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Analysis and Design of Four Switch Buck Converter for DC-DC Power Supply Applications

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ABSTRACT: The operation of the buck converter is fairly simple, with an inductor and four switches that control the inductor. It alternates between connecting the inductor to source voltage to store energy in the inductor and discharging the inductor into the load. Buck Converter for DC-DC power supply applications often require an output voltage within a wide range of input voltages. While in the design of two switch Buck-Boost converters will come with a heavy penalty in terms of component stresses and losses. To overcome these stresses and losses, Four Switch Buck converter is proposed to achieve high efficiency within the line range and the highest efficiency around the nominal input. A 48V(36-75V) input 24V/2A output two-stage prototype composed of the proposed converter and a Full Bridge converter is built in the lab. The experimental results verified the analysis.

KEYWORDS: Wide line range, Four Switch Buck converter, High efficiency, High power density.

I. INTRODUCTION

A buck converter is a step-down DC to DC converter. Its design is similar to the step-up boost converter, and like the boost converter it is a switched-mode power supply that uses two switches (a transistor and a diode), an inductor and a capacitor.[1-3]

The simplest way to reduce a DC voltage is to use a voltage divider circuit, but voltage dividers waste energy, since they operate by bleeding off excess power as heat; also, output voltage isn't regulated (varies with input voltage). Buck converters, on the other hand, can be remarkably efficient (easily up to 95% for integrated circuits) and self-regulating, making them useful for tasks such as converting the 12-24V typical battery voltage in a laptop down to the few volts needed by the processor.[4]

DC-DC modular power supplies are widely used in telecommunication applications, they demands for high power density, high reliability and fast transient response [1,2].The voltage of the telecommunication power system usually has a wide range, e.g., the range of nominal voltage of 48V is 36V to 75V, which makes it difficult to design a DC-DC modular power supply, which has a high efficiency over the line range.

Three-level converters can operate in three-level mode and two-level mode over the line range, and the transformer ratio can be properly designed to increase the efficiency [3,4]. However, the topology is very complex and the control is very complicated, it is not suitable for low voltage applications.

Two-stage approach is popular for the wide line range applications, the first stage regulates the wide line range input to a constant voltage, and the second stage can be optimally design [5,6]. The important issue is how to conventional topologies, Buck derived converters achieve the highest efficiency at high line, thus they are not suitable for the wide line range applications. The objective of this paper is to design the first stage converter with a high

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efficiency, the four-switch Buck (FSB) converter is taken as the topology, and the focus of this paper is on the control scheme for the FSB converter to obtain a high efficiency over the line range, especially at around the nominal line voltage.[5]

II. FOUR-SWITCH BUCK CONVERTER

For a two-stage converter, there are several approaches according to the galvanic isolation and control strategies.[6-8] The galvanic isolation can be realized in either first-stage or second-stage, and the two stages can be tightly regulated, or only one is tightly regulated and the other is roughly regulated or unregulated. Here we choose a roughly regulated non-isolated converter followed by a tightly regulated isolated one. The full-bridge converter is taken as the isolated converter, it is not discussed in this paper since it has been analyzed extensively [7,8].

As the line range is very wide, such as 36V to 75V for nominal voltage of 48V, in order to achieve high efficiency at nominal input voltage, we can regulate the output voltage of the first-stage at the value of nominal input voltage, so the topology needs to have the both functions of voltage step-up and step-down. Among the six basic non-isolated converters, Buck-Boost, Cuk, Sepic and Zeta have the functions. However, the output voltages of Buck-Boost and Cuk output are in inverse polarity of the input voltage, and the power devices suffer high voltage stress, meanwhile, Sepic and Zeta are very complicated and also suffer high voltage stress.[9]

Two switch Buck-Boost converter [9,10] is a cascaded converter of Buck and Boost as shown in Figure 1(a).When the output voltage is very low, the diodes D_2 and D_3 can be replaced by MOSFET Q_2 and Q_3 to form synchronous rectifier (SR), as shown in Figure 1(b), to increase the efficiency. Therefore, there are four switches in the non-invert Buck-Boost converter, it can be called four-switch Buck (FSB) converter.[10-12]

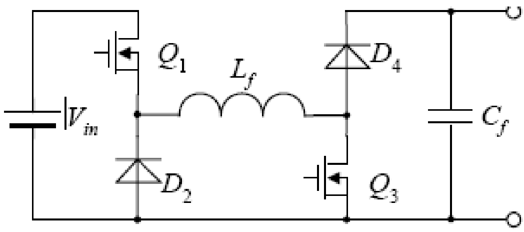

Figure 1(a) Two switch Buck-Boost converter

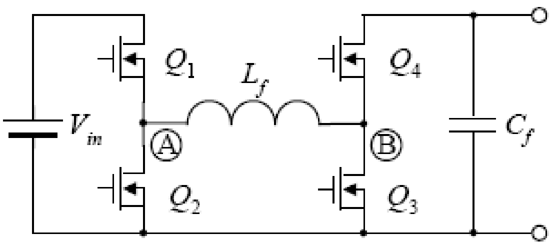

Figure 1(b) Four Switch Buck Converter

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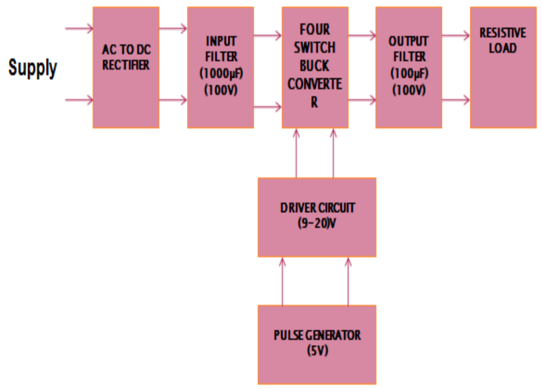
BLOCK DIAGRAM:



III. SIMULATION CIRCUIT

This Figure (2) shows the simulation circuit of the four switch Buck converter:

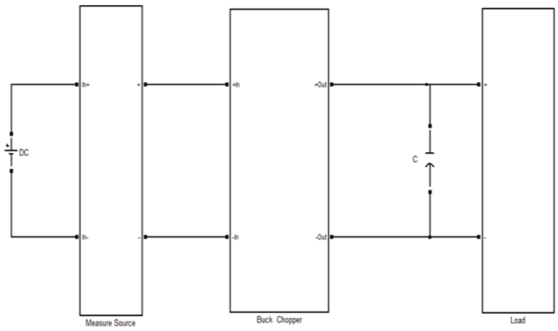


Figure 2(a) MATLAB Circuit

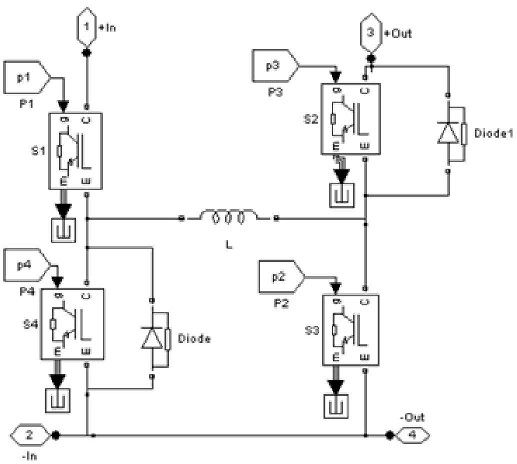


Figure 2(b) Four switch Buck converter circuit

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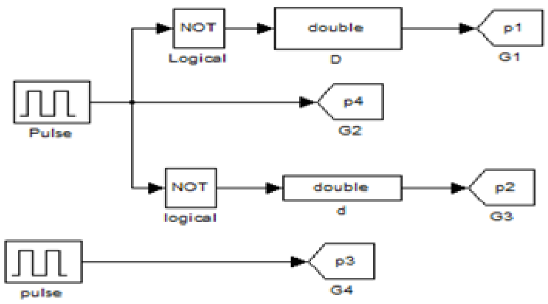
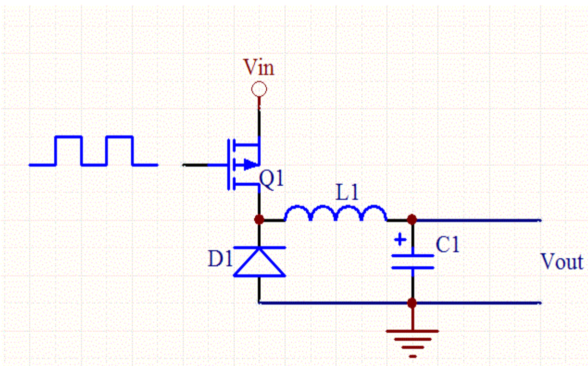


Figure 2(c) Control Circuit

IV. DESIGN EQUATION OF BUCK CONVERTER

The buck converter is a high efficiency step-down DC/DC switching converter. [13]The converter uses a transistor switch, typically a MOSFET, to pulse width modulate the voltage into an inductor. Rectangular pulses of voltage into an inductor result in a triangular current waveform. We'll derive the various equations for the current and voltage for a buck converter and show the tradeoffs between ripple current and inductance. For this discussion we assume that the converter is in the continuous mode, meaning that the inductor's current never goes to zero.



First, here are some definitions:

Peak inductor current	i_{pk}
Min inductor current	i_o
Ripple Current	$\Delta i \equiv (i_{pk} - i_o)$
Ripple Current Ratio to Average Current	$r \equiv \Delta i / i_{ave}$
Duty Cycle	$D \equiv T_{on} / T$

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Switch On Time	$T_{on} = D/f$
Average and Load Current	$i_{ave} \equiv \Delta i/2 \equiv i_{load}$
RMS Current for a Triangular Wave	$i_{rms} = \sqrt{i_o^2 + (\Delta i)^2/12}$

The relationship of voltage and current for an inductor is:

$$V = L\frac{di}{dt}$$,or -------------(1)

$$i = \frac{1}{L}\int_o^t V dt + i_o$$ ------------(2)

The relationship of voltage and current for an inductor is:

$$V = L\frac{di}{dt}$$,or ------------(3)

$$i = \frac{1}{L}\int_o^t V dt + i_o$$ -------------(4)

For a constant rectangular pulse:

$$i = \frac{Vt}{L} + i_o$$

From this we can see that the current is a linear ramp, when the voltage is a constant pulse.

When the transistor switches on the current is:

$$i_{pk} = \frac{(V_{in} - V_{Trans} - V_{out})T_{on}}{L} + i_o$$, or -------(5)

$\Delta i = \frac{(V_{in} - V_{Trans} - V_{out})T_{on}}{L}$	----------------(6)

and when the transistor switches off the current is:

$$i_o = i_{pk} - \frac{(V_{out} - V_D)T_{off}}{L}$$, or -------------(7)

$$\Delta i = \frac{(V_{out} - V_D)T_{off}}{L}$$ --------------(8)

Where V_D is the voltage drop across the diode, and V_{Trans} is the voltage drop across the transistor. Note that the continuous/discontinuous boundary occurs when i_o is zero.

By equating through delta i, we can solve for Vout:

$$\frac{(V_{in} - V_{Trans} - V_{out})T_{on}}{L} = \frac{(V_{out} - V_D)T_{off}}{L}$$

$$V_{in}T_{on} - V_{Trans}T_{on} - V_{out}T_{on} = V_{out}T_{off} - V_D T_{off}$$

$$V_{in}T_{on} - V_{Trans}T_{on} - V_{out}T_{on} = V_{out}T_{off} - V_D T_{off}$$

$$V_{out}T_{on} + V_{out}T_{off} = V_D T_{off} + V_{in}T_{on} - V_{Trans}T_{on}$$

$$V_{out} = \frac{V_D T_{off} + V_{in}T_{on} - V_{Trans}T_{on}}{T}$$ -------(9)

$$V_{out} = (V_{in} - V_{Trans})D + V_D(1 - D)$$

We can also solve for the duty cycle as follows,

$$V_{out} + V_D = (V_{in} - V_{Trans} + V_D)D$$

$$D = \frac{V_{out} - V_D}{(V_{in} - V_{Trans} - V_D)}$$

If we neglect the voltage drops across the transistor and diode then:

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$V_{out} = DV_{in}$ ---------------(10)

So it is clear that the output voltage is related directly to the duty cycle of the pulses.

V. CONTROL SCHEME FOR FSB CONVERTER

The voltage conversion ratio of the FSB converter is

$$V_o = \frac{D_1}{1-D_2} V_{in}$$ -------------(11)

where D_1 and D_2 are the duty cycle of Q_1 and Q_3 respectively. Eq.(1) implies that the output voltage can be regulated by D_1 and D_2, so there will several control schemes for the FSB converter. Here we set the output voltage reference at the nominal input voltage, $Vin_{nom.}$

A. One-Mode Control Scheme

The simplest control scheme is to let D_1=D_2, which is identical to the traditional Buck-Boost converter, we call this control scheme as one-mode control. However all the four switches are switched at high frequency, the switching loss is very large, resulting in a low efficiency.

B. Tight Regulation Three-Mode Control Scheme

In fact, we can only control two switches, where one is the SR switch, which switches in complementary with the main switch. When $V_{in} < V_{in\ nom}-\Delta V$, we let D_1=1, and D_2 is controlled to regulate the output voltage, in this case, FSB works in Buck mode; When $V_{in\ nom}-\Delta V \leq V_{in} \leq V_{in\ nom}+\Delta V$, we let D_1=D_2, and they are controlled to regulate the output voltage, in this case, FSBB works in Buck mode. The hysteresis ΔV is introduced to avoid the fluctuation of the duty cycles. [14]We call this control scheme as three-mode control. As only two switches work at high frequency in most input voltage range, the total switching loss can be reduced significantly, so the efficiency can be higher than that when D_1=D_2.

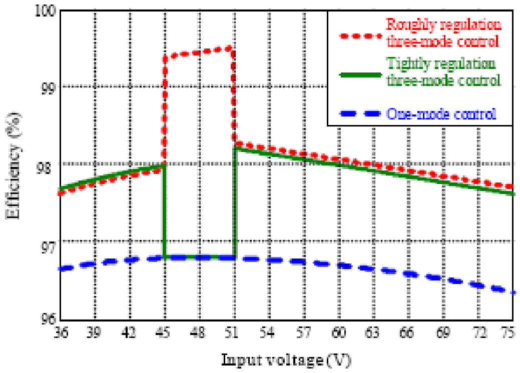

Figure 3 Calculated efficiency of different control scheme

Figure.3 shows the comparison of the calculated efficiency of the FSB converter over the line range at full load between the one-mode control and the three-mode control. It can be seen that the three-mode control has a higher efficiency than the one-mode control. However, in the region of [$V_{in\ nom}-\Delta V$, $V_{in\ nom}+\Delta V$], the efficiency is lower than the other region due to the high-frequency switching of all the four switches. *[15]*

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C. Rough Regulation Three-Mode Control Scheme

In order to increase the efficiency at the region of [$V_{in\ nom}-\Delta V$, $V_{in\ nom}+\Delta V$], we can let D_1=1, and D_2 =0, which means that the FSB works in open loop and acts as a filter. Figure.3 shows the comparison of the efficiency of the tight regulation and rough regulation three-mode control schemes, it can be seen that the efficiency at the region of [$V_{in\ nom}-\Delta V$, $V_{in\ nom}+\Delta V$] is very high for the rough regulation three-mode control scheme, in which all the switches do not switch, so no switching loss occurs.

Figure.4 shows the output voltage and the duty cycles D_1 and D_2 over the line range, at the region of [$V_{in\ nom}-\Delta V$, $V_{in\ nom}+\Delta V$], the output voltage equals to the input voltage, so the entire output voltage has a small range of [$V_{in\ nom}-\Delta V$, $V_{in\ nom}+\Delta V$]. In order to solve this problem, we can set the output reference voltage as $V_{in\ nom}-\Delta V$ and $V_{in\ nom}+\Delta V$ when the input voltage is lower than $V_{in\ nom}-\Delta V$ and higher than $V_{in\ nom}+\Delta V$, respectively.

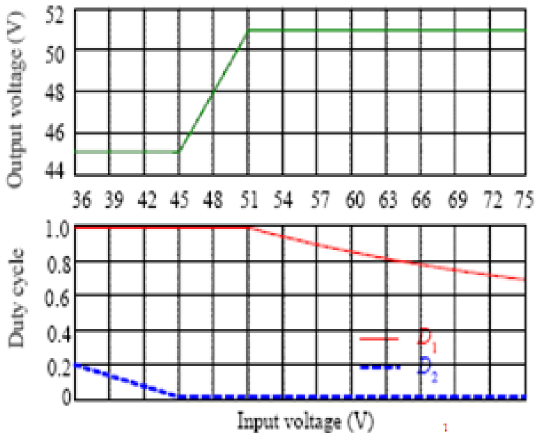

Figure 4 Output voltage and duty cycle of different input

Figure.4 shows the output voltage and the duty cycles D_1 and D_2 over the line range, it can be seen that no voltage step occurs, and the range of the output voltage is the same as that when the output reference voltage is set at $V_{in\ nom}$. As the output voltage of the FSB converter has a small variation, the second-stage full-bridge converter needs to be tight regulated.

D. Modified Rough Regulation Three-Mode Control Scheme

In practical circuit design, the drivers of Q_1 & Q_2 and Q_3 & Q_4 are realized by the boot-strap structures (as shown in Figure.5).In order to provide energy for the boot-strap capacitor, the lower switch should be turned on, so we let D_1 =0.98 and D_2=0.02 with frequency of 10kHz, thus a 200ns is left for the lower switches Q_2 and Q_3, to turn on to charge the boot-strap capacitors.

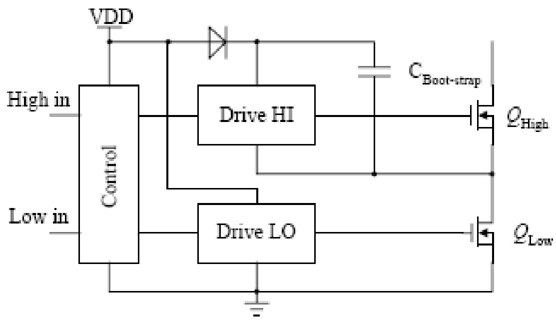

Figure 5 Drive circuit of Boot-strap

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VI. HARDWARE

A 48V (36V~75V) input and 24V/2A output prototype, as shown in Figure.6, is built in the lab, the first stage is the roughly regulated FSB converter and the second stage is the tightly regulated full-bridge converter. The prototype has a quarter brick size with the power density of 180 W/inch^3, which meets the requirement of future telecom power supply.

Figure 6(a) Shows the prototype of the control circuit. This circuit is used to control he Pulse with modulation(PWM) signal sent to the buck converters. It receives the anagol signals of output voltage and current from other circuit boards.

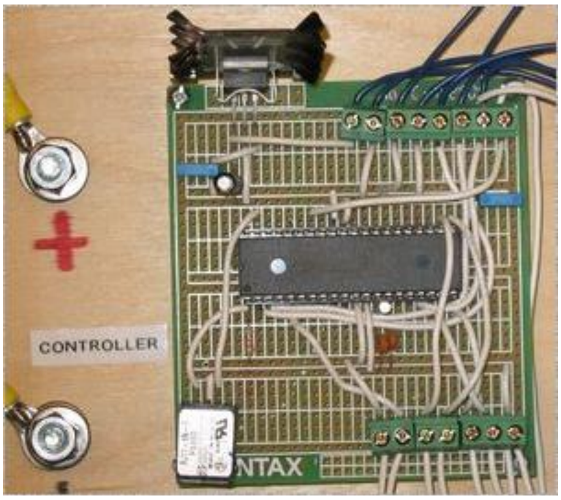

Figure 6(a) Control module

Figure 6(b) shows the Buck converter circuit module.

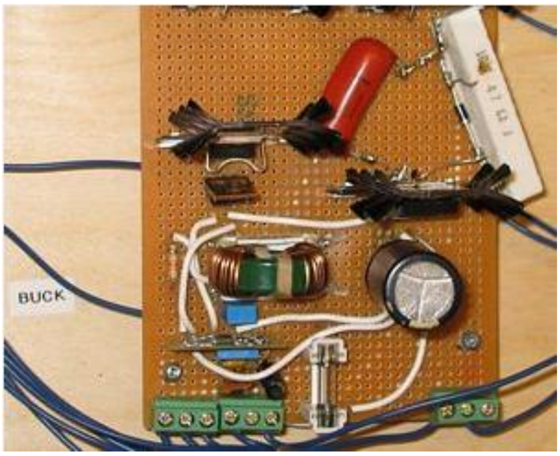

Figure 6(b) Buck converter circuit

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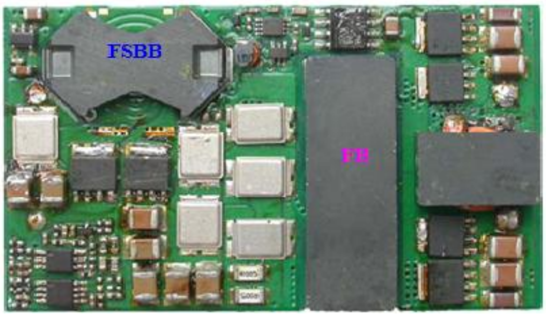

Figure 6(c) Photograph of the prototype

VII. SIMULATION RESULTS AND DISCUSSION

Figure 7(a),(b),(c) shows the voltage waveforms of point A & B (refer to Figure 1) and output voltage ripple of FSB under the input of42V (Boost mode), 48V (filter mode) and 60V (Buck mode).

The output voltage ripple is composed of two parts, one is due to the FSB filter, and the other is due to the injection voltage of the full-bridge converter. It can be seen that the output voltage ripple in filter mode is very small, and it is almost

Same as the injection ripple of FB converter.

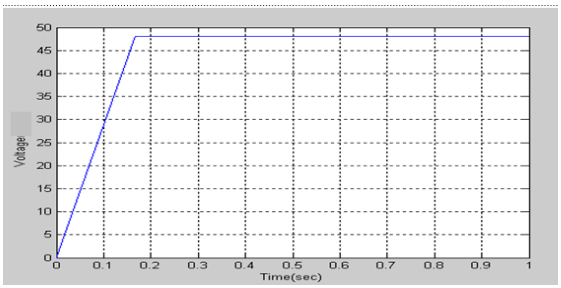

Figure 7(a) Input Voltage

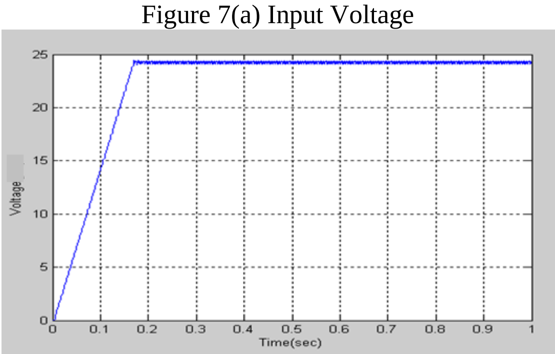

Figure 7(b) Output Voltage

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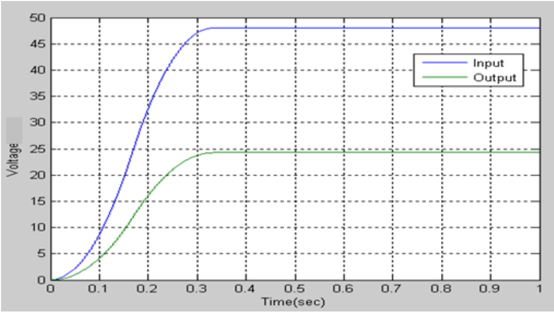

Figure 7(c) Comparison of Input and Output Voltage

Figure 8 shows the conversion efficiency of FSB and the whole power module at full load over the line range, it can be seen that the overall efficiency of the power module is higher than 95% at full load over the line range, and the efficiency of FSB at full load under nominal input (48V) is 98.9%.

Figure 9 shows the efficiency of the power module at different load under nominal input (48V), the efficiency is 96.1% at full load under 48V input.

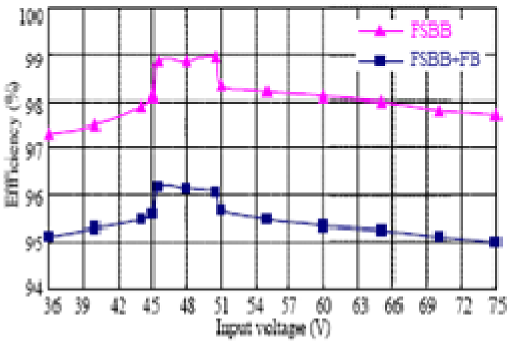

Figure 8 Efficiency of full load over the line range

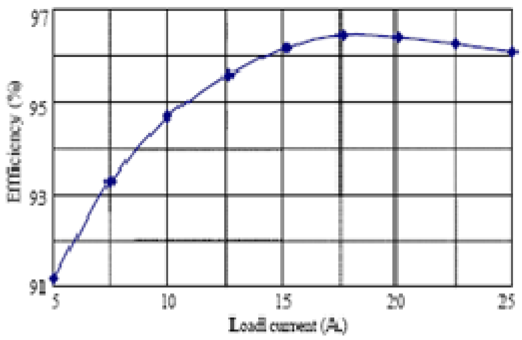

Figure 9 Over all efficiency of power module at different load under 48V input

VIII. CONCLUSIONS

In order to achieve high efficiency of the DC-DC converters for the wide line range applications, a two-stage configuration, consisting of the four-switch Buck-Boost converter and full-bridge converter is proposed. Three kinds of control schemes, i.e., one-mode control, tightly regulated three-mode control and roughly regulated three-mode control, for the FSB converter are discussed, among which, the roughly regulated three-mode control scheme has the highest efficiency. For the roughly regulated three-mode control scheme, a voltage hysteresis with the nominal voltage as the centre is introduced, which divides the input voltage into three regions. In the region of the voltage hysteresis, the output voltage of the FSB converter is unregulated, and in the regions outsides the voltage hysteresis, the output voltage is well regulated at a voltage or at different voltages, where one is voltage of the first boundary and the other is second boundary. The later has no voltage step in the output voltage of the FSB converter and avoids severe perturbation of the output voltage of the second stage converter. A 48V(36V~75V) input and 24V/2A output prototype, which has a quarter brick size with the power density of 180 W/inch^3 is built in the lab, the efficiency of the FSB at full load under nominal input (48V) is 98.9%, and the overall efficiency of the power module is higher than 95% at full load over the line range.

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