Title: Green-Mode for High Power Buck Controllers using DCR Current Sensing

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1.0 Introduction

In battery-operated systems, low quiescent current consumption during stand-by has become an intrinsic performance parameter as it partially determines the battery life. Many DC/DC controllers defined for high power applications do not support modes for low current operation during stand-by. In this paper, a technique is proposed for practical realization of Green mode operation using low-cost, simple circuit added externally to the DC/DC converters. The technique makes it possible to achieve high efficiencies at lower loads and consume lower current under no-load or stand-by conditions. The implementation is done using lossless DCR current sensing circuit ensuring high efficient operation. This paper also proposes improved DCR current sensing technique to obtain a good resolution in the inductor current measurement ensuring Green node operation even at light loads as low as 10mA. The proposed technique is implemented and tested with 24V input, 12V/240W output DC-DC converter using TPS40170. Experimental results are presented for different operating conditions. Applying this technique, no-load current of the 240W power supply has been brought down from 40mA to less than 1mA using Green mode.

2.0 Criticality of losses in Battery Powered Systems

Energy limited, battery powered system requires the utmost in efficiency in order to provide full system capability and maximum battery life. Elements which require high instantaneous power, such as transmitters, microprocessors, backlit displays and flash memory can be switched to a low power standby mode when not needed. Applications include portable computers, hand-held instruments, wireless telecommunications, automotive systems, etc.
To fully realize such systems DC-DC converters are needed which can (a) regulate the load voltage with (ideally) zero load current; (b) operate at high efficiency with many orders of magnitude variation in the load current; (c) operate efficiently at low output voltages.
Losses in a switch mode converter can be classified as

- Load dependent conduction losses (due to transistor resistance, diode forward voltage drop, inductor winding resistance, capacitor equivalent series resistance)
- Fixed losses (due to controller standby current, leakage currents of transistors, diodes, etc)
- Frequency dependent switching losses (due to transistor and diode output capacitance charge and discharge, gate drive losses, voltage / current overlap at switching transitions, inductor core losses, controller frequency dependent power consumption)

Conduction losses can only be minimized by choosing the components with lower resistance / voltage drops. Fixed losses are inevitable and are bare minimum for a system. Switching losses are the losses that can be reduced with different techniques.
Switching losses do not scale with load and hence light-load efficiency is becomes poor. Also it is difficult to maintain output voltage regulation when converter is unloaded. An approach to the above problem is to allow the switching regulator to operate in burst mode at light loads. This approach has been shown to yield significantly improved efficiency at light loads and is currently supported by dedicated controllers. There are some systems that do not support this feature and the same can be externally implemented to improve efficiency at light loads.

3.0 Green-Mode Description

The Green Mode is capable of operating in bursts, in which the power MOSFET turns on intermittently based on light load demand, thus reducing the switch loss and quiescent current at the same time. This mode of operation is also popularly known as Burst mode, Pulse Skip mode, Eco mode, etc. Most of the regulators especially those that are designed for battery powered applications have this mode to save on battery life but there are some switching regulators that do not have these features and hence limit their usage is battery powered critical applications.

3.1 Operation

When the regulator operates in burst mode, each burst event can last from a few cycles with long sleep intervals under light load to almost continuously cycling with short sleep intervals under moderate load. Between these burst sleep events, the power switch and any unnecessary circuits are turned off to reduce the quiescent current. In this sleep status, the load current is supplied solely by the output capacitor. Along with the output voltage drops, the feedback voltage decreases below the sleep threshold, and the BURST comparator is signaled to trip and turn the power MOSFET on. This process repeats at a rate depending on the load condition. The BURST comparator is a typical bilateral hysteresis comparator and the hysteresis window determines the output ripple voltage in the burst mode.

It is common sense that overshoot voltage is harmful for apparatus, but it does exist in most multi-mode controlled regulators. As a solution, different reference voltages from PWM mode to burst mode are helpful to suppress the overshoot voltage between the mode transitions.

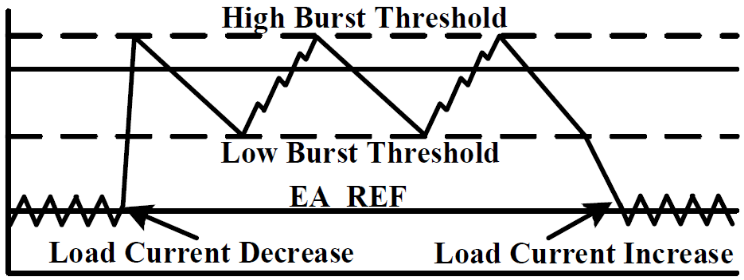

Figure 3.1 Performance of mode transitions

During burst mode operation, the controller sets the output voltage slightly higher / lower than normal output voltage during PWM mode, allowing additional headroom for voltage increment / decrement during a load transient. As shown in Figure 3.1, when the load is heavy, the regulator works in PWM mode. When the output voltage rises above the high burst threshold, then the power MOSFET turns off and the regulator gets into the burst mode operation. Conversely, if the load changes from light to heavy, the output voltage will decrease below the EA_REF and the regulator will turn back to the PWM mode operation.

4.0 Use of DCR Current Sensing Technique

The basic idea for this technique is taken from the resistive-based current sensing using external sense resistor method. At higher frequencies, the parasitic equivalent inductance of resistor Rsense appears. Hence, it is necessary to compensate for the parasitic inductance. The equivalent circuit of Rsense for this case is given in Figure 4.1.

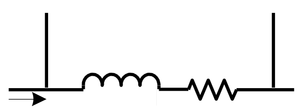

Figure 4.1 Equivalent circuit of R_{sense}

Voltage V_{sense} is given by (4.1).

$$V_{sense}(s) = (R_{sense} + Ls)I_{sense}(s) = K * I_{sense}(s) \tag{4.1}$$

At lower frequencies, voltage Vsense is proportional to current Isense. At higher frequencies, gain K increases due to the parasitic inductance. A proper low pass filter, which can be active or passive, is required for compensating the gain K. If a passive RfCf low pass filter is used, the voltage across the filter (VCf) is then given by (4.2).

$$V_{cf} = \left(\frac{R_{sense} + Ls}{1 + R_f C_f s}\right) I_{sense}(s) \tag{4.2}$$

Inductor windings have DCR or internal resistance RL. It is possible to use the DCR of inductor L as Rsense and inductor L itself as parasitic inductor in above case. Therefore, the filter-based current sensing technique uses the resistor RL of inductor L and passive filter RfCf, as shown in Figure 4.2, for accurate current sensing. The total impedance of the RfCf filter is same as the total impedance of L and RL. This technique is currently popular because of its accuracy, lossless and high bandwidth. Other advantages of this technique include; continuous current measurement, low cost, PCB space saving, and power efficiency improvement.

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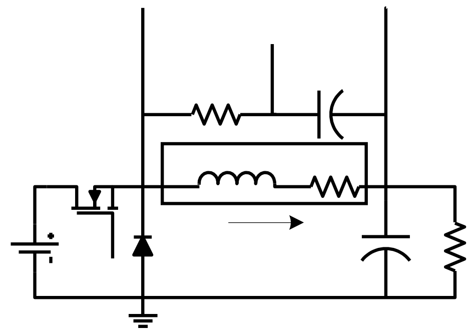

Figure 4.2 Filter-based current sensing technique

This technique detects the current IL signal by sensing capacitor Cf voltage (VCf). Voltage VCf is given by (4.3).

$$V_{c4}(s) = I_L(s)\left(\frac{R_L + L_2 s}{1 + R_{12} C_4 s}\right)$$

4.3

The parallel RfCf filter is designed in such a way that (4.4) and (4.5) are satisfied.

$$R_{12} C_4 = \frac{L_2}{R_L}$$

4.4

$$\frac{L}{R_L} \gg T$$

4.5

where τL = L/RL is an inductor time constant and τC = RfCf is a low pass filter time constant. It is very difficult to satisfy (4.4). However, it is easy to satisfy (4.5) because the switching frequency is usually in the order of a few hundred kHz and resistance RL is in mili-ohms.

If (4.4) and (4.5) are satisfied, the inductor current IL is given by (4.6).

$$V_{c4} = I_L R_L$$

4.6

5.0 Practical implementation of Green-Mode using TPS40170

The complete schematic of TPS40170 DC / DC including Green mode circuitry is shown in Figure 5.1.

5.1 Operation

Green mode circuit consists of three sections:

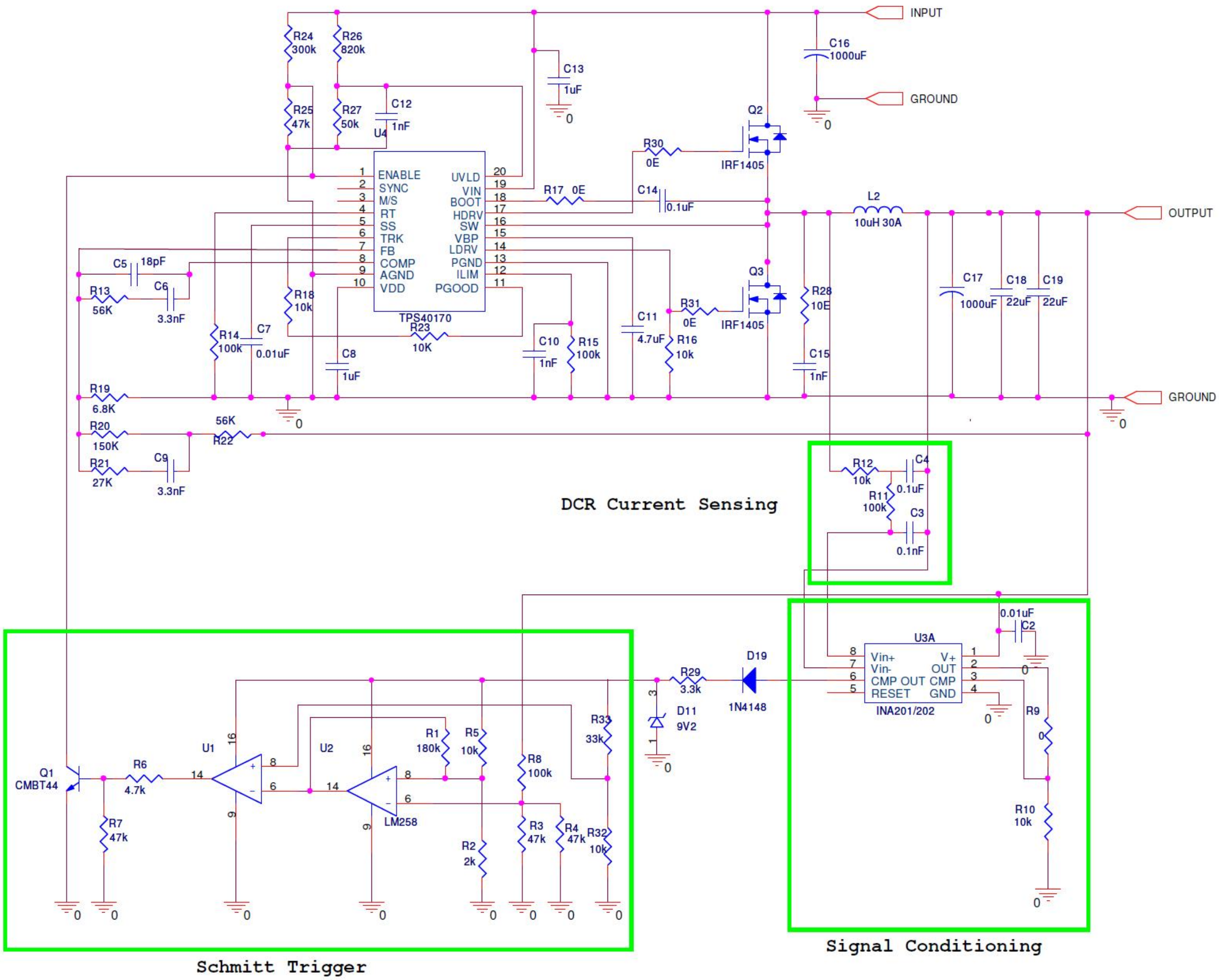

Figure 5.1 24V to 12V DC/DC converter with Green-Mode using TPS40170

5.1.1 DCR current sensing

The operation of DCR current sensing is described in section (4.0) in detail and hence the output of DCR circuit would be a triangular signal that would be proportional to the voltage across DC resistance of output inductor which in turn is proportional to the current flowing through it.

5.1.2 Signal Conditioning

This part of the circuit amplifies the weak signal to the level where it can be used to compare and make decision. It is basically a simple differential or an instrumentation amplifier whose gain should be adjusted to get required output signal level. This in turn is given to a comparator that compares output current to a threshold to determine whether to enable or disable Green mode.

5.1.3 Schmitt Trigger

The function of Schmitt trigger is to define two thresholds (upper and lower) which are below nominal output voltage and enable or disable the DC / DC controller whenever output voltage hits the thresholds based on whether Green mode is enabled or disable (through signal conditioning circuit).

When the output current goes low and reaches Green mode threshold, the output voltage is at nominal. Upon detection, signal conditioning circuit enables the Schmitt trigger circuit to function. Since the output is higher than upper threshold, Schmitt trigger turns OFF the DC/DC. Output current to the load is supplied solely by the output capacitor and hence output slowly drops. The rate at which output drops is dependent on the load current requirement. Once output reaches the lower threshold, Schmitt trigger turns ON the DC/DC allowing it to regulate the output voltage to the nominal output voltage. Even before output voltage reaches the nominal level, upper threshold will be hit and hence Schmitt turns OFF the DC / DC again. This cycle repeats till the load current requirement is below the Green threshold. Once the load current goes high, green mode will be turned OFF and device runs in normal PWM mode. This makes output voltage to swing between upper and lower thresholds as long as the device is in Green Mode at frequencies depending on the load.

The waveforms from Figure 5.2 through Figure 5.5 show phase node characteristics of the DC/DC and also the impact of Green Mode. Channel A is the output voltage and Channel B is the switching waveforms. The quiescent current without green mode was 50mA and with the current with green mode is mentioned below.

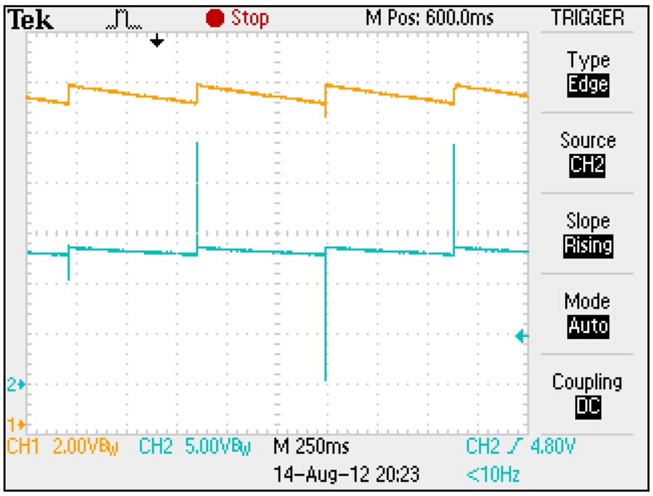

Figure 5.2 Iout = 0A, Iin = 1mA

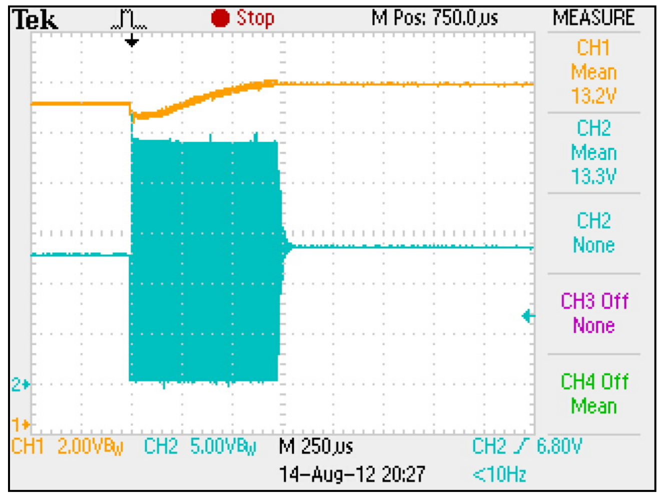

Figure 5.3 Iout = 0mA, Iin = 1mA

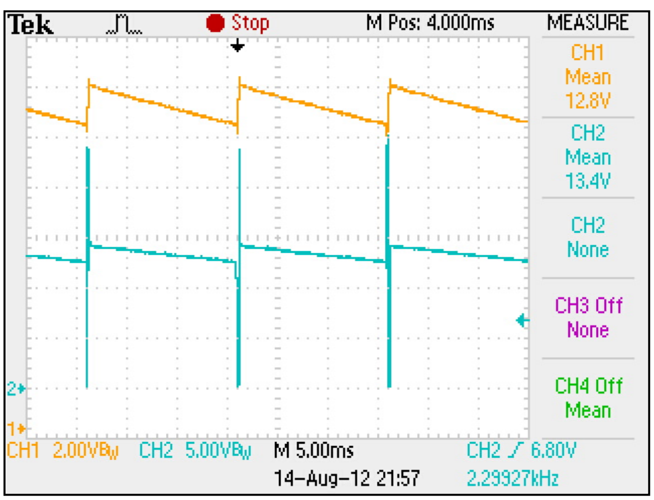

Figure 5.4 Iout = 100mA, Iin = 65mA

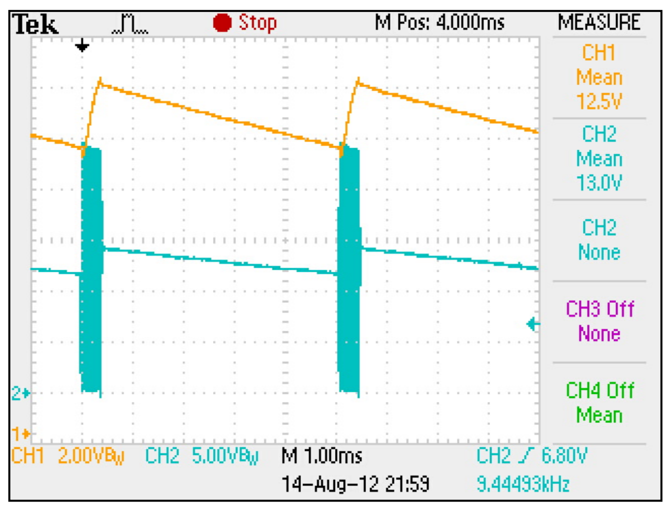

Figure 5.5 Iout = 500mA, Iin = 290mA

6.0 Conclusion

The paper presented and described how to reduce quiescent current and improve light load efficiency of a DC/DC current by adding a circuit externally. The external circuit added is quite simple and is designed considering cost as the primary factor. The quiescent current has been brought down from 50mA to 1mA by implementing Green-Mode which can be brought even lower by using better performing comparator in Schmitt trigger.