Modeling and Analysis of Voltage Controlled Positive Output Synchronous buck-boost converter

Narasimharaju B. L, *Member*, *IEEE*, Goutham Bharma,
Vijay Babu Koreboina, *Student Member*, *IEEE* and Ramanjaneya Reddy U
Department of Electrical Engineering, NIT Warangal
blnraju@nitw.ac.in, vbkeed@nitw.ac.in and urreddy89@nitw.ac.in.

***Abstract*— Now a day's use of portable devices increasing more. Such as cellular phones, digital cameras and high efficient power managing modules etc. are demanding for low output voltage ripple with fast transient response. The terminal voltage of the battery used in portable applications varies particularly depending on state of their charging conditions. In this paper, Li-ion battery is considered that provides 4.2V when it is fully charged and drops to 2.7V when fully discharged. However, the system requires a constant output voltage of 3.3V under varying load conditions. Thus, this work addresses the design and modeling of voltage controlled positive output synchronous buck-boost converter. Simulation model is developed using MATLAB/Simulink and results analysis has been carried out.**

Index Terms--- Buck Boost converter, Voltage controller, Mathematical modeling.

I. Introduction

Rapid growths of semiconductor technology, more portable electronics are come into picture in the market. The most versatile thing for portable applications is battery that supplies power to the battery and it also determines service life of product. So power management module is needed to have high efficiency, low output voltage ripple, and fast transient response at the same time [1]. The terminal voltage of the battery used in portable applications varies particularly depending on state of their charging conditions. For example, the Li-ion battery considered for this project provides a voltage of 4.2V when fully charged and the voltage supplied drops to 2.7V when fully discharged [2].

To improve life time of battery, a superior power managing approach should have high conversion efficiency and also take the advantage of full battery voltage range. For this work switched mode regulators chosen due to their inherent property of high efficiency compared to conventional linear regulators. Positive output synchronous Buck-Boost converter is chosen to increase usable battery voltage range.

The output voltage polarity of conventional inverting buck boost converter is reverse, so it requires isolation driver. The transformer design in flyback converter makes the design complexity. Whereas in case of SEPIC, CUK and ZETA converters need more inductors and capacitors, it increases the size of converter large. In this work, Positive output synchronous Buck-Boost converter is chosen with single inductor and capacitor [3-5]. However, the system requires a constant output voltage of 3.3V under varying load conditions. Therefore, the dc-dc converter that is to be employed for portable device should be capable operate in buck as well boost mode. Since the four switch synchronous non-inverting converter yield high efficiency and impresses low stress on components, it has been chosen for the project work.

This paper is organized as follows Modes of operations are clearly given in Section-II, Switching scheme is explained in Section–III, and Mathematical model is given in Section-IV. Detailed simulated results have been discussed in Section-V. Conclusive remarks are given in Section-VI.

II. Modes of Operation

The positive output synchronous buck-boost converter topologies along with it buck power stage and boost power stage is shown in Fig.1. In buck cell the switch S1 is the main switch and the S2 is the freewheeling switch, both operate complimentary to each other with a duty cycle of D_{buck}. In boost cell the switch S3 is the main switch and the S4 is the freewheeling switch, both operate complimentary to each other with a duty cycle of D_{boost}.

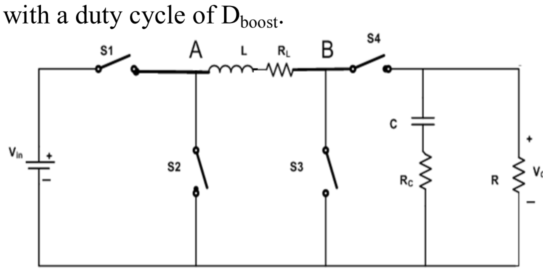

Fig.1 Power Stage of positive output synchronous buck-boost Converter

$$V_o = \frac{D_{Buck}}{1 - D_{Boost}} V_{in} \tag{1}$$

Equation (1) represents the input and output voltage relationship of a positive output synchronous buck-boost converter. It is observed that the output voltage can be regulated by D_{buck} and D_{boost}, here D_{buck} and D_{boost} can be controlled independently.

The terminal voltage of the battery used in portable applications varies particularly depending on state of their charging conditions. For example the Li-ion battery considered for this project varies from 2.7V to 4.2V, whereas a constant output voltage of 3.3V is desired. To achieve this, the positive output synchronous Buck-Boost converter is

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operated in three modes i.e. buck mode, boost mode and buck-boost mode. The selection of mode is based on the range of terminal voltage of the battery shown in Fig.2

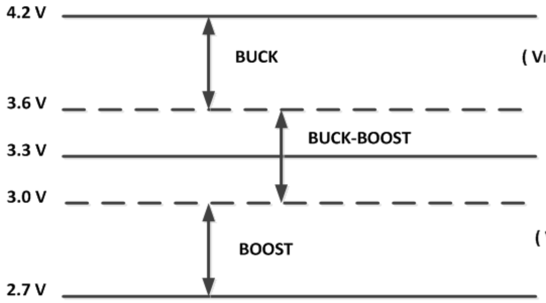
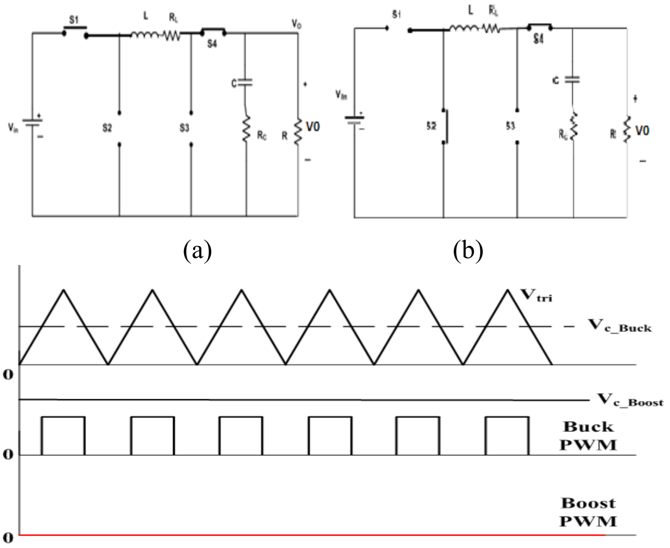


Fig.2 Input Voltage Range for Mode Selection

Buck mode: When $V_{in} > V_{out}$ Switches S1 are S2 are turned ON alternatively, while S3 is always turned OFF and S4 is always turned ON. Fig.3 shows its equivalent circuit in the buck mode during ON period, OFF period and PWM waveform required for buck mode of operation.

$$V_o = DV_{in} \tag{2}$$

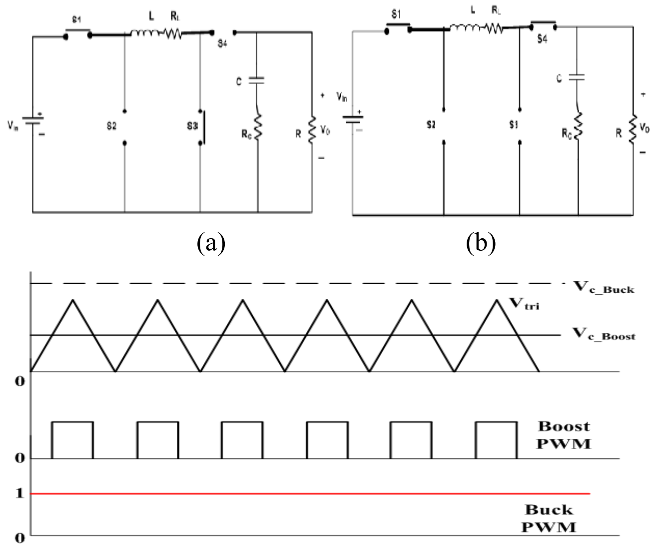

(a) (b)

(c)

Fig.3 Equivalent circuits of Buck Mode (a) During ON period, (b) During OFF period (c) PWM Signals during Buck Mode of operation

Boost Mode: When $V_{in} < V_{out}$ switches S3 are S4 are turned ON alternatively, while S1 is always turned ON and S2 is always turned OFF. Fig.4 shows its equivalent circuit in the boost mode during ON period, OFF period and PWM waveform required for boost mode of operation.

$$V_o = \frac{D}{1-D} V_{in} \tag{3}$$

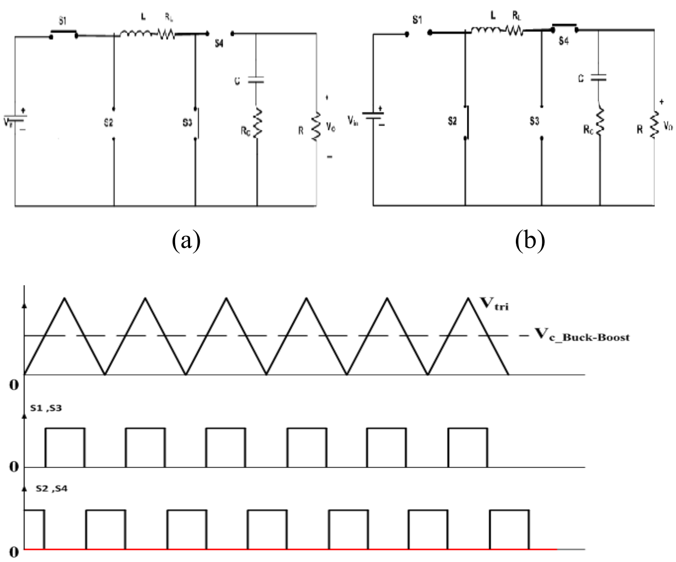

(a) (b)

(c)

Fig.4 Equivalent circuits of Boost Mode (a) During ON period, (b) During OFF period (c) PWM Signals during Boost Mode of operation

Buck-Boost Mode: When $V_{in} \approx V_{out}$ all switches are toggled in every switching period. Therefore, compared to buck and boost mode switching losses will be more in Buck-boost mode. The switching process of positive output synchronous Buck-Boost converter is shown in Fig.5, it consist of two phases in switching cycle. Switches S1 and S3 are turned on and off simultaneously, while S2 and S4 are turned off and on simultaneously.

$$V_o = -\frac{D}{1-D} V_{in} \tag{4}$$


(a) (b)

(c)

Fig.5 Equivalent circuits of Buck-Boost Mode (a) During ON period, (b) During OFF period (c) PWM Signals during Buck-Boost Mode of operation

III. SWITCHING SCHEME

In buck mode, one end of inductor is fixed at output node, so average inductor current is same as load current [10].

$$I_{Lbuck}\ (avg) = I_{Load} \tag{5}$$

Where as in case of boost and buck–boost mode

$$I_{Lboost}\ (avg) = I_{LBuk-Bost}\ (avg) = \frac{I_{Load}}{1-D} \tag{6}$$

Duty ratio (D) is close to 0 and 0.5 for buck and buck-boost mode, when V_{in} gets close to V_{out}. When V_{in} is same as V_{out} their average inductor currents are

$$I_{Lboost}\ (avg) = I_{Load} \tag{7}$$

$$I_{Lbuckboost}\ (avg) = 2I_{Load} \tag{8}$$

From Eq (7) and Eq (8) the conduction losses are double in buck-boost mode compared to boost or buck mode. This leads to reduction in converter efficiency.

The aim is avoid the operation in buck-boost mode using the conventional switching scheme. This can be achieved by operating the converter as a combination of buck and boost mode. Under this condition the average inductor current can be expressed as

$$I_L(avg) = \frac{I_{Boost}\ (avg) + I_{Buck}\ (avg)}{2} \tag{9}$$

The normalized DC gain of buck and boost region is shown in Fig.6. The dc gain of large-signal models in the buck region is linear, whereas it is quite non-linear in the boost region [6].

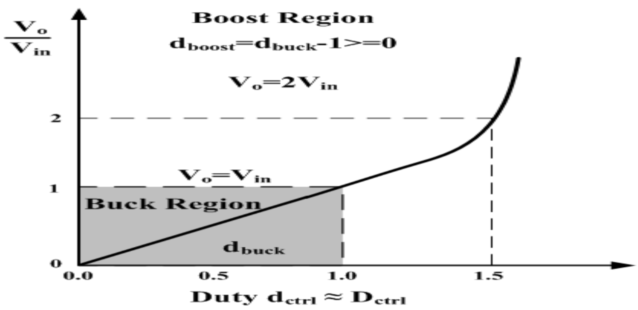


Fig.6 Normalized DC gain of Buck and Boost Operation

IV. MATHEMATICAL MODEL

The mathematical model of the synchronous positive output buck-boost converter is shown in Fig.7. The system controller generates the duty cycles for buck and boost mode of operation i.e. D_{buck} and D_{boost}.

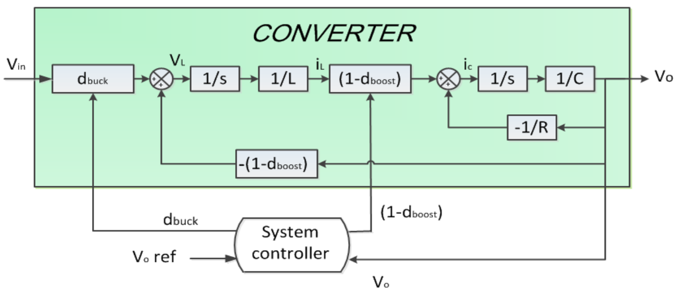


Fig.7 Mathematical Model of positive output synchronous buck boost Converter

The system controller generates D_{buck} duty cycle for switch S1 and (1- D_{boost}) duty cycle for switch S4. In buck mode, during ON period, D_{buck} = 1 and (1- D_{boost}) = 1, so the voltage across inductor is (V_{in}–V_o). During OFF period, D_{buck} = 0 and (1- D_{boost}) = 1 as a result the voltage across inductor is (–V_o). The relation between I_L, I_c and I_o throughout the switching cycle i.e. $I_c = I_L - I_o$ holds good as (1-D_{boost}) is always equals to 1.

In boost mode, during ON period, D_{buck} = 1 and (1- D_{boost}) = 0, hence the voltage across inductor is (–V_o). During OFF period, D_{buck} = 1 and (1-D_{boost}) = 1, this causes a voltage of (V_{in}-V_o) to appear across inductor. During ON period Ic = (-Io) as holds good as (1- D_{boost}) = 0 and During OFF period Ic = (I_L – I_o), since (1- D_{boost}) = 1.

The mathematical model representation in Simulink is shown below.

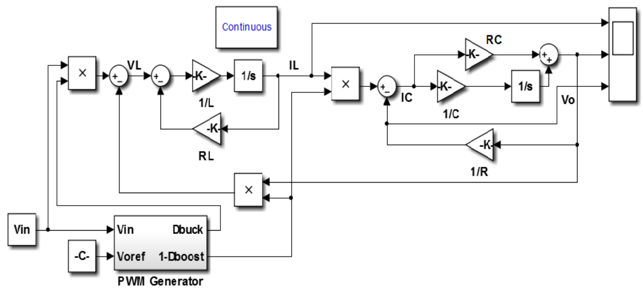


Fig.8 (a) Simulink Model of positive output synchronous Buck-Boost converter

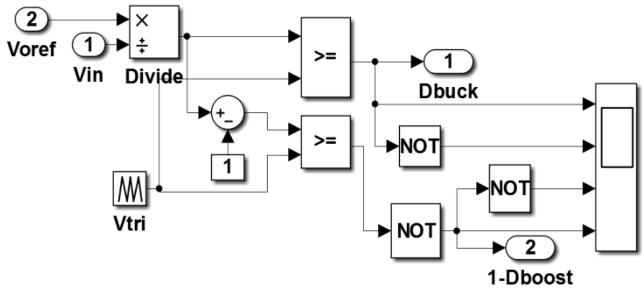


Fig.8 (b) PWM Generator for positive output synchronous Buck-Boost Converter

Centre edge modulation technique is used to generate PWM signals, with a triangular waveform V_{tri} as carrier signal. The buck PWM, D_{buck} is generated by comparing the V_{tri} with V_o/V_{in} [7-9]. The boost PWM is generated by comparing the V_{tri} carrier wave with the value derived from the D_{buck} by shifting it below a value that is equal to the height of the carrier waveform, since D_{boost} = (D_{buck}–1). Complementary of D_{boost} gives (1- D_{boost}). The PWM generator provides D_{buck} and (1-D_{boost}) for the mathematical model of the positive output synchronous buck-boost converter.

V. SIMULATION RESULTS AND DISCUSSIONS

A. Duty Cycles for Switches in Buck Mode

Since the input voltage is 4.2V, positive output synchronous buck-boost converter must operate in buck mode. Fig.9 shows the duty cycle required for this mode. With a switching frequency of 7 kHz or switching period of 142µsec and D_{buck} of 0.7857, calculated using equation (2), the turn on period of the PWM signal for the switch S1 is 0.112 msec.

This has been indicated in the simulation result for D1. Similarly, for switch S2 is .03 msec. Duty cycle for switches S3 and S4 is 0 and 1 respectively as shown in D3 and D4 in Fig.9.

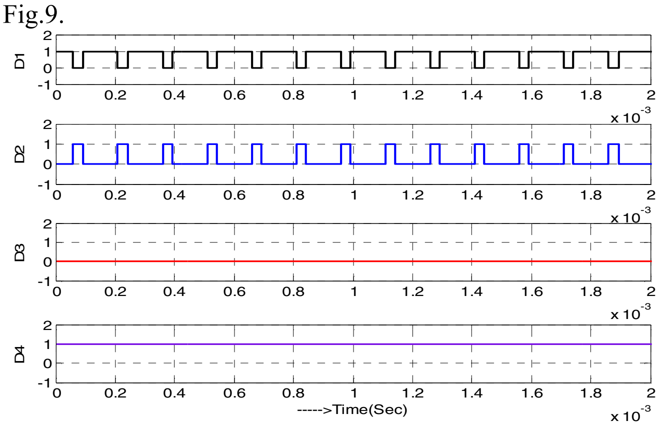


Fig.9 Duty Cycles for Various Switches with $V_{in} = 4.2V$

B. Duty Cycles for Switches in Boost Mode

With an input voltage of 2.7V, positive output synchronous buck-boost converter has to operate in boost mode. Fig.10 represents the duty cycle required for this mode. With a switching frequency of 7 kHz or switching period of 142μsec and d_{boost} of 0.1818, calculated from using equation (3), the turn on period of the PWM signal for the switch S3 is 25.95 μsec. This has been indicated in the simulation result for D3. Similarly, for switch S4 is 0.11 msec. Duty cycle for switches S1 and S2 is 1 and 0 respectively as shown in D1 and D2 in Fig.10.

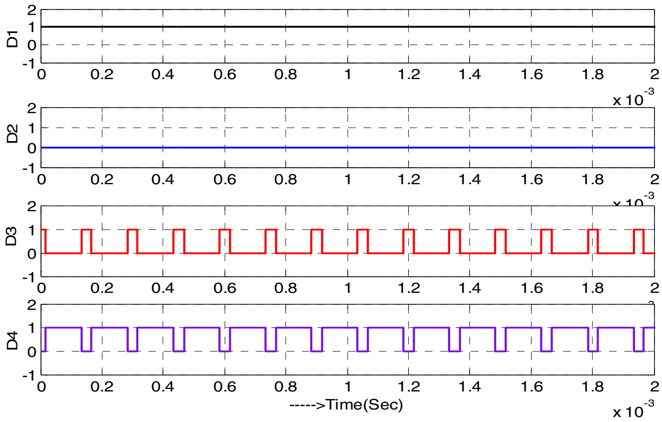


Fig.10 Duty Cycles for Various Switches with $V_{in} = 2.7V$

The model for the positive output synchronous buck-boost converter is simulated for various input voltage level with maximum and minimum loading condition. Fig.11 illustrates wave forms of inductor current I_L, output voltage Vo and output current Io, when $V_{in} = 4.2V$ and load resistance is 8.25ohms. The ripple in inductor current in steady state is Δi_L = 0.25mA and its average value is 400mA. The average output current is same as the average inductor current as the positive output synchronous buck-boost converter operates in buck mode for $V_{in} = 4.2V$. The output voltage settles down to its steady state value after 6msec. The average output voltage is 3.3V, with a ripple of $\Delta V_o = 0.15V$ i.e. % ripple = 4.5

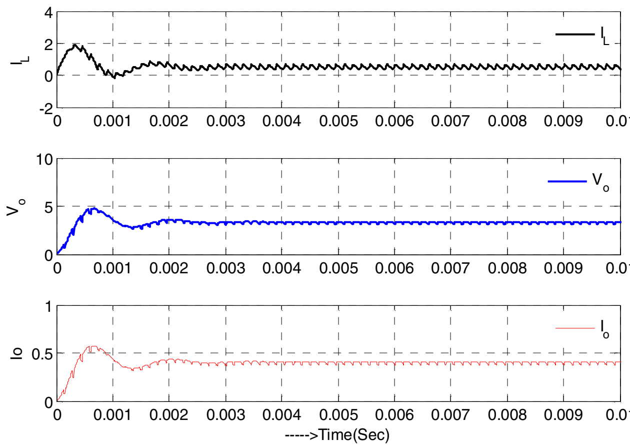


Fig.11 Buck Mode operation With V_{in} = 4.2and Io = 400mA

Fig.12 illustrates wave forms of inductor current I_L, output voltage V_o and output current Io, when $V_{in} = 4.2V$ and load resistance is 66 ohms. The ripple in inductor current in steady state is Δi_L = 0.1mA and its average value is 50mA. The average output current is same as the average inductor current as the positive output synchronous buck-boost converter operates in buck mode for $V_{in} = 4.2V$. The output voltage settles down to its steady state value after 5msec. The average output voltage is 3.3V, with a ripple of $\Delta V_o = 0.18V$ i.e % ripple = 5.4.

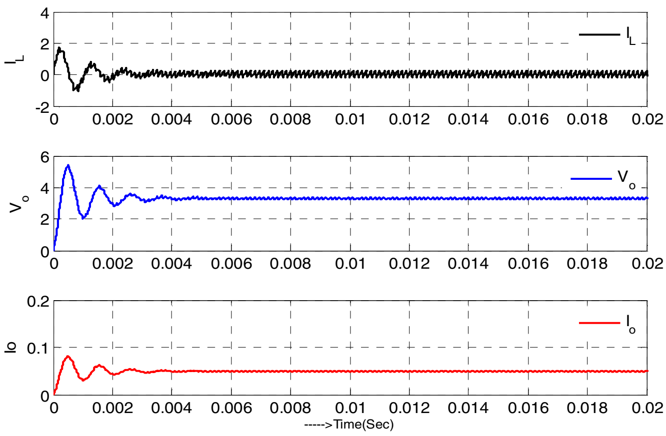


Fig.12 Buck Mode operation With V_{in} = 4.2 and Io = 50mA

Fig.13 shows wave forms of inductor current I_L, output voltage V_o and output current Io, when $V_{in} = 2.7V$ and load resistance is 8.25 ohms. The ripple in inductor current in steady state is Δi_L = 300mA and its average value is 500mA. The average output current is 400mA, which is lower than the average inductor current since the non-inverting buck-boost converter operates in boost mode for $V_{in} = 2.7V$. The output voltage settles down to its steady state value after 4msec. The average output voltage is 3.3V, with a ripple of $\Delta V_o = 0.24V$ i.e. % ripple = 7.2.

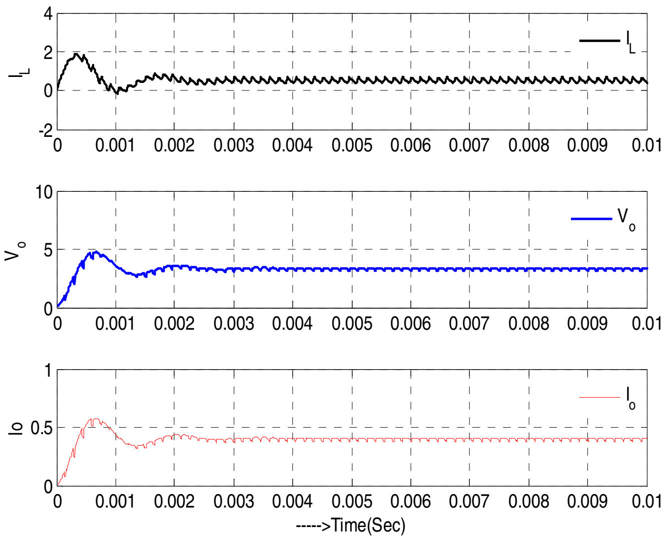


Fig .13 Boost Mode operation With V_{in} = 2.7 and Io = 400mA

VI.CONCLUSION

In this paper, mathematical model of voltage controlled synchronous positive output buck-boost converter is developed and simulated using MATLAB. Synchronous rectification technique is used to improve efficiency by reducing the switching loss due to the low on-state resistance (R_{ds}) of MOSFET switches, in addition to this the converter is improved by avoiding operation in buck-boost mode using traditional switching scheme. Performance analysis has been carried-out to confirm the effectiveness of voltage controller. Result evaluation confirms that the good voltage regulation and fast transient response under wide load variations (from 50mA to 400mA) and input-line variations (from 2.7V to 4.2V). Due to its high efficiency and fast transient response this converter is suitable for cellular application and energy management in solar cell systems.

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