Controlled Auxiliary Circuit with Measured Response for Reduction of Output Voltage Overshoot in Buck Converters

Eric Meyer (Student Member, IEEE), Zhiliang Zhang (Student Member, IEEE), Yan-Fei Liu (Senior Member, IEEE)

Queen's Power Group, www.queenspowergroup.com
Department of Electrical and Computer Engineering, Queen's University, Kingston, Ontario, Canada, K7L 3N6
eric.meyer@ece.queensu.ca, zhiliang.zhang@ece.queensu.ca, yanfei.liu@queensu.ca

Abstract – **In order to adhere to voltage regulation criteria, capacitor selection of a Buck converter must be based on the worst possible scenario. It is well known that, for a low duty cycle Buck converter, the output voltage deviation of a Buck converter undergoing an unloading transient will be significantly larger than that of a corresponding loading transient of equal magnitude. Therefore, in this paper, an auxiliary circuit and corresponding control method is presented to reduce the output voltage overshoot of a Buck converter undergoing an unloading transient. The proposed auxiliary circuit diverts a constant controlled current from the output of the converter to the input of the converter thereby significantly reducing the output voltage overshoot. In addition, the proposed auxiliary controller estimates the magnitude of the unloading transient and sets the auxiliary current to an appropriate level based on a pre-defined set of criteria. This allows for greater design flexibility and increases the auxiliary circuit efficiency for unloading transients of lesser magnitude. As demonstrated through simulation and experimental results, the proposed converter successfully estimates the unloading transient magnitude and diverts a proportional amount of current from the converter output.**

I. INTRODUCTION

As the voltage regulation criteria tightens for Buck converter applications, it has become increasingly important to improve the converter's transient performance without significantly increasing its size/cost. Thus, the placement of additional output capacitors should be avoided, if possible. While non-linear control methods [1]-[3] may improve a converter's transient response to virtually optimal levels, it is clear that the Buck topology itself limits performance. Following an unloading (load current step-down) transient, the relatively slow slew rate of the inductor current causes large output voltage overshoots and long settling times compared to that of a loading (load current step-up) transient. Therefore, capacitor selection must be based on the larger voltage overshoot condition.

In order to address the large overshoots typical of voltage regulator module (VRM) applications, numerous auxiliary circuits have been proposed for the Buck converter [4]-[10].

In [4]-[5], a transformer is connected across the impedance of the output trace of a Buck converter in order to inject/absorb excess load current to improve the dynamic performance.

In [6], an auxiliary switch is used to bypass the output inductor of a Buck converter in order to provide a very low inductance path to the output. The switch remains full-on for the duration that the output voltage deviation exceeds a pre-determined threshold.

An auxiliary switch in series with a small inductor is utilized in [7] to recover excess current to the input during step-down load transients. The circuit also provides a low-impedance auxiliary path for step-up load transients. The auxiliary circuit is controlled using a differentiator in an attempt to instantaneously track the capacitor current.

In [8], the output of an isolated DC-DC converter is connected through an auxiliary circuit (similar to [7]) to a voltage rail (fed by the rectified voltage of the secondary winding) in order to inject/absorb excess current. The auxiliary circuit is controlled linearly based on the magnitude of the voltage overshoot.

An auxiliary circuit (similar to [7]) is connected to the output of a Buck converter in [9]. The switch is turned full-on for the duration that the output voltage deviation exceeds a pre-determined threshold.

In [10], an auxiliary circuit is presented which operates by disconnecting the output node of the main inductor and routing it to the converter input during an unloading transient.

While these topology modifications improve the transient response of a converter during a load transient, they suffer from at least one of the following conditions:
1. Complicated transformer design [4]-[5]
2. Auxiliary switch control susceptible to noise caused by the auxiliary switching [7]
3. Unpredictable auxiliary switching frequencies [7], [9]
4. No direct current-mode control of the auxiliary circuit resulting in unpredictable and potentially damaging currents [6], [8]-[9]; this may be particularly problematic for [6] which relies on the trace and switch inductance to limit the auxiliary current slew rate
5. High auxiliary peak current to average current ratio resulting in the necessity of relatively large auxiliary switches for desired dynamic performance [7]-[9]
6. An additional switch must be present in the converter's power path for [10]; therefore, the conduction loss of the

circuit is increased even when no load transient event is occurring.

In [11], an auxiliary circuit and control method is introduced that improves the voltage overshoot, due to an unloading transient, without possessing the above drawbacks. The circuit operates by diverting a fixed current from the output to the input at a relatively constant switching frequency. While the improved converter yielded promising results, it exhibited two drawbacks that have been addressed and rectified in this paper:

1. The auxiliary circuit utilized a differentiator in order to estimate the output capacitor current. This configuration may be susceptible to the auxiliary switching noise if proper bandwidth limiting is not employed.

2. The auxiliary circuit current magnitude was designed for the maximum rated unloading transient. While this allows for an excellent response following full-load transients, the auxiliary circuit must perform remedial actions following smaller unloading transients in order to prevent a large voltage undershoot due to over-compensation. Furthermore, the loss due to the auxiliary circuit operation could be reduced if the average auxiliary current were reduced for smaller unloading transients.

In this paper an auxiliary circuit is proposed, that behaves similar to the method in [11], but is able to provide a "measured" auxiliary circuit response depending on the magnitude of the unloading transient. The proposed method significantly improves the voltage overshoot due to an unloading transient by rapidly transferring excess inductor current from the output of a Buck converter to its input. In order to estimate the capacitor current, the auxiliary controller does not use a differentiator configuration, as proposed in [11]; therefore, the circuit is less susceptible to noise and is more robust.

A converter utilizing the auxiliary circuit (during unloading transients) and a non-linear control method, as proposed in [1]-[3], (for loading transients) would yield superior dynamic performance with significantly reduced output capacitor requirements.

II. CONCEPT OF OPERATION

Fig. 1 illustrates the hardware implementation of the auxiliary circuit. As observed, the auxiliary circuit resembles a small Boost converter connected in anti-parallel with the Buck converter. The auxiliary circuit is only active during unloading transients; thus, it has no effect on the converter's efficiency when the converter is operating in steady-state.
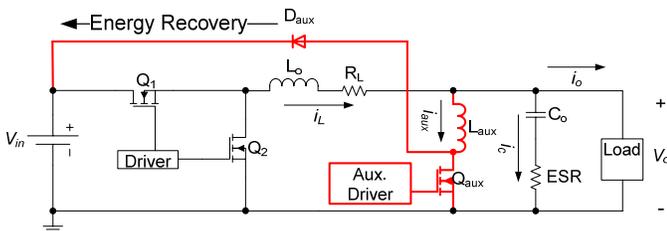
Fig. 1   Hardware implementation of auxiliary circuit

When active, the auxiliary switching is controlled using a peak-current mode, constant off-time scheme as shown in Fig. 2. The auxiliary current may be sensed using the MOSFET R_{ds_on}, a current sense resistor or an RC network in parallel with the auxiliary inductor. For this paper, a current sense resistor was utilized.
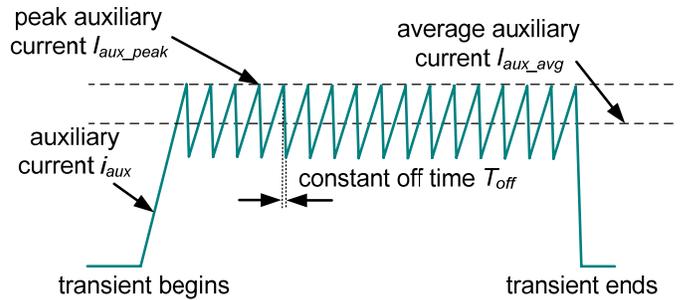
Fig. 2   Peak current-mode, constant off time operation of auxiliary circuit

L_{aux} is typically chosen to be 1/10 of L_o. Due to the short duration of operation, Q_{aux} can be chosen based on its pulsed current limit (allowing for the use of SOT-23 MOSFETs for I_{aux_avg} < 15A). Since the duty cycle of the diode is typically very small (<15%), a small Schottky diode may also be utilized.

The auxiliary circuit switches at a relatively fixed frequency and transfers a constant average current from the output of the converter to its input for the duration of an unloading transient event. The auxiliary current frequency f_{aux} and the auxiliary current ripple I_{aux_pk-pk} is dependent on the selection of the auxiliary inductor L_{aux} and the constant off time period T_{off} and is calculated in (1) and (2) respectively.

$$f_{aux} \approx \frac{V_o - R_{ds\_on\_aux} \cdot I_{aux\_avg}}{T_{off}(V_{in} + V_{diode} - R_{ds_{on_{aux}}} \cdot I_{aux_{avg}})} \quad (1)$$

$$I_{aux\_pkpk} \approx \frac{(V_{in} + V_{diode} - V_o) \cdot T_{off}}{L_{aux}} \quad (2)$$

The average auxiliary current I_{aux_avg} is calculated in (3).

$$I_{aux\_avg} \approx \frac{2 \cdot I_{aux\_peak} \cdot L_{aux} - (V_{in} + V_{diode} - V_o) \cdot T_{off}}{2 \cdot L_{aux}} \quad (3)$$

As is apparent in (3), assuming that the input voltage V_{in}, the output voltage V_o and the auxiliary forward diode voltage V_{diode} remain relatively constant, the average auxiliary current I_{aux_avg} can be controlled by varying the auxiliary peak current I_{aux_peak}.

The block diagram of the full system is illustrated in Fig. 3. As illustrated in Fig. 3, the proposed method monitors the time-averaged output voltage derivative by subtracting a phase shifted version of the output voltage from the output voltage. Phase shifting is accomplished by use of an all-pass filter (APF).
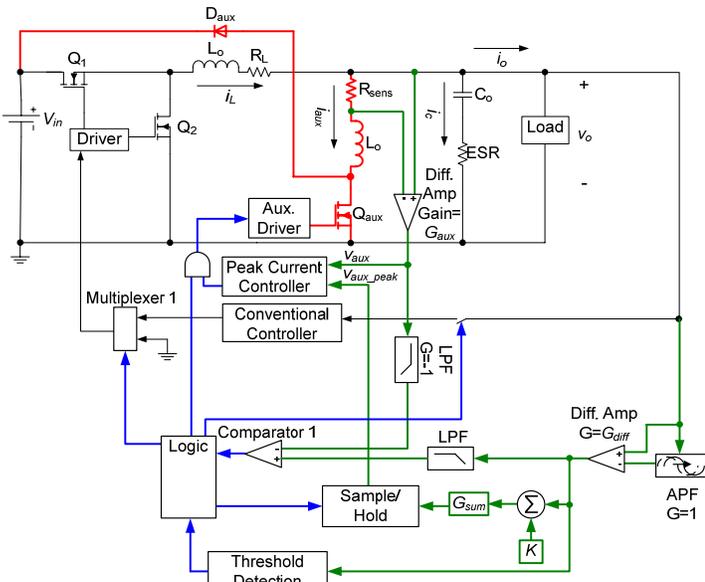
Fig. 3   Block diagram of proposed circuit

An APF maintains the original magnitude of the input signal with a phase delay. An APF can be easily implemented using a single Op-Amp. Since the phase delay of an APF varies linearly with frequency (for a wide range of frequencies), the APF produces a relatively constant time delay, which will be represented by T_{del}.

This method of estimating the voltage derivative possesses higher noise immunity than a pure differentiator since high frequency components are not amplified toward infinity. However, the accuracy of such a circuit is slightly decreased due to the linearization of the output voltage derivative over T_{del}. An implementation of the capacitor current estimator is illustrated in Fig. 4.
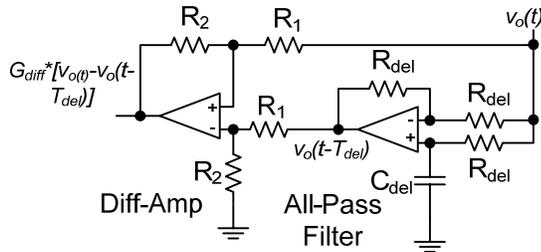
Fig. 4   Capacitor current estimator

The output of the capacitor current estimator is calculated in (4).

$$G_{diff}[v_o(t) - v_o(t - T_{del})]$$
$$\approx \frac{R_2}{R_1}\left[i_c\left(t - \tfrac{1}{2}T_{del}\right) \cdot \frac{T_{del}}{C_o} + ESR\,\frac{i_c(t) - i_c(t - T_{del})}{T_{del}}\right] \quad (4)$$

T_{del} is calculated in (5).

$$T_{del} = 2 \cdot R_{del} \cdot C_{del} \quad (5)$$

In this example, the auxiliary current is measured using a small series resistor and a differential amplifier. In order to normalize the capacitor current estimator voltage with that of the auxiliary current sensor, the differential amplifier gain G_{diff} should be set equal to (6).

$$G_{diff} = \frac{R_2}{R_1} = \frac{C_o \cdot G_{aux} \cdot R_{sens}}{T_{del}} \quad (6)$$

where G_{aux} is the gain of the auxiliary current sensor differential amplifier and R_{sens} is the value of the current sense resistor.

The operation of the proposed circuit can be described in three steps:

Step 1: Detect Unloading Transient (t₀)

When the time-averaged output voltage derivative exceeds a pre-determined threshold and the output voltage is above the reference voltage, the auxiliary circuit is activated and the duty cycle of the main switch is set to 0%. The pre-determined threshold is such that it is only triggered by a large unloading transient and will not be triggered by the steady-state voltage ripple. The activation of the auxiliary circuit is illustrated in Fig. 5. Due to the sharp rise in output voltage following an unloading transient (due to ESR, ESL and capacitor charging) the transient is detected virtually instantaneously.

During transient operation, the error voltage of the main controller is held constant to prevent major control loop upsetting.

Step 2: Estimate Load Current Transient Magnitude and Set I_aux_peak (t_samp)

As illustrated in Fig. 5, after detection of an unloading transient, the auxiliary controller samples and holds the output voltage time-averaged derivative at t_{samp} in order to estimate the magnitude of the load current transition.
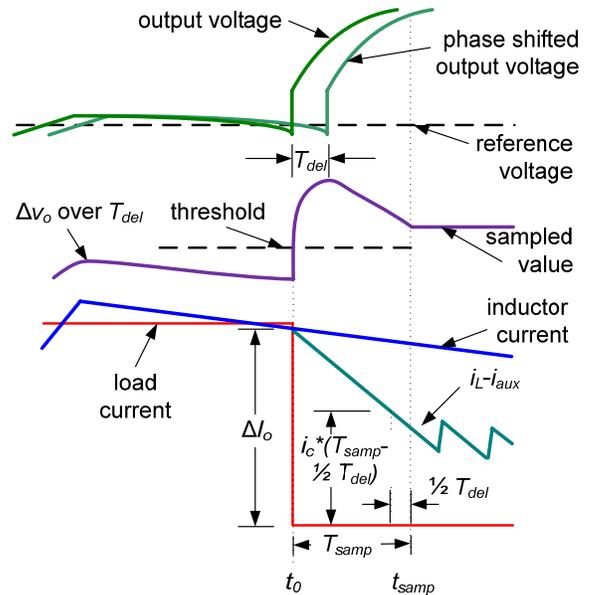
Fig. 5   Operation of auxiliary circuit during unloading transient: zoomed in (t_0-t_{samp})

The controller sets I_{aux_peak} based on this information for the duration of the transient event. For proper operation, T_{samp} should be greater than T_{del} and the auxiliary switch should be kept on for T_{samp}.

As illustrated in Fig. 3, the output of the capacitor current estimator is added to a constant K and multiplied by a constant G_{sum}. This can be accomplished by a simple weighted summer. These variables are user-defined based on the converter parameters and the desired operation of the auxiliary controller as will be described Section III.

Step 3: Terminate Auxiliary Circuit (t₁)

As illustrated in Fig. 6, the auxiliary operation is terminated when the inductor current equals the new load current. At this point, the auxiliary switch is kept off and the converter is again controlled by a conventional linear controller. Since $i_L = i_{aux} + i_c + I_o$, it is possible to estimate t_1 by comparing the filtered output of the capacitor current sensor with the inverted filtered output of the auxiliary current sensor (see Fig. 3). Fig. 7 shows a simulated example of this detection method. Small inaccuracies of this method include the ESR and the capacitor current delay effect; however, the precise determination of t_1 is not critical to the operation of the circuit.

III. DESIGN EXAMPLES AND SIMULATION

A Buck converter was designed and simulated with the following parameters: V_{in}=12V, V_o=1.5V, L_o=1uH, C_o=190uF, f_s=400kHz, L_{aux}=100nH, T_{off} = 60ns, f_{aux}=2MHz, ESR=1mΩ, ESL=100pH. The capacitor current estimator parameters are: T_{del}=400ns, T_{samp}=700ns, G_{diff}=7V/V.

As previously mentioned, the peak auxiliary current is calculated by use of the sampled voltage derivative and the user-defined parameters G_{sum} and K (see Fig. 3). The auxiliary circuit may be set for two separate modes of operation:
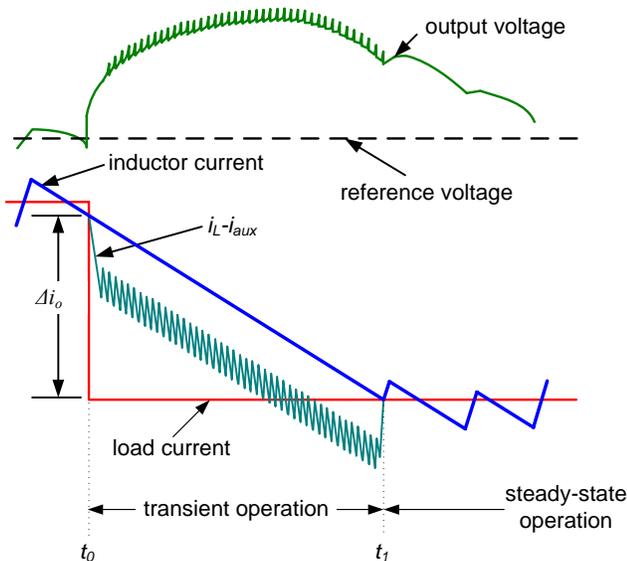
Fig. 6   Operation of auxiliary circuit during unloading transient: zoomed out (t_0-t_1)
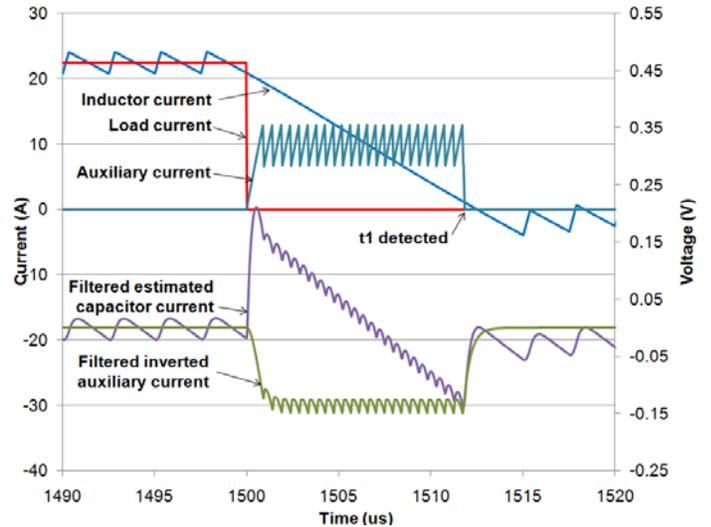
Fig. 7   Simulated example of t_1 detection method

A. Proportional Response

The average auxiliary current is set to a user-defined fraction of the unloading transient magnitude. For this mode of operation, G_{sum} is set equal to the desired fraction and K is defined in (7).

$$K = r_m \cdot \left(K_{ESR} + K_{samp\_del} + K_{rip} \right) \qquad (7)$$

where r_m equals the transimpedence of the capacitor current estimator and is equated in (8). K_{ESR}, K_{samp_del} and K_{rip} correct for ESR, the sampling period delay and the difference between the average auxiliary current and the peak auxiliary current; the variables are defined in (9)-(11) respectively.

$$r_m = \frac{G_{diff} \cdot T_{del}}{C_o} \qquad (8)$$

$$K_{ESR} = V_o \cdot (L_{aux}^{-1} + L_o^{-1}) \cdot ESR \cdot C_o \qquad (9)$$

$$K_{samp\_del} = V_o \cdot (L_{aux}^{-1} + L_o^{-1}) \cdot (T_{samp} - \tfrac{1}{2}T_{del}) \qquad (10)$$

$$K_{rip} = \tfrac{1}{2}I_{aux\_pk-pk}/G_{sum} \qquad (11)$$

For example, if it were desired that the average auxiliary current be equal to 40% of the load current transient magnitude (for the previously defined converter), set G_{sum}=0.4V/V and K=0.3V.

In order to avoid overcompensation of an unloading transient, G_{sum} should always be set less than 50%. This will ensure that the inductor current reaches the new load current before the output voltage returns to its reference voltage.

The designed system was simulated undergoing a 20A unloading transient and a 10A unloading transient, as shown in Fig. 8. As depicted, the average auxiliary current is close to the target auxiliary current. A small discrepancy is apparent due to the linearization of the output voltage derivative over T_{del}.
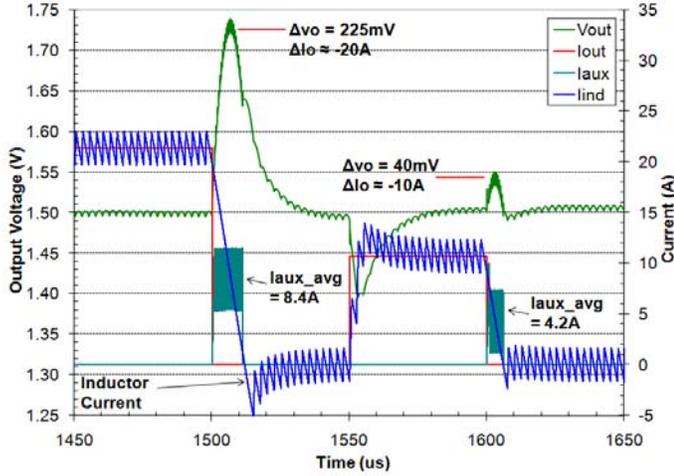
Fig. 8   Simulated proportional response $I_{aux\_avg} = 0.4 * \Delta I_o$

B. *Fixed Equivalent Current Transient Response:*

In this mode, $|\Delta I_o|$–I_{aux_avg} equals a fixed value ΔI_{eq}. This will yield a relatively constant output voltage overshoot for $|\Delta I_o| \geq \Delta I_{eq}$. For this mode of operation, G_{sum} is equal to 1 and K is defined in (12).

$$K = r_m \cdot (K_{ESR} + K_{samp\_del} + K_{rip} - \Delta I_{eq}) \quad (12)$$

For example, if it were desired that the average auxiliary current be equal such that $|\Delta I_o|$–I_{aux_avg}=12A for the previously defined converter, set G_{sum}=1V/V and K=0.04V.

The designed system was simulated undergoing a 21A unloading transient and a 16A unloading transient, as shown in Fig. 9. As expected, the resultant voltage overshoot is relatively constant regardless of the load current transient magnitude. An overshoot of 215mV roughly corresponds to the resultant voltage overshoot of a 12A unloading transient without the use of the auxiliary circuit.

IV.   LOSS ANALYSIS

In this section, the conduction and switching losses, caused by the auxiliary circuit, are analyzed and evaluated for the
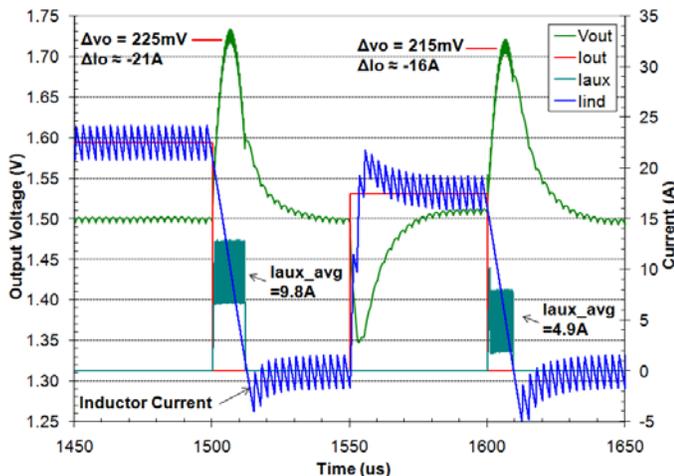
Fig. 9   Simulated fixed equivalent current transient response $|\Delta I_o|$–I_{aux_avg}=12A

previously designed converter. It is important to note that the auxiliary circuit is only active during an unloading transient event; therefore, for scenarios in which load transients occur at low frequencies, the auxiliary circuit loss will become insignificant.

A.   Conduction Loss

There are three main sources of conduction loss pertaining to the auxiliary circuit: a) the auxiliary inductor L_{aux}, b) the auxiliary FET Q_{aux}, and c) the auxiliary diode D_{aux}.

In order to calculate the conduction loss of the inductor, the root mean square (RMS) current must first be calculated. The auxiliary inductor RMS current (a DC current with a superimposed linear ripple) is calculated using (13).

$$I_{L\_aux(rms)} = I_{aux\_avg}\sqrt{1 + \frac{1}{3}\left(\frac{I_{aux\_pk-pk}}{2 \cdot I_{aux\_avg}}\right)^2} \quad (13)$$

By calculating the RMS auxiliary current in (13), the inductor conduction loss can be calculated using (14).

$$Pcon_{L\_aux} = I_{L\_aux(rms)}^2 \cdot R_{L\_aux} \quad (14)$$

The RMS current for the auxiliary FET and the auxiliary diode (a pulsating current with a linear ripple) can be calculated using (15) and (16) respectively.

$$I_{Q\_aux(rms)} = I_{aux\_avg} \cdot \sqrt{D_{aux}}\sqrt{1 + \frac{1}{3}\left(\frac{I_{aux\_pk-pk}}{2 \cdot I_{aux\_avg}}\right)^2} \quad (15)$$

$$I_{D\_aux(rms)} = I_{aux\_avg}$$
$$\cdot \sqrt{1 - D_{aux}}\sqrt{1 + \frac{1}{3}\left(\frac{I_{aux\_pk-pk}}{2 \cdot I_{aux\_avg}}\right)^2} \quad (16)$$

D_{aux} can be calculated using (17).

$$D_{aux} = 1 - f_{aux} \cdot T_{off} \quad (17)$$

The conduction loss for the auxiliary FET and the auxiliary diode can be calculated using (18) and (19) respectively.

$$Pcon_{Q\_aux} = I_{Q\_aux(rms)}^2 \cdot R_{Q\_aux} \quad (18)$$

$$Pcon_{D\_aux} = I_{D\_aux(rms)} \cdot V_{D\_aux} \quad (19)$$

The resultant conduction loss for the auxiliary circuit can be calculated using (20).

$$P_{con} = f_{IO}\frac{\Delta I_o \cdot L_o}{V_o}(Pcon_{L\_aux} + Pcon_{Q\_aux} + Pcon_{D\_aux}) \quad (20)$$

f_{Io} equals the frequency at which the load current varies and ΔI_o equals the magnitude of the load current change.

B. Switching Loss

The switching loss of the auxiliary FET is analyzed in this sub-section. Since a Schottky diode is utilized, it is assumed

that the switching loss of the diode is small compared to the FET switching loss and the total conduction loss. The switching loss for the auxiliary FET can be calculated using (21).

$$Psw_{Q\_aux} = \tfrac{1}{2} f_{aux} \cdot V_{in} \cdot \left(T_{rise} \cdot I_{on} + T_{fall} \cdot I_{off} \right) \qquad (21)$$

T_{rise} and T_{fall} equals the typical rise time and fall time of the auxiliary FET respectively. I_{off} equals the instantaneous auxiliary current when Q_{aux} is turned off which is equal to the chosen peak auxiliary current. I_{on} equals the instantaneous auxiliary current when Q_{aux} is turned on and can be calculated using (22). The resultant switching loss for the auxiliary circuit is calculated in (23).

$$I_{on} = I_{aux\_peak} - I_{aux_{pk}-pk} \qquad (22)$$

$$P_{con} = f_{IO} \frac{\Delta I_o \cdot L_o}{V_o} Psw_{Q\_aux} \qquad (23)$$

For the previously designed converter, a small (SOT-23) Fairchild FDN359BN was used for Q_{aux}. The MOSFET parameters are: $R_{(ds)on}$=30mΩ, T_{rise}=5ns, T_{fall}=2ns. It should be noted that a larger MOSFET (and/or synchronous operation) can be easily implemented for lower conduction loss and better efficiency. A Schottky diode with a forward voltage of V_{d_aux}=0.32V was used for D_{aux}. Under these conditions, it was analysed that for a load transient magnitude of 20A (with I_{aux_avg}=8A) and a load transient frequency such that the auxiliary circuit is active 10% of the time, the power loss is equal to 1% of the output power.

V. EXPERIMENTAL RESULTS

A prototype of the converter described in Section III was built and tested in order to verify functionality. The prototype was set to estimate the load current transient magnitude and set the average auxiliary current to 40% of the load step.

Using a fast resistive load (able to produce load slew rates greater than -150A/us), the converter was subjected to a load step of approximately -20A.

For reference, Fig. 10 illustrates the converter's reaction to the aforementioned current step change with the auxiliary circuit disabled.

Fig. 11 illustrates the converter's reaction with the auxiliary circuit activated. As illustrated, the auxiliary circuit reacts to the unloading transient and activates the auxiliary circuit with very little delay.

The measured average auxiliary current was 8.4A (42% of the load current transient magnitude) and the measured auxiliary switching frequency was 1.9MHz.

It is observed that the output voltage overshoot is reduced from 530mV to 220mV (a reduction of 58%).

In order for the converter to achieve a 220mV overshoot (without the auxiliary circuit) the output capacitor would need to be increased from 190uF to 600uF.

For reference, Fig. 12 illustrates the converter's reaction to a -10A current step change with the auxiliary circuit disabled.
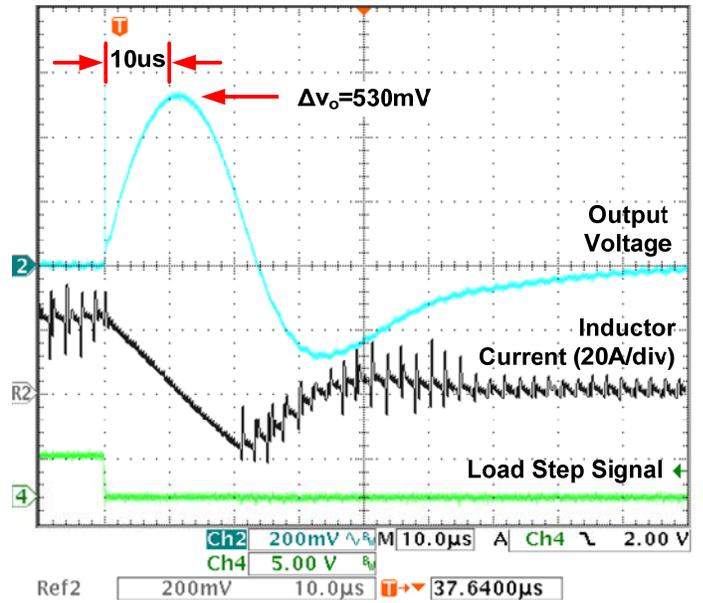
Fig. 10   Output voltage response of a Buck converter undergoing a 20A→0A load step change (auxiliary circuit disabled)
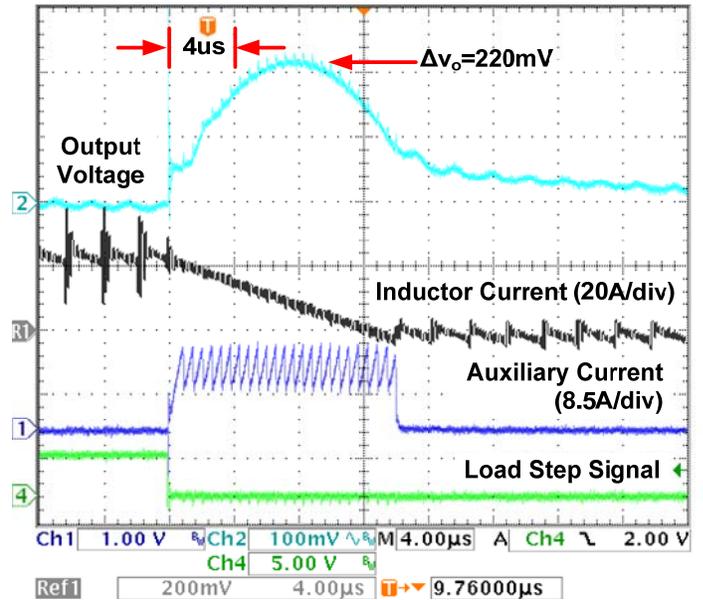
Fig. 11   Output voltage response of Buck converter undergoing a 20A→0A load step change (auxiliary circuit enabled, $I_{aux\_avg} = 0.4*\Delta I_o$)

Fig. 13 illustrates the converter's reaction with the auxiliary circuit activated.

At approximately 700ns following the unloading transient, the time-averaged output voltage derivative is sampled and the peak auxiliary current is set. As shown, the controller set the average auxiliary current to a modest 4.2A for the lesser magnitude load step thus reducing associated losses for smaller load steps. The measured auxiliary switching frequency was 1.9MHz.

It is observed that the output voltage overshoot is reduced from 160mV to 45mV (a reduction of 72%). In order for the converter to achieve a 45mV overshoot (without the auxiliary circuit) the output capacitor would need to be increased from 190uF to 750uF.
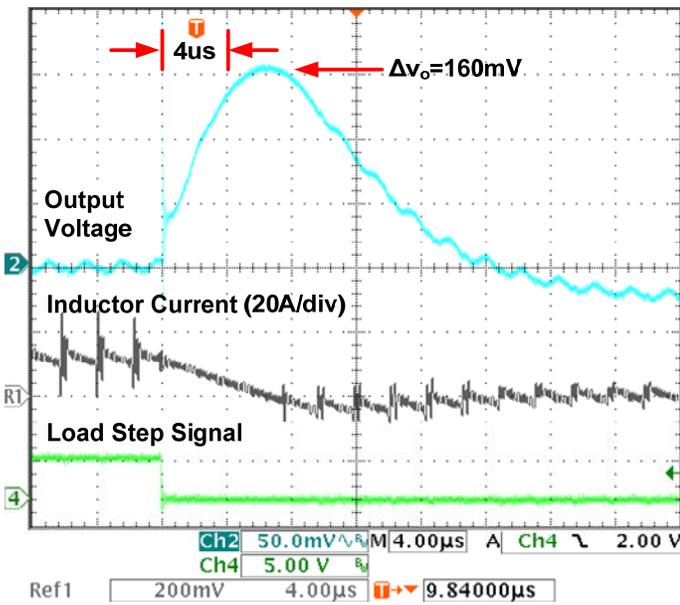
Fig. 12   Output voltage response of a Buck converter undergoing a
10A→0A load step change (auxiliary circuit disabled)
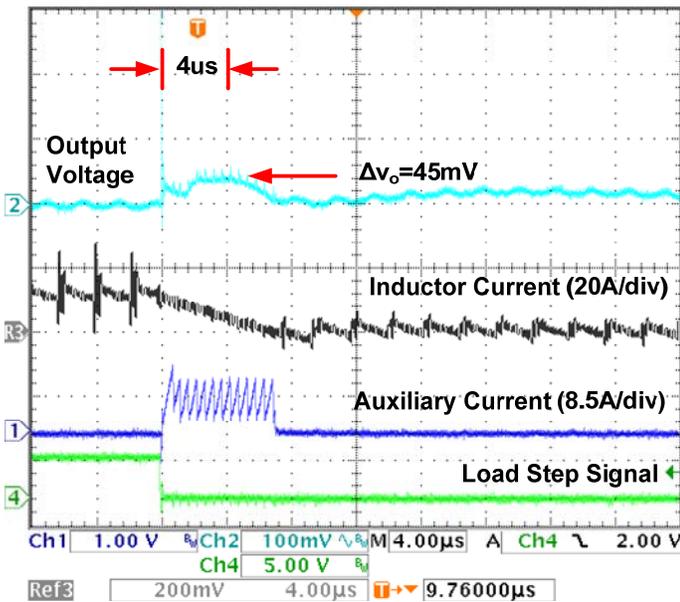
Fig. 13   Output voltage response of Buck converter undergoing a 10A→0A
load step change (auxiliary circuit enabled, $I_{aux\_avg} = 0.4*\Delta I_o$)

VI.   CONCLUSION

For low duty cycle Buck converter applications, voltage overshoots tend to be much larger than voltage undershoots for load current transients of equal magnitude. Unfortunately, engineers must design for the larger overshoot criteria when choosing output capacitors. The proposed overshoot reduction method allows for a more balanced overshoot/undershoot response of a Buck converter, allowing an engineer to meet voltage criteria with fewer output capacitors. The circuit is relatively low-cost as it operates with a small MOSFET, diode and inductor. Through simulation and experimental results, it was shown that the proposed auxiliary circuit control method successfully

estimates the unloading transient magnitude and provides a measured response allowing for higher efficiency operation for smaller load steps.

VII.   REFERENCES

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