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Online Inductor Parameters Identification by Small Signal Injection for Sensorless Predictive Current Controlled Boost Converter

Chen Chen, Linkai Li, Qiao Zhang, *Member, IEEE*, Qiaoling Tong, *Member, IEEE*, Kan Liu, *Member, IEEE*, Dian Lyu, and Run Min

Abstract—In a sensorless predictive current controlled boost converter, parameterizing the inductor plays an important role in controller performance. In this paper, a solution for inductor parameters online identification is investigated. A small signal injection strategy is proposed to create a transient state, and convergence problem of inductance identification in steady state can be avoided. Then a charge balance current observer (CBCO), derived from capacitor current charging balance concept, is adopted to estimate the inductor current for inductance identification. Since inductance is not used in CBCO, current estimation is not affected by inductance identification error. Because of rank-deficient problem, instead of identifying inductor parasitic resistance solely, the inductor equivalent parasitic resistance is derived. By applying it into the conventional current observer for current control loop, the accuracy of current estimation can still be guaranteed since more parasitic effects are included. To improve the accuracy of inductance identification, a load identification method is investigated. Furthermore, the effect of the equivalent series resistance (ESR) of output capacitor on the proposed algorithm is analyzed. Finally, its effectiveness is verified by experimental results.

Index Terms—Sensorless, boost converter, inductor parameters, online identification, small signal injection.

I. INTRODUCTION

THE research on current mode control for dc-dc converters have been an important topic for a long time due to their higher response speed and larger loop gain bandwidth than conventional voltage mode control [1]–[8]. However, a precise and high speed current sensor is required to detect the inductor current and this increases the cost. Moreover, its signal processing module introduces delay and noise to the control loop. As an alternative approaches, V^2 control is studied [9]–[11]. In V^2 control, equivalent series resistance (ESR) of

output capacitor is utilized instead of traditional current sensing resistors. It has the advantages of fast load transient characteristics and is widely applied in buck converters. For digitally controlled boost converters, sensorless predictive current control (SPCC) has become more and more popular, because it inherits the advantages of predictive current control without extra hardware cost. To realize SPCC, the predictive current control (PCC) and sensorless current control need to be combined together. From published literatures on PCC, in [12], Chen proposed an algorithm to eliminate the inductor current disturbance in one switching cycle for peak, average and valley current control modes. Lai further investigated PCC based peak current mode control in [13]. The effectiveness to eliminate the disturbance in limit cycles by PCC with leading edge PWM modulation scheme was verified by theoretical derivation [14]. To realize sensorless current control, a current observer is normally used. The performance of current estimation relies on modeling accuracy of current observer. An accurate current observer model was established for sensorless current control [15]. However, the model is too complex to implement. In [16], an algorithm for average current sensorless control was proposed. With consideration of a number of parasitic parameters, the current estimation is relatively accurate. In [17], to eliminate the voltage steady state error and achieve high accuracy current estimation, a comprehensive compensation strategy was proposed and it can eliminate the effects of component parasitic parameters and nonlinear factors.

With the aforementioned research achievements, the performance of sensorless predictive current controlled boost converters keeps improving all the time. However, there is still a big challenge in producing good performance that relies on accurate component parameters acquisition for model update, because working environments, loading levels and aging effects can cause the component parameters to change over time. A practical solution is to use the online parameter identification to track the parameter variations. There are several publications focusing on power converters online parameter identification [18]–[21]. In [22], a comparison between an algebraic parameter identification algorithm and classical asymptotic observers for the load of a boost converter was carried out. The algebraic algorithm, unlike the asymptotic observers, does not have stability and convergence issues. The algebraic identification algorithm for load and input voltage identification was proposed in [23]. With the identified parameters, the Generalized Proportional Integral indirect adaptive controller can be tuned online accordingly. A

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real-time detection technique of the capacitance (C) and its ESR for boost converters was investigated in [24]. Based on the sampling of capacitor current and ripple voltage, the capacitor parameters are obtained by using Kalman filter. Further, Yao proposed an online identification algorithm for output capacitor's ESR and C without using any current sensor [25]. Only an output voltage sampling at particular moment in a switching cycle needs to be added. The above literatures provide solutions for the load, capacitance, and its ESR online identification of boost converters.

For SPCC based boost converters, because the current is estimated through a current observer, its performance is even more sensitive to parameter variations. As an essential element in current observer modeling and controller design, the inductance identification with accuracy can affect the current estimation and controller performance. Since no current sensor is utilized, more difficulties such as current estimation accuracy, algorithm convergence, etc. exist in the inductor parameters identification. There has not yet been any publication to investigate online inductance identification for SPCC based boost converters.

There are three main issues to realize accurate inductor parameters identification. One is the inductance identification cannot be executed during steady state, because the inductance calculation result is not convergent. Secondly, if the same model is used for inductance identification and current estimation, the two processes are coupled with each other, leading to the inductance estimation falling into self-iteration status. This means the estimated inductance value remains at its initial setting. The last issue is the inductor current estimation error caused by parasitic parameters which effects the inductance identification. Furthermore, the inductor parasitic resistance couples with other parasitic parameters due to model rank-deficient, so it is hard to identify independently.

Aiming at finding out solutions for aforementioned three issues, a small signal injection scheme is proposed for inductance identification. A low amplitude and short duration disturbance is injected into the voltage reference to build a transient state in which the inductance can be identified. CBCO is introduced for current estimation in the inductance identification process. Since conventional current observer is still used for current estimation in the current control loop, the current estimation can be carried out independently between current control and inductance identification processes. Finally, the inductor equivalent parasitic resistance which consists of the parasitic resistance of the inductor, turn-on resistance of MOSFET, etc. is derived instead of identifying the inductor parasitic resistance itself. Then it is applied to the conventional current observer. With this approach, the accuracy of current estimation can be guaranteed because more accurate parasitic effects are taken into account and the independent inductor parasitic resistance identification is omitted.

The paper is organized as follows. In Section II, three main issues of inductor parameters online identification in SPCC based boost converter are investigated. In Section III, the strategy for inductance identification is proposed at first, i.e. a short and small voltage reference disturbance is applied to

create a transient state for inductance identification. Then, CBCO is introduced for current estimation in inductance identification process. With this approach, the current estimation accuracy cannot be affected by inductance identification error. After that, the inductor equivalent parasitic resistance is also derived to guarantee the current estimation accuracy. In addition, a load estimation scheme is investigated in this section for improving inductance estimation accuracy. Since output capacitor ESR is not included in inductor equivalent parasitic resistance, its effect on the proposed algorithm is analyzed in Section IV. Finally, the experimental results and their analysis are given in Section V.

II. THE ISSUES OF INDUCTOR PARAMETERS IDENTIFICATION

The control diagram of SPCC based boost converter is shown in Fig.1. There are two control loops: voltage control loop is the outer loop that generates the reference current, while the inner current control loop applies conventional current observer other than current sensor to obtain the inductor current. With the above configuration, there are three issues for inductor parameters identification. The first one, which is actually not exclusive to SPCC based system, is the non-convergence in inductance value calculation and it stays infinite in steady state. The other two issues are identical in SPCC based system. One is that the current estimation and inductance identification couple with each other, which leads the inductance calculation to a self-iteration state. The other is inductor parasitic resistance R_L identification. Because of the rank-deficient problem, it cannot be identified independently. In this case, the current estimation accuracy cannot be guaranteed.

Fig. 1. Structure of conventional sensorless current control for boost converter

A. The issue of inductance estimation in steady state

When the boost converter works in CCM mode, considering the inductor parasitic resistance R_L , inductor current function during the k th switching cycle in discrete time domain is expressed as

$$L \frac{I_L(k+1) - I_L(k)}{T} = V_{IN}(k) - D'(k)V_O(k) - I_L(k)R_L. \quad (1)$$

The basic current estimator is also expressed in (1), where L is the inductance, $I_L(k)$ represents the inductor current, $V_O(k)$ is the average output voltage, $V_{IN}(k)$ is the input voltage, $D(k)$ is the duty ratio, $D'(k)$ equals $1 - D(k)$ and T is the switching period. The inductance can be derived from (2).

$$L = \frac{V_{IN}(k) - D'(k)V_O(k) - I_L(k)R_L}{I_L(k+1) - I_L(k)} T. \quad (2)$$

When system is in steady state, the inductor current in neighbouring two switching cycles stays constant. If L is identified depending on (2), its calculation result goes infinite which means the identification result is not convergent.

B. The issue of coupling between current estimation and inductance identification

Since inductor current and inductance have to be estimated and identified by using inductor current function, if (1) is used for current estimation and (2) is used for inductance identification, the two processes coupled with each other lead to L staying at its initial value. In addition, the inductor current accuracy cannot be high if L is not updated in real time. To decouple these two processes, a new current observer is necessary for inductance identification.

C. The issue of inductor parasitic resistance estimation

According to (1) and (2), in order to estimate current and identify inductance accurately, R_L should be obtained beforehand. In steady state, R_L can be described as (3) and it also couples with the inductor current.

$$R_L = \frac{V_{IN}(k) - D'(k)V_O(k)}{I_L(k)} \quad (3)$$

If the circuit parasitic parameters such as switch conducting resistance R_{DS} , diode forward conducting resistance R_D and diode forward conducting voltage V_D are considered during the system modelling, the inductor current model in turn-on and turn-off status are described in (4) and (5). All these parasitic parameters change along with the environmental and working conditions, so in (4) and (5), together with R_L , these four parasitic parameters are variables. Therefore R_L cannot be derived based on (4) and (5) due to rank-deficiency. In addition, for digital control system, $V_O(t)$ is substituted by the sampled output voltage. The measurement errors caused by R_C and the output voltage measurement noises are brought to the inductor current model, and then the difficulty of R_L identification can be further increased.

$$L \frac{dI_L(t)}{dt} = V_{IN}(t) - I_L(t)(R_L + R_{DS}) \quad (4)$$

$$L \frac{dI_L(t)}{dt} = V_{IN}(t) - [V_O(t) + V_D] - I_L(t)(R_L + R_D) \quad (5)$$

III. THE PROPOSED ONLINE INDUCTOR PARAMETERS IDENTIFICATION ALGORITHM

In this section, an online inductor parameters identification algorithm for peak current mode SPCC based boost converter system is investigated. With the proposed algorithm, the issues mentioned in Section II are solved without adding any extra hardware cost and finally L and R_L can be identified accurately. The structure of the boost converter with proposed online inductor parameters estimation algorithm is shown as Fig. 2. The current control loop uses a conventional current observer to realize sensorless predictive peak current control mode. Compared with Fig. 1, the controller parameters and system

model are updated online according to the identified inductor parameters L and R_L to achieve optimal performance.

Fig. 2. Control structure of SPCC based boost converter with inductor parameters online estimation

In the proposed algorithm, a low amplitude and short duration step signal is added to the voltage reference V_{REF} . With this approach, a transient state is created for inductance identification. With sampled input and output voltages, the average current during turn off period $I_{AV}(k)|D'$ is derived from the charge balance current observer at first. Then they are used to identify L and R_L .

For the inductor parameters, temperature, loading levels, and aging effects can cause them to change over time. Since the aging constant is very large, the variations of inductor parameters caused by aging effects are very small in a short time. So the time period of inductor parameters identification should not be set too short, otherwise it will cause a waste of hardware resources. While the temperature constant is much smaller than the aging constant and the load levels may change in any time, a short time period should be set to ensure timely monitoring. Taking these factors into consideration, the voltage reference signal injection is conducted once every second in real application. The injected signal level is low and its duration is short, so this approach does not compromise much of the system performance.

A. Inductance identification through small signal injection

The voltage reference signal injection is done at the beginning of a switching cycle. Its duration is 50μs and its amplitude is 3% of designed output voltage. The duration of signal injection is chosen based on the dynamic time required for the inductance identification algorithm. The selection principles of injection amplitude are as follows: 1) the amplitude should be large enough to reduce the influences of the output voltage measurement noises and quantization errors on the accuracy of inductance identification. This can also improve the convergence of the inductance identification algorithm; 2) the disturbance caused by the signal injection will not greatly influence the system performance. If the system has a high resolution AD converter, the injection amplitude can be smaller.

The inductor current during this process is described as Fig. 3. The PWM modulation scheme is “leading edge modulation”. Because $D(k)$ is calculated in the $(k-1)$ th cycle, the system is still in steady state in the k th cycle. However, the duty ratio of

$(k+1)$ th cycle changes in order to follow the change of voltage reference and the transient state is created.

Fig. 3. The inductor current waveform during the signal injection process

During this transient state, the inductance is derived from (2). However, (2) is equivalent to (1). For L identification, (1) should not be used again to avoid the identification process falling into a self-iteration state. According to the charging principle of output capacitor, a new inductor current observer is derived and it is shown in (6).

Since L is not included in (6), the current estimation accuracy cannot be affected by inductance identification, which is the design purpose of this new current observer. In addition, CBCO is proposed for the first time to achieve accurate current estimation for L identification process. Although the current estimation has one switching cycle delay and this delay may cause some oscillation in conventional current estimation, it is very suitable for inductor current estimation. Because L identification process takes several switching cycles to finish, this one cycle delay should not affect it.

$$C \frac{V_o(k+1) - V_o(k)}{T} = D'(k) I_{AV}(k) | D' - \frac{V_o(k)}{R}, \quad (6)$$

where $I_{AV}(k) | D'$ and $V_o(k)$ are the average current during turn off period and sampled output voltage at the very beginning of the k th cycle respectively. Then $I_{AV}(k) | D'$ can be obtained by (7).

$$I_{AV}(k) | D' = C \frac{V_o(k+1) - V_o(k)}{TD'(k)} + \frac{V_o(k)}{RD'(k)} \quad (7)$$

In the transient state, peak current $I_p(k)$ and whole cycle average current $I_{AV}(k)$ can be derived from $I_{AV}(k) | D'$. They are presented by (8) and (9).

$$I_p(k) = I_{AV}(k) | D' + \frac{M_2(k) D'(k) T}{2}, \quad (8)$$

$$I_{AV}(k) = I_{AV}(k) | D' + \frac{T}{2} [M_1(k) D^2(k) - M_2(k) D(k) D'(k)], \quad (9)$$

where $M_1(k)$ is the positive slope of inductor current in the k th switching cycle, and $M_2(k)$ is the absolute value of negative slope. They are described in (10) and (11) respectively.

$$M_1(k) = \frac{V_{IN}(k) - I_{AV}(k) R_L}{L} \quad (10)$$

$$M_2(k) = \frac{V_o(k) - V_{IN}(k) + I_{AV}(k) R_L}{L} \quad (11)$$

With (7), (8) and (9), I_L can be derived in the transient state which is then used for inductor parameters identification.

Next, in order to identify the inductance accurately, a more precise model other than (2) is needed. The relationship between peak inductor currents in adjacent two switching cycles is

$$I_p(k+1) = I_p(k) + T [D(k) M_1(k) - D'(k) M_2(k)]. \quad (12)$$

Substituting (10) and (11) into (12), then

$$L \frac{I_p(k+1) - I_p(k)}{T} = V_{IN}(k) - D'(k) V_o(k) - I_{AV}(k) R_L. \quad (13)$$

(13) is the precise conventional current observer model and it is used in the current control loop.

As shown in Fig. 3, when the signal injection happens, the system still stays in the steady state in the k th cycle, then $I_p(k+1) = I_p(k)$. So the right side of (13) equals zero.

$$V_{IN}(k) - D'(k) V_o(k) - I_{AV}(k) R_L = 0 \quad (14)$$

Substitute (8) into (13) then use (14) for simplification, L can be identified, the results is represented as L_{EST} , shown as (15).

$$L_{EST} = \frac{V_E(k) D'(k) - V_E(k+1) D'(k+1)}{2 [I_{AV}(k+1) | D' - I_{AV}(k) | D']} T, \quad (15)$$

where $V_E(k) = V_o(k) - V_{IN}(k) + I_{AV}(k) R_L$.

The divergence and accuracy issues of inductance estimation can be solved by (15). In (15), $V_{IN}(k)$ and $V_o(k)$ are sampled, $I_{AV}(k) | D'$ and $I_{AV}(k)$ are derived from (7) and (9) respectively.

B. The inductor parasitic resistance identification

The estimation process of R_L can be carried out in steady state, such as the cycle in which the small signal injection begins. According to (14), R_L is obtained through

$$R_L = \frac{V_{IN}(k) - D'(k) V_o(k)}{I_{AV}(k)}. \quad (16)$$

In the steady state, the average current during the turn-off period is equal to the whole switching cycle average current, so $I_{AV}(k)$ can be replaced by $I_{AV}(k) | D'$. Finally, the identified value of R_L is named as R_{LEST} , is expressed as (17). Compared with (16), the computational complexity of (17) is lower because the calculation of (8) and (9) is avoided.

$$R_{LEST} = \frac{V_{IN}(k) - D'(k) V_o(k)}{I_{AV}(k) | D'} \quad (17)$$

However, the parasitic parameters such as R_{DS} , R_D , and V_D can affect the identification result of (17). Considering all the parasitic parameters, $M_1(k)$ and $M_2(k)$ can be described as (18) and (19).

$$M_1(k) = \frac{V_{IN}(k) - I_{AV}(k) (R_L + R_{DS})}{L} \quad (18)$$

$$M_2(k) = \frac{V_o(k) - V_{IN}(k) + V_D + I_{AV}(k) (R_L + R_D)}{L} \quad (19)$$

Substituting (18) and (19) into (12), then

$$L \frac{I_p(k+1) - I_p(k)}{T} = V_{IN}(k) - I_{AV}(k) [R_L + R_{DS} D(k) + R_D D'(k)] - D'(k) [V_o(k) + V_D] \quad (20)$$

Comparing (17) with (20), all the parasitic parameters reflected into R_{LEST} can be describe in (21). As shown in (21), R_{LEST} derived from (17) includes not only R_L , but also the effects of R_{DS} , R_D , and V_D on inductor current estimation. This is the equivalent parasitic resistance of the inductor.

$$R_{LEST} = R_L + R_{DS}D(k) + R_D D'(k) + \frac{V_D D'(k)}{I_{AV}(k)} \quad (21)$$

The inclusion of other parasitic parameters makes R_{LEST} deviate from R_L . Substituting (21) into (13), the modified equation is equivalent to (20). This means that the estimated inductor current can be described as (20) after R_L is replaced by R_{LEST} . Compared with (13), the current estimation is more accurate because more parasitic effects are considered.

C. Load identification

As shown in (7), load R is required for inductance identification. In order to get accurate identification results, the load variation should be considered. R needs to be estimated along with the inductance estimation process. Its estimation can be achieved by simply adding an extra point for output voltage sampling in one chosen switching cycle.

Fig. 4. Output voltage waveform in steady state

Fig. 4 shows the output voltage waveform in steady state. At the beginning of each switching cycle, which is point B, the output voltage is sampled. A is the added sampling point which is ahead of B for time T_o within the previous cycle's turn-on period. During this turn-on period, the relationship between output voltage and load current is

$$C \frac{dV_o(t)}{dt} = -\frac{V_o(t)}{R}. \quad (22)$$

The output voltage curve is approximated as a falling linear slope when the switch is on. Then the relationship between the output voltage in A and B is derived from integrating both sides of (22).

$$C \frac{V_B - V_A}{T_o} = -\frac{V_A + V_B}{2R} \quad (23)$$

Then the load value is

$$R = \frac{T_o (V_A + V_B)}{2C (V_A - V_B)}. \quad (24)$$

Considering the variations of capacitance, C that exists in (7) and (24) can be tuned by using the online capacitance identification algorithm which is proposed in [25].

D. Algorithm steps summary

Fig. 5. Procedure of the proposed algorithm

After all the above derivations, the whole process of the proposed algorithm is illustrated as Fig.5, which is summarized as the following steps:

1) Injecting a small signal into V_{REF} in the k th switching cycle and adding an output voltage sampling point in this cycle for the calculation of load.

2) Calculating R according to (24) in the $(k+1)$ th switching cycle, then $I_{AV}(k)|D'$ can be estimated by (7) in this switching cycle.

3) According to the estimated $I_{AV}(k)|D'$, R_{LEST} can be obtained in the $(k+1)$ th switching cycle. L_{EST} has to be calculated in the $(k+2)$ th cycle because the system starts to enter a transient state in the $(k+1)$ th cycle.

4) In the $(k+2)$ th switching cycle, the $M_1(k)$, $M_2(k)$ and controller parameters are updated according to L_{EST} and R_{LEST} .

The proposed algorithm overcomes the aforementioned issues for inductor online parameters identification. With this approach, the system model and controller parameters are updated online and optimal performance can be expected.

IV. ANALYSIS OF ESR EFFECT

Apart from R_C of the output capacitor, the other parasitic parameters are all included in R_{LEST} . Therefore, any variation in these parasitic parameters can be updated by R_{LEST} identification. However, since R_C is not included, its effect on the proposed algorithm should be analyzed.

Because of the effect of R_C , the output voltage is not equal to capacitor voltage. Including R_C , the relationship between average output voltage $V_o(k)$ and average voltage of capacitor $\bar{V}_C(k)$ is

$$V_o(k) = \bar{V}_C(k) + I_C(k)R_C, \quad (25)$$

where $I_C(k)$ is the average current of capacitor which is equal to the right side of (6). Then

$$I_C(k) = D'(k)I_{AV}(k)|D' - \frac{V_o(k)}{R}. \quad (26)$$

The capacitor voltage at the beginning of the k th switching cycle is $V_C(k)$, its relationship with $V_O(k)$ is $V_O(k) \approx V_C(k) - V_O(k)R_C/R$. According to the voltage and current characteristics of the output capacitor, and combined with (25) and (26), the accurate relationship between $V_C(k)$ and inductor current is

$$C \frac{V_C(k+1) - V_C(k)}{T} = D'(k)I_{AV}(k) \left| D' \frac{R}{R+R_C} - \frac{\bar{V}_C(k)}{R+R_C} \right|. \quad (27)$$

In order to reduce the derivation complexity, this approximation $\bar{V}_C(k) \approx V_C(k)$ can be made. In addition, R_C is in the milliohm range which is far lower than load R , so the actual inductor current $I'_{AV}(k) \left| D' \right|$ can be obtained from (28).

$$I'_{AV}(k) \left| D' \right| = C \frac{V_C(k+1) - V_C(k)}{TD'(k)} + \frac{V_C(k)}{RD'(k)} \quad (28)$$

The inductor current estimation error is $\Delta I(k) = I'_{AV}(k) \left| D' \right| - I_{AV}(k) \left| D' \right|$. Comparing (7) with (28), the current estimation error can be derived as (29).

$$\Delta I(k) = CR_C \frac{V_O(k+1) - V_O(k)}{TRD'(k)} + \frac{V_O(k)R_C}{R^2D'(k)} \quad (29)$$

According to (15) and (16), the inductor current estimation error can affect the identification accuracy of L_{EST} and R_{LEST} .

The slopes of the two continuous switching cycles can be regarded as constant because the switching period is relatively short, so $M_2(k+1) \approx M_2(k)$, then $V_E(k+1) \approx V_E(k)$. Finally (15) can be simplified as

$$L_{EST} = \frac{V_E(k)[D'(k) - D'(k+1)]}{2[I'_{AV}(k+1) \left| D' \right| - I_{AV}(k) \left| D' \right|]} T. \quad (30)$$

The actual inductance is L' , and it can be described as (31).

$$L' = \frac{V_E(k)[D'(k) - D'(k+1)]}{2[I'_{AV}(k+1) \left| D' \right| - I'_{AV}(k) \left| D' \right|]} T \quad (31)$$

The identification error of inductance is $\Delta L = L' - L_{EST}$. Subtracting (30) from (31) and substituting (29), the relative error of inductance estimation is

$$\frac{\Delta L}{L'} = \frac{K_1[V_O(k+1) - V_O(k+2)] + K_2[D'(k+1) - D'(k)]}{I_{AV}(k+1) \left| D' \right| - I_{AV}(k) \left| D' \right|}, \quad (32)$$

where $K_1 = CR_C/TRD'(k)$ and $K_2 = V_O(k)R_C/R^2D'(k)D'(k+1)$. As mentioned previously, R_C is normally very low, so the values of K_1 and K_2 are low. In addition, $V_O(k+1) - V_O(k+2)$ and $D'(k+1) - D'(k)$ are close to 0, while $I_{AV}(k+1) \left| D' \right| - I_{AV}(k) \left| D' \right|$ is relatively large in the transient state. So the value of (32) is almost equal to 0, which means that the effect of R_C on inductance identification is negligible.

With the similar derivation process for the inductance estimation, the relative error of equivalent parasitic resistance is

$$\frac{\Delta R_L}{R'_L} = -\frac{\Delta I(k)}{I_{AV}(k) \left| D' \right|}, \quad (33)$$

where $\Delta R_L = R'_L - R_{LEST}$ and R'_L is the actual value of the inductor equivalent parasitic resistance.

The identification of R_L is done in the steady state. Simplifying (29) with $V_C(k) = V_C(k+1)$, then substituting it into (33), finally (34) is obtained.

$$\frac{\Delta R_L}{R'_L} = -\frac{V_O(k)R_C}{R^2D'(k)I_{AV}(k) \left| D' \right|} \quad (34)$$

According to (34), $\Delta R_L/R'_L \approx 0$, so the effect of R_C on R_L identification is also negligible.

The output voltage measurement noises can also affect the proposed algorithm. For inductor parasitic resistance identification, the influence of the measurement noises is very small. For inductance identification, its accuracy is inversely proportional to the measurement noises. By decreasing C and increasing $I_{AV}(k+1) \left| D' \right| - I_{AV}(k) \left| D' \right|$, the effect of the measurement noises can be reduced. In addition, the common mode rejection circuits and high performance measurement circuit should be designed to reduce the measurement noises. On this basis, the effect of the output voltage measurement noises on inductance estimation is relatively small, which can be verified by the experimental results in section V.

V. EXPERIMENTS

In order to verify the proposed algorithm, a digitally controlled boost converter is built for experimental verification. Its specifications are shown in Table I.

TABLE I
SPECIFICATIONS OF THE TESTED BOOST CONVERTER

Input voltage	6V
Output voltage	12V
Switching frequency	100kHz

A. Experimental settings

The system hardware contains a control board and a power board. A Texas Instruments digital signal processor (DSP) TMS320F2812 is the core part of control board used to implement the control algorithm.

The power board includes the power stage and signal level shifting circuits. The switching device is an Infineon BSZ110N06NS3 MOSFET. The output capacitor type is Panasonic EEHZA1J560P. Chosen diode is NXP PMEG045V050EPD. The specifications for these components are shown in Table II. The switching frequency is 100kHz.

For monitoring, the estimated peak current I_p is output synchronously by a 12-bit DAC TVL5616. The actual inductor current i_l is measured by a current probe with a resolution of 200mV/A.

For R identification, the related parameters T_o is set as $0.8DT$. The identification process is carried out every second, and results shown in the Fig.7 are for a period of 60 seconds. All the identified values given in the paper are their average values.

TABLE II
SPECIFICATIONS OF HARDWARE PLATFORM

Inductance of the power inductor	28μH
Inductor winding resistance	50mΩ
Capacitance of the output capacitor	56μF
ESR value of the output capacitor	30mΩ
Load resistance	10Ω
MOSFET R_{DS}	11mΩ
Diode forward Voltage	0.42V
Diode forward resistance	0 mΩ

B. Experiment Results and analysis

1) Inductance identification result

Fig. 6. Output voltage waveform when voltage injection happens

Fig.6 shows both AC and DC components of the output voltage when the pulse signal is injected for inductance identification. As Fig.6 shows, the voltage rises by 0.32V because of the reference voltage injection. When the injection finishes, the output voltage goes back to 12V. The whole process lasts 200 μ s. During this period, the inductance identification and control parameters updating are also processed. Output voltage variation is less than 3% of the rated output voltage which means the system can still be judged as steady state during the identification process.

The identification results of R , L_{EST} and R_{LEST} are shown as Fig.7a, Fig.7b and Fig.7c respectively. As can be seen from the figures, the identified values of R , L_{EST} and R_{LEST} are 10.06 Ω , 26.509 μ H and 0.138 Ω . Compared with their rated values, the identification errors of R and L_{EST} are all less than 6%. Because R_{LEST} is only used for the current observer of current control loop, its identification performance can be verified by the current estimation waveforms presented next.

Fig. 7a. Identification results of R during 60 seconds time, Fig. 7b. Identification results of L_{EST} during 60 seconds time, Fig. 7c. Identification results of R_{LEST} during 60 seconds time.

Fig. 8a. Estimated peak current and actual current waveforms without R_{LEST} identification, Fig. 8b. Estimated peak current and actual current waveforms with R_{LEST} identification.

For inductor current estimation performance verification, Fig. 8a shows the actual inductor current and estimated inductor peak current without identifying R_{LEST} . The estimated inductor peak current is 3.32A while actual peak current is 3.02A, with a 0.3A error between them. However, Fig. 8b presents the same signals as Fig. 8a but with R_{LEST} identification. It shows that the estimated inductor peak current is 3.07A which is very close to its actual value.

In order to verify the dynamic performance of the proposed algorithm and compare the performance between the systems with the proposed algorithm and without parameters identification, experiments are carried out under load and line voltage disturbance conditions.

2) Experiment with line voltage variations

Fig. 9a and Fig. 9b are the output voltage waveforms for the system with the proposed algorithm and the system without parameters identification respectively when the line voltage jumps from 6V to 7.2V. As Fig.9a shows, with the proposed algorithm, the output voltage rises by 0.22V and stabilizes within 260 μ s. While for the system without parameters identification function, as shown in Fig.9b, the voltage rise is 0.25V (an increase of 14%) and the stabilization time is 600 μ s which is 131% longer.

Fig. 9a. Output voltage waveform with proposed algorithm when line voltage changes, Fig. 9b. Output voltage waveform without parameters identification when line voltage changes

For the parameters identification results, R , L_{EST} and R_{LEST} are shown as Fig.10a, Fig.10b and Fig.10c respectively. In the beginning 30s, the line voltage is 6V. It changes to 7.2V at 30.5s and last for another 30s. The identification results are summarized as TABLE III.

TABLE III
COMPARISON OF THE PARAMETERS IDENTIFICATION DURING LINE VOLTAGE VARIATIONS

Line Voltage	6V	7.2V
R	10.060 Ω	10.028 Ω
L_{EST}	26.509 μ H	26.891 μ H
R_{LEST}	0.138 Ω	0.173 Ω

The results presented in TABLE III suggest that the identification of R and L_{EST} maintains its high accuracy despite the variations in line voltage. With line voltage variations, the

system stabilizes in a new state, while the inductor current and duty cycle are changed. According to (21), the value of R_{LEST} should deviate from 0.138Ω , as shown in TABLE III. To further verify the performance of R_{LEST} identification, Fig. 11 shows the actual inductor current and estimated inductor current with R_{LEST} identification after the change of line voltage. The actual peak current and estimated inductor peak current are 2.55A and 2.59A, respectively. The estimation error is very small, which indicates that the estimated peak current can be effectively corrected by R_{LEST} identification even though line voltage changes.

Fig. 10a. Identification results of R during 60 seconds time under line voltage variations, Fig. 10b. Identification results of L_{EST} during 60 seconds time under line voltage variations, Fig. 10c. Identification results of R_{LEST} during 60 seconds time under line voltage variations

Fig. 11. Estimated peak current and actual current waveforms with R_{LEST} identification after line voltage changes

3) Experiment with load variations

The output voltage waveforms for system with proposed algorithm and system without parameters identification under load variations (10Ω to 5Ω) are shown in Fig. 12a and Fig. 12b respectively. As shown in Fig. 12a, with proposed algorithm, the output voltage drops to 10.85V and stabilizes within 260μs.

However, for the system without parameters identification, as shown in Fig. 12b, the voltage drops to 10.75V and takes 600μs to stabilize (131% longer than proposed algorithm).

Fig. 12a. Output voltage waveform with proposed algorithm when load changes, Fig. 12b. Output voltage waveform without parameters identification when load changes

R , L_{EST} and R_{LEST} identification results are shown as Fig. 13a, Fig. 13b and Fig. 13c respectively. In the beginning 30s, the load is 10Ω . It changes to 5Ω at 30.5s and last for another 30s. The identification results are summarized as TABLE IV.

Fig. 13a. Identification results of R during 60 seconds time under load variations, Fig. 13b. Identification results of L_{EST} during 60 seconds time under load variations, Fig. 13c. Identification results of R_{LEST} during 60 seconds time under load variations.

TABLE IV
COMPARISON OF THE PARAMETERS IDENTIFICATION DURING
LOAD VARIATIONS

Load Value	10Ω	5Ω
R	10.060Ω	5.032Ω
L_{EST}	26.509μH	26.587μH
R_{LEST}	0.138Ω	0.094Ω

As can be seen from the results in TABLE IV, the load identification can follow the actual load variations while the inductance identification maintains its high level of accuracy despite the variations of load value. The deviation of R_{LEST}

identification is caused by the variations of the inductor current and duty cycle in steady state. R_{LEST} identification performance can be verified by the current estimation waveforms shown in Fig. 14. The estimated inductor peak current is 5.65A which is very close to its actual value (5.56A). It indicates that R_{LEST} identification is also accurate even though load changes.

Fig. 14. Estimated peak current and actual current waveforms with R_{LEST} identification after load changes

As the experimental results show, even the system is under sudden load and line voltage disturbances, with proposed algorithm it will still be able to quickly respond and track to a new steady state. In addition, the parameters identification algorithm shows good robustness.

VI. CONCLUSION

Three issues of inductor parameters online identification of SPCC based boost converter have been solved in this paper. First, by using the small signal injection method, convergent issue of inductance identification in steady state is solved. Then, a CBCO is proposed to overcome the coupling issue. Finally, the inductor equivalent parasitic resistance is derived to guarantee the current estimation accuracy. With the above strategy, the inductor parameters online identification is realized and maintains good accuracy in various working conditions. On this basis, the control parameters are also optimized according to the updating of the parameters identification. Experimental results show that the proposed identification strategy is accurate and effective, and it should have good potentials in various practical applications.

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