New No R_{SENSE} Controllers Deliver Very Low Output Voltages

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Introduction

Digital system voltages are dropping ever lower, yet battery voltages are not. This forces DC/DC step-down converters in portable products to operate at lower duty cycles. Unfortunately, low duty cycle operation decreases efficiency due to both increased switching losses and the increased importance of I^2R losses at low output voltages. Furthermore, conventional control architectures often have difficulty operating with very short switch on-times. The LTC1778 and LTC3711 with VID address these problems with a new architecture for buck regulators that delivers the low output voltages and high efficiencies that modern portable supplies require.

The LTC1778 is a step-down controller that provides synchronous drive for two external N-channel MOSFET switches. It comes with a variety of features to ease the design of very high efficiency DC/DC step-down converters. The true current mode control architecture has an adjustable current limit, can be easily compensated, is stable with ceramic output capacitors and does not require a power-wasting sense resistor. An optional discontinuous mode of operation increases efficiency at light loads. The LTC1778 operates over a wide range of input voltages from 4V to 36V and output voltages from 0.8V up to 90% of V_{IN}. Switching frequencies up to nearly 2MHz can be chosen, allowing wide latitude in trading off efficiency for component size. Fault protection features include a power-good output, current limit foldback, optional short-circuit shutdown timer and an overvoltage soft latch. The LTC3711 is essentially the same as the LTC1778 but includes a 5-bit VID interface.

Valley Current Control Enables $t_{ON(MIN)}$ < 100ns

Power supplies for modern portable computers require that voltages as high as 24V from a battery pack or wall adapter be converted down to levels from 2.5V to as low as 0.8V. Such a large ratio of input to output voltage means that a buck regulator must operate with duty cycles down to 3%. At 300kHz operation, this implies a main switch on-time of only 110ns. Conventional current mode regulators have difficulty achieving on-times this short, forcing lower frequency operation and the use of larger components.

To overcome this limitation, the LTC1778 family uses a valley current control architecture that is illustrated in Figure 1. Current is sensed by the voltage drop between the SW (or $SENSE^+$) and PGND (or $SENSE^-$) pins while the bottom switch, M2, is turned on. During this time the negative

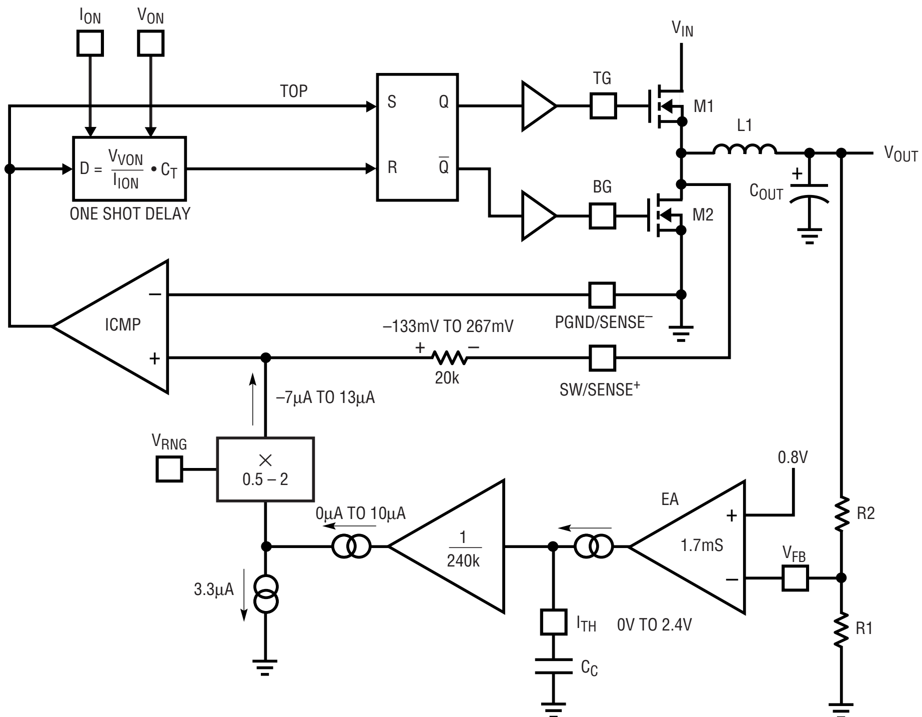

Figure 1. LTC1778 main control loop

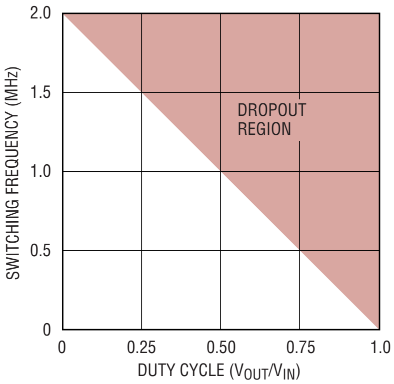

Figure 2. Maximum switching frequency vs duty cycle

voltage across inductor L1 causes the current flowing through it to decay. When it reaches the level set by the current-control threshold (I_{TH}) voltage, the current comparator (ICMP) trips. This sets the latch, turning off the bottom switch and turning on the top (or main) switch, M1. After a controlled delay determined by a one-shot timer, the top switch turns off again and the cycle repeats. The current-control threshold is set by an error amplifier (EA) that compares the divided output voltage with a 0.8V reference in order to keep the threshold at a level that matches the load current.

This control loop has several advantages compared to peak-current controllers that use an internal oscillator. Because only a one-shot timer determines the top switch on-time, it can be made very short for low duty cycle applications. Another advantage is that slope compensation is not required. Furthermore, response to a load step increase can be very fast since the loop does not have to wait for an oscillator pulse before the top switch is turned on and current begins increasing.

Flexible One-Shot Timer Keeps Frequency Constant

Although the LTC1778 does not contain an internal oscillator, switching frequency is kept approximately constant through the use of a flexible one-shot timer that controls the top switch on-time. A current entering the I_{ON} pin (I_{ION}) charges an internal timing capacitor (C_T) to the voltage applied at the V_{ON} pin (V_{VON}) to determine the on-time: $t_{ON} = C_T \bullet V_{VON}/I_{ION}$. For a buck regulator running at a constant frequency, the on-time is proportional to V_{OUT}/V_{IN}. By connecting a resistor (R_{ON}) from V_{IN} to the I_{ON} pin and connecting V_{OUT} to the V_{ON} pin (if available), the one-shot duration can be made proportional to V_{OUT} and inversely proportional to V_{IN}. The converter will then operate at an approximately constant frequency equal to $(R_{ON} \bullet C_T)^{-1}$. In most applications, the output voltage is not intended to change. Thus, some versions of the LTC1778 do not make the V_{ON} pin available and it defaults internally to 0.7V. By adjusting the value of R_{ON}, a wide range of operating frequencies can be selected. However, an important limit is set by the 500ns minimum off-time of the top switch. This is the minimum time required by the LTC1778 to turn on the bottom switch, sense the current and then shut it off. At a given switching frequency, it places a limit on the maximum duty cycle as illustrated in Figure 2. For example, at 200kHz operation, the LTC1778 can accommodate duty cycles up to 90%. Attempting to

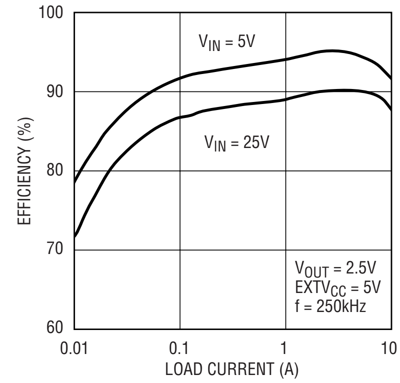

Figure 4. Efficiency vs load current for Figure 3's circuit

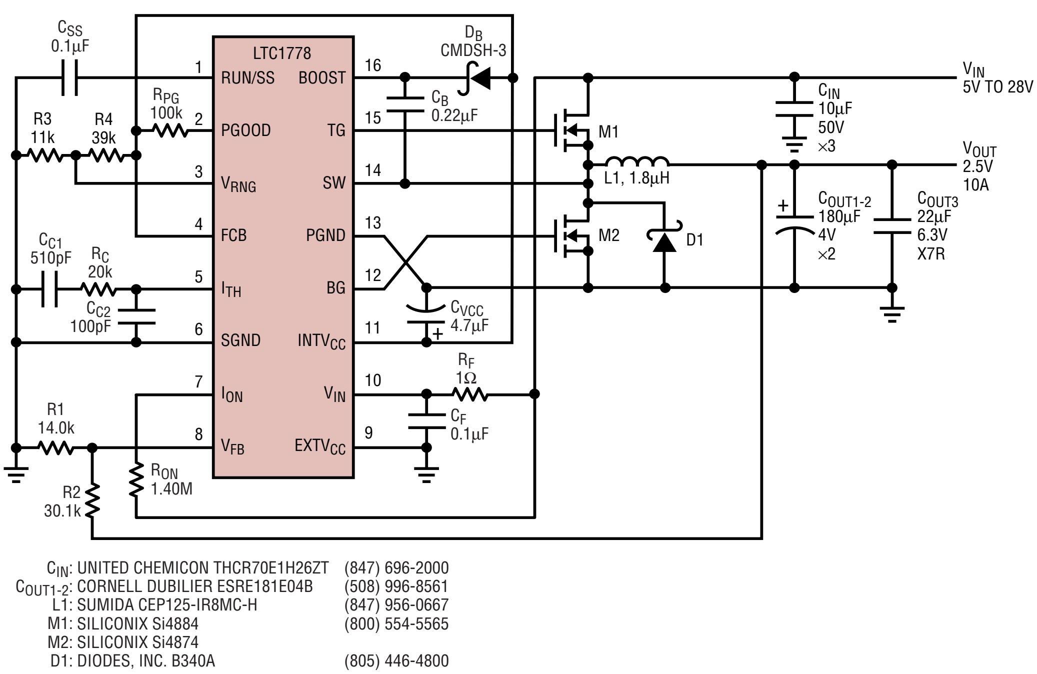

Figure 3. 2.5V/10A converter switches at 250kHz

operate at duty cycles above this limit will cause the output voltage to drop out of regulation, down to a value that satisfies the duty cycle limit. Thus, the LTC1778 can be used in exceptionally high frequency buck converters, provided that the duty cycle is low enough. For example, a 10V to 2.5V converter can be run at frequencies as high as 1.5MHz.

No R_{SENSE} Operation Raises Efficiency at Low V_{OUT}

The LTC1778 offers true current mode control without the need for a sense resistor, an expensive component that is sometimes difficult to procure. The current comparator monitors the voltage drop between the SW and PGND pins, determining inductor current using the on-resistance of the bottom MOSFET. In addition to eliminating the sense resistor, this technique also simplifies the board layout and improves efficiency. The efficiency gain is especially noticeable in low output voltage applications where the resistor sense voltage is a significant fraction of the output voltage. For example, a 50mV sense voltage reduces efficiency by 5% in a 1V output converter.

The LTC1778 allows the current sense range to be adjusted using the V_{RNG} pin to accommodate a variety of MOSFET on-resistances. The power supply designer can easily trade off efficiency and cost in the choice of MOSFET on-resistance. The voltage presented at the V_{RNG} pin should be ten times the nominal sense voltage at maximum load current, for example, V_{RNG} = 1V corresponds to a nominal sense voltage of 100mV. Connecting this pin to $INTV_{CC}$ or ground defaults the nominal sense voltage to 140mV or 70mV, respectively. Current is limited at 150% and –50% of the nominal level set by the V_{RNG} pin.

For those applications that require more accurate current measurement, the LTC3711 and some versions of the LTC1778 make available one or both of the current comparator inputs as separate $SENSE^+$ and $SENSE^-$ pins. Connecting the inputs to a precise sense resistor placed in series with the source of the bottom MOSFET switch determines current more accurately. This is especially beneficial for applications that need a more accurate current limit or seek to actively position the output voltage as the load current varies.

Output is Protected from a Variety of Faults

The LTC1778 comes with a number of fault protection features. The output voltage is continuously monitored for out-of-range conditions. If it deviates by more than ±7.5% from the regulation point, an open drain power-good output will pull low to indicate the out-of-regulation condition. In an overvoltage situation, the top switch will be turned off and the bottom switch turned on until the output is pulled back below the power-good threshold. In an undervoltage condition, if the output falls by 25%, a short-circuit latch-off timer will be started. If the output has not recovered within this time, both switches will be shut off, stopping the converter. Undervoltage/short-circuit latch-off can be overridden. In this case, if the output voltage continues to fall below 50% of the regulation point, the current limit will be reduced, or folded back, to about one fourth of its maximum value.

Popular Features from Other Controllers Remain

Continuous synchronous operation at light loads reduces efficiency due to the large amount of current consumed by switching losses. Efficiency is improved by operating the converter in discontinuous mode. In this mode, the bottom switch is turned off at the instant that inductor current starts to reverse, even though the current control threshold (I_{TH}) is below that level. The top switch, however, is not turned on until the I_{TH} level rises back to the point corresponding to zero inductor current. During the time both switches are off, the output current is provided solely by the output capacitor and switching losses are avoided. The switching frequency becomes proportional to the load current in this mode of operation.

The LTC1778 contains its own internal low dropout regulator that provides the 5V gate drive required for logic-level MOSFETs. However, it is also able to accept an external 5V to 7V supply if one is available. Connecting such a supply to the $EXTV_{CC}$ pin disables the internal regulator; all controller and gate drive power is then drawn from the external supply. If the external drive comes from a high efficiency source, overall efficiency can be improved. Furthermore, connecting the V_{IN} and $EXTV_{CC}$ pins together to an external 5V supply allows the controller to convert low input voltages such as 3.3V and 2.5V.

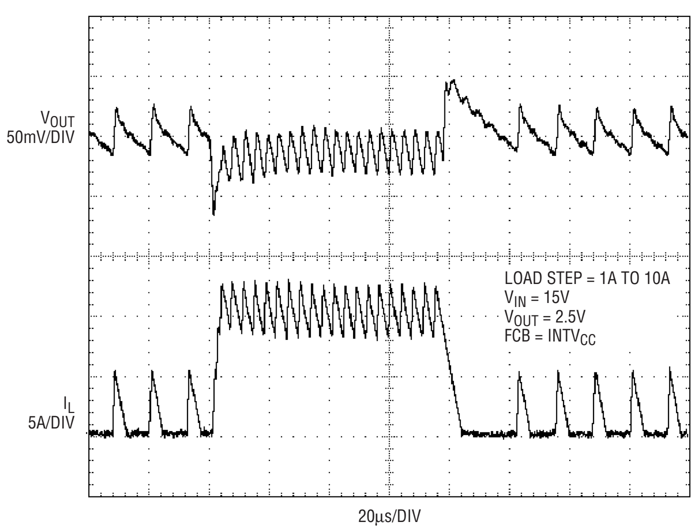

Figure 5. Transient response of Figure 3's circuit

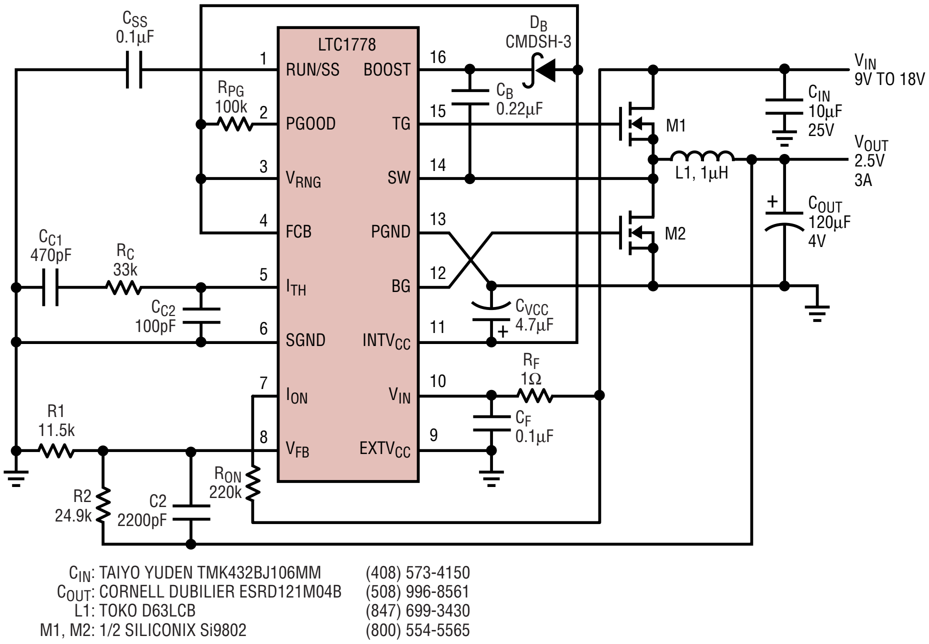

Figure 6. 2.5V/3A converter switches at 1.4MHz

Design Examples

Figure 3 shows a typical application circuit using the LTC1778EGN. This 16-pin SSOP version of the part does not make all of the pin functions available. The V_{ON} input is internally set to 0.7V and the $SENSE^+$ and $SENSE^-$ pins are cobonded with the SW and PGND pins, respectively. The circuit delivers a regulated 2.5V output at up to 10A from input voltages between 5V and 28V. The power MOSFETs from Siliconix are optimized for low duty cycle applications. The 1.4MΩ R_{ON} sets the 250kHz switching frequency. This switching frequency yields good efficiency with reasonable component sizes. Figure 4 shows that the efficiency of this circuit ranges from 90% to 95%, depending upon output current and input voltage. At light loads, below about 2A, the circuit enters discontinuous mode to keep the efficiency high. The response to a 1A to 10A load step is shown in Figure 5. Note the discontinuous mode operation with the 1A load and the rapid increase in inductor current after the load step.

Figure 6 shows a very high switching frequency buck regulator that allows the use of small power components. This circuit delivers a 2.5V output at up to 3A while switching at 1.4MHz. The minimum off-time constraint limits the duty cycle in this circuit to below 30%, as illustrated in Figure 2. Thus, the minimum permissible V_{IN} to avoid dropout is 9V. A pair of low-gate-charge MOSFETs in a single SO-8 package was chosen to minimize the significant switching losses at this high frequency. Efficiency runs about 80% to 85% with a 12V input.

Unlike many other current mode controllers, the LTC1778 can also be used in applications with a high output voltage, nearly up to the full input voltage. Figure 7 illustrates this with a 12V output circuit that can deliver up to 5A. This circuit uses the LTC1778EGN-1, which replaces the PGOOD pin with the V_{ON} pin. Tying this pin high sets the internal V_{ON} level to 2.4V, reducing the required value of the R_{ON} resistor for 300kHz operation. This circuit has excellent efficiency, reaching 97% at 5A with a 24V V_{IN}.

LTC3711 Adds VID Interface for 0.9V – 2.0V Microprocessor Core Supplies

Many low voltage microprocessors now require digital control of the output voltage and active voltage positioning to improve load transient response. The LTC3711 specifically addresses these needs. It uses the LTC1778 control architecture for handling the low duty cycles while adding a 5-bit VID interface. The VID code selects an output voltage in the range of 0.9V to 2.0V, compatible with Intel mobile Pentium® processors. The LTC1778 and LTC3711 both include a trimmed error amplifier

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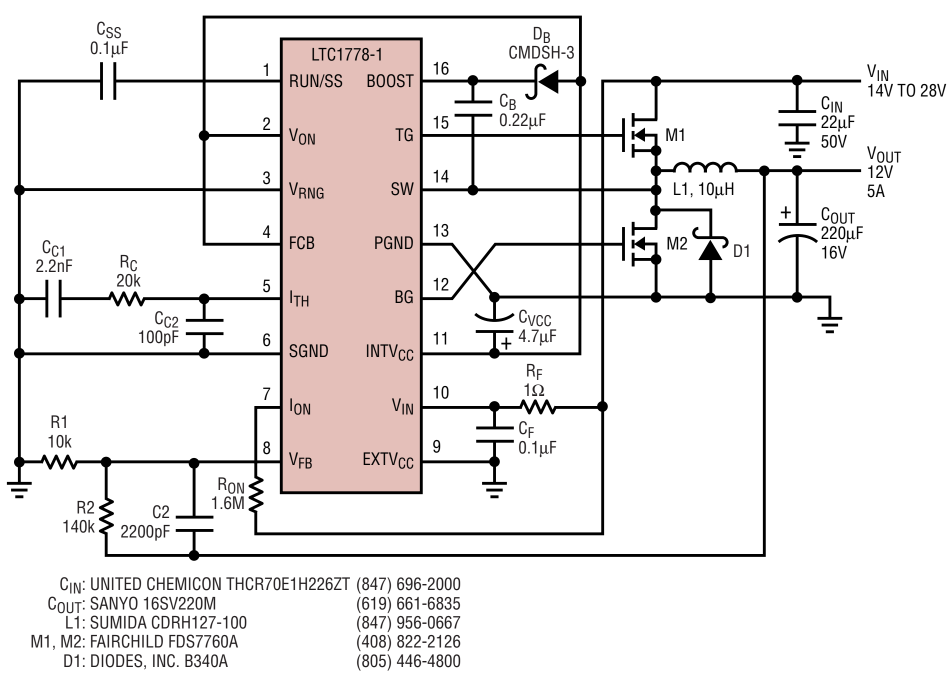
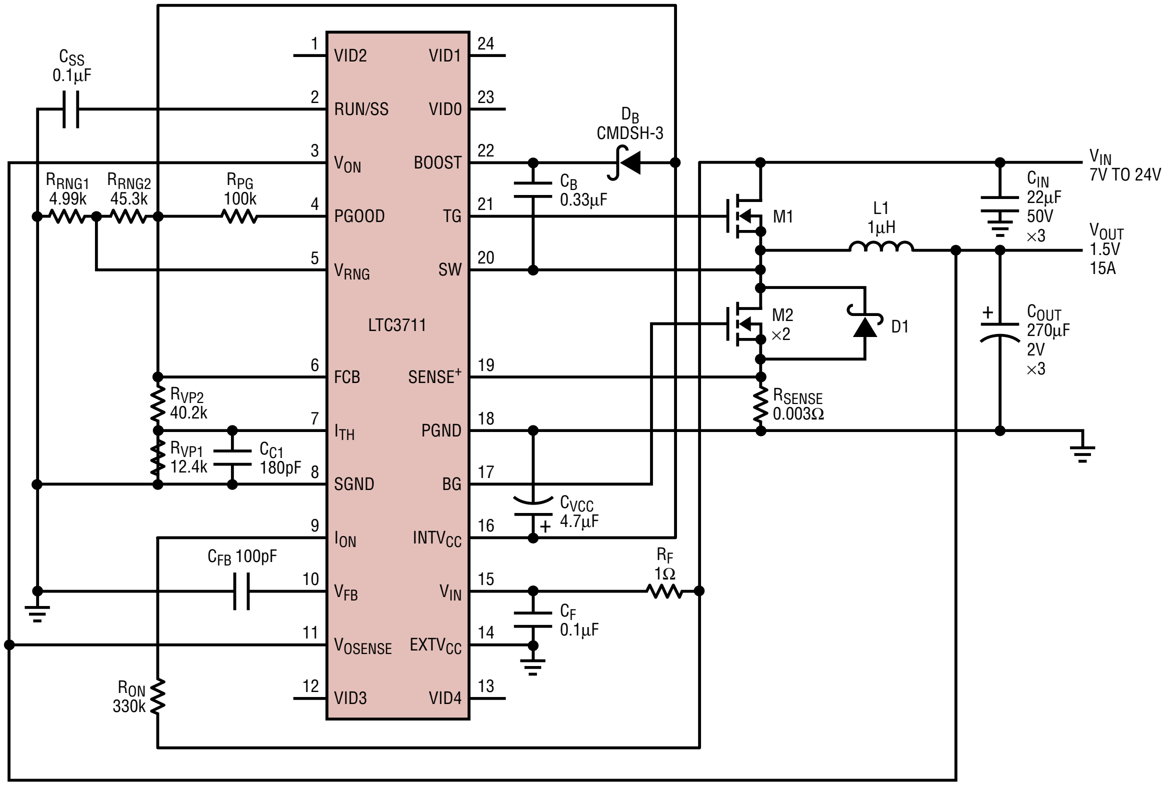


Figure 7. 12V/5A converter switches at 300kHz



C_{IN}: UNITED CHEMICON THCR70E1H26ZT (847) 696-2000
C_{OUT}: CORNELL DUBILIER ESRE271M02B (508) 996-8561
L1: SUMIDA CEP125-IR0MC-H (847) 956-0667
M1: INTERNATIONAL RECTIFIER IRF7811A (310) 332-3331
D1: MICROSEMI UPS840 (617) 926-0404

Figure 8. 1.5V/15A CPU core voltage regulator with active voltage positioning

transconductance that is constant over temperature. This feature allows more aggressive compensation of the control loop for faster transient response as well as enabling accurate active voltage positioning. Active voltage positioning lowers the output voltage in a controlled manner as the load current increases. This is useful in microprocessor power supplies where large load current transients are the main cause of output voltage error.

An example of a VID controlled LTC3711 application with active voltage positioning is shown in Figure 8. To facilitate the voltage positioning, the SENSE+ pin is used with a current sense resistor at the source of M2. The voltage positioning gain is accurately set using resistors R_{VP1} and R_{VP2} along with the trimmed transconductance of the error amplifier. This circuit positions the output voltage about 65mV above a 1.5V nominal output at no load, drooping to 65mV below the nominal output at full load. Voltage positioning allows the number of output capacitors to be reduced from five to three and still maintain a ±100mV specification on the output voltage.

Conclusion

The LTC1778/LTC3711 step-down DC/DC controllers are designed for power supplies operating over a wide input and output range. The valley current control architecture enables very low voltage outputs to be obtained from high input voltage sources such as battery packs and wall adapters. Eliminating the sense resistor improves efficiency and saves both board space and component cost. The LTC1778 and LTC3711 are excellent choices for delivering the low output voltages and high efficiencies required by modern portable power supplies.