Analysis and Modeling of Transformerless High Gain Buck-Boost DC-DC Converters

Vu Tran
Department of Electrical and Computer Engineering,
University of Massachusetts
Lowell, USA

Mufeed Mahd
Department of Electrical and Computer Engineering,
University of Massachusetts
Lowell, USA

***Abstract*—This paper proposes a transfomerless switched capacitor buck boost converter that is based on a traditional buck boost topology. The proposed converter achieves high voltage gain and higher efficiency when compared to the conventional buck boost converter. The average model based on state-space description is analyzed in the paper. The simulation results are presented to confirm the capability of the converter to generate high-voltage ratios. The proposed converter is suitable for applications which require high step-up DC-DC converters such as DC micro-grids and solar electrical energy.**

Keywords—buck-boost converter; state-space description; averagedmodel; simulation.

I. INTRODUCTION

In recent years, extensive use of electrical equipment has increased rapidly. As the demand for power is significantly increasing, renewable energy sources have received a lot of attention as an alternatives way of generating directly electricity. Using renewable energy system can eliminate harmful emissions from polluting the environment while also offering inexhaustible resources of primary energy. There are many sources of renewable energy, such as solar energy, wind turbines, and fuel cells. However, fuel cells and solar cells have low output voltage [1], [2], [3]. Thus, a high efficiency and step-up DC-DC converter is desired in the power conversion systems to increase the voltage supplied to the grid or be compatible in other applications.

Theoretically, the conventional boost DC-DC converter can provide a very high voltage gain by using an extremely high duty cycle. However in actual application, for a very high duty cycle, the voltage gain is reduced because of the non ideal elements in circuits such as inductors, capacitors, switches, diodes, etc. Moreover, extremely high duty cycle can create electromagnetic interference [4] [5], which might diminish the efficiency of the operation of circuits.

Several researchers have designed models that can achieve high voltage gain. Step-up converter using transformer is presented in [6] [7] [8]. They can control the voltage gain by creating a conversion ratio function of the duty ratio and the transformer turns ratio. However, its efficiency will dramatically degrade by losses associated with the leakage inductance, and may cause power losses and heat dissipation problems [9] [10]. Another disadvantage is the size and weight of the transformer, which is often desired to be as compact as possible. In [4] [9] [11] [12] [13] [14] [15], high step up converters using coupled-inductor technique is introduced. Coupled inductors were modeled to provide a high step up voltage and reduce the switch voltage stress, and the reverse recovery problem of the diode was reduced. However, the electromagnetic interference and efficiency is reduced due to the leakage inductance [16] [14], and the designing of the converter is relatively complex [17].

High gain can also be achieved by cascading two or more step-up converter stages [16] [17] [18] [19]. Extreme duty cycle can be avoided by setting an intermediate voltage between the two stages. However, additional components are required, the control circuit is more sophisticated and the total efficiency is reduced [5] [20].

An integration of a switched-capacitor (SC) circuit with a boost converter is proposed in [1] [14] [21] [22]. The voltage gain can be improved by increasing number of charge pumps. However, the voltage gain will be reduced significantly if the input voltage is as small as the voltage dropping on two diodes [23]. The other limitation is charge pump itself, if the switching frequency is not sufficiently fast, the capacitors will block the DC current, making the system less efficiency.

In order to deal with low-voltage photovoltaic (PV) arrays and the required higher voltage of the grid, a novel buck boost converter is proposed based on the traditional buck boost converter. The model is simple, which includes only one inductor, two capacitors and four power switches and two diodes, and thus, it is very easy to implement. With this model, we are able to save the wasted energy in the *OFF* state of the switches used in the circuit. Therefore, the proposed converter can not only provide with high voltage gain, but also reduce the extremely high duty cycles of power switches, and increase the efficiency of the converter.

The paper is organized as follow. The new circuit schematic is described in Section II. Its steady-state topologies are analyzed by using state-space approach in Section III. Section IV presents the simulation results for averaged model and pulse width modulation (PWM) model. Conclusion is presented in Section V.

II. CIRCUIT DESCRIPTION

The traditional buck boost converter is presented in Fig. 1. When the switch is *ON*, the energy from the power supply (PV panel) V_g is stored in the inductor. When the switch is

OFF, it is easy to see that this energy is wasted. For example, if the duty cycle is 60%, at least 100% - 60% = 40% of power is wasted. The new model of buck boost converter is proposed to save that wasted energy, which is illustrated in Fig. 2.

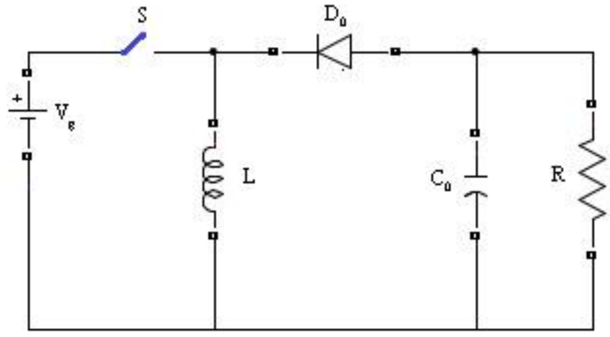


Fig. 1. Traditional buck boost converter

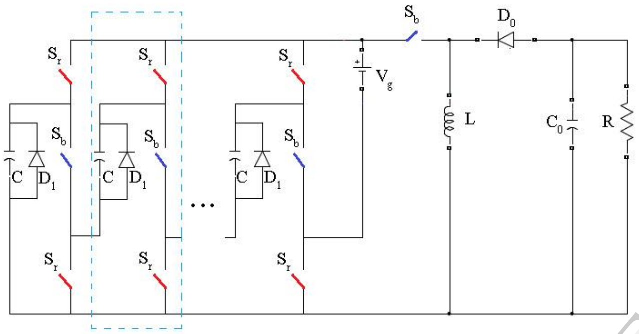


Fig. 2. Switched-capacitor buck-boost converter with high voltage gain

In the *OFF* state, energy from power source is stored in capacitors *C*, then, in the *ON* state, it is pushed back to the circuit. Hence, the energy is saved and the efficiency is improved when compared with that of the traditional buck boost converter.

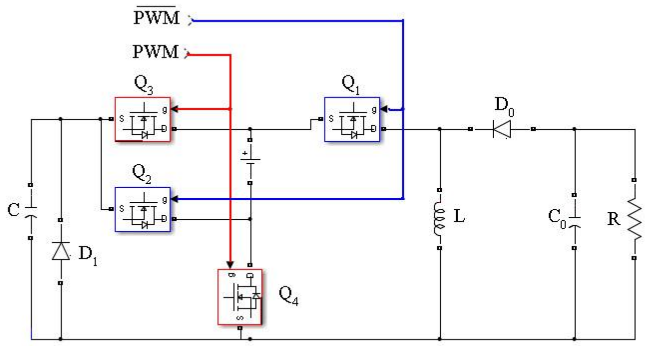


Fig. 3. One stage switched-capacitor buck-boost converter

The model can be extended to increase the voltage gain by simply increasing the stage, which includes the capacitor *C*, diode D_1, switch S_b, and two switches S_r. For simplicity, we consider the case of one stage as in Fig. 3. Adding more stages can be treated similarly.

In *OFF* state, the circuit is modeled in Fig. 4. Two switches Q_1 and Q_2 are *OFF*, Q_3 and Q_4 are *ON*, the current flows through Q_3 and Q_4, energy from power source $V_g$is charged for the capacitor *C*. Diode D_0 is forward biased, which allows the current to go through the inductor to charge for capacitor C_0 and provide for the output simultaneously.

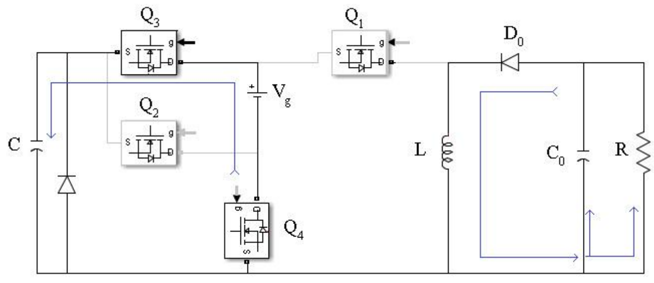


Fig. 4. Switching topology of proposed circuit in OFF state

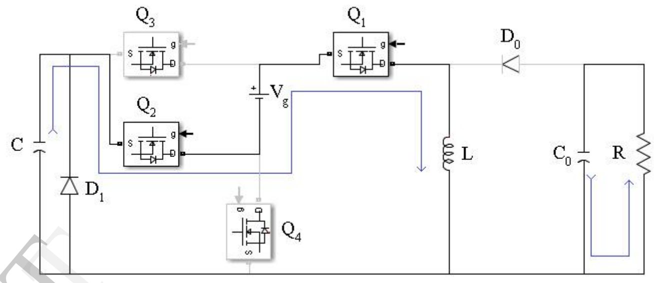


Fig. 5. Switching topology of proposed circuit in ON state

Fig. 5 describes the circuit in the *ON* state. Two switches Q_1 and Q_2 are *ON*, Q_3 and Q_4 are *OFF*. Voltage source V_g combined with the voltage on *C* create a higher voltage, which will be pushed to the inductor *L*. More energy will be stored in the inductor compared with the traditional buck-boost converter. Diode D_1 acts as a free-wheeling diode.

III. STATE-SPACE MODEL OF THE SWITCHED CAPACITOR BUCK-BOOST CONVERTER

In this section, the equivalent circuits of traditional model and proposed model are analyzed for *ON* and *OFF* states. In both models, when the diode operates in forward bias region, it is replaced by a voltage source V_D. When it is in reverse biasregion, it blocks thecurrent, hence it is replaced by an open circuit. MOSFET switches are controlled by PWM signals. When MOSFET is *OFF*, it works like an open circuit. When it is *ON*, it works like a resistor with the resistance R_{ON}.

Let the duty cycle of the PWM signal be *D* and the DC voltage supply be V_g. The input is $u = [V_g V_D]^T$.

A. *State-space description of the traditional model*

Let the state of the traditional buck-boost converter be

$$X_T = [I_L V_0]^T.$$

In *ON* state, the equivalent circuit is described in Fig. 6

Apply *the* KVL equations for this circuit, we have

$$L\frac{dI_L}{dt} = V_g - (R_{ON} + R_L)I_L$$

$$C_0\frac{dV_0}{dt}=-\frac{V_0}{R}$$

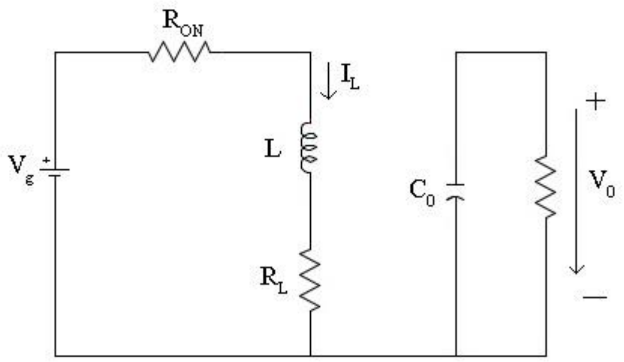


Fig. 6. Traditional buck boost converter's equivalent circuit in *ON* state

The state-space description of the circuit can be represented as $X'_T(ON)=A_{01}X_T+B_{01}u$

In which,

$$A_{01}=\begin{bmatrix}-\frac{R_{ON}+R_L}{L} & 0\\ 0 & -\frac{1}{RC_0}\end{bmatrix}$$

And

$$B_{01}=\begin{bmatrix}\frac{1}{L} & 0\\ 0 & 0\end{bmatrix}$$

In *OFF* state, the equivalent circuit is described in Fig. 7

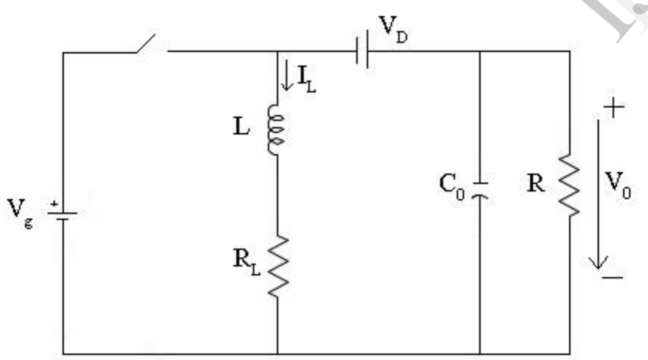


Fig. 7. Traditional buck boost converter's equivalent circuit in *OFF* state

Similarly, applying the KVL equations for this circuit yields

$$L\frac{dI_L}{dt}=V_0-V_D-R_LI_L$$

$$C_0\frac{dV_0}{dt}=-\frac{V_0}{R}-I_L$$

The state-space description of the circuit can be represented as $X'_T(OFF)=A_{02}X_T+B_{02}u$

In which,

$$A_{02}=\begin{bmatrix}-\frac{R_L}{L} & \frac{1}{L}\\ -\frac{1}{C_0} & -\frac{1}{RC_0}\end{bmatrix}$$

and

$$B_{02}=\begin{bmatrix}0 & -\frac{1}{L}\\ 0 & 0\end{bmatrix}$$

Under the assumption of high frequency and ideal switching, the average model can be described as

$$X_T=DX_T(ON)+(1-D)X_T(OFF)$$

$$X'_T=(DA_{01}+(1-D)A_{02})X_T+(DB_{01}+(1-D)B_{02})u \qquad (1)$$

At steady state, the state of the circuits can be consideredstable, or $X'(t)=0$. Solve the equations (1) with the conditionof steady state $X'_T=0$, we have the state of the circuit X_T.

$$X_T=-(DA_{01}+(1-D)A_{02})^{-1}(DB_{01}+(1-D)B_{02})u \qquad (2)$$

From equation (1) we have the output voltage V_0.

$$V_0=-\frac{R(1-D)(DV_g-(1-D)V_D)}{DR_{ON}+R_L+(1-D)^2R} \qquad (3)$$

We will not consider the full range [0,1] of duty cycle due to the nonidealities. For very large or very small duty cycle, the averaged model does not reflect precisely the real circuit. Since there is no benefit in increasing the duty cycle beyond the value where the minimal output voltage is reached, we would prefer to limit the duty cycle in a smaller range. For the above example, we may limit $D\in[0.1, 0.85]$.

Assumed that the resistors R_{ON} and R_L are much smallerthan R, and V_D is much smaller compared to V_g. The equation(3) can be simplified as

$$V_0\approx-\frac{D}{1-D}V_g \qquad (4)$$

B. State space description of the proposed model

Let the state of the traditional buck-boost converter be

$$X_N=[I_L \quad V_0 \quad V_C]^T.$$

In *ON* state, the equivalent circuit is described in Fig. 8

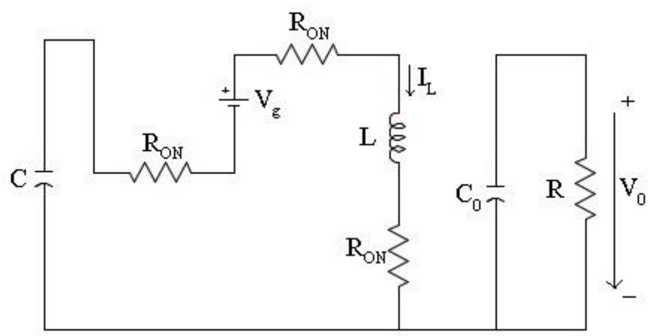


Fig. 8. Switched capacitor buck boost converter's equivalent circuit in *ON* state

KVL equations for this circuit is as follows

$$L\frac{dI_L}{dt} = V_g - (2R_{ON} + R_L)I_L + V_C$$
$$C_0\frac{dV_0}{dt} = -\frac{V_0}{R}$$
$$C\frac{dV_c}{dt} = -I_L$$

The state space description is $X'_N(ON) = A_{11}X_N + B_{11}u$

In which,

$$A_{11} = \begin{bmatrix} -\frac{2R_{ON}+R_L}{L} & 0 & \frac{1}{L} \\ 0 & -\frac{1}{RC_0} & 0 \\ -\frac{1}{C} & 0 & 0 \end{bmatrix}$$

and

$$B_{11} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

In *OFF* state, the equivalent circuit is described in Fig. 9

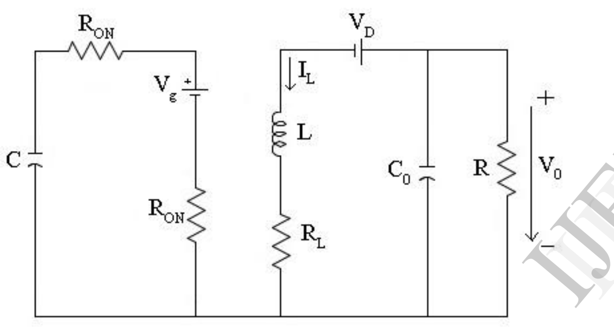


Fig. 9. Switched capacitor buck boost converter's equivalent circuit in *OFF* state

Apply the KVL equations for this circuit

$$L\frac{dI_L}{dt} = V_0 - R_L I_L - V_D$$
$$C_0\frac{dV_0}{dt} = -\frac{V_0}{R} - I_L$$
$$C\frac{dV_c}{dt} = \frac{V_g - V_C}{2R_{ON}}$$

The circuit can be described as $X'_N(OFF) = A_{12}X_N + B_{12}u$

In which,

$$A_{12} = \begin{bmatrix} -\frac{R_L}{L} & \frac{1}{L} & 0 \\ -\frac{1}{C_0} & -\frac{1}{RC_0} & 0 \\ 0 & 0 & -\frac{1}{2R_{ON}C} \end{bmatrix}$$

and

$$B_{11} = \begin{bmatrix} 0 & -\frac{1}{L} \\ 0 & 0 \\ \frac{1}{2R_{ON}C} & 0 \end{bmatrix}$$

Under the assumption of high frequency and ideal switching, the average model can be described as

$$X_N = DX_N(ON) + (1 - D)X_N(OFF)$$

and

$$X'_N = (DA_{11}+(1\text{-}D)A_{12})X_N+(DB_{11}+(1\text{-}D)B_{12})u \qquad (5)$$

Under the same above assumption, the state of the circuit is represented in (6).

$$X_N = -(DA_{11}+(1\text{-}D)A_{12})^{-1}(DB_{11}+(1\text{-}D)B_{12})u \qquad (6)$$

From (1), the output voltage V_0 is calculated in (7)

$$V_0 = -\frac{R(1-D)(2DV_g-(1-D)V_D)}{2DR_{ON}+R_L+2D^2LR_{ON}+(1-D)^2R} \qquad (7)$$

V_0 can be approximated as

$$V_0 \approx -\frac{2D}{1-D}V_g \qquad (8)$$

Hence, with the proposed switched capacitor buck boost circuit, the expected gain is doubled when compared with traditional buck boost converter. Generally, when we have *n* stages, by similarly calculation, the output gain is *n* times than the traditional one. The following part will demonstrate how the simulated circuit is working.

IV. SIMULATION RESULTS

In this section, we constructed two simulation models, one is a state-space model based on the averaged circuit, which is called the averaged model. The other is a simulated circuit using SimPower in MatLab, which is called the PWM model. We will use this two circuits to demonstrate the theoretically results we obtain from section III. The parameters for the circuit are given as follow: $L=0.1mH$, $R_L=0.3\Omega$, $C_0=0.33mF$, $C=0.047mH$, $R=48\Omega$, $R_{ON}=0.018\Omega$, $V_g=3V$, $V_D=0.3V$.

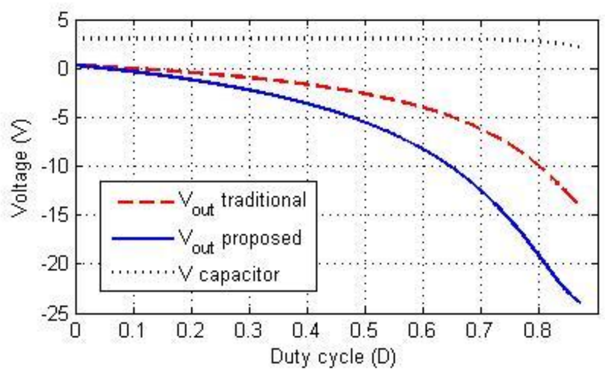
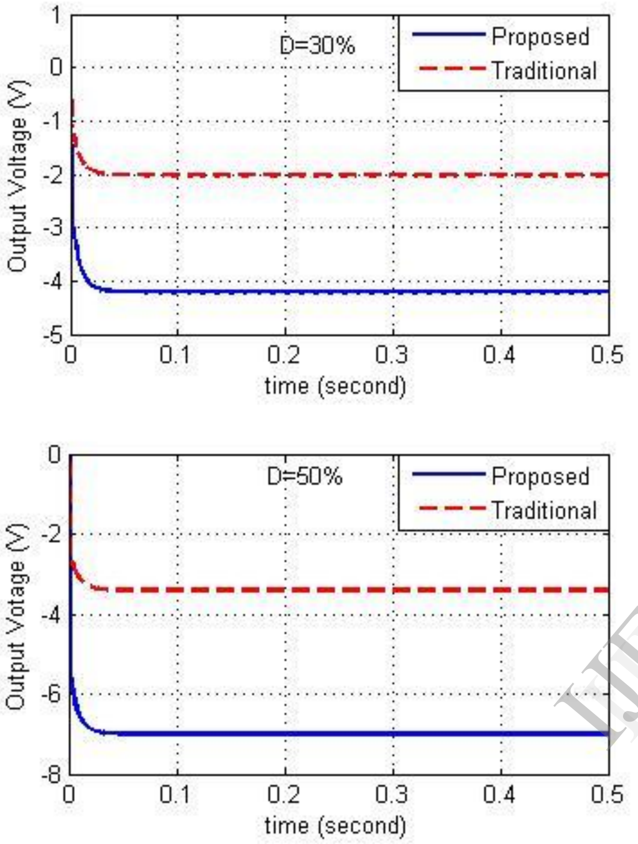


Fig. 10. Output of averaged model

Fig. 10 shows results for the averaged model based on the averaged equations (3) and (7). In not a very high duty cycle region, energy from power source is stored in capacitor *C*, the voltage V_C is equal to V_g. When it is pushed back to the circuit, the input becomes $V_g + V_C = 2V_g$. The output voltage of the proposed circuit is almost doubled compared with that of traditional buck-boost converter.

Fig. 11 shows the simulation result. In this figure, the output voltage of traditional buck-boost converter is plotted as the red curve; and the output of the proposed converter is represented as the blue curve. Four difference sub figures associated with the duty cycles being 30%, 50%, 70%, and 80% are plotted.We can see that the output voltages of the proposed model are almost doubled compared with the traditional one. This empirical result confirms the feasibility of the proposed model.



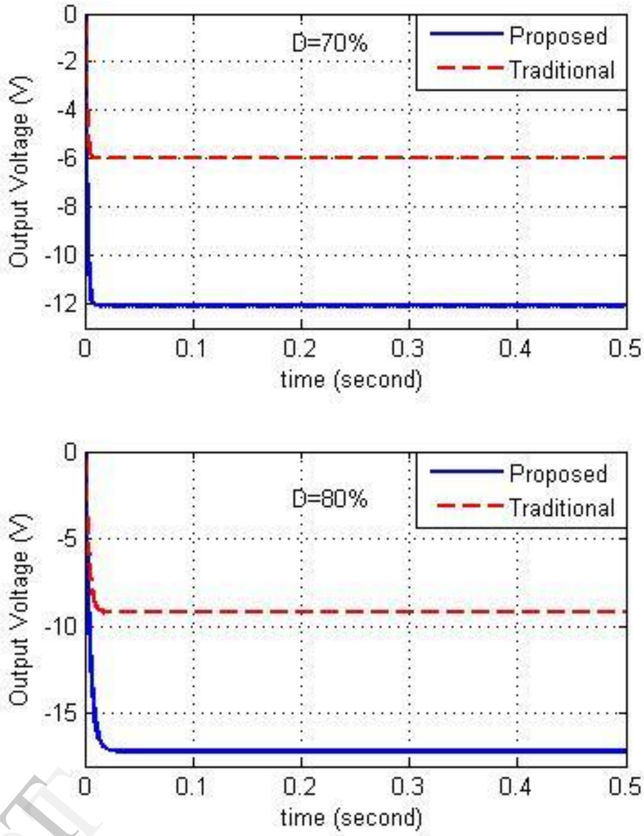


Fig. 11. Output voltage of simulink model compared with traditional buck boost circuit with D=30%, 50%, 70%, and 80%

V. CONCLUSION

A novel buck boost converter with a switched capacitor for high step-up converter is presented in this paper. Adding one more stage of switched capacitor significantly improves the voltage gain compared to the traditional one. Efficiency is also improved through the process of storing energy in the capacitor and then pushing it back to the circuit. The simulation results validate the theoretical results. The proposed converter is applicable in many applications in which high efficiency model is required.

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