An Improved Robust Adaptive Parameter Identifier for DC-DC Converters Using H-infinity Design

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***Abstract*—The paper presents the theoretical analysis, practical design considerations, and experimental verification of an improved robust adaptive parameter identifier for dc-dc power electronic converters. The proposed method improves the performance of a conventional linear switched adaptive parameter identifier by designing the observer gain using H_∞ performance criteria. The design approach ensures the optimality of the observer gain as well as provides a degree of robustness to measurement noise and circuit non-idealities. We develop the design methodology for the robust adaptive parameter identifier and present experimental results that validate the achievable improvement in real-time parameter identification. The results indicate wide parameter tracking ranges (10% to 66% parameter deviations) and sub-second convergence, exceeding the performance of classically designed adaptive parameter identifiers.**

I. Introduction

Adaptive parameter identification is widely used in many power electronic applications, including for adaptive and predictive control systems, fault prognosis and diagnosis, and condition and health monitoring. For instance, in [1]–[3], various parameter identification techniques have been investigated for control purposes in ac-dc converters. Similarly, real-time parameter identification for control, fault prognosis and condition monitoring of dc-dc converters are proposed in [4]–[8].

However, classically designed adaptive parameter identifiers can exhibit instabilities in the presence of measurement noise or circuit non-idealities. Moreover, the design of estimation and adaption gains are ad-hoc, leading designers to trade-off between faster parameter convergence and algorithmic stability. This results in sub-optimal performance and does not provide guarantees of robustness or stability.

In this paper, we present an improved robust adaptive parameter identifier for dc-dc converters designed using an H_∞ performance criteria based linear-switched state observer [9]. The proposed design methodology enables faster identification of converter component parameters for a wide range of deviations in the presence of measurement noise, circuit non-idealities and system disturbances. Essentially, the H_∞ performance based observer gain improves the stability and convergence speed of the conventional parameter identifier and enables a broader set of stable adaption gains in presence of arbitrary exogenous disturbances.

In order to illustrate the performance of the proposed parameter identifier, we experimentally validate the algorithm with a dc-dc boost converter and track a set of parameter step change deviations in the converter passive components.

The remainder of the paper is organized as follows. Section II develops the mathematical model and design methodology for the proposed robust adaptive parameter identifier. Section III presents a simulation study of the algorithm under a range of operating conditions. Section IV presents the experimental implementation and results that validate the proposed parameter identifier in real time. Section V concludes the paper.

II. Design mehodology for robust adaptive parameter identifier

Consider a linear switched state space model of a dc-dc switching power converter given by:

$$\dot{\mathbf{x}}(t) = \mathbf{A}_{\sigma(t)}\mathbf{x}(t) + \mathbf{B}_{\sigma(t)}\mathbf{u}(t) + \mathbf{H}_1\mathbf{w}(t) \quad (1)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{H}_2\mathbf{w}(t) \quad (2)$$

where $\mathbf{x}(t)$ and $\mathbf{y}(t)$ are the states and outputs of the converter respectively; $\mathbf{u}(t)$ is the converter inputs; $\sigma(t)$ is a continuous-time switching signal that indicates the active switch configuration of the circuit; $\mathbf{w}(t)$ models an arbitrary exogenous disturbance; and $\mathbf{H}_1$ and $\mathbf{H}_2$ are scaling matrices that weight the disturbance $\mathbf{w}(t)$ appropriately for the state and output dynamics. With this formulation, we can design a closed-loop state observer as follows:

$$\dot{\mathbf{z}}(t) = \mathbf{A}_{\sigma(t)}\mathbf{z}(t) + \mathbf{B}_{\sigma(t)}\mathbf{u}(t) + \mathbf{L}(\mathbf{y}(t) - \hat{\mathbf{y}}(t)) \quad (3)$$

$$\hat{\mathbf{y}}(t) = \mathbf{C}\mathbf{z}(t) \quad (4)$$

where $\mathbf{z}(t)$ and $\hat{\mathbf{y}}(t)$ are respectively the estimated states and outputs of the system. $\mathbf{L}$ is a user-defined gain matrix that satisfies the criteria that the eigenvalues of $\mathbf{A}_{\sigma(t)} - \mathbf{LC}$ are strictly negative for all $\sigma(t)$.

Our objective is to *optimally* minimize the error $\mathbf{e}(t) = \mathbf{y}(t) - \hat{\mathbf{y}}(t)$ in the presence of arbitrary exogenous disturbances $\mathbf{w}(t)$. In order to do so, the proposed design of $\mathbf{L}$ is generated using an H_∞ robust performance criteria. In

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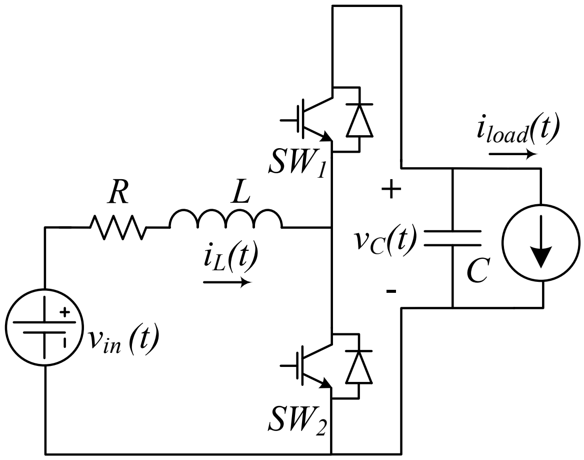

Fig. 1: Circuit topology for a dc-dc boost converter.

particular, the error dynamics $\mathbf{e}(t)$ are bounded as a function of the disturbance $\mathbf{w}(t)$ as:

$$\int_0^{\infty} \mathbf{e}^T(t)\mathbf{e}(t)dt < \gamma^2 \int_0^{\infty} \mathbf{w}^T(t)\mathbf{w}(t)dt \tag{5}$$

where the structure of $\mathbf{L}$ is constrained by the following bounded real lemma:

$$\begin{bmatrix} \mathbf{A}_{\sigma(t)}^T\mathbf{P} - \mathbf{C}^T\mathbf{F}^T + \mathbf{P}\mathbf{A}_{\sigma(t)} - \mathbf{F}\mathbf{C} & \mathbf{H}_1^T\mathbf{P} & \mathbf{C}^T \\ \mathbf{H}_1^T\mathbf{P} & -\gamma^2\mathbf{I} & \boldsymbol{H}_2^T \\ \boldsymbol{C}^T & \boldsymbol{H}_2^T & -\mathbf{I} \end{bmatrix} \prec 0 \tag{6}$$

where $\mathbf{P} = \mathbf{P}^T > 0$ and γ is the *performance index*. The linear matrix inequality given in (6) is readily solveable using MATLAB, from which we can obtain an optimal observer gain matrix $\mathbf{L} = \mathbf{P}^{-1}\mathbf{F}$ that satisfies the H_∞ robust performance criteria.

With an appropriately designed $\mathbf{L}$, we can combine the robust closed-loop state estimation given in (3) and (4) with a gradient-type adaptive parameter identification scheme. Such a combined robust state and parameter estimation scheme can be designed as follows:

$$\dot{\mathbf{z}}(t) = \hat{\mathbf{A}}_{\sigma(t)}\mathbf{z}(t) + \hat{\mathbf{B}}_{\sigma(t)}\mathbf{u}(t) + \mathbf{L}\mathbf{e}(t) \tag{7}$$

$$\dot{\boldsymbol{\theta}}(t) = \boldsymbol{G}\mathbf{H}^T(t)\mathbf{e}(t) \tag{8}$$

where $\boldsymbol{\theta}$ contain the parameters of interest in $\mathbf{A}_{\sigma(t)}$ and $\mathbf{B}_{\sigma(t)}$, $\boldsymbol{G}$ is the *adaption gain* for the gradient estimation, and the dynamics of $\mathbf{H}(t)$ are governed by:

$$\dot{\mathbf{H}}(t) = (\hat{\mathbf{A}}_{\sigma(t)} - \mathbf{L}\mathbf{C})\mathbf{H}(t) + \mathbf{W}_{\sigma(t)}(\mathbf{z}, \mathbf{u}) \tag{9}$$

where $\mathbf{W}_{\sigma(t)}(\mathbf{z}, \mathbf{u})$ is time varying matrix. Note that hat symbol on $\hat{\mathbf{A}}_{\sigma(t)}$ and $\hat{\mathbf{B}}_{\sigma(t)}$ indicate that the estimator model is being continually updated with the parameter values in $\boldsymbol{\theta}$. Further details on the gradient-type adaptive parameter identification scheme are given in [6], [8].

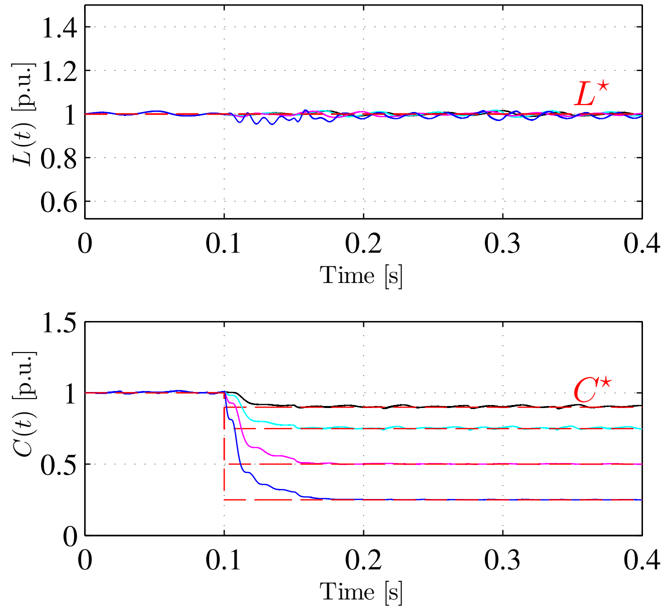

Fig. 2: Simulation results for a step change in capacitance $C^\star$ between 10% and 75% of the nominal capacitance. Inductance $L^\star$ is unchanged.

III. Simulation Study

In this section, we present a simulation study of the proposed parameter identifier for a dc-dc boost converter given in Fig. 1. The complete mathematical model of robust adaptive parameter identifier is given below:

$$\mathbf{z}(t) = \hat{\mathbf{y}}(t) = \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix}, \mathbf{u}(t) = \begin{bmatrix} v_{in}(t) \\ i_{load}(t) \end{bmatrix}, \mathbf{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

$$\mathbf{A}_{\sigma(t)} = \begin{bmatrix} -\frac{R}{L} & -\frac{s_1}{L} \\ \frac{s_1}{C} & 0 \end{bmatrix}, \mathbf{B}_{\sigma(t)} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} \end{bmatrix}, \boldsymbol{\theta}(t) = \begin{bmatrix} \frac{1}{L(t)} \\ \frac{1}{C(t)} \end{bmatrix},$$

$$\mathbf{L} = \begin{bmatrix} 1067.0 & -126.1 \\ 147.9 & 876.7 \end{bmatrix}, \mathbf{G} = \begin{bmatrix} 1 \cdot e7 & 0 \\ 0 & 5 \cdot e7 \end{bmatrix},$$

$$\mathbf{W}_{\sigma(t)} = \begin{bmatrix} -Ri_L(t) - s_1 v_C(t) + v_{in}(t) & 0 \\ 0 & s_1 i_L(t) - i_{load}(t) \end{bmatrix}$$

Table I shows the possible values for the switching signal $\sigma(t)$, where $s_k = 0$ indicates open switch SW_k, and $s_k = 1$ indicates closed switch SW_k, $k \in [1, 2]$. Simulation and experimental parameters are shown in Table II.

TABLE I: Possible open/close switch positions for SW_k

$\sigma(t)$	1	2
s_1	0	1
s_2	1	0

TABLE II: Simulation and experimental parameters.

Boost converter	
R	0.082 Ω
L (nominal)	5.0 mH
C (nominal)	2.85 mF
Nominal operating point	
$v_{in}(t)$	100 V
$v_C(t)$	380 V
$i_{load}(t)$ (nominal)	2.5 A
Converter switching frequency	10 kHz
Parameter identifier	
γ	1.2
Estimation time step	500 ns
Controller time step	500 ns

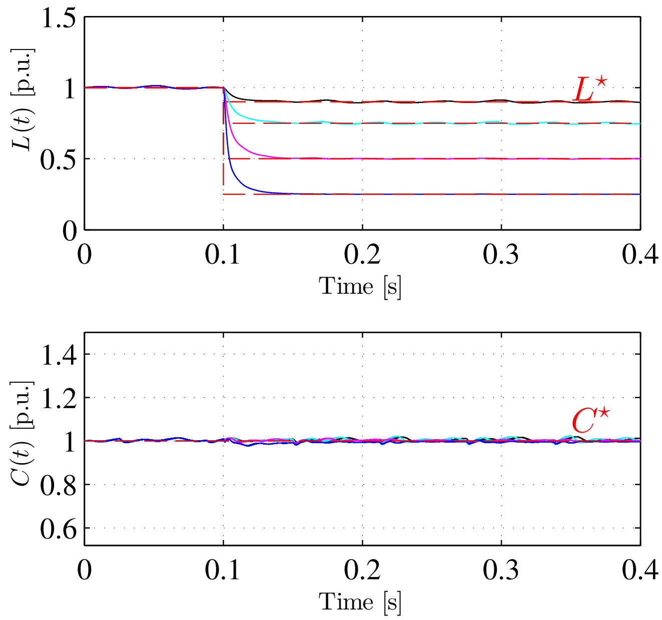

Fig. 3: Simulation results for a step change in inductance $L^\star$ between 10% and 75% of the nominal induxtance. Capacitance $C^\star$ is unchanged.

A. Change in single parameter

The tracking capability and convergence speed of the proposed parameter identifier are demonstrated for step changes in a single parameter. Note that $C^\star$ and $L^\star$ represent the 'true' value of the converter parameters.

Fig. 2 shows the tracking of the converter output capacitance $C^\star$ for step changes between 10% and 75% of the nominal value, each injected at $t = 0.2$ s. As shown, $C(t)$ converges to $C^\star$ within 80 ms. The inductance estimate $L(t)$ matches the converter inductance $L^\star$ during the capacitance step change.

Similarly, Fig. 3 shows the tracking of the converter input inductance $L^\star$ for step changes between 10% and 75% of the nominal value, each injected at $t = 0.2$ s. The time to convergence for $L(t)$ is within 50 ms. The capacitance estimate $C(t)$ matches the converter capacitance $C^\star$ during the inductance step change.

B. Change in multiple parameters

Fig. 4 shows the tracking capability and convergence speed when step changes in multiple parameters are injected simultaneously. As shown, both $C(t)$ and $L(t)$ converge to $C^\star$ and $L^\star$ respectively. Note that time to convergence for each parameter is independent of the other parameter condition.

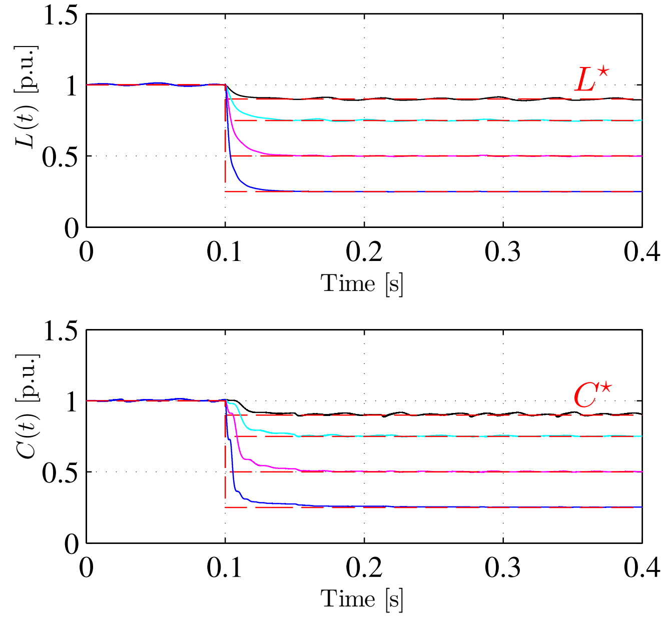

Fig. 4: Simulation results for simultaneous step changes in capacitance $C^\star$ and inductance $L^\star$ between 10% and 75% of the nominal values.

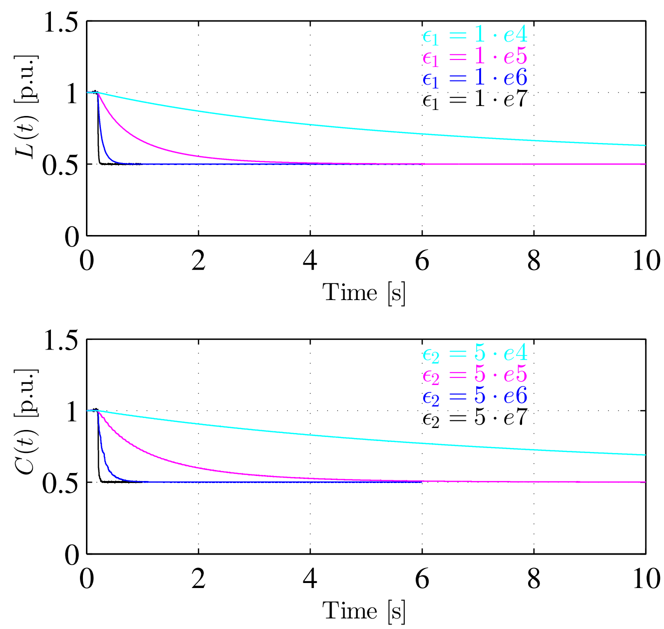

Fig. 5: Parameter estimation convergence times for various adaption gains.

C. Influence of the adaption gain

The influence of the adaption gain $\mathbf{G} = \text{diag}(\epsilon_1, \epsilon_2)$ on the operation of the proposed parameter identifier is presented in Fig. 5. As shown, a smaller adaption gain increases the time to convergence for both parameters. For instance, when $\mathbf{G} = \text{diag}(1 \cdot e4, 5 \cdot e4)$, the convergence speed is 18 s, while for $\mathbf{G} =$

diag$(1 \cdot e7, 5 \cdot e7)$, the convergence speed is less than 80 ms. Thus, the convergence speed of each parameter is directly related to its adaption gain. Moreover, the proposed parameter identifier ensures parameter convergence for a wide range of adaption gains in presence of multiple parameter deviations.

D. Influence of the input excitation

The influence of excitations in input $\mathbf{u}(t)$ on the operation of the proposed parameter identifier is presented in Figs. 6 and 7. In conventional parameter identification schemes, large input excitations are often a cause of algorithmic instability. As shown in the simulation results, the proposed robust parameter identifier is largely robust to these variations.

Moreover, input excitations are one of the necessary conditions to ensure sufficient persistency of excitation provided in $\mathbf{H}(t)$ (see [8]). In such cases, both the magnitude and frequency of these excitations affect the parameter convergence speed. Again, Figs. 6 and 7 corroborate this behavior.

Fig. 6 shows the convergence for each parameter when the ripple content Δi_{pk-pk} in the load current $i_{load}(t)$ varies. As shown, the inductance estimate $L(t)$ converges to $L^\star$ irrespective of the excitations. However, the capacitance estimate $C(t)$ converges when $\Delta i_{pk-pk} \neq 0$ and its convergence speed is faster for higher ripple content.

Similarly, Fig. 7 shows the convergence for each parameter estimate when the amount of ripple content Δv_{pk-pk} in the input voltage $v_{in}(t)$ varies. Here also, the inductance estimate $L(t)$ converges to $L^\star$ irrespective of the excitations. However, the capacitance $C(t)$ converges when $\Delta v_{pk-pk} \neq 0$ and its convergence speed is faster for higher ripple content.

This implies that the switching dynamics in the inductor current $i_L(t)$ contributes towards sufficient richness of the excitation function $\mathbf{H}(t)$ to enable convergence of the inductance estimate. However, it does not ensure this for capacitance estimate, which requires exogenous excitation in $\mathbf{u}(t)$ to ensure convergence. Moreover, the proposed parameter identifier ensures parameter convergence for a wide range of input excitations in the presence of multiple parameter deviations.

IV. Experimental Implementation and Results

The proposed parameter identifier is implemented on an FPGA which enables low latency execution and high computation speed. The programmed FPGA is experimentally validated on a dc-dc boost converter. Further details on the testbed are available in [6]. Experimental results are presented in Fig. 8 and 9 for step changes in a single parameter.

A. Step changes in C

The nominal capacitance ($C = 2.85$ mF) is decreased to three different values by controlling solid state switches such that parallel capacitors can be removed from the circuit. Fig. 8 shows the convergence of the capacitance $C(t)$ estimate to $C^\star$ in the experimental testbed. The inductance estimate $L(t)$ correctly matches $L^\star$. Table III shows the convergence time for each step change.

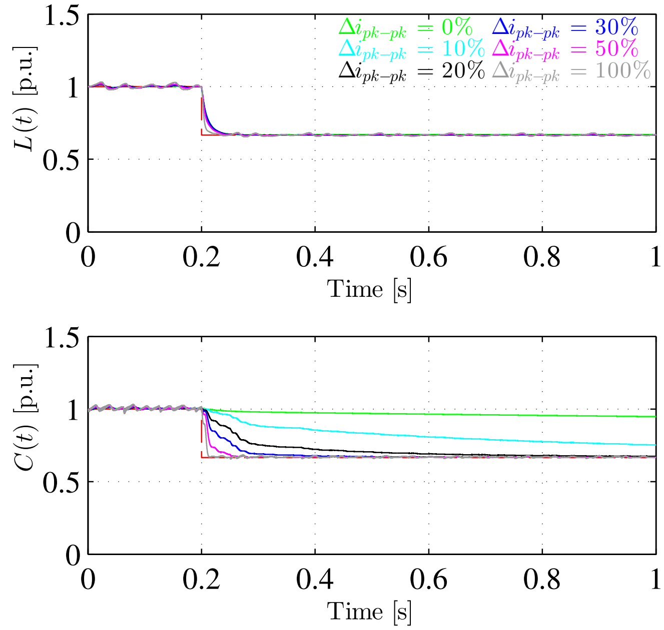

Fig. 6: Parameter estimation convergence times for various perturbation magnitudes in the load current $i_{load}(t)$.

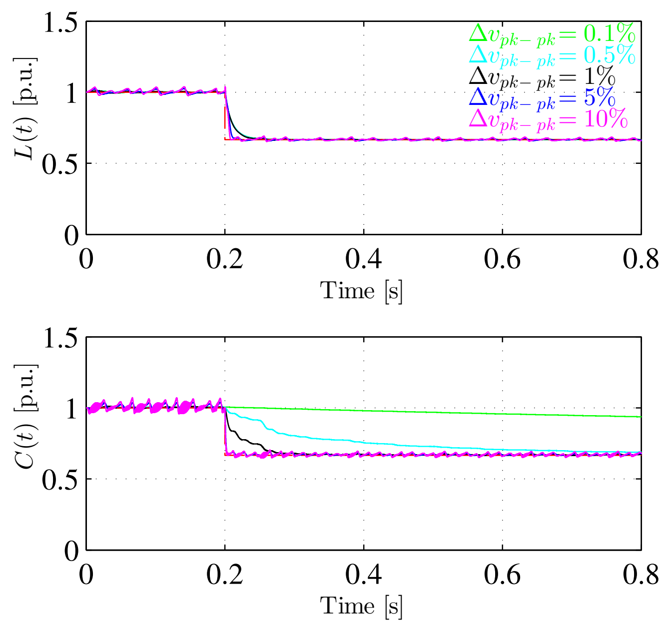

Fig. 7: Parameter estimation convergence times for various perturbation magnitudes in the input voltage $v_{in}(t)$.

B. Step changes in L

The nominal inductance ($L = 5$ mH) is decreased to three different values by controlling solid state switches such that series inductors can be removed from the circuit. Fig. 9 shows the convergence of the inductance estimate $L(t)$ to $L^\star$ in the experimental testbed. The capacitance estimate $C(t)$ correctly matches $C^\star$. Table III shows the convergence time for each step change.

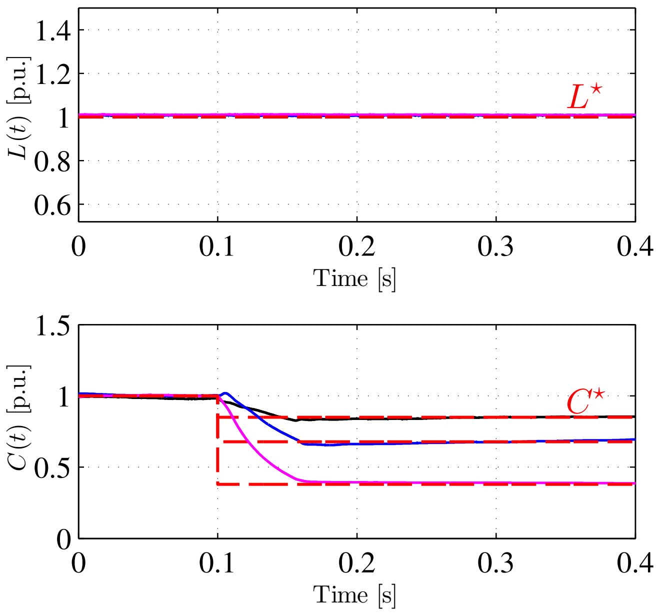

Fig. 8: Experimental results for a step change in capacitance $C^{\star}$ between 10% and 66% of the nominal capacitance. Inductance $L^{\star}$ is unchanged.

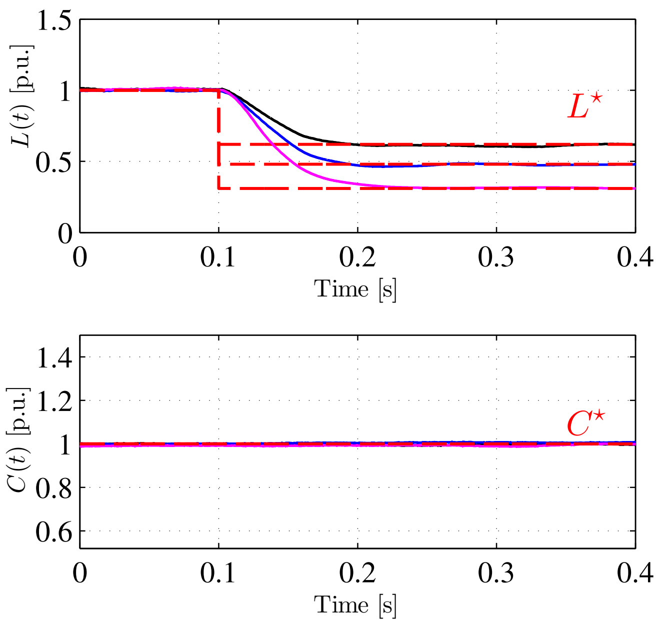

Fig. 9: Experimental results for a step change in inductance $L^{\star}$ between 10% and 66% of the nominal inductance. Capacitance $C^{\star}$ is unchanged.

V. Conclusions

This paper presents the design, analysis and experimental verification of an improved robust adaptive parameter identifier for dc-dc converter applications. The improvement over

TABLE III: Time to convergence for different values of parameter change.

Capacitance Step Change	Time to Convergence
−10%	50 ms
−33%	52 ms
−66%	53 ms
Inductance Step Change	Time to Convergence
−33%	80 ms
−50%	82 ms
−66%	100 ms

conventional adaptive parameter identifiers is a result of the integration of a closed-loop linear switched state observer designed using H_∞ robust performance criteria. The proposed parameter identifier is validated for a dc-dc boost converter in real time. The simulation and experimental results demonstrate faster convergence speed for a wide range of passive parameter deviations in presence of arbitrary exogenous disturbances.

The applications for the proposed parameter identifier include: 1) condition and health monitoring of passive converter components for incipient faults; 2) diagnosis and prognosis of multiple faults (both soft and catastrophic failures) in real time; 3) online automatic adjustment of the controllers during parameter variations; and 4) estimation-based control policies.

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