A Third Generation Dual, Opposing-Phase Switching Regulator Controller

by Steve Hobrecht

Introduction

The LTC1628 is the newest member of Linear Technology's third generation of DC/DC controllers. (The latest single-output members include the LTC1735, LTC1735-1 and the 5-bit VID controlled LTC1736.) These controllers use a similar constant frequency, current mode architecture and Burst Mode operation as the previous generation LTC1435–LTC1439 controllers but with improved features. A key new feature is control circuitry that drives the two top switches 180 degrees out of phase to minimize the input capacitance requirement *and* reduce conducted and radiated EMI. The resultant input ripple is effectively half the amplitude and double the frequency of nonphased controllers, significantly reducing the input capacitance requirement. OPTI-LOOP™ compensation, 5V and 3.3V standby regulators, new protection circuitry, tighter load regulation and strong MOSFET drivers make these controllers ideal for current and future generations of CPU and/or system power applications.

New Features of LTC's Third Generation of DC/DC Controllers

- Dual controllers have opposing-phase top MOSFET turn-on timing.
- OPTI-LOOP compensation and Burst Mode operation reduce the output capacitance requirement while optimizing transient response and minimizing peak-to-peak output voltage ripple at all output current levels.
- A 0.8V, 1% reference allows lower output voltage operation (down to 0.8V).
- 0.2% load and line regulation
- The maximum current sense voltage has been reduced from 150mV to 75mV. This reduces the power lost in the sense resistor by a factor of two.
- The gate drivers are three to four times the strength of those in the previous generation of products, the LTC1435–39. This equates to faster rise and fall times when driving the same MOSFETs plus the capability to drive larger MOSFETs with less transition loss and higher efficiency.
- Overvoltage "soft latch"
- Undervoltage lockout at 3.5V
- Foldback current limiting and defeatable overcurrent latch-off
- The current comparators' common mode range includes ground. This allows operation of the switching regulator controller in a grounded sense resistor application while retaining full operation of all controller features.
- Three operating modes (the third item is new)
  —Forced PWM: inefficient but can be low noise
  —Burst Mode: very efficient but can generate noise, depending upon the load
  —Burst disable: reasonably efficient and low noise due to constant frequency operation down to approximately 1% of maximum designed load current.
- Minimum on-time < 200ns allows high V_{IN} to V_{OUT} ratios and high frequency operation without skipping cycles.
- Logical-control of fault coupling on the LTC1628 between the two controllers
  —Both controllers can be forced into continuous mode
  —A normally operating controller can be shut down when a short-circuit fault is sensed on the other controller (both are shut down and latched off).
- A standby mode on the LTC1628 provides two functions:
  —A common pin to pull down both RUN/SS pins for reset
  —A control pin that, when pulled high, turns on both the 5V and 3.3V standby regulators even when neither controller is turned on.

2-Phase Operation

The LTC1628 dual, high efficiency DC/DC controller brings the considerable benefits of 2-phase operation to portable applications for the first time. Notebook computers, PDAs, handheld terminals and automotive electronics will all benefit from the lower input filtering requirement, reduced electromagnetic interference (EMI) and increased efficiency associated with 2-phase operation.

Why the need for 2-phase operation? Up until the LTC1628, constant frequency dual switching regulators operated both channels in phase (1-phase operation). This means that both switches turned on at the same time, causing current pulses of up to twice the amplitude of those for one regulator to be drawn from the input capacitor and battery. These large amplitude current pulses increased the total RMS current flowing from the input capacitor, requiring the use of more expensive input capacitors and increasing both EMI and losses in the input capacitor and battery.

With 2-phase operation, the two channels of the dual switching regulator are operated 180 degrees out of phase. This effectively interleaves the current pulses coming from the switches, greatly reducing the overlap time where they add together. The result is a significant reduction in total RMS input current, which, in turn, allows less expensive input capacitors to be used, reduces

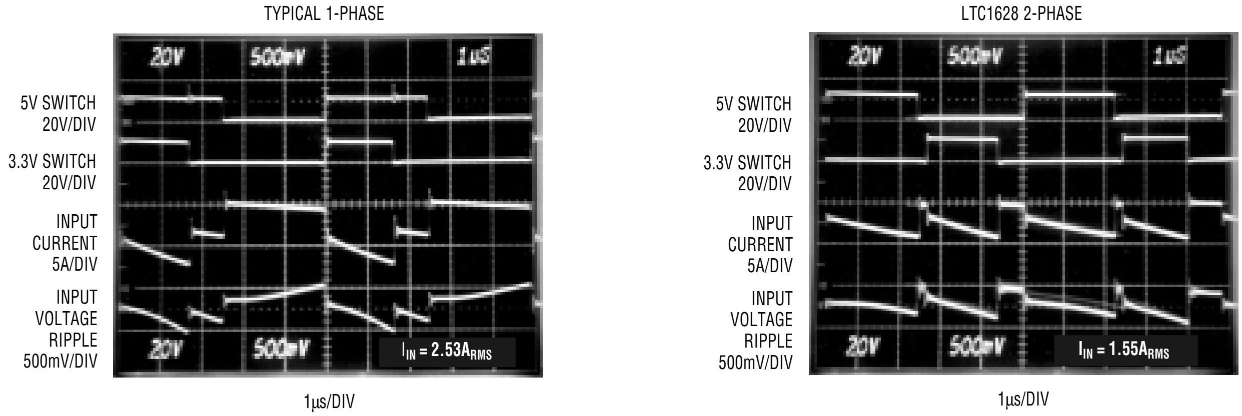

Figure 1. Input waveforms, comparing 1-phase and 2-phase operation for dual switching regulators converting 12V to 5V and 3.3V at 3A each: the reduced input ripple with the LTC1628 2-phase regulator allows the use of less expensive input capacitors, reduces shielding requirements for EMI and improves efficiency.

shielding requirements for EMI and improves overall operating efficiency.

Figure 1 compares the input waveforms for a representative 1-phase dual switching regulator to the LTC1628 2-phase dual switching regulator. An actual measurement of the RMS input current under these conditions shows that 2-phase operation decreases the input current from 2.53A_{RMS} to 1.55A_{RMS}. While this is an impressive reduction in itself, remember that the power losses are proportional to I^2_{RMS}, meaning that the actual power wasted is reduced by a factor of 2.66. The reduced input ripple voltage also means less power lost in the input power path, which could include batteries, switches, trace/connector resistances and protection circuitry. Improvements in both conducted and radiated EMI also directly accrue as a result of the reduced RMS input current and voltage.

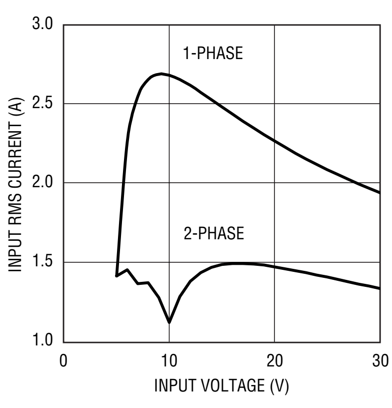

Figure 2. RMS input current vs input voltage; V_{O1} = 5V/3A; V_{O2} = 3.3V/3A

Of course, the improvement afforded by 2-phase operation is a function of the dual switching regulator's relative duty cycles, which in turn are dependent upon the input voltage, V_{IN} (duty cycle = V_{OUT}/V_{IN}). Figure 2 shows how the RMS input current varies for 1-phase and 2-phase operation for 3.3V and 5V regulators, each with a 3A constant load, over a wide input voltage range. It can be readily seen that the advantages of 2-phase operation are not limited to a narrow operating range, but in fact extend over a wide region. A good rule of thumb is that, in most applications, 2-phase operation will require the same input capacitance as one channel of a single-phase circuit operating at maximum current and 50% duty cycle.

Now, a final question: if 2-phase operation offers such an advantage over 1-phase operation for dual switching regulators, why hasn't it been done before? The answer is that, while simple in concept, it is hard to implement. Constant frequency, current-mode switching regulators require an oscillator-derived slope compensation signal to allow stable operation of each regulator at over 50% duty cycle. This signal is relatively easy to derive in 1-phase dual switching regulators, but required the development of a new proprietary technique to allow 2-phase operation. In addition, isolation between the two channels becomes more critical with 2-phase operation because switch transitions in one channel could potentially disrupt the operation of the other channel.

The LTC1628 is proof that these hurdles have been surmounted. The new device offers unique advantages for the ever-expanding number of high efficiency power supplies required in portable electronics.

Additional Features

The LTC1628 contains two synchronous step-down switching regulator controllers to drive external N-channel power MOSFETs using a programmable, fixed frequency OPTI-LOOP architecture. OPTI-LOOP compensation effectively removes the constraints placed on C_{OUT} by other controllers for proper operation. A maximum duty cycle limit of 99% provides low dropout operation, which extends operating time in battery-operated systems. A forced-continuous control pin reduces noise and RF interference and can assist secondary winding regulation by disabling Burst Mode when the main output is lightly loaded. Soft-start is provided for each controller by an external capacitor that can be used to properly sequence supplies. The operating output current levels are set by external current sense resistors. A wide input-supply range allows operation from 3.5V to 30V (36V maximum).

Protection

New internal protection features in the LTC1628 controllers (also included in the single-output versions) include foldback current limiting, short-circuit detection, optional short-circuit latch-off and overvoltage protection. These features protect the PC board, the MOSFETs and the load itself against faults.

Fault Protection: Overcurrent Latch-Off

The RUN/SS pins, in addition to providing soft-start capability, also provide the ability to shut off the controller and latch off when an overcurrent condition is detected. The RUN/SS capacitor, C_{SS} (refer to Figure 5), is used initially to turn on and limit the inrush current of the controller. After the controller has been started and given adequate time to charge the output capacitor and provide full load current, C_{SS} is used as a short-circuit timer. If the output voltage falls to less than 70% of its nominal output voltage after C_{SS} reaches 4.2V, it is assumed that the output is in a severe overcurrent and/or short-circuit condition and C_{SS} begins discharging. If the condition lasts for a long enough period, as determined by the size of C_{SS}, the controller will be shut down until the RUN/SS pin voltage is recycled.

This built-in latch-off can be overridden by providing >5µA at a compliance of 4V to the RUN/SS pin (refer to the LTC1628 data sheet for details). This external current shortens the soft-start period but also prevents net discharge of the RUN/SS capacitor during a severe overcurrent and/or short-circuit condition.

Why should you defeat overcurrent latch-off? During the prototyping stage of a design, there may be a problem with noise pickup or poor layout causing the protection circuit to latch off. Defeating this feature will allow easy troubleshooting of the circuit and PC board layout. The internal short-circuit detection and foldback current limiting still remain active, thereby protecting the power supply system from failure. After the design is complete, you can decide whether to enable the latch-off feature.

A logic input pin, FLTCPL, can direct the internal control circuitry to shut down a normally operating controller when a fault results in the shutdown of either controller. In addition, this pin can direct both channels to operate in a forced continuous (PWM) mode when the FCB pin falls below a 0.8V threshold.

Table 1. Overvoltage protection comparison

Operating Condition	Soft Latch	Hard Latch
Fast Transients	Controls Overshoot	Latches Off
Output Shorted to 5V	Output Clamped at OVP	Latches Off
VID Voltage Decrease	Regulates New Voltage	Latches Off
Noise	Controls Output	Latches Off
Shorted Top MOSFET	Bottom MOSFET Overloads	Bottom MOSFET Overloads
Output Voltage Can Reverse	No	Yes
When Overload is Removed	Resumes Normal Operation	Remains Latched Off
Troubleshooting Faults	Easy DC Measurements	Difficult; May Require Digital Oscilloscopes

Fault Protection: Current Limit and Current Foldback

The LTC1628 current comparators have a maximum sense voltage of 75mV, resulting in a maximum inductor current of 75mV/R_{SENSE}. The LTC1628 includes current foldback to help further limit load current when the output is shorted to ground. If the nominal output voltage falls by more than 30%, the maximum sense voltage is progressively lowered from 75mV to 30mV. Under short-circuit conditions with very low duty cycle, the LTC1628 will begin cycle skipping in order to limit the short-circuit current. In this situation, the bottom MOSFET will be on most of the time, conducting the current. The average short-circuit current will be approximately 30mV/ R_{SENSE}. Note that this function is always active and is independent of the short circuit latch-off.

Fault Protection: Output Overvoltage Protection (OVP)

An output overvoltage crowbar turns on the synchronous MOSFET to either force a protected-wall-adapter power source into a current/power limiting mode or blow a system fuse in the input lead when the output of the regulator rises much higher than nominal levels. The crowbar can cause huge currents to flow, greater than in normal operation. This feature is designed to protect the load against a shorted top MOSFET or shorts to higher supply rails.

Previous latching crowbar schemes for overvoltage protection have a number of problems (see Table 1). One of the most obvious, not to mention most annoying, is nuisance trips caused by noise or transients momentarily exceeding the OVP threshold. Each time this occurs with latching OVP, a manual reset is required to restart the regulator. Far more subtle is the resulting output voltage reversal. When the synchronous MOSFET latches on, a large reverse current is loaded into the inductor while the output capacitor is discharging. When the output voltage reaches zero, it does not stop there, but rather continues to go negative until the reverse inductor current is depleted. This requires a sizable Schottky diode across the output to prevent excessive negative voltage on the output capacitor and load.

A further problem on the horizon for latching OVP circuits is their incompatibility with on-the-fly CPU core voltage changes. If an output voltage is reprogrammed from a higher voltage to a lower voltage, the OVP will temporarily indicate a fault, since the output capacitor will momentarily hold the previous, higher output voltage. With latching OVP, the result will be another latch-off, with a manual reset required to attain the new out-

Table 2. FCB possible states

FCB Pin	Condition
DC Voltage: 0V–0.7V	Burst Disabled/ Forced Continuous, Current Reversal Enabled
3.5V > DC Voltage > 0.9V	Burst Mode, No Current Reversal
Feedback Resistors	Regulating a Secondary Winding
DC Voltage = 5V	Burst Mode Disabled, No Current Reversal

put voltage. To prevent this problem, the OVP threshold must be set above the maximum programmable output voltage, which would do little good when the output voltage was programmed near the bottom of its range.

In order to avoid these problems with traditional latching OVP circuits, the LTC1628 uses a new "soft-latch" OVP circuit. Regardless of operating mode, the synchronous MOSFET is forced on whenever the output voltage exceeds the regulation point by more than 7.5%. However, if the voltage then returns to a safe level, normal operation is allowed to resume, thereby preventing latch-off caused by noise or voltage reprogramming. Only if a true fault, such as a shorted top MOSFET, exists will the synchronous MOSFET remain latched on until the input voltage collapses or the system fuse blows.

The new soft-latch OVP also provides protection and easy diagnosis of other overvoltage faults, such as a lower supply rail shorted to a higher voltage. In this scenario, the output voltage of the higher regulator is pulled down to the OVP voltage of the soft-latched regulator, allowing the problem to be easily diagnosed with DC measurements. On the other hand, latching OVP provides only a transient glimpse of the fault as it latches off, forcing the use of expensive digital oscilloscopes for troubleshooting.

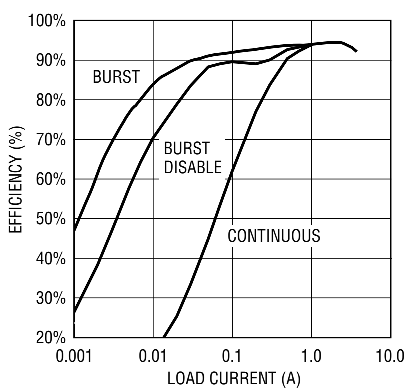

Figure 3. Efficiency vs load current for three modes of operation (V_{IN} = 15V, V_{OUT} = 5V)

Three Operating Modes/ One Pin: Forced PWM, Burst and Burst Disable

The FCB pin is a multifunction pin that controls the operating mode of the LTC1628. When the FCB pin drops below a 0.8V threshold (or is grounded), continuous mode operation is forced on the first controller if V_{FLTCPL} = 0V or on both controllers if V_{FLTCPL} = 5V. In continuous mode, the top and bottom MOSFETs continue to be driven synchronously regardless of the load on the output. The inductor current is allowed to go negative at low load currents in order to maintain a secondary output voltage. The voltage derived from a secondary winding can be resistively divided down and fed into the FCB pin to force continuous operation momentarily or continuously as required to regulate the secondary output voltage. This allows a secondary output voltage to be regulated, regardless of the load on the primary output.

When the FCB pin is left open, Burst Mode operation is enabled. Burst Mode operation allows intermittent on/off PWM operation of the output MOSFETs, as required to keep the output in regulation. This maximizes efficiency at the expense of a slight increase in output voltage ripple (20mV–30mV).

The burst disable mode is selected by tying the FCB pin to the $INTV_{CC}$ pin. The burst disable mode uses a constant frequency, discontinuous inductor current method. This mode is not as efficient as Burst Mode, but allows low noise, constant frequency operation down to approximately 1% of the maximum designed load current and does not allow the inductor current to reverse. At very low currents, cycles are skipped to maintain proper output voltage.

Table 2 summarizes the possible states available on the FCB pin.

Figure 3 gives a comparison of efficiencies in a regulator for the three operating modes: forced continuous operation, burst disable (pulse-skipping) mode and Burst Mode operation.

Speed

The LTC1628 is designed to be used in higher current applications than the LTC1435–39 family. Stronger gate drive allows paralleling multiple MOSFETs or higher operating frequencies. The LTC1628 has been optimized for low output voltage operation by reducing the minimum on-time to less than 200ns. Remember, though, that transition losses can still impose significant efficiency penalties at high input voltages and high frequencies. The LTC1628 can operate at 300kHz but that doesn't mean it should be used there in every application. Figure 4 shows a plot of MOSFET charge current versus frequency.

Linear Current Comparator Operation

Since the trend in the marketplace has forced output voltages to lower and lower values, the current sense inputs have been optimized for low voltage operation. The current sense comparator has a linear response characteristic, without discontinuities, for output voltages from 0V to 6V. In the LTC1435–LTC1439, two input stages are used to cover this

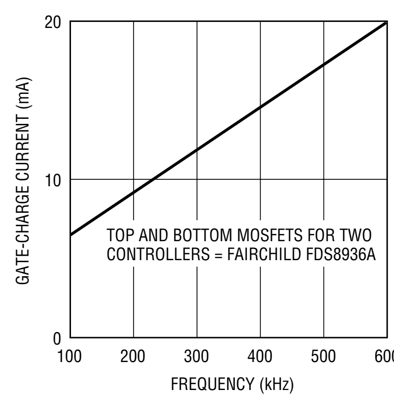

Figure 4. Gate-charge current vs frequency (V_{IN} = 15V, V_{GATE} = $5V_{P-P}$)

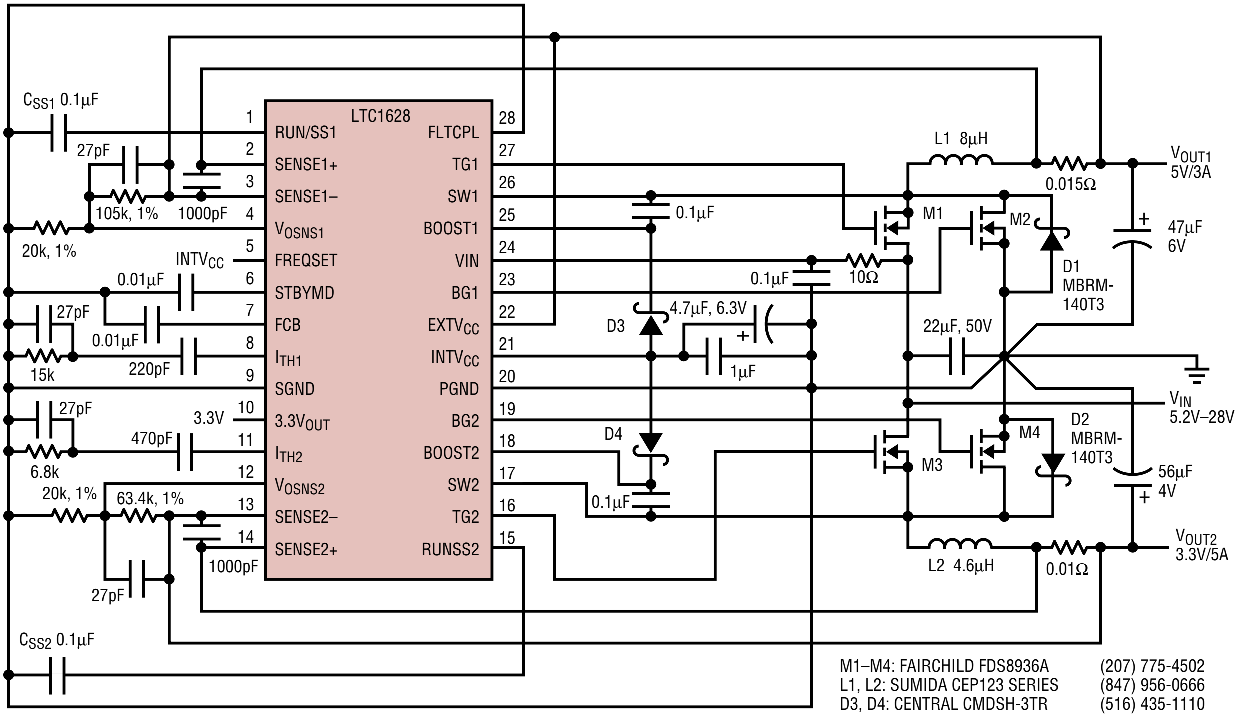

Figure 5. High efficiency 5V/3A, 3.3V/5A, small-footprint system power design

range, so an overlap (with a transition region) exists. All third-generation products, including the LTC1628 uses only one input stage and includes slope compensation that operates over the full output voltage range. This allows the third generation controllers to be operated in grounded R_{SENSE} applications.

Remote Output Voltage Sensing

The LTC1628 also has remote sense capability. A resistive divider is connected between the output load and SGND. The SGND pin can be tied to the load return, allowing a Kelvin connection for remotely sensing the output voltage directly across the load, eliminating any PC board–trace resistance errors.

Table 3. Comparison of LTC1628 controller with LTC1438/LTC1439 controllers

Parameter	LTC1628	LTC1438/LTC1439
Reference	0.8V, 1%	1.19V, 1%
Load Regulation	0.05% Typ, 0.3% Max	0.5% Typ, 0.8% Max
Max Current Sense	75mV	150mV
Minimum On-Time	200ns	400ns
Opposing Phase	Yes	No
Standby Voltages	5V, 3.3V	5V
Undervoltage Lockout	3.5V	No
Current Foldback	Internal	External
Overvoltage Protection	Yes	No
Overcurrent Latch-Off	Optional	No
Fault Coupling	Overcurrent Latch-Off	No
MOSFET Drivers	3×	1×

Applications

Figure 5 shows a 5V/3A, 3.3V/5A application using the LTC1628. The input voltage can range from 5V to 28V. Table 3 compares the third-generation LTC1628 with LTC's second generation LTC1438/LTC1439 dual controllers.

Conclusion

The LTC1628 is the latest member of Linear Technology's third generation family of constant frequency, N-channel, high efficiency controllers. With opposing phase, new protection features, OPTI-LOOP compensation and strong MOSFET drivers, the LTC1628 is an ideal choice for many system power applications. The third generation controllers have been designed specifically to minimize both the overall power system cost and the physical size and number of the external components in order to meet the size/performance requirements of new products. The high performance of these controllers, with their wide input voltage range, 1% output voltage accuracy and tight line and load regulation, makes them ideal for next generation designs.