. Note that while the voltage sense lines are normally connected as close to the load as possible, the controller's supply is taken from close to the power stage such that line drops, the current sensing resistor, and blocking diode (if present) all tend to raise the chip supply voltage, rather than reduce it.

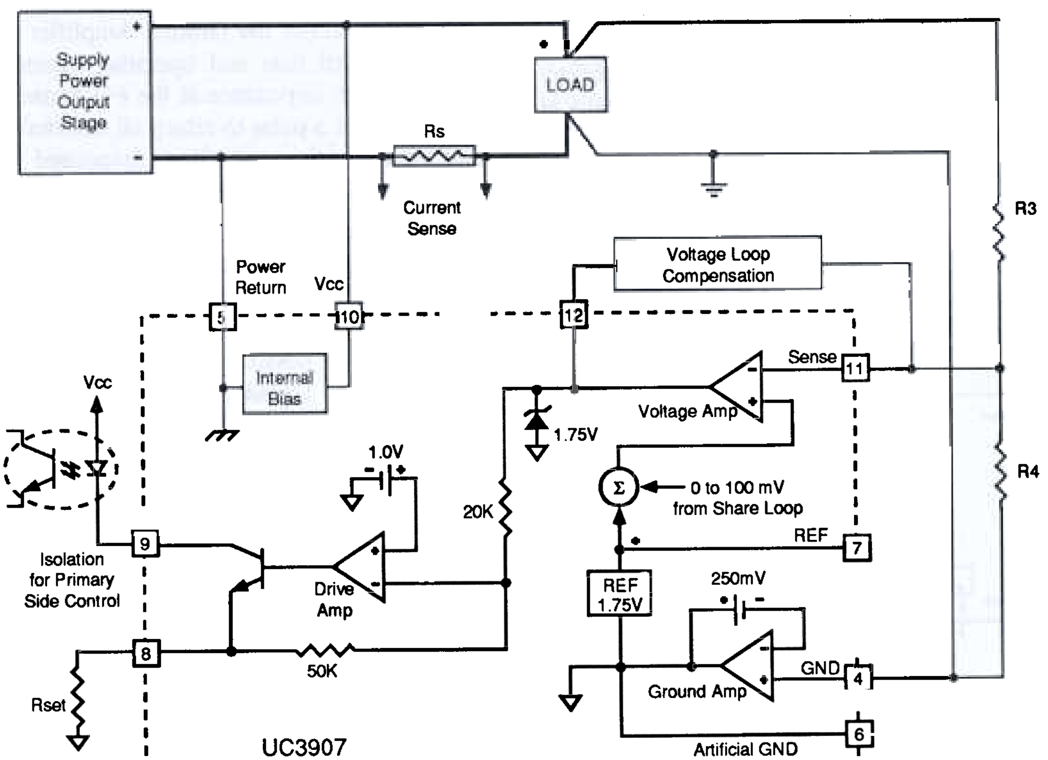

Fig 13. - Voltage Control Loop Elements in the UC1907

Application Issues

System start-up: Since the current share loop will normally have a bandwidth limited to something less than 500Hz, there are dynamic factors to consider in designing a multiple-module power system. The addition of C1 to the Adjust Amplifier will limit its slew rate to the value defined by its maximum output current of 200uA. Since the voltage feedback loop will probably be significantly faster, the start-up characteristics shown in Figure 14 will be typical. These curves assume four paralleled modules with nominal references 10mV apart, ranging from 1.98V on module #4 to 2.01V for module #1. It is further assumed that the load is light enough that current limiting does not come into play. Under these conditions, at T0 the load voltage and current rise with the speed of the voltage control loop until the module with the highest reference regulates the output at T1. At this time, the other three modules with lower references are contributing nothing and the full load current is coming from module #1. During this time, the Adjust Amplifiers in modules #2, 3, and 4 are responding but with a lesser slew rate. At T2 the internal threshold of the reference adjust circuitry is reached and the references on the lower-output modules begin to rise. At T3, module #2 matches module #1 and it picks up half the load current, dropping the module #1 current to 50%. At T4 and T5 the other modules have completed their adjustment and sharing is complete at T5 with each one conducting 25%.

The point of all this is to show that at turn-on, one module may initially attempt to supply the entire load current and, if the load were heaver, go into current limiting. This would be no problem unless the modules are equipped with over-current shutdown which might prevent the system from starting as different units alternately start up and shut down. Several solutions are possible: A faster current adjust loop (although stabilization may be difficult), a soft-start in the power stage to slow the initial voltage ramp-up to less than the Adjust Amplifier slew rate, or a delay in the over-current shutdown function.

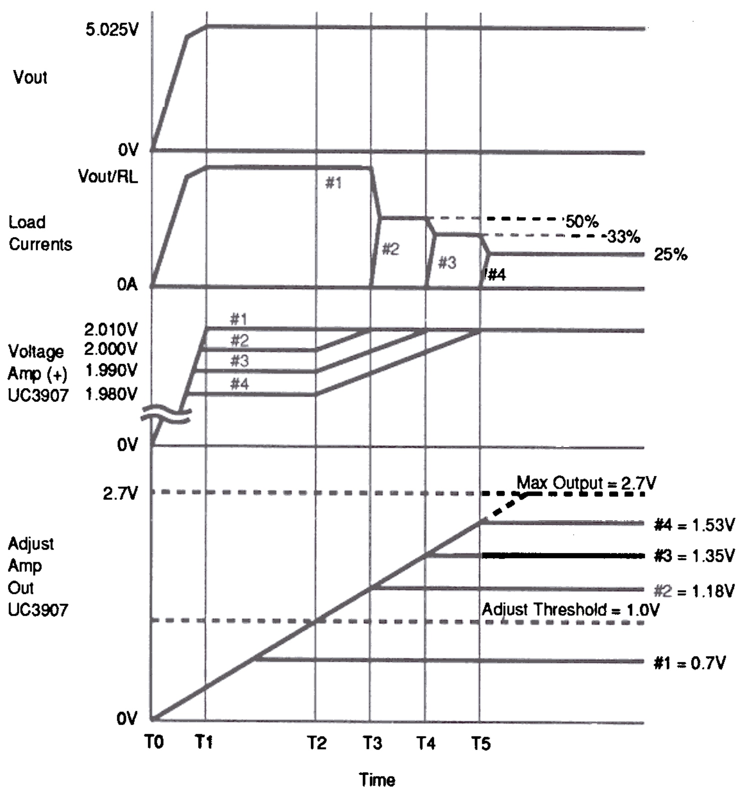

Fig 14. - Start-up Timing, 4-Module System (without soft-start or current limiting).

Transformer Current Sensing: While the UC1907 was designed anticipating that its primary use would be with a low-voltage-drop, current-sensing resistor, in high current applications these resistive shunts are less desirable. In switch-mode power supply applications, it is feasible to current sense ahead of the output rectifiers, using a current transformer to develop a higher voltage signal with minimal power dissipation. Figure 15 shows a way of accomplishing this with a forward converter. The load current signal is converted to a voltage waveform across RCS. Assuming that R2 is much greater than RCS, the voltage on C2 will follow the rising inductor current during the on-time of the power switches. During the off-time, C2 discharges slowly through R2 to approximate the down-slope of inductor current. In this manner, the average voltage on C2 can be made equivalent to the average load current through the inductor.

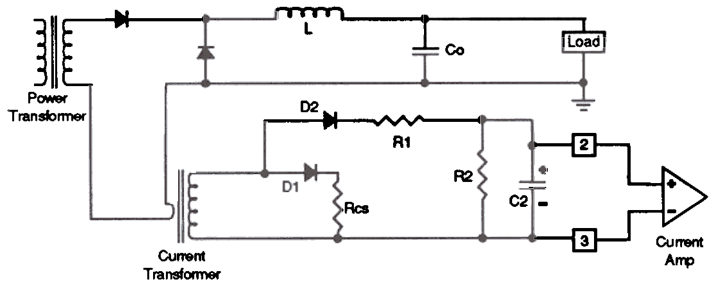

Fig 15. - Current Sense Transformer and Averaging Circuit Eliminates High Power Current Shunt

An Off-Line Load Share Application

A possible application for the UC1907 in an off-line, isolated flyback design is shown in Figure 16. Here all the control intelligence is provided by the UC1907 on the secondary side of the power transformer. An optocoupler passes the control information over to the primary side pulse-width modulator. This modulator could be implemented with any of a variety of approaches, including either voltage or current mode control. Note that in this application, the Reference, Voltage Amplifier, and Opto-Driver would be needed under any circumstances and the UC1907 merely adds current sharing.

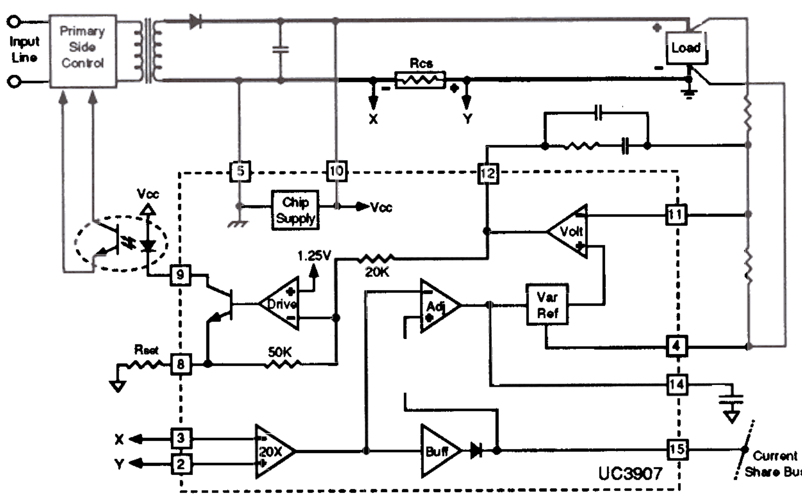

Fig 16. UC1907 Load Sharing with Off-Line, Isolated Supply

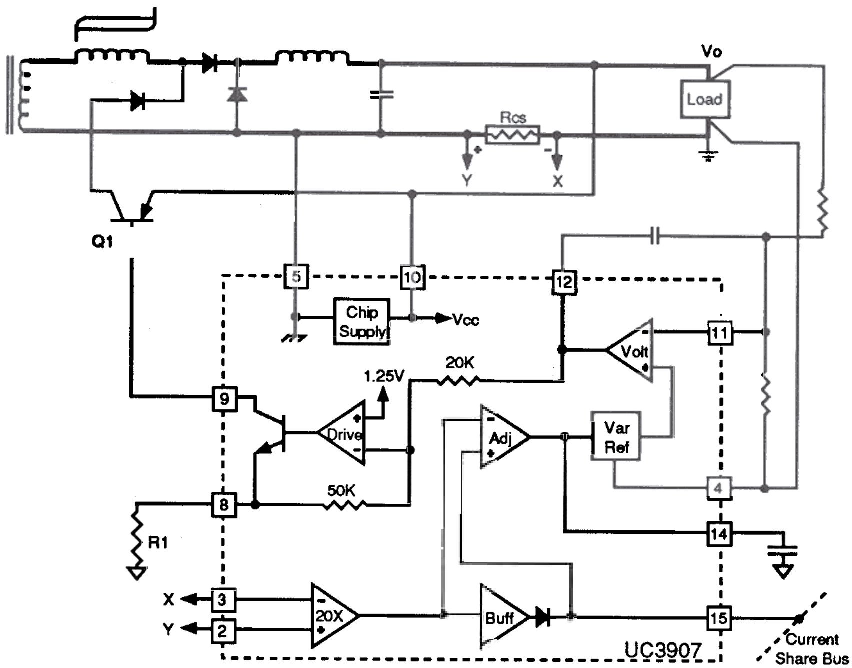

Fig 17. - UC1907 Output Amplified by Q1 Provides Reset Current for MagAmp Regulator

Load Sharing with Mag Amp Control

The use of a saturable reactor, or mag amp, is a popular approach for power control where the power source is an AC square-wave or pulse-width modulated supply. Controlling a mag amp is accomplished by varying its reset current which, as shown in Figure 17, is done by driving Q1 with the output from the Drive Amplifier. Here again, the UC1907 provides all the regulating circuitry while adding current sharing. Note that in this application, the control is self-powered, using the module's regulated output as a source of power for both control bias and the mag amp reset current. To provide short-circuit current limiting for a mag amp, an auxiliary power source would be required.

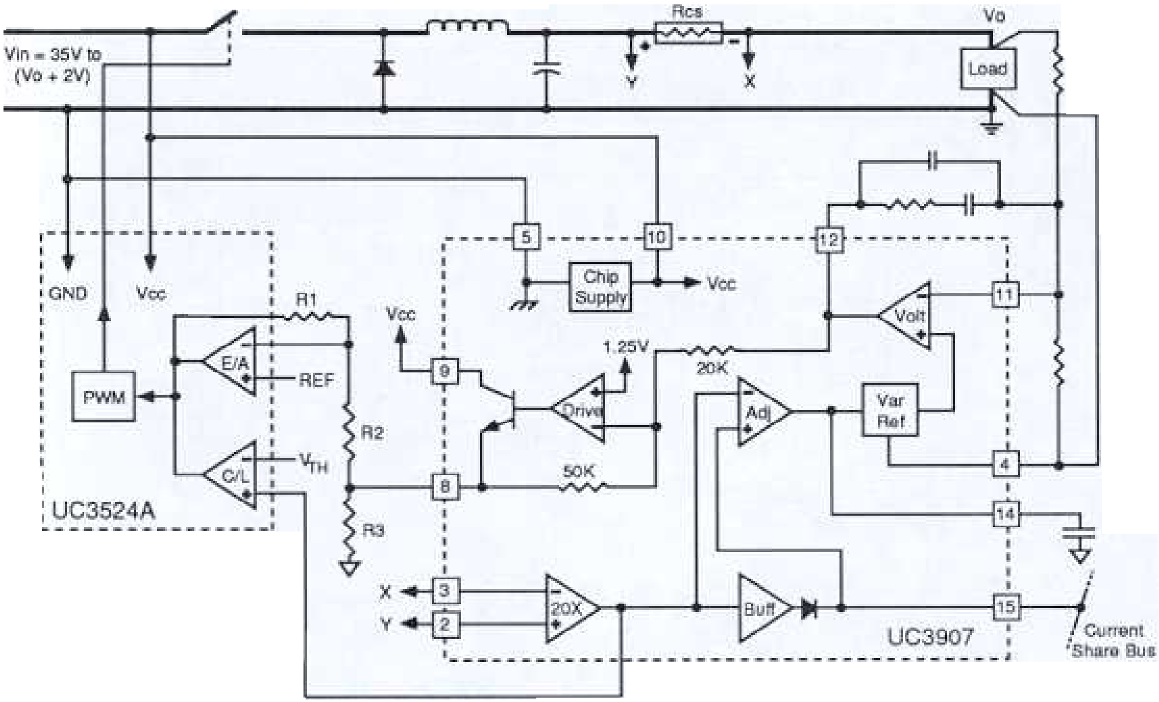

Fig 18. - Non-Isolated DC/DC Converter with Load Sharing

Non-Isolated DC-to-DC Converter Applications

With a non-isolated source providing power for multiple modules, all driving the same load, current sensing must be done on the high side as shown in Figure 18. The reason for this is that with a common source—and a common load—all the sense resistors in the return path would effectively be in parallel, defeating their ability to monitor individual module currents. The only limitation which the UC1907 presents to this configuration is that the current amplifier has a maximum common-mode range of VCC–2V which must be accommodated by either raising the supply voltage to the controller —as shown in Figure 18—or level-shifting the current sense voltage.

Since an optocoupler is not required, the feedback signal from the Voltage Amplifier in the UC1907 is taken from the Iset pin of the Drive Amplifier. With two inversions between the voltage sense input and the ISET pin, another reversal is required and is provided by the error amplifier within the UC1524A. This amplifier is set for unity or low gain inversion to be compatible with the 0.3 to 4.0V range of the ISET terminal.

In this application, the same sense resistor used for current sharing is also shown providing information for current limiting of the PWM controller. The Current Amplifier provides both a fixed gain of twenty and level shifting to a ground reference.

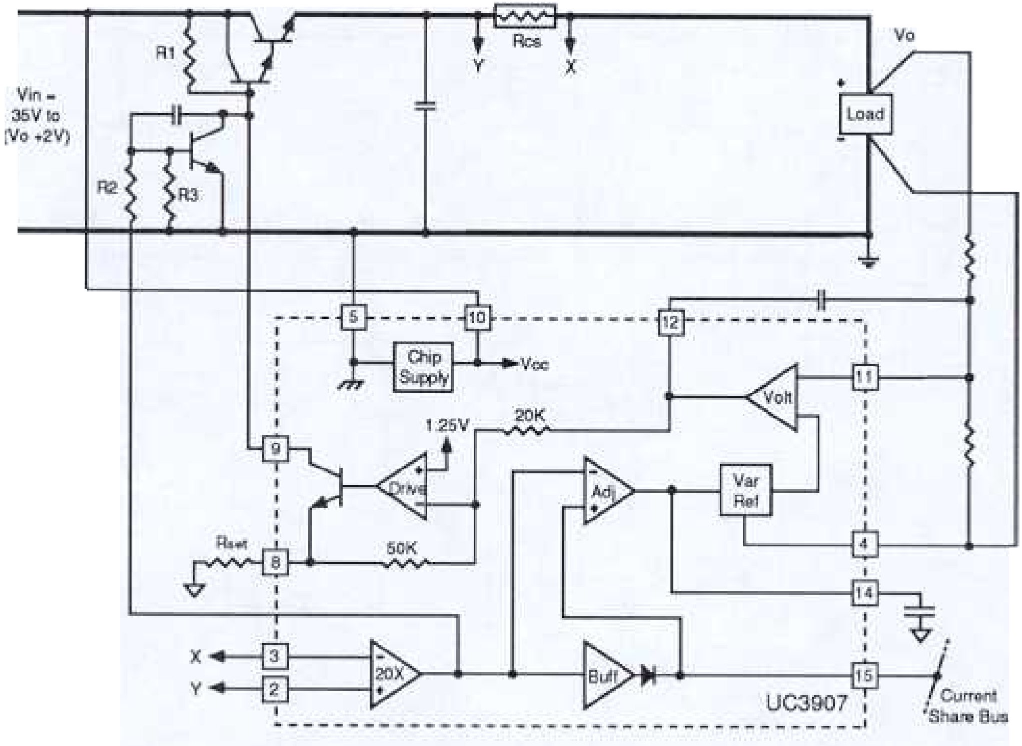

Fig 19. - UC1907 Controls a Linear Regulator with Current Limiting

A Linear Regulator Example

Figure 19 shows the use of the UC1907 as a load sharing controller for a linear regulator. The only added components are a Darlington power stage, plus a transistor which uses the Current Amplifier output to provide current limiting in addition to its primary function of load sharing. As this is another non-isolated example, current sensing must be done again in the positive power line and common-mode range considerations must be made.

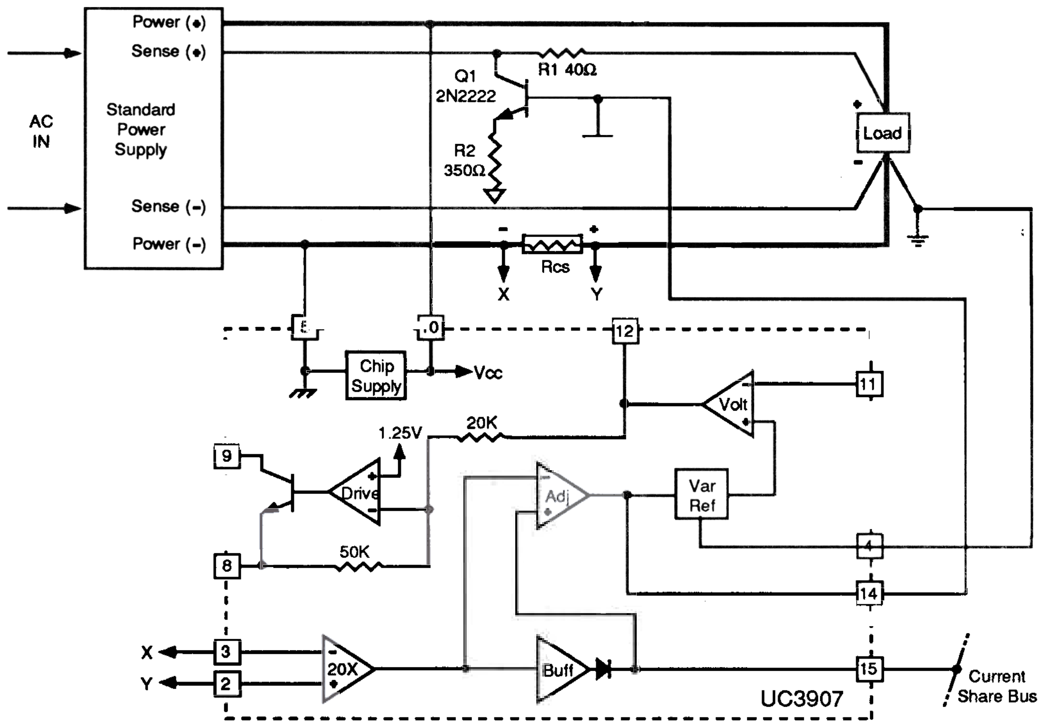

Fig 20. - Load Sharing Added to Existing Power Modules

Adding Load Sharing to Existing Power Modules

While the UC1907 is most efficiently utilized by incorporating it into the initial design of a power supply, it can also be used as in Figure 20 to retrofit existing modules as long as provisions for remote sensing have been provided. In this application, the voltage feedback portions of the UC1907 are unused as the voltage loop is already closed within the supply. However, current is sensed and the Adjust Amplifier is used to drive added transistor Q1, providing a variable voltage drop across R1. This accomplishes the same function as varying the reference voltage. Thus, the UC1907 can be used as a stand-alone add-on for power supplies designed without a built-in load sharing feature.

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