Single-Variable Accurate Load Estimation for Optimized Transient Mitigation in Boost-Type Converters

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***Abstract*— This paper introduces an optimal transient mitigation controller for boost-type converters that is enabled by an accurate load estimation procedure. The controller incorporates a peak current programmed mode control for steady-state operation and a nonlinear, state-plane-based transient-mode control schemes for load transients. The load estimation procedure operates on present information alone, without the need for prior knowledge of the system parameters. The operation of the controller and the load estimation procedure is experimentally verified on a 2-15V to 3.3V non-inverting buck-boost converter, demonstrating accurate load estimations for various loading events thus enabling optimized recovery patterns to steady-state.**

Keywords – Digital control, state-space control, non-inverting buck-boost, load estimation.

I. Introduction

Tighter output voltage regulation, faster response time to load changes, and lower volume are of major concern in the design of modern switch-mode power supplies. To obtain fast transient response, beyond the small-signal bandwidth, some transient oriented controllers, among them time-optimal controllers have been introduced [1]-[9]. These controllers implement nonlinear, state-variable-based control laws, which allow convergence to large-signal perturbations that is only limited by the physical limitations of the reactive components, e.g., inductor current slew-rate. For system performance improvement and total volume reduction of the converter, in particular for boost-type converters, decreasing of the components' stress has been assigned as the primary performance goal [1],[10]. This goal can be achieved by redefining the control objective from reducing the recovery time to minimizing the output voltage deviation and lowering the peak inductor current [10]-[12]. Implications of the control method on the resultant response may vary from one converter configuration to another. For example, with direct energy transfer converters, e.g., buck or forward, the time-optimal control produces the fastest possible dynamic response to load transients with the minimum possible output voltage deviation. However, when applying time-optimal control on indirect energy transfer converters, e.g., boost or flyback, the fast dynamic response comes at the cost of higher output voltage deviation and peak inductor current. On the other hand, minimum output voltage deviation for boost type converters results in prolong transient time, infinite in the ideal case [1].

In the majority of the applications, merging between linear and nonlinear controller types has demonstrated benefits at steady-state operation as well as transient [13]-[14]. While the transient requirements are satisfied by the nonlinear control, the linear controller (i.e., PI or PID) achieves zero steady-state error by simple means [15] and allows constant operating frequency, which simplifies the design of the power converter. While the design of the steady-state control has variety of closed-form approaches, in the transient-oriented controllers several aspects that have significant influence on the end-performance, still are undefined. Particularly for indirect energy-transfer converters, a significant bottleneck is the issue of load information, which is a pivotal part for any transient-oriented controller type. This is since the system's charge balance status, which determines the recovery pattern and overall performance cannot be directly extracted from the state variables, as oppose to the case in buck-derived converters.

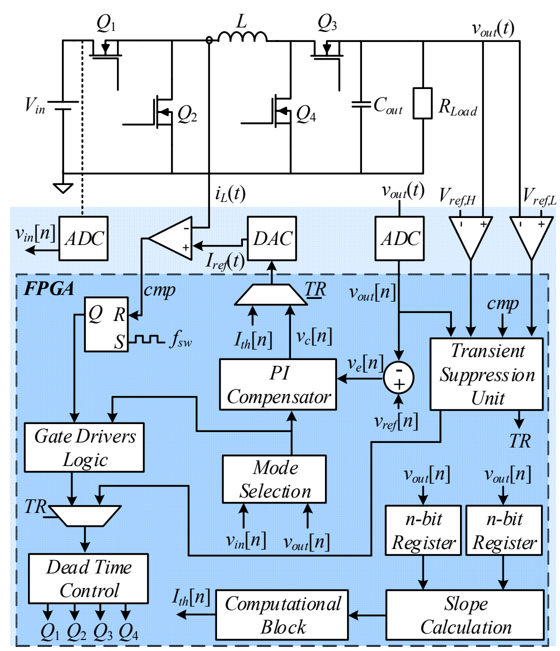


Fig. 1. Simplified schematic diagram, of a non-inverting buck-boost converter with current-programmed controller and the dedicated load-estimation blocks.

Since direct measurement of the load current is prohibitive for the vast majority of applications, due to either reliability or efficiency concerns, the task of accurate estimation of the load status has become challenging. Methods to obtain the load information are typically based on calibration process, knowledge of the system parameters, or switching pattern change from the desired one [1],[13]-[14],[16]. These efforts often require non-negligible computing resources and potential additional hardware, but moreover, the accuracy of the current loading status depends on precision of many factors such as past measurements, system configuration, components, and calculations. It would be very beneficial to facilitate a single-event-driven accurate procedure for the loading status and value.

The objective of this paper is therefore to introduce an optimal transient mitigation controller for boost-type converters that is enabled by an accurate load estimation procedure. A generalized realization of hybrid-type controller as a part of a noninverting buck-boost converter (NIBB) system is presented in Fig. 1. It is constructed on a steady-state peak current-programmed mode (CPM) architecture, and incorporates a non-linear state-space based control for the transient recovery. Together with the transient-event-driven load extraction method, the controller accurately executes time-optimal, minimum-deviation or any programmable-deviation transient recovery. As opposed to variety of adaptive control methods, which improve based on previous transient events, the presented procedure operates on present information alone, without the need for prior knowledge of the former performance neither of the system parameters. The state variables required are the output voltage and average inductor current. Consequently, the overall resources (hardware as well as computational) are equal or less to those needed for CPM execution, making the solution lean on hardware and extremely attractive for integration into any controller platform.

The excellent transient performance that is achieved translates into significant reduction in the total volume of the SMPS, in particular in the size of the passive components. When compared to conventional CPM, the output capacitance can be dramatically trimmed down thanks to lower voltage deviation as well as shorter recovery time. The peak inductor current can be governed without compromising on the recovery features, resulting in smaller magnetics.

The rest of the paper is organized as follows: The load estimation procedure, in the context of state-space optimal control, alongside the theoretical foundations of the method are delineated in detail in Section II. A simulation case-study of consecutive transient case is described in Section III. Section IV details key issues related to the practical implementation of the method. Experimental validation of the load estimator and resultant transient response are provided in Section V. Section VI concludes the paper.

II. LOAD ESTIMATION PROCEDURE

A. *Principle of operation*

The load estimation procedure developed in this study applies for boost-type converters and is described with the aid of the NIBB converter sub-circuits shown in Fig. 2 and the flowchart of Fig. 3. For simplicity, the procedure is explained on a case of single loading transient event, and can be implemented on any transient-oriented controller, and loading profile as will be demonstrated later in section III. It is based on samples of the output voltage during transient and reading of the average inductor current.

The enabler of accurate reading of the load status is the capability to control the converter's output current, and by doing so, reducing the order of complexity to extract the charge balance at the output capacitor. Assuming that the output current is regulated during transient, then the output voltage is a direct, and single, indicator to whether the load current is supplied by the converter. Toggling between subcircuits of Fig. 2a and Fig. 2c, under CPM operation, the average inductor current can be regulated to any value, regardless of the voltage conversion ratio.

Upon detection of a loading transient, the controller estimates the new load current in a two-step process, each with a time duration equals to Δt_e. First, the output voltage is sampled at the beginning of the load estimation process and its value, $V_{out}^{(1)}[n]$, is stored in a dedicated n-bit register. For that pre-defined time interval, Δt_e, the converter operates in the configuration shown in Fig. 4a, referred to as "*step 1 operation*" in the flowchart. During this step, the load is fed by the the output capacitor, C_{out}, and the constant output current of the converter, I_1. During this step, to assure tight current regulation that outputs I_1, the controller operates as a sliding mode controller defined by the following set of equations:

$$\begin{aligned} &\sigma_i(v_C, i_L) = i_L - i_{Lth} \\ &on: \ \sigma_i < 0 \quad , \\ &off: \ \sigma_i > 0 \end{aligned} \tag{1}$$

where i_L is the inductor current and i_{Lth} is assigned so that constant current of I_1 is outputted as shown in the time diagram of Fig. 5 (detailed further in Section IV). At the end of first step, the output voltage is sensed again to produce a digital representation of the output voltage value $V_{out}^{(2)}[n]$.

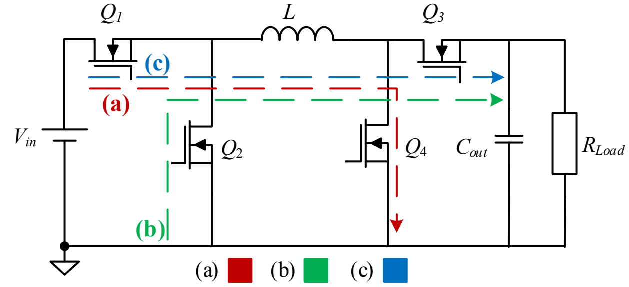


Fig. 2. Equivalent circuit of the non-inverting buck-boost converter in various stages of operation

The output voltage deviation, $\Delta V_{out}^{(1)}[n]$, is obtained by the following:

$$\Delta Vout^{(1)}[n] = Vout^{(1)}[n] - Vout^{(2)}[n] \qquad (2)$$

which is the discrete-time equivalent of the output voltage deviation, and can be expressed as:

$$\Delta Vout^{(1)} = \frac{I_{Load}^{new} - I_1}{C_{out}} \Delta t_e \qquad (3)$$

During the second step, Q_1 and Q_4 are kept on and the pair Q_2-Q_3 remains off, as shown in Fig. 2a. The load is fed solely by the output capacitor, C_{out} (Fig. 4b). At the end of the second step, the output voltage is sampled once again and the output voltage deviation can be expressed as:

$$\Delta Vout^{(2)}[n] = Vout^{(2)}[n] - Vout^{(3)}[n] \qquad (4)$$

Similarly, this correlates to the output voltage deviation during the second step, expressed by:

$$\Delta Vout^{(2)} = \frac{I_{Load}^{new}}{C_{out}} \Delta t_e \qquad (5)$$

The new load current can be extracted from (3) and (5) without prior knowledge of the output capacitor value, C_{out}, or the duration of each step, Δt_e. This can be obtained by simple arithmetic operations in continuous-time or discrete-time expressions, as follows:

$$I_{Load}^{new} = \frac{\Delta Vout^{(1)}}{\Delta Vout^{(2)} - \Delta Vout^{(1)}} I_1 \qquad (6)$$

$$I_{Load}^{new}[n] = \frac{\Delta Vout^{(1)}[n]}{\Delta Vout^{(2)}[n] - \Delta Vout^{(1)}[n]} I_1[n] \qquad (7)$$

At the end of the load estimation process the new reference for the inductor current is assigned by the controller. In a controller that realizes current-constrained recovery [17] as shown in Fig. 5, once the inductor current reaches the assigned threshold, the controller moves along the boundary $I_L = I_{L\_new}$ in a sliding-mode operation, causing the output voltage to rise without changing the inductor current, thus achieving convergence with no current overshoot. When the output voltage is recovered, the reference inductor current for the steady-state controller is updated based on the load estimation result to achieve seamless transition between the transient and the steady-state controllers.

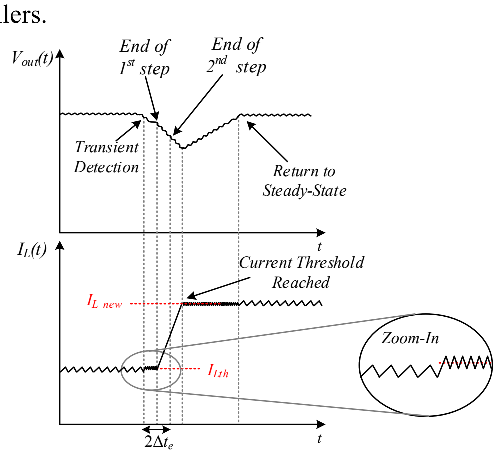


Fig. 3. Illustrative load estimation process for a loading transient when operating in constrained-current mode.

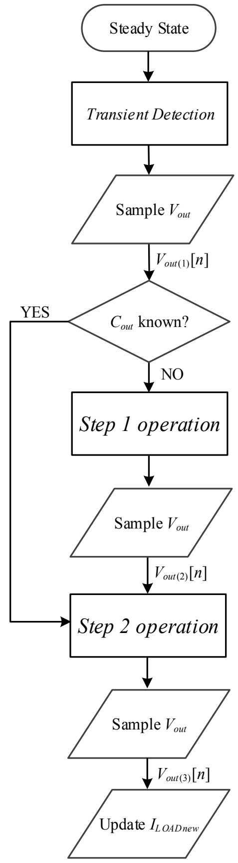


Fig. 4. Flowchart of the load estimation process

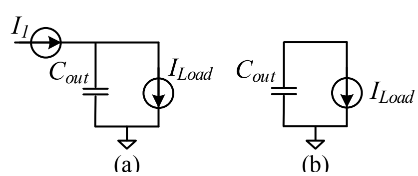


Fig. 5. Equivalent circuits of the converter. (a) step 1 operation. (b) step 2 operation.

B. *Relationship Between I_{LOAD_new} and i_{L_new}*

The post-transient inductor current reference assigned by the DAC is a function of the load estimation result and the operating mode of the NIBB, i.e. step-up or step-down. In direct energy transfer configuration, the average output current is equal to the average inductor current. Therefore, the new steady-state average current can be expressed as follows:

$$i_{L\_new} = i_{Load\_new} \qquad (8)$$

However, for indirect energy transfer the average inductor current is higher than the load current by factor of the duty ratio. For example, in a boost configuration, the new inductor current setting will be:

$$i_{L\_new} = i_{Load\_new} \frac{1}{1 - D_{boost}}, \; D_{boost} = \frac{V_{out} - V_{in}}{V_{out}} \qquad (9)$$

Following the same load estimation procedure as prescribed above, it can support both step-up and step-down configurations with a minor modification of the final inductor current reference assignment.

C. Estimation of the Effective Output Capacitance Value

The performance of the steady-state controller might deviate from its optimal compensation goals due to variations of the passive components, in particular the output capacitance may significantly vary under different bias voltages, which further intensifies as the voltages are higher. There are several cases that the steady-state controller, and the compensator design can benefit from accurate knowledge of the effective output capacitance value. This can assist in improving the performance of the compensation by covering stability for wider operation range as well as to minimize the steady-state error. Utilizing the load estimation process described earlier, the output capacitance value can be extracted as follows:

$$C_{out} = \frac{I_{Load\_new}}{\Delta Vout^{(2)}} \Delta t_e \tag{10}$$

The information obtained can also be used to enhance the overall performance of the current estimation process by reducing calculation efforts. Based on the extracted output capacitor value, the new load current can be estimated through a single step, reducing the total estimation period to Δt_e. Here, once a load transient is detected, the converter operates in the configuration shown in Fig. 5b for a pre-defined time interval of Δt_e. Two samples of the output voltage are sufficient in this case to accurately estimate the new load. The load estimation can be expressed as:

$$I_{Load\_new} = C_{out} \frac{\Delta Vout}{\Delta t_e} \tag{11}$$

III. Simulation Case-Study

Using the analysis and observations from previous sections, a set of simulations have been conducted in PSIM (PowerSim, Inc.) to verify the effectiveness of the new load estimation procedure in a closed-loop operation of a current-constrained controller. A consecutive transient case, which modern SMPS are required to support is discussed in this chapter.

The case of consecutive loading events of different magnitudes for a step-down mode of operation (V_{in}=8V, V_{out}=3.3V) is shown in Fig. 6. The consecutive transients result in different output voltage deviations but converge to steady-state based on the two-step load estimation process described in II, as shown in Fig. 6a (red). The reference inductor current is updated after the estimation procedure is complete as described in II which results in a recovery pattern without any current overshoot and seamless transition between the transient and the steady-state controller. State-space representation of the inductor current and output voltage during the transient recovery and the return to steady-state operation is shown in Fig. 6d. Utilizing the analysis in section II-C, based on the availability of the effective output capacitor value, it is shown in Fig. 6a (blue) that the output voltage deviation and total convergence time are improved as a result of carrying out the single-step estimation procedure. Here, the inductor current is ramped-up immediately after the transient detection of the second loading event, as can be seen in the zoom-in of Fig. 6b.

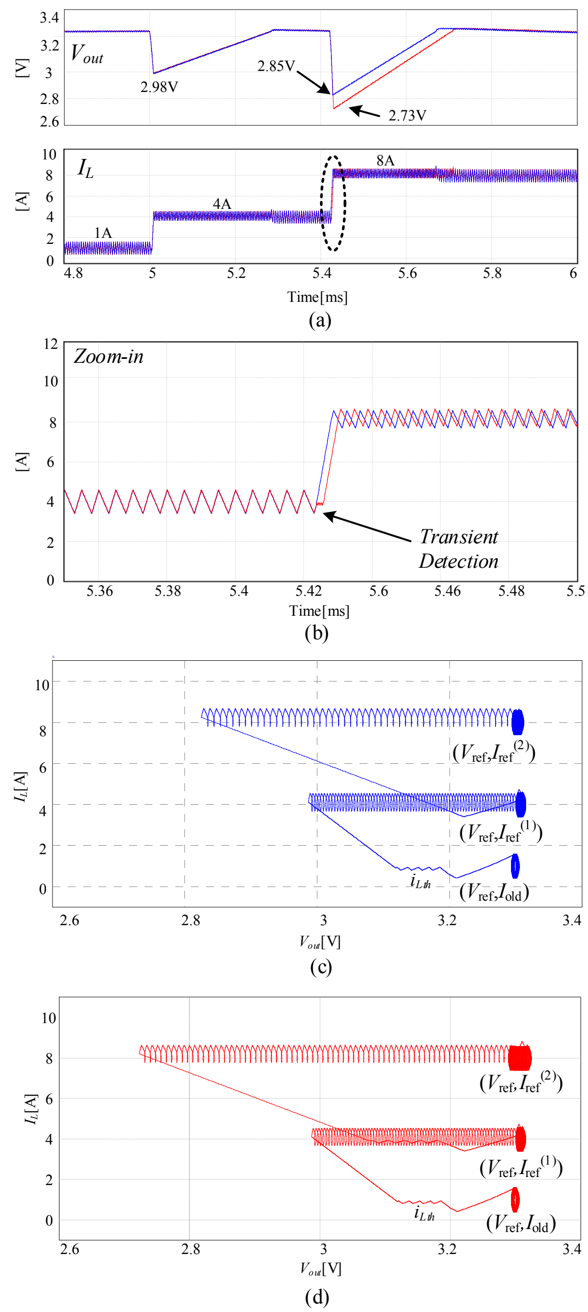


Fig. 6. NIBB converter's response and state-plane representation to a 1-4-8 A consecutive loading transients using the current constrained controller using the two-step load estimation procedure (red) and combined single and two-step procedure (blue). (a) Output voltage (top) and inductor current (bottom). (b) Zoom-in on the inductor current (red: two-step procedure, blue: single-step procedure). (c) State-plane representation of the inductor current and output voltage for single and two-step procedure. d) State-plane representation of the inductor current and output voltage for the two-step procedure

IV. Practical Implementation

A. I_1 Calculation

As previously described, I_1, which is the output current that is drawn by the load is generated using sliding-mode operation of the converter. In this study, conventional buck-boost setup has been chosen to support load transients for both step-up and step-down configurations. The current reference during the first step of the load estimation process, i_{Lth} is chosen according to the value in steady-state and is assigned by the DAC. I_1 is assigned as follows:

$$I_1 = i_{Lth}(1 - D_{buck\_boost})$$
$$D_{buck\_boost} = \frac{V_{out}}{V_{out} + V_{in}} \quad (12)$$

To suppress the effect of the varying output voltage during the transient event on the output current supplied to the load, an approximation based on the output voltage samples can be derived by:

$$\overline{Vout} = \frac{Vout^{(1)} + Vout^{(2)}}{2}$$
$$\overline{D} = \frac{\overline{Vout}}{\overline{Vout} + Vin} \quad (13)$$
$$I_1 = (1 - \overline{D})i_{Lth}$$

B. *Transient Detection*

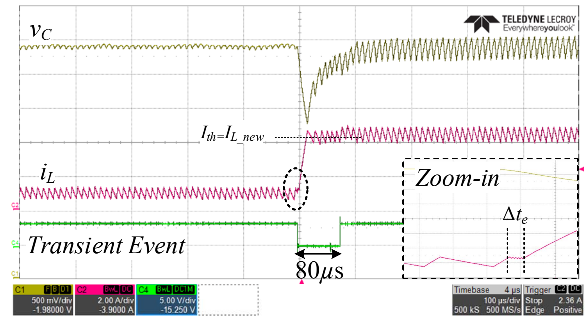
The early detection of a transient event is essential for the overall performance of the transient controller. In particular, when the converter is connected to a resistive-type load (as opposed to a constant current) the estimation process is to be performed in proximity to the loading event to achieve best results.

One way to perform transient detection is by comparing the output voltage samples to predefined threshold values, above and below the output voltage's reference value, as have been widely presented in the literature [1],[10],[18]. When the output voltage is within the thresholds, the steady-state's CPM controller is active, otherwise, transient is detected. A relatively slow sampling rate may cause delayed transient detection and as a result an increased output voltage deviation. For the cases where the delay caused by this detection method is unacceptable, a simple dedicated transient detection circuit can be implemented as shown in Fig. 1.

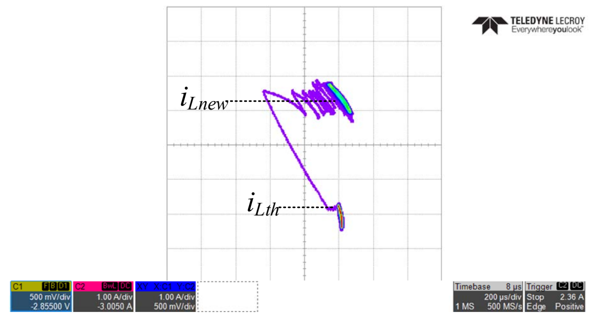
V. EXPERIMENTAL VERIFICATION

In order to validate the operation of the load estimation procedure, a 2-15V to 3.3V non-inverting buck-boost prototype has been built and tested, using an 8.2uH inductor, 30uF output capacitance and operating frequency of 100-200KHz. The converter is digitally controlled by a steady-state voltage-mode compensator and a transient-mode controller as shown in Fig. 1. The digital controller has been entirely realized on altera Cyclone IV FPGA and the total number of logic elements used is 980 for the entire controller. The transient controller performance and the effectiveness of the load estimation procedure for various loading transients and operation modes is depicted in Fig. 7-8.

Fig. 7 shows the loading transient recovery of the current-constrained controller for a 0.8-2.9A loading transient while operating in step-up configuration with a zoom-in on the controlled inductor current during the first step of the load estimation procedure.

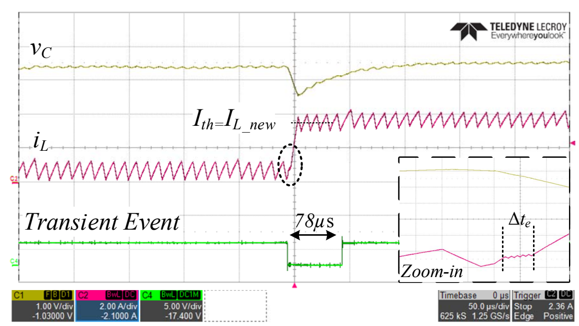


(a)

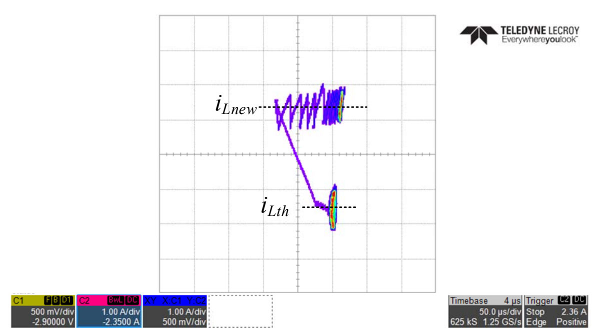


(b)

Fig. 7. NIBB converter's response and state-plane representation to a 0.8-2.9A loading event using current constrained controller and load estimation procedure in step-up configuration. (a) Output voltage (top-yellow) 500mv/div, inductor current (middle - red) 2A/div, transient event (bottom – green), time scale 100us/div. (b) State-plane representation of inductor current and output voltage



(a)



(b)

Fig. 8. NIBB converter's response and state-plane representation to a 0.8-3.6A loading event using current constrained controller and load estimation procedure in step-down configuration. (a) Output voltage (top-yellow) 1v/div, inductor current (middle - red) 2A/div, transient event (bottom – green), time scale 100us/div. (b) State-plane representation of inductor current and output voltage.

The inductor current reference was chosen according to (9), which results in output voltage deviation of 1V and total transient time of 80us with no current overshoot.

Fig.8 shows the loading transient recovery of the current-constrained controller for a 0.8-3.6A while operating in step-down configuration with a zoom-in on the inductor current. The current reference was chosen to be equal to the new estimated load, which results in output voltage deviation of 0.8V and total transient time of 78us with no current overshoot.

VI. CONCLUSION

An accurate two-step load estimation procedure for boost-type converters has been presented, and verified through simulation and experimental data. It is based on samples of a single variable, V_{out}, and is implemented in a hybrid-type controller of a non-inverting buck-boost converter. The estimation procedure operates on the present information alone, without the need for prior knowledge of the system parameters or previous transient events.

Experimental results of a 2-15V to 3.3V non-inverting buck-boost prototype are provided. For loading transients of different magnitudes, the loading estimation procedure produces an accurate estimation of the new load when operating in both step-up and step-down configurations.

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