Combined feedback–feedforward control of Ćuk CCM converter for achieving fast transient response

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Abstract
The Ćuk converters operating in continuous conduction mode (CCM) can be preferred in applications such as microprocessor power delivery and pulsed load because these circuits have advantages of being able to step up/down, a small number of power components, and low input/output current ripples. However, they show poor transient performance due to right-half-plane-zeros (RHPZs) in the closed-loop transfer function of the Ćuk CCM converter. To enhance the transient response, a combined feedback–feedforward control for the Ćuk CCM converter is proposed. The proposed control scheme comprises a feedback control signal based on a Lyapunov function and a duty-ratio feedforward control signal. A Lyapunov-function-based controller (LBC) achieves fast dynamic response even under large-signal variations from the operating point. The duty ratio feedforward controller (DFFC) is developed to predict the effect of the disturbances and compensate it, while alleviating the burden of LBC. The proposed control logic makes the closed-loop system of the Ćuk CCM converter globally exponentially stable and thus provides a fast transient response even under large-signal variations. To construct the proposed controller, the authors make use of the large-signal averaged model of the Ćuk CCM converter, and consider the parasitic elements. To verify the proposed control scheme, numerical simulations and experimental tests are conducted.

1 | INTRODUCTION

A Ćuk converter, which is a widely used dc/dc converter, provides an output voltage less than or greater than the input voltage depending on the duty ratio. Also, it has low input and output current ripples due to the inherited inductors at the input and output sides. Furthermore, the Ćuk converter is more efficient with lower current ripple when it operates in (CCM) than when it operates in discontinuous conduction mode (DCM). Thus, the Ćuk CCM converter can be preferred in applications such as microprocessor power delivery and pulsed load. However, the Ćuk CCM converter shows poor transient response due to RHPZs in its transfer function [1, 2]. Therefore, the output regulation of the Ćuk CCM converter is a difficult challenge.

In control design of the Ćuk converter operating in CCM, the use of its small signal model around a fixed operating point has been popular due to its simplicity [3, 4]. Using this linearised model, the control that has been applied to Ćuk converters includes proportional-integral (PI) control [5], PI fuzzy control [6], PI and sliding mode control (SMC) [7, 8], cascaded PI-SMC [9], and optimal control via a jump parameter technique [10]. However, the linearised model cannot reflect the Ćuk CCM converter completely, especially when large variations from the operating point occur. For this reason, these control schemes show poor transient performance caused by large signal variations. Variable structure control (VSC) is a robust control technique, which has low sensitivity to parameter variations and unmodelled dynamics [11]. Nevertheless, in applying VSC to switching power converters, the output voltage error in the steady state, variation of switching frequency, and chattering are still problems that need to be solved. One-cycle control is a non-linear control method, which has the ability to follow the control reference instantly [12]. However, its input stage may exhibit an oscillation as a result of Neimark–Sacker bifurcation. The oscillation increases the voltage stress on the input stage switch. To reduce the oscillation, [13] proposed to use a time-delay feedback controller and correctly chose the delayed time and feedback gain.

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A Lyapunov function-based control (LBC) scheme generally guarantees globally asymptotically stability of the closed-loop system while achieving excellent dynamic response [14–16]. For this control scheme, a control signal is constructed to ensure that the total system energy is constantly dissipated and thus the tracking error of the control system asymptotically converges to zero. However, no published research has considered compensating for the use of the LBC for Ćuk CCM converters. Furthermore, the use of the LBC only would not achieve a fast transient response because it adopts feedback signal to implement its control input, and this feedback signal would generate the inevitable delay in control. Therefore, the LBC should be combined with other types of control techniques.

Herein, the authors propose a combined feedback–feedforward control for a Ćuk CCM converter under large variations of operating points. The proposed control scheme is composed of a feedback control signal based on a Lyapunov function and a duty-ratio feedforward control signal, which is constructed based on the large signal dynamic model. The Lyapunov function-based controller (LBC) guarantees global exponential stability and exhibits a fast dynamic response even under large-signal variations from the operating point. This controller is supplemented with duty-ratio in the feedforward loop that helps the regulation of the output voltage. Moreover, the authors deal with parasitic components to build the dynamic model and proposed control scheme of the Ćuk CCM converter. They performed experimental tests to demonstrate the remarkable tracking precision of the proposed control scheme.

Section 2 introduces the modelling of the Ćuk CCM converter with parasitic components. Section 3 proposes a controller scheme for the Ćuk CCM converter and shows corresponding stability analysis. Section 4 presents the simulation and experimental results, and Section 5 provides the conclusion.

## 2 | MODELLING OF THE ĆUK CCM CONVERTER WITH PARASITIC COMPONENTS

The circuit of a Ćuk CCM converter (Figure 1) consists of input voltage source $V_i$, inductor $L_1$, controllable switch $S_1$, capacitor $C_1$, transformer $T$ with turns ratio $n = N_p/N_o$, capacitor $C_2$, diode $D_1$, inductor $L_2$, capacitor $C_3$, and output load resistance $R_o$. The parasitic components are presented as the direct current resistance $r_1$ of $L_1$ and $r_2$ of $L_2$ [17]. The equivalent series resistances of used capacitors are very small, so they are neglected here.

The circuit is designed to operate in CCM, and experiences two phases in each switching period: (1) switch turned on and diode turned off; (2) switch turned off and diode turned on (Figures 2 and 3). When $S_1$ is turned on and $D_1$ is turned off, the current through $L_1$ increases and $L_1$ stores energy; $C_1$ is discharged and $T$ transmits the energy to the secondary part of the circuit; $C_2$ is also discharged and the energy is transmitted to the output stage formed by $L_2$, $C_3$, and $R_o$. When $S_1$ is turned off and $D_1$ is turned on, the currents of both $L_1$ and $L_2$ decrease, and $C_1$ and $C_2$ are charged by the energy stored in $L_1$.

By applying Kirchhoff’s voltage law and Kirchhoff’s current law, the state-space equations are obtained as follows.

### Phase 1 (switch turned-on):

$$L_1 \frac{di_1}{dt} = -r_1 i_1 + V_i,$$

$$L_2 \frac{di_2}{dt} = -r_2 i_2 + v_{12} - v_o,$$

$$C_2 \frac{dv_{12}}{dt} = -i_2,$$

### Phase 2 (switch turned-off):

$$L_1 \frac{di_1}{dt} = -r_1 i_1 + V_i,$$

$$L_2 \frac{di_2}{dt} = -r_2 i_2 + v_{12} - v_o,$$

$$C_2 \frac{dv_{12}}{dt} = -i_2.$$

![Figure 1](image1.png)  
**Figure 1** Circuit diagram of the Ćuk continuous conduction mode (CCM) converter with parasitic components. $i_1$ is the current through $L_1$, $i_2$ is the current through $L_2$, $v_1$ is the voltage across $C_1$, $v_2$ is the voltage across $C_2$, and $v_o$ is the output voltage.

![Figure 2](image2.png)  
**Figure 2** Current and voltage waveforms of the Ćuk continuous conduction mode (CCM) converter.
where \( i_1 \) is the current through \( L_1 \), \( i_2 \) is the current through \( L_2 \); \( v_{12} = n v_1 + v_2 \), where \( v_1 \) is the voltage across \( C_1 \), \( v_2 \) is the voltages across \( C_2 \); \( C_{12} \) is \( C_1 C_2 / (C_1 + n^2 C_2) \); \( v_o \) is the output voltage.

Using the average modelling technique, the averaged model of the Cuk CCM converter can be obtained as

\[
L_1 \frac{di_1}{dt} = -r_1 i_1 - \frac{v_{12}}{n} + V_i, \\
L_2 \frac{di_2}{dt} = -r_2 i_2 - v_o, \\
C_{12} \frac{dv_{12}}{dt} = \frac{i_1}{n}, \\
C_o \frac{dv_o}{dt} = i_2 - \frac{v_o}{R_o},
\]

where \( 0 < u < 1 \) is the control duty and \( i_1, i_2, v_{12}, \) and \( v_o \) are averaged values of \( i_1, i_2, v_{12}, \) and \( v_o \), respectively, for one switching period.

### 3 | COMBINED FEEDBACK–FEEDFORWARD CONTROLLER DESIGN

The purpose of controlling the Cuk CCM converter is to keep \( v_o \) track \( V_o \). To enhance the dynamic response even under large-signal variations from the operating point, the authors propose an LBC. To reduce the burden that this controller imposes, a duty-ratio feedforward controller (DFFC) is also proposed and supplemented in the feedforward loop. Moreover, the global exponential stability of the Cuk CCM converter system can be ensured. In this section, the feedback plus feedforward control scheme is first derived, then, the stability of this closed-loop control system is analysed.

#### 3.1 | Duty-ratio feedforward controller

The desired current of \( L_1 \) and \( L_2 \) as \( I_1 \) and \( I_2 \), the desired current of \( C_{12} \) as \( V_{12} \), and the desired output voltage as \( V_o \) are first defined. Assuming that the Cuk CCM converter operates in the steady state, substituting \( I_1, I_2, V_{12} \) and \( V_o \) into \( i_1, i_2, v_{12} \) and \( v_o \), and setting \( \frac{di_1}{dt} = 0, \frac{di_2}{dt} = 0, \frac{dv_{12}}{dt} = 0 \) and \( \frac{dv_o}{dt} = 0 \) in the average model, we have

\[
r_1 I_1 + (1 - u_{ff}) \frac{V_{12}}{n} = V_i, \\
-r_2 I_2 + u_{ff} V_{12} = V_o,
\]
\[(1 - \text{uff}) \frac{I_1}{n} = \text{uff} I_2, \quad (15)\]

\[I_2 = \frac{V_o}{R_o}, \quad (16)\]

where \(\text{uff}\) is duty-ratio feedforward control input.

Substituting Equation (16) into Equations (14) and (15) yields

\[V_{12} = \frac{(r_2 + R_o)V_o}{\text{uff} R_o}, \quad (17)\]

\[I_1 = \frac{n\text{uff} V_o}{(1 - \text{uff}) R_o}. \quad (18)\]

Then substituting Equations (17) and (18) into Equation (13) yields

\[
\frac{n r_1 \text{uff} V_o}{(1 - \text{uff}) R_o} + \frac{(1 - \text{uff})(r_2 + R_o)V_o}{n \text{uff} R_o} = V_i, \quad (19)
\]

which in turn can be arranged as

\[
\left(\frac{n^2 r_1 + r_2 + R_o V_o + V_i}{n R_o}\right) u_{ff}^2
- 2 \left(\frac{r_2 + R_o}{n R_o} V_o + \frac{V_i}{2}\right) u_{ff} + \left(\frac{r_2 + R_o}{n R_o} V_o\right) = 0. \quad (20)
\]

\(u_{ff}\) can then be calculated from Equation (20) as

\[u_{ff} = \frac{G_1 \pm G_2}{G_3}, \quad (21)\]

where

\[G_1 = \left(\frac{r_2 + R_o}{n R_o} V_o + \frac{V_i}{2}\right), \quad (22)\]

\[G_2 = \sqrt{\left(\frac{n^2 r_1 + r_2 + R_o V_o + V_i}{n R_o}\right)^2 - \left(\frac{n^2 r_1 + r_2 + R_o V_o + V_i}{n R_o}\right) \left(\frac{r_2 + R_o}{n R_o} V_o\right)}, \quad (23)\]

\[G_3 = \left(n^2 r_1 + r_2 + R_o V_o + V_i\right). \quad (24)\]

Between the two values of \(u_{ff}\), the one with the plus sign makes the inductor current become too large \((u_{ff} > 1)\). Thus, the following feedforward signal is used

\[u_{ff} = \frac{G_1 - G_2}{G_3}. \quad (25)\]

\(u_{ff}\) predicts the effect of the disturbances and compensates it, thus it significantly improves the transient response. In practice, \(u_{ff}\) itself cannot very accurately determine \(v_o\) of the Cuk CCM converter because of converter parameters deviation, but it alleviates the burden of the LBC. Therefore, a high gain is not required in the feedback loop.

### 3.2 Lyapunov function-based feedback controller

In constructing the LBC, \(u_{ff}\) is first applied to the averaged model and the error dynamics of the Cuk CCM converter derived. Defining the inductor current errors as \(e_i = i_1 - I_1\) and \(e_i = i_2 - I_2\), the capacitor error as \(e_{c_{v_{12}}} = \bar{v}_{12} - V_{12}\), the output voltage error as \(e_v = \bar{v}_o - V_o\) and the feedback control term as \(u_{fb} = u - u_{ff}\). Substituting \(e_i, e_{v_{12}}, e_{c_{v_{12}}}, e_v\) and \(u_{fb}\) into Equations (9)–(12), the following is obtained

\[L_1 e_i = -r_1 e_i - \frac{1 - u_{ff}}{n} e_{v_{12}} + \frac{V_{12}}{n} u_{fb}, \quad (26)\]

\[L_2 e_{v_{12}} = -r_2 e_{v_{12}} + u_{ff} e_{v_{12}} - e_v + (e_v - V_{12}) u_{fb}, \quad (27)\]

\[C_{12} e_{v_{12}} = -\frac{1 - u_{ff}}{n} e_i - u_{ff} e_{v_{12}} - \left(\frac{e_i}{n} + e_{v_{12}} + \frac{I_1}{n} + I_2\right) u_{fb}, \quad (28)\]

\[C_{3} e_v = e_v - \frac{e_{c_v}}{R_o}. \quad (29)\]

The error dynamics in Equations (26)–(29) can be compactly represented as

\[\dot{e} = Ae + (Be + b)u_{fb}, \quad (30)\]

where

\[e = \begin{bmatrix} e_i \\ e_{v_{12}} \\ e_v \\ e_{c_v} \end{bmatrix}, \quad (31)\]
Asymptotically stable. Moreover, the system becomes exponentially stable if
\[ V \cdot e \leq - \frac{1}{n} \]
where \( V \) is negative definite, then the system is globally asymptotically stable.

According to Lyapunov's direct method, if a radially unbounded scalar function \( V(x) \) is positive definite and \( V(x) \) is negative definite, then the system is globally asymptotically stable. Moreover, the system becomes exponentially stable if \( V(x) \) satisfies \( a_1 \|x\|^2 \leq V(x) \leq a_2 \|x\|^2 \) and \( V(x) \leq -a_3 \|x\|^2 \) where \( c_1 \), \( c_2 \) and \( c_3 \) are strictly positive constants.

If a Lyapunov function is chosen as the energy stored in the cuk circuit, the following is obtained
\[
V(e) = \frac{1}{2n} L_1 e_1^2 + \frac{1}{2} L_2 e_2^2 + \frac{1}{2} C_{12} e_{v_{12}}^2 + \frac{1}{2} C_3 e_3^2 + \frac{1}{2} \]
where \( P = \text{diag}[L_1/n \quad L_2 \quad C_{12} \quad C_3] \), its time derivative can be computed:
\[
\dot{V}(e) = \frac{1}{2} e^T \dot{P}e + \frac{1}{2} e^T (A^T P + P A)e + \frac{1}{2} \mu_{f} e^T (B^T P + P B)e + u_{f/b} b^T Pe.
\]

Defining
\[
Q = -\frac{1}{2} (A^T P + P A) = \begin{bmatrix} \frac{1}{n} & 0 & 0 & 0 \\ 0 & r_2 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{R_c} \\ 0 & 0 & 0 & \frac{1}{R_c} \end{bmatrix} \geq 0.
\]

and using \( e^T (B^T P + P B)e = 0 \), \( V \) becomes
\[
\dot{V}(e) = -e^T Qe + u_{f/b} b^T Pe,
\]

When the LBC is chosen as
\[
u_{f/b} = -a b^T Pe,
\]

where \( a > 0 \), the derivative of the Lyapunov function becomes
\[
\dot{V}(e) = -e^T Qe - a(b^T Pe)^T (b^T Pe)
\]
\[
= -e^T \{ Q + a (b^T P)^T (b^T P) \} e < 0
\]
where
\[
(b^T P)^T (b^T P) = \begin{bmatrix} \left( \frac{V_{12}}{n^2} \right)^2 & 0 & 0 & 0 \\ 0 & V_{12}^2 & 0 & 0 \\ 0 & 0 & \left( \frac{I_1 + n I_2}{n} \right)^2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \geq 0.
\]

Note that \( Q + a (b^T P)^T (b^T P) \) is positive definite matrix, even though third diagonal term in \( Q \) and fourth diagonal term in \( (b^T P)^T (b^T P) \) are both zero.

Using Lyapunov's direct method, it can be concluded that \( e_1 \to 0 \), \( e_2 \to 0 \), \( e_{v_{12}} \to 0 \) and \( e_{v_{3}} \to 0 \) as \( t \to \infty \). Moreover, from Equations (35) and (40), \( V(x) \) and \( \dot{V}(x) \) hold that
\[
\frac{1}{2} \lambda_{\min}(P) \|e\|^2 \leq V(e) \leq \frac{1}{2} \lambda_{\max}(P) \|e\|^2 \quad \text{and} \quad \dot{V}(e) \leq -\lambda_{\min}(Q + a (b^T P)^T (b^T P)) \|e\|^2.
\]

Thus, we can conclude that the closed-loop system of the cuk CCM converter becomes globally exponentially stable.

The complete control input is obtained from Equations (25) and (39) as
\[
u = u_{f/f} + u_{f/b} = \frac{G_1 - G_2}{G_3} - a b^T Pe.
\]
The proposed control scheme consists of two control components: the DFFC term that predicts the effect of the disturbances and compensates it while alleviating the burden imposed by the LBC, and the LBC term that drives the closed-loop system to become exponentially stable.

Remark 1 The proposed control strategy requires more sensors to measure the current flowing through the inductor and voltage across the capacitor. However, its control accuracy is very high compared to the control accuracy when conventional controllers are used. In the data centre application, the backup battery unit should supply the constant voltage to the load under the load variation at the steady state. Thus, in the data centre application, the proposed control strategy is needed for the converters, which determine the output voltage of the backup battery unit. Also, the pulsed voltage should be developed to generate the electric field in the electroporation of the skin. In that case, the converter should generate the accurately controlled pulsed voltage for the skin electroporation device, because a very small voltage surge is able to present an electric shock to the patient. Therefore, the proposed control strategy is also required for the converter used in the skin electroporation application.

TABLE 2 Specification of the transformer

| Property                      | Value                   |
|-------------------------------|-------------------------|
| Transformer size              | PQ3535                  |
| (Length/width/height)         | (35.5/39.1/37.6 mm)     |
| Core shape                    | 0T43535UG, Magnetetics  |
| Core material                 | Ferrite T material, Magnetetics |
| Turns ratio, n                | 1                       |
| Primary winding, N_P          | 15 turns, 16AWG × 2     |
| Secondary winding, N_S        | 15 turns, 16AWG         |
| Magnetic inductance           | 67 μH                   |
| Primary-side                  | 0.42 μH                 |
| Leakage inductance            |                         |

FIGURE 4 Prototype of the Ćuk continuous conduction mode (CCM) converter

TABLE 1 Parameters and components used in simulation and experimental platform

| Parameters                  | Symbols | Value                        |
|-----------------------------|---------|------------------------------|
| Switching frequency         | f_s     | 50 kHz                       |
| Transformer turns ratio     | N_p / N_s | 15:15                        |
| Primary inductance          | L_1     | 200 μH                       |
| Secondary inductance        | L_2     | 200 μH                       |
| Primary capacitance         | C_1     | 20 μF                        |
| Secondary capacitance       | C_2     | 20 μF                        |
| Output capacitance          | C_o     | 10 μF                        |
| Primary inductor resistance | r_1     | 0.05 Ω                       |
| Secondary inductor resistance| r_s    | 0.05 Ω                       |
| Output load                 | R_o     | 20 Ω                         |
| Components                  | Symbols | Part number                  |
| MOSFET                      | S_1     | IPP200N25N3G                 |
| Diode                       | D_1     | C2D05120 A                   |
| Gate driver                 |         | HCPL-3120                    |
| Current sensor              |         | L18P010D15                   |
| Op amp                      |         | LM358                        |

FIGURE 5 Total system configuration of the Ćuk CCM converter
4 | SIMULATION AND EXPERIMENT

To examine the transient performance of the Ćuk CCM converter under variations of $V_o$ and $R_o$, simulations in PSIM V11.1.7 were first conducted. Then experiments were performed using a prototype of the Ćuk CCM converter (Figure 4) implemented on a TMS320F28377D microcontroller. The major parameters and components of the Ćuk CCM converter are listed in Tables 1 and 2. The total system configuration is shown in Figure 5.

**Figure 6** Simulation waveforms of the Ćuk CCM converter under variations of $V_o$: (a) VC; (b) CC; (c) SC; (d) proposed control scheme

**Figure 7** Simulation waveforms of the Ćuk CCM converter under variations of $R_o$: (a) VC; (b) CC; (c) SC; (d) proposed control scheme
TABLE 3 Performance comparison of simulation results

| $V_o$ Variation | $R_o$ Variation |
|-----------------|-----------------|
| $t_r$ | $t_s$ | $PO$ | $t_r$ | $t_s$ |
| VC | $0\%$ | 9.3 ms | 18.6 ms | 17.3% | 8.9 ms |
| CC | 1.5% | 3.4 ms | 9.2 ms | 15.3% | 13.5 ms |
| SC | 66.9% | 0.3 ms | 7.8 ms | 18.0% | 8.2 ms |
| LBC | $0\%$ | 0.7 ms | 3.0 ms | 10.1% | 2.4 ms |

Abbreviation: CC, current mode controller; LBC, Lyapunov-function-based controller; PO, percentage overshoot; SC, sliding mode controller; $t_r$ is the rising time; $t_s$ is the settling time; VC, voltage mode controller.

4.1 Simulation

Simulations were conducted to evaluate the transient performance of the Cuk CCM converter under variations of $V_o$ and $R_o$. $V_o$ changed from 15 V to 24 V under $V_i = 12$ V and $R_o = 20$ Ω. For comparison, a voltage mode controller (VC), a current mode controller (CC) and a sliding mode controller (SC) were also simulated.

The different controllers produce different patterns of $v_o$ tracking $V_o$. Under variations of $V_{0,v}$ when VC was utilised, $v_o$ tracked $V_o$ rather slowly (Figure 6a). When CC was utilised, $v_o$ tracked $V_o$ faster than VC did, but the settling time was too long (Figure 6b). When SC was used, $v_o$ showed the large overshoot and very small oscillation before settling to $V_o$ (Figure 6c), but the settling time became faster than that in Figures 6(a) and (b). When the Lyapunov function-based feedback controller (LBC) was adopted, $v_o$ tracked $V_o$ with a significantly reduced overshoot and settling time (Figure 6d). Simulation waveforms of $v_o$ and $V_o$ under output load variations (Figure 7) were similar to those under desired output voltage variations.

To evaluate the performance of the proposed controller, the rising time, settling time, and percentage overshoot (PO) of the transient responses were examined under output voltage variation conditions. Also, the PO and settling time were also measured under output load variation conditions. The proposed controller exhibits the faster response compared with other controllers (Table 3).

4.2 Experiment

Experiments were also carried out to evaluate the transient performance of the Cuk CCM converter under variations of $V_o$ and $R_o$. $V_o$ alternated between 15 V and 24 V and $R_o$ alternated between 10 Ω to 20 Ω; both patterns ran at 2.5 Hz.

The observed tracking results were similar to the simulated results. Under desired output voltage variations, when VC was used, $v_o$ tracked $V_o$ rather slowly (Figure 8a). When CC was used, $v_o$ tracked $V_o$ faster than VC, but the settling time was too long (Figure 8b). Even when the controller gain was increased to improve tracking during transient periods, the transient response was not improved noticeably. When SC was used, $v_o$ tracked $V_o$ with an acceptably short time (Figure 8c). When the LBC was applied, its global exponential stability allowed $v_o$ to track $V_o$ well even during the transient period.

FIGURE 8 Experimental waveforms of the Cuk CCM converter under variations of $V_o$: (a) VC; (b) CC; (c) SC; (d) proposed control scheme
Experimental results were also analysed in terms of the rising time, settling time, and PO of the transient responses under output voltage and load variation conditions (Table 4). The proposed controller exhibits a faster response compared with other controllers.

5 | CONCLUSION

A combined feedback–feedforward control strategy for the Čuk CCM converter is presented herein. The LBC ensures global exponential stability of the Čuk CCM converter and thus provides superior transient performance even under large-signal variations; the DFFC is supplemented to predict the effect of the disturbances and compensate it while reducing the burden of LBC, thereby illustrating that the proposed control strategy is suitable for applications such as fast processors and pulsed loads. In the proposed control scheme, the authors used the large-signal averaged model of the Čuk CCM converter while considering the parasitic components. They conducted numerical simulations and experimental tests to validate the superior performance of the proposed control scheme.

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