Improved Energy Balance Control for Boost Converters Without Estimating Circuit Energy Losses

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This work was supported in part by the State Key Program of National Natural Science Foundation of China under Grant U1866210, and in part by the Project funded by China Postdoctoral Science Foundation under Grant 2019M662910.

ABSTRACT The previously developed control methods based on the conservation of energy in circuits require the accurate estimation of energy losses, which is difficult to measure and calculate for boost converters. Consequently, there always exist steady-state errors in the output voltage if neglecting such circuit energy losses. To address this issue, an improved energy balance control (IEBC) method is proposed in this paper by integrating a simplified energy balance controller (SEBC) with a PI controller. The proposed IEBC can reduce the steady-state output voltage errors without requiring the estimation of circuit energy losses. Furthermore, the proposed IEBC can operate in both the continuous current mode (CCM) and the discontinuous current mode (DCM), thus accurate static and fast dynamic performances are achieved over the entire load operation range. Moreover, the stability of the IEBC is proved using the Lyapunov stability criterion. Compared with that of the SEBC, both simulations and experiments validate the feasibility and robustness of the proposed IEBC method.

INDEX TERMS Boost converter, energy balance, steady-state error, dynamic performance.

I. INTRODUCTION
With the expanding of power converters applications, the requirement for the performance of power converters has become increasingly high, for instance, small size, light weight, high efficiency and so on. In this case, the conventional PID controller, although having the advantages of simple control principle and strong robustness, cannot fulfill the rising requirements of converters, e.g., fast dynamic response [1], [2]. Then an anti-windup PI controller has been proposed. By switching between the saturation and linear regions, improved dynamic response was implemented to the load variation. However, a switch condition first have to determine and there is no significant improvement on the input variations or disturbances [3], [4]. Recently, to get superior static and dynamic performances, various control methods were developed, such as hysteresis control, sliding-mode control, fuzzy control, etc [5]–[10]. As an attempt to obtain excellent performances, the law of energy conservation, which states that the total amount of energy in a system is constant, has been introduced into the control field. It was firstly introduced to control the rigid body of active magnetic bearings, which provided a new view on the closed loop control [11]. Up to now, the application areas based on such a principle covered stability control of power systems, hamiltonian system, photovoltaic systems, active power filters, converters and so on [12]–[16].

As for converter applications, the conservation of energy was introduced to obtain the reference current and voltage of converters in a hybrid control scheme [17], [18], then improved dynamic performances were achieved. However, this scheme is only suitable for the critical discontinuous current mode (CDCM) and the discontinuous current mode (DCM). Under the continuous current mode (CCM), it is difficult to obtain a reference current, since not all the energy absorbed by an inductor can be released in full at the end of one switching cycle. A controller covering entire load operating ranges was presented in [19], [20] based on the law of energy conservation. Simulation results of a buck converter illustrate that it is not vulnerable to changes of converter operation modes (CCM, CDCM, DCM) and can offer fast dynamic performances. A switching control scheme (SCS)
using the law of energy conservation was presented for controlling buck converters [21]. By considering the energy losses of a circuit when maintaining the energy conservation in the circuit, the SCS achieved accurate static and fast dynamic performances. Similarly, by considering the energy losses of the circuit, accurate static and fast dynamic performances were achieved based on the energy balance in boost converters [22]. However, the mathematical calculation of energy losses in a circuit is complex. Moreover, parasitic parameters of circuit components are usually unknown and difficult to be measured in actual circuits, which leads to the inaccurate estimation of such energy losses. Thus the energy losses in a circuit are usually neglected, as a result, leading to degraded performance, mainly the steady-state errors of the output voltage. To reflect this phenomenon, according to degraded performance, mainly the steady-state errors of the output voltage. Under the assumption that the converter is emulated by an equivalent resistance, the stored energy of the inductor is firstly derived in this paper. Then combined with a voltage control (SEBC) method, which neglect energy losses of circuits, an IEBC method is proposed to tackle the energy losses of a circuit when maintaining the energy conservation in the circuit, the SCS achieved accurate static and fast dynamic performances. Similarly, by considering the energy losses of the output voltage. It is generally known that a PI controller attempts to minimize the error over time by adjusting the control variable \( u(t) \) so as to force a measured process variable \( y(t) \) to follow a desired value \( r(t) \). It means that the merit of the PI controller is to eliminate the errors between a control objective and a controlled object, and as a result, the PI controller relays only on the response of the measured process variable, not on the exact mathematical model. In consideration of such features of PI controller, the voltage PI controller is introduced to modify the SEBC method for eliminating the steady-state errors of the output voltage \( \Delta u_{\text{steady}} \) due to neglecting the energy losses of the circuit. To implement the PI voltage controller, the following changes are made to equation (2) of SEBC.

Firstly, the converter is emulated by an equivalent resistance \( R_e \) shown in Fig. 2, thus \( i_L \) is expressed as

\[
i_L = \frac{u_{in}}{R_e}.
\]

\[i_L(t) = (u_{\text{ref}} - u_{in})L_0T_s + \int_{(n-1)T_s}^{(n-1)T_s + T_L} u_{in}i_L dt + \int_{(n-1)T_s}^{(n-1)T_s + T_L} u_{L_L}i_L dt + \int_{(n-1)T_s}^{(n-1)T_s + t_{\text{on}}} i_L^2R_e dt
\]

\[\int_{(n-1)T_s}^{(n-1)T_s + t_{\text{on}}} u_{in}i_L dt = (u_{\text{ref}} - u_{in})L_0T_s + u_{L_L}i_L T_s + i_L^2R_e T_s
\]
Based on (3), the following equation can be deduced,

\[ R_e = \frac{u_{in}}{i_e}. \]  \hfill (4)

Multiplying both sides of (2) by \( \frac{R_e}{R_e} \), (5) is derived from (2). Based on (3) and (4), (5) is changed into (6), where \( u_m = u_{ref}/R_s \), which is obtained from the PI voltage controller \([23]\], as shown in FIGURE 2. The proportional term \( K_p \) of the PI voltage controller is designed to be high enough, so that the dynamic response is not slowed down.

Thus, the control equation of the proposed IEBC method is derived as (6). With the high robustness of the PI controller, the steady-state errors of the output voltage due to the neglect of circuit energy losses can be eliminated.

### B. THE IMPLEMENTATION OF THE IEBC

As shown in FIGURE 2, the implementation of the IEBC method is described as below. The control reference \( (u_m - i_e R_s)T_s + \frac{u_i T_s}{u_m} \) is calculated instantaneously, which is calculated at the beginning of every sampling period and kept as the same during the entire sampling period. After getting the control reference, the proposed IEBC method is implemented by integration and comparison. The implementation of a CCM boost converter using the proposed IEBC method is described as below: the integral begins in the time instant when \( S_1 \) is turned on by a clock pulse with a fixed frequency. Over time, the integral \( W_{int} \) keeps increasing from its initial value as follows:

\[ W_{int}(t) = \int_{(n-1)T_s}^{(n-1)T_s + T_m(n)} i_e^2 R_s dt \]

\[ (t \in ((n - 1)T_s, (n - 1)T_s + T_s)) \]  \hfill (7)

and \( W_{int} \) is constantly compared with the control reference. At the moment when \( W_{int}(t) \) reaches to the control reference, a reset pulse is generated by the comparator in FIGURE 2 to reset the RS flip-flop as \( Q = 0 \), which turns off \( S_1 \). In the meantime, the integral is reset. \( S_1 \) keeps as the off-state until the next clock pulse arrives, then the \( (n+1) \)th switching cycle starts. Since a DCM boost converter has the similar implementation procedures with that of CCM, it is not presented in detail here.

### IV. STABILITY ANALYSIS OF THE IEBC BOOST CONVERTER

Under the steady-state conditions, the inductor absorbs and releases equal energy, which means \( W_i(t) = 0 \). Thus, neglecting \( W_i \), (6) is rewritten as follows:

\[ \int_{(n-1)T_s}^{(n-1)T_s + T_m(n)} i_e^2 R_s dt = (u_m - i_e R_s)T_s \]  \hfill (8)

Then the average model of (8) is obtained as:

\[ \bar{i}_e^2 R_s = (u_m - i_e R_s)T_s \]  \hfill (9)

From (9), \( d \) can be derived as:

\[ d = \frac{(u_m - i_e R_s)T_s}{i_e^2 R_s} \]  \hfill (10)

And such a boost converter can be described as:

\[ \frac{di}{dt} = \frac{u_m}{L} - \frac{1 - s}{L} u, \]

\[ \frac{du}{dt} = -\frac{u}{RC} + \frac{1 - s}{C} i \]  \hfill (11)

where \( s = 1 \) represents the on-state of switch \( S_1 \), \( s = 0 \) represents the off-state of switch \( S_1 \).

Substituting \( s = 1 \) in (11) with the value of \( d \) derived above, the state-space averaged model of the energy balance controlled

\[ \frac{R_e}{R_e} \int_{(n-1)T_s}^{(n-1)T_s + T_m(n)} u_{in} i_e dt = \frac{R_e}{R_e} (u_{ref} - u_{in})T_s + \frac{R_e}{R_e} u_i T_s \]

\[ \int_{(n-1)T_s}^{(n-1)T_s + T_m(n)} \frac{u_{in} i_e R_s dt}{R_e} = \frac{u_{ref} R_s}{R_e} (u_m - i_e R_s)T_s + \frac{R_e}{R_e} u_i T_s \]  \hfill (5)

\[ \int_{(n-1)T_s}^{(n-1)T_s + T_m(n)} \bar{i}_e^2 R_s dt = (u_m - i_e R_s)T_s + \frac{u_i T_s}{u_m} \bar{i}_e^2 R_s \]  \hfill (6)
The boost converter is obtained as follows.

\[
\frac{di}{dt} = \frac{u_m}{L} - \frac{u}{L} [1 - \frac{(u_m - i_t R_s) i_o}{i_t^2 R_s}],
\]

\[
\frac{du}{dt} = -\frac{u}{RC} - \frac{i}{C} [1 - \frac{(u_m - i_t R_s) i_o}{i_t^2 R_s}]
\]

(12)

Let the values of \( \frac{di}{dt} \) and \( \frac{du}{dt} \) in (12) equal to 0, then the equilibrium point is obtained as follows:

\[
V = \frac{u_m^2 u_{in}}{u_t^2 R},
\]

\[
I = \frac{u_m u_{in}}{u_t}
\]

(13)

The Jacobian matrix evaluated at this equilibrium point is derived as follows

\[
J = \begin{pmatrix}
-\frac{v^2 (u_m - u_s)}{L u_t R_s^2} & \frac{1}{L} & \frac{2(u_m - u_s)V}{u_t JRL}
\end{pmatrix}
\]

(14)

Substituting (13) into the jacobian matrix gets

\[
J = \begin{pmatrix}
-\frac{(u_m - u_s) u_t R}{L u_m} & \frac{u_m - 2u_s}{C u_t R}
\end{pmatrix}
\]

(15)

By solving the characteristic equation \( \text{det} [\lambda J - J] = 0 \), the following characteristic quasi-polynomial equation is obtained:

\[
f(\lambda) = (\lambda + \frac{(u_m - u_s) u_t R}{L u_m}) (\lambda + \frac{u_m}{C u_t R}) - \frac{u_m - 2 u_s}{L C u_m}
\]

\[
= \lambda^2 + \frac{(u_m - u_s) u_t R}{L u_m} + \frac{u_m}{C u_t R} \lambda + \frac{u_m - 2 u_s}{L C u_m}
\]

(16)

By performing a second-order Pad approximation, (16) can be written as follows:

\[
a_2 \lambda^2 + a_1 \lambda + a_0
\]

(17)

where \( a_2 = 1, a_1 = \frac{(u_m - u_s) u_t R}{L u_m} + \frac{u_m}{C u_t R} \) and \( a_0 = \frac{u_m - 2 u_s}{L C u_m} \).

It is clear that \( a_2 > 0 \). Since \( u_m = \frac{u_{ref} R_s}{R_e} \), \( u_m > 0 \) and \( u_m - u_s > 0 \) by combining with (4), thus \( a_1 > 0 \) and \( a_0 > 0 \) are obtained, which satisfies the Routh—Hurwitz criterion. Hence, the IEBC is stable.

V. SIMULATION AND EXPERIMENTAL RESULTS

Simulation and experimental results are used to demonstrate the superior performances of the IEBC. And a current-mode PID controller and the SEBC method are built for comparative study. The parameters of the boost converters designed in this research are as follows: \( u_m = 15 \, \text{V}, \, u_{ref} = 30 \, \text{V}, \, f_s = 2 \, \text{kHz}, \, L = 800 \, \mu\text{H}, \, C = 1000 \, \mu\text{F}, \, R = 10 \, \Omega \). The sample time is \( T_s = 10 \, \mu\text{s} \). The boost converters are designed for the case of a low-voltage high-current application using a lower switching frequency. In such a case, the steady-state errors, due to the neglection of energy losses, are more severe.

A. SIMULATION COMPARISON RESULTS

FIGURES 3 illustrate the simulation results of the boost converter using the IEBC in the entire operation range. From the figure, it is observed that the IEBC is capable of operating stably in the entire operation range (CCM, CDCM and DCM).

1. At \( t = 0 \), the system starts operation with \( R = 10 \, \Omega \) and \( u_{in} = 15 \, \text{V} \). As shown in FIGURES 3, the converter operates in CCM and \( u_o \) settles at the pre-set value 30 V with ripples limited within 0.8 V.

2. At \( t = 0.1 \, \text{s} \), the load is stepped to 27 \( \Omega \) abruptly. The converter changes its operation mode from CCM to CDCM. \( u_o \) jumps to 30.8 V due to such a sudden load step but soon settles to the pre-set value 30 V. The system does not become unstable.

3. At \( t = 0.15 \, \text{s} \), the converter enters the perfect DCM when the load is further changed to 47 \( \Omega \). As shown in FIGURES 3, the converter still operates stably and \( u_o \) keeps at the pre-set value.

To demonstrate the superior performances of the IEBC method, compared with the SEBC method and a
current-mode PID controller, the responses to load and input voltage disturbances of the converter are discussed as follows. By using the SISO tool box in MATLAB, the PID controller is established with the 382 Hz cross-over frequency and the 54.5 degrees phase margin. Step changes in loads, which is 10 Ω → 27 Ω → 47 Ω, are applied. At t = 0.22 s, the load is changed back to 10 Ω. Then step changes in the input voltage as 15 V → 18 V → 15 V are applied. FIGURES 4 and 5 show the responses of the converter to such load and input voltage step changes. The results demonstrate that, compared with the PID, the voltage peak overshoot Δu₀ is reduced from 2.2 V (using the PID) to 0.8 V (using the IEBC) under the case that the load steps from 10 Ω to 27 Ω. And the settling time t_settling is shortened to 4 ms (using the IEBC) from 13 ms (using the PID). These comparison results of the responses are summarized in TABLE 1, which shows that, compared with that of the PID, Δu₀ of the IEBC is significantly reduced and t_settling of the IEBC are significantly shortened.

Meanwhile, from FIGURES 4 and 5, it reveal that, under various operation conditions, u₀ using the SEBC cannot settle to the pre-set value but has certain steady-state errors u₀_steady after reaching steady states. For example, under operation conditions of R = 10 Ω, u₀ has the steady-state errors as 1.6 V to the pre-set value 30 V. TABLE 2 summarizes the steady-state value of u₀ and the steady-state errors Δu₀_steady using the SEBC under various operation conditions. In contrast, the results in FIGURES 4 and 5 demonstrate that, there are no steady-state errors in u₀ using the IEBC because of the function of the PI voltage controller.

B. EXPERIMENTAL COMPARISON RESULTS

Based on a dSPACE DS1104, an experimental boost converter prototype is constructed. The current and voltage are
TABLE 3. Experimental comparison results under cases of load and input voltage variations.

| Disturbance (R or u_in) | IEBC | SEBC | PID controller |
|------------------------|------|------|----------------|
|                         | Δu_o (V) | t_settling (ms) | Δu_o (V) | t_settling (ms) | Δu_o (V) | t_settling (ms) |
| 10 Ω → 27 Ω            | 0.9   | 4    | 0.8           | 16       | 2.2       | 13            |
| 27 Ω → 47 Ω            | 0.3   | 3    | 0.2           | 13       | 0.8       | 15            |
| 47 Ω → 10 Ω            | 1.2   | 5    | -1           | 11       | -3.2      | 15            |
| 15 V → 18 V            | 0.5   | 4    | 0.4           | 14       | 0.8       | 8             |
| 18 V → 15 V            | -0.4  | 3    | -0.4         | 12       | -1        | 8             |

TABLE 4. The experimental results of u_o and Δu_steady with the SEBC under various operation conditions.

| Operation conditions (u_in/R) | 15 V/10 Ω | 15 V/27 Ω | 15 V/47 Ω | 18 V/10 Ω |
|-------------------------------|------------|------------|------------|------------|
| u_o (V)                       | 28.4       | 29.2       | 29.4       | 28.8       |
| Δu_steady (V)                 | 1.6        | 0.8        | 0.6        | 1.2        |

FIGURE 7. The experimental results of the responses of u_o using the proposed IEBC to input voltage variations. a: From 15 V to 18 V; b: From 18 V to 15 V.

measured by HALL sensors (CHV-25P and CHB-25NP/6A), respectively. The gate drivers of the IGBT are SKYPER 32R. The experimental results using the IEBC, the SEBC and the PID controllers are shown in FIGURES 6-11. In order to provide a intuitive and clear display of steady-state errors, the experiment tests are made under the disturbances in both loads and source voltages.

The comparative results of FIGURES 6-11 reveal the static performance under various operation conditions and the dynamic responses to load and input voltage step changes. TABLE 3 summarizes the comparison results of Δu_o and t_settling under all the dynamic cases. From FIGURES 6, 7, 10, 11 and TABLE 3, it is observed that the experiments get consistent results with the simulation, which show that Δu_o using the IEBC is significantly reduced and t_settling using the IEBC is significantly shorter compared with that of the PID controller. And from FIGURES 8 and 9, it is observed that although Δu_o using the SEBC is reduced and t_settling is shortened by comparing with that of the PID, yet there are certain steady-state errors Δu_steady after reaching steady states under various operation conditions. FIGURE 8a illustrate that u_o under operation conditions of R = 10 Ω and R = 27 Ω has steady-state errors as 1.6 V and 0.8 V to the pre-set value 30 V, respectively. The experimental results of u_o and Δu_steady using the SEBC under various operation conditions is summarized in TABLE 4. It is observed from TABLE 4 that, using the SEBC, steady-state errors are
produced due to the negligence of circuit energy losses. The differences of $\Delta u_{\text{steady}}$ under various operation conditions are due to the different value of the energy losses (mainly the energy loss of the inductor parasitic DC resistance).

VI. CONCLUSION

In this research, the IEBC method has been proposed and implemented effectively for controlling boost converters. On the basis of the control principle of the previously developed control methods based on the conservation of energy in circuits, in the proposed control method, a PI voltage controller is added, as a result, the output voltage steady-state errors due to the negligence of circuit energy losses is removed. Furthermore, the stability of the converter controlled by the IEBC has been proved using the Routh-Hurwitz criterion.

Simulation and experimental results demonstrate the proposed IEBC method can settle the output voltage to a pre-set value though circuit energy losses are not considered. Meanwhile, the comparison to the PID controller reveals that the IEBC keeps the advantage of the previously developed control methods based on the conservation of energy in circuits, which is superior dynamic performance, in terms of smaller voltage shoots and shorter settling times under the step changes of input voltage and load current. These results demonstrate that, using the IEBC, accurate static and fast dynamic performances are achieved even though circuit energy losses are neglected due to the complexity in their measurement and calculation.

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