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DESIGN AND ANALYSIS OF TWO STAGE BOOST CONVERTER WITH IMPROVED CONTROL

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Abstract: In this article, a high-gain two-stage boost converter with improved control is proposed. In order the increase the regulation quality and power density a common control strategy introduced. In the proposed control method, each boost stage is controlled by the same controller. This method provides easy control and low cost and allows the use of lower voltage capacitors at the output of first boost stage. The converter is designed in two stages to increase from 12 VDC input voltage to 42 VDC and 150 VDC. Detailed theoretical analysis of the proposed converter is carried out and validated with a prototype having 100 W output power. Using the results obtained from the application circuit, the proposed boost converter with improved control is compared with the conventional two-stage boost converter operated under the same conditions.

Keywords: Two Stage Step-Up Converter, PWM Control, Improved Control, High Voltage Gain, High Efficiency, Low Cost

Geliştirilmiş Kontrole Sahip İki Aşamalı Boost Dönüştürücünün Tasarımı ve Analizi

Öz: Bu makalede, geliştirilmiş kontrole sahip, yüksek kazançlı, iki aşamalı bir yükseltici dönüştürücü önerilmiştir. Regülasyon kalitesini ve güç yoğunluğunu artırmak amacıyla ortak kontrol stratejisi tanıtılmıştır. Önerilen kontrol yönteminde her yükseltici katı aynı kontrolcü tarafından kontrol edilir. Bu sayede kolay kontrol ve düşük maliyet sağlanır. Ayrıca ara yükseltici katı çıkış gerilimlerinde kontrole bağlı oluşan gerilim yükselmeleri önlenir ve daha düşük gerilimli kondansatör kullanımına olanak sağlanır. Dönüştürücü devresi, 12 VDC giriş geriliminden 42 VDC ve 150 VDC'a çıkacak şekilde iki aşamalı olarak tasarlanmıştır. Önerilen dönüştürücüye ait detaylı teorik analizler yapılmış ve 100 W çıkış gücüne sahip prototip ile doğrulanmıştır. Uygulama devresi üzerinden alınan sonuçlar kullanılarak, önerilen geliştirilmiş kontrole sahip yükseltici dönüştürücü ile geleneksel iki aşamalı yükseltici dönüştürücü karşılaştırılmıştır.

Anahtar Kelimeler: İki Aşamalı Yükseltici Dönüştürücü, PWM Kontrol, Geliştirilmiş Kontrol, Yüksek Gerilim Kazancı, Yüksek Verimlilik, Düşük Maliyet

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1. INTRODUCTION

Nowadays, with the development of technology, the need for energy has increased. Thus, the importance of electrical energy and renewable energy sources has increased and efficient conversion of energy obtained from renewable energy sources has gained importance (Diaz-Saldierna et al., 2021; Bodur et al., 2021). PWM DC-DC converters are widely used in the energy conversion applications such as solar energy systems, electric vehicles, battery charging, defense industry etc. High efficiency operation of these converters is a requirement for the power electronics field (Bodur and Yıldırmaz, 2017; Zhao and Lee, 2003; Navamani et al., 2022).

The importance of converters working with high efficiency and power density has increased and many studies are being carried out today. Increasing power efficiency and density provides advantages in terms of cost and sizes. As the switching frequency increases, the filter sizes get smaller however the switching losses become dominant (Zhang et al., 2022).

In general, the output voltages of the renewable energy sources are relatively low so that the converters used in this field have high voltage gain. In addition, DC-DC converters used in the renewable field must have low input current ripple. As a result, inrush current ripples can damage the devices.

The conventional boost converter is used to increase the DC voltage applied to the input and obtain high voltage at the output. Circuit structure consists of a coil that stores energy in a magnetic field, a semiconductor switching element that switches at high frequency, and a fast diode. In addition, boost converter is widely used in industry due to its natural compatibility with power factor correction circuits (Ozdenturk and Akkaya, 2020;).

The duty cycle D is increased to obtain high output voltage in conventional DC-DC boost converters. However, increasing duty cycle D too much causes high current ripple, lower efficiency and difficulty in control (Bodur et al., 2020; Bodur et al., 2013).

The boost converter has nonlinear voltage as shown in Figure 1. The voltage gain increases from 0 to the optimum point D_{opt}. Higher duty cycle than D_{opt} results in less output power and lower efficiency (Upadhyay and Kumar, 2019).

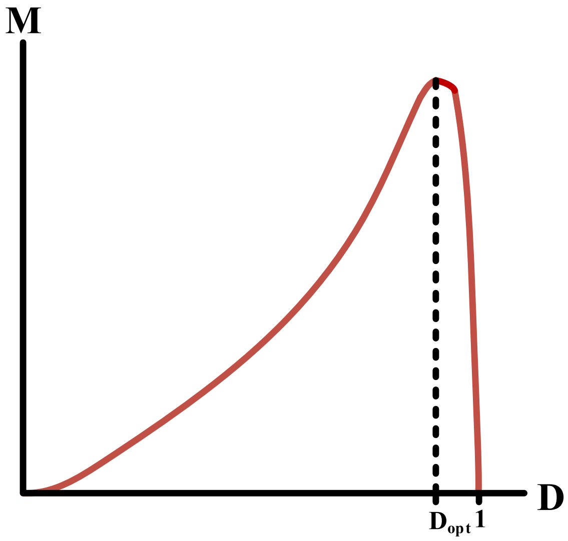


Figure 1:
Conventional Boost Converter's Gain(M) – Duty Cycle (D) Graph.

In the conventional boost converter, as the duty cycle increases, the switching element conducts for a longer period, while the conduction time of the diode becomes shorter. Thus, inductor current ripple increases. Today, this drawback resulted the duty cycle limit feature to appear in boost converter controllers (Zhang and Park, 2022; Tarzamni et al., 2023).

Two-stage circuits have been proposed to solve the duty cycle problem in the boost converter. Although two-stage circuits have high regulation quality, efficiency is low because the power is processed twice. These circuits have high dynamic response time, high cost and complex circuit structure. (Isilay, Haci and Abdulkerim, 2022).

In order to achieve high voltage-gain and overcome duty cycle limitations, a two-stage boost converter proposed in this paper. Also, a common stage control is used to provide simplified circuit structure, reduced costs, fast transient response and higher power density.

The converter is obtained by using two-series converter in a cascade structure. The gain of the converter improved. Since power is processed twice, power losses increased. As a matter of fact, the gain of the circuit increased at the expense of decreasing power efficiency. (Navamani et al., 2018)

Circuit structure is given in Figure 2.

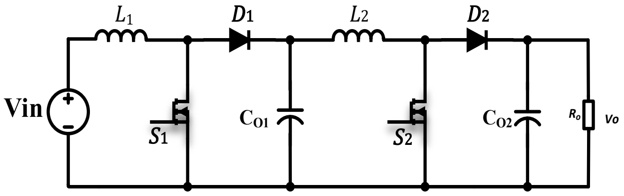


Figure 2:
Two-Stage Boost Converter.

2. MATERIAL AND METHODS

2.1. Control Method

The conventional two-stage boost converter uses two separate controllers for each stage as shown in Figure 3. The controls are independent of each other and each stage is controlled according to its own output voltage as proposed (Gragger et al., 2008; Siouane et al., 2019; Aamir and Shinwari, 2010). Thus, the converter stages are separately designed.

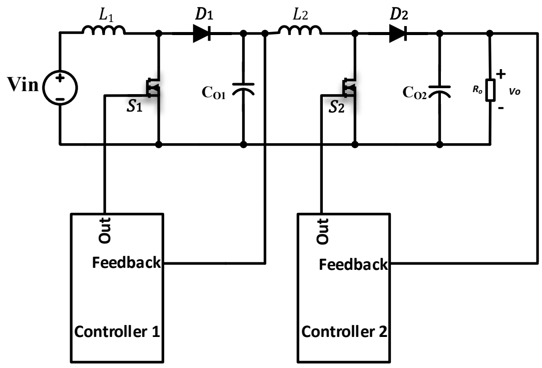


Figure 3:
Traditional Control Method of Two-Stage Boost Converter.

In this paper control for Stage 1 and Stage 2 are combined so that single controller is used instead of two separate controllers. In proposed control method, feedback received from output voltage of the Stage 2 and the voltage gain ratio of the two converter stages are same, so the duty cycles gets equal. This method simplifies the control and provides lower cost by reducing the number of controllers and components. Furthermore it provides fast response thanks to single feedback loop. Suggested control structure diagram is given in the Figure 4 below.

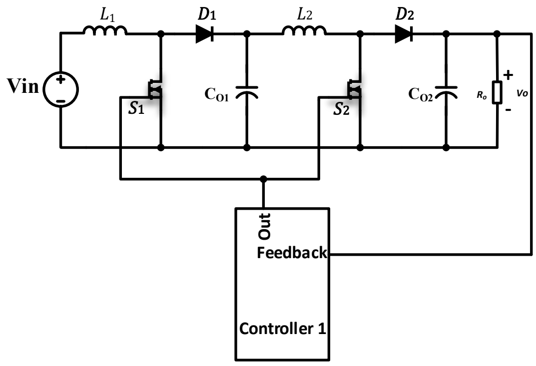


Figure 4:
Proposed Control Method of Two-Stage Boost Converter.

2.2. Operating Principles and Analysis of Proposed Converter

The proposed two stage boost converter is given in Figure 5 below.

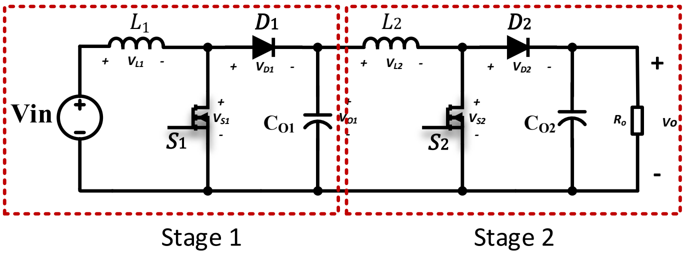


Figure 5:
Proposed Two–Stage Boost Converter.

The following equations have been used while performing the proposed converter analysis.

1. S_1 and S_2 are the switches of the converter.
2. $D_1$and D_2 are the output diodes of the converter.
3. $C_{O1}$and C_{O2} are the output capacitors of each converter stages.
4. L_1 and L_2 are the boost inductances of each converter stages.
5. V_{in} is the input voltage and V_o is the output voltage.
6. Semiconductor power devices are ideal.
7. The input voltage and output voltages are constant over a switching period.
8. Converter operates in boundary conduction mode.

The proposed converter has 2 operating intervals. The key waveforms for each stage are given in Figure 6 and Figure 7 below.

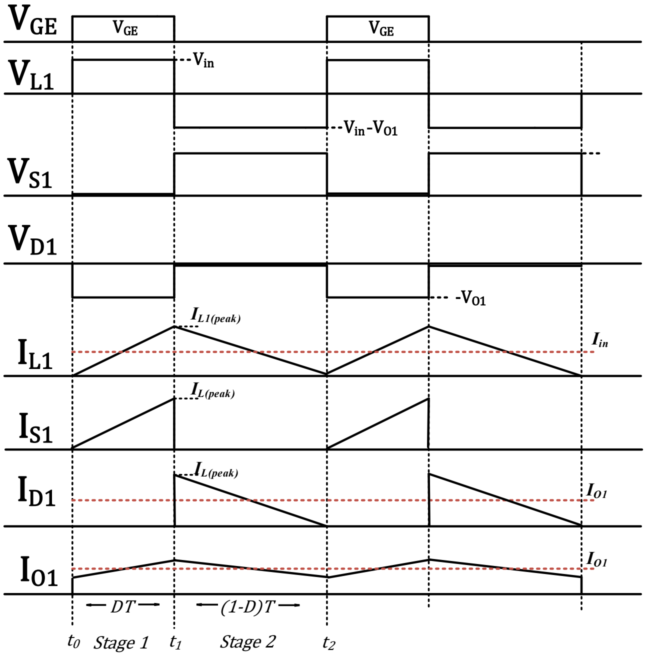


Figure 6:
Waveforms of the Stage 1 of the Converter.

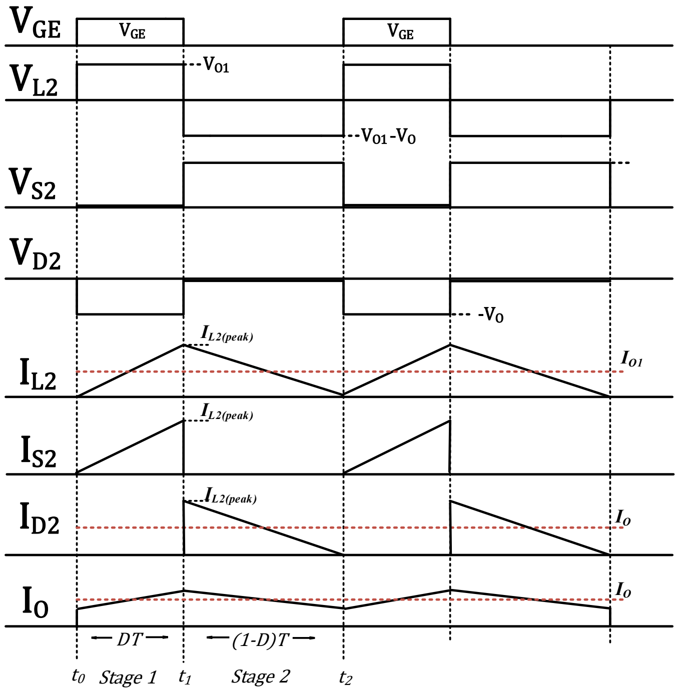


Figure 7:
Waveforms of the Stage 2 of the Converter.

Mode 1: PWM On Interval ($t_0 - t_1$) (Figure 8)

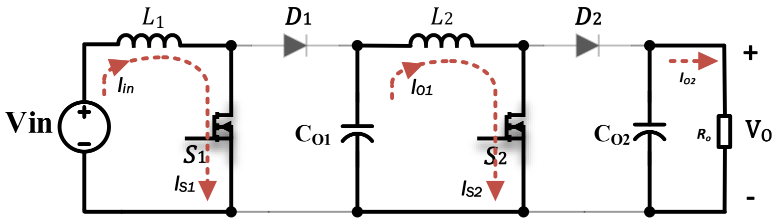


Figure 8:
Conduction Mode of the Converter.

The gate signals of the switch S_1 and S_2 are applied at $t = t_0$. Voltage V_{in} is applied on L_1 and voltage V_{O1} is applied on L_2. I_{in} and I_{O1} starts to increase linearly. S_1 current I_{S1} is equal to I_{in} and S_2 current I_{S2} is equal to I_{O1}. In this time interval, the output current of each stage separately is supplied from $C_{O1}$and C_{O2} capacitors.

Mode 2: PWM Off interval ($t_1 - t_2$) (Figure 9)

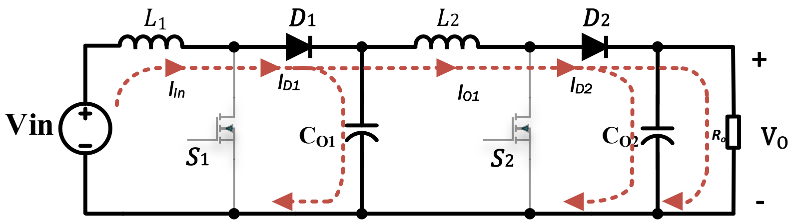


Figure 9:
Cut-Off Mode of the Converter.9

In the t_1 - t_2 time PWM off interval, the gate signals of the switches are removed. The energy stored in the inductances are transferred to the outputs. In this time interval, a voltage of $V_{in} - V_O$ is applied to inductor L_1 and a voltage of $V_{O1} - V_O$ applied to inductor L_2.

Following equations are valid for the converter.

$$I_{in} = I_{L1} \quad (1)$$

$$I_{S1} = I_{L1} x D \quad (2)$$

$$I_{O1(av)} = I_{D1(av)} = I_{L1}\, x\, (1 - D) \quad (3)$$

$$I_{O1(av)} = I_{L2} \quad (4)$$

$$I_{S2} = I_{L2} x D \quad (5)$$

$$I_{O2(av)} = I_{D2(av)} = I_{L2}\, x\, (1 - D) \quad (6)$$

2.3. Converter Design Considerations

The design parameters of the converter are given in Table 1.

Table 1. Converter Design Parameters.

Parameter	Value
Input Voltage	12 V_{DC}
Output Voltage of Stage 1	42 V_{DC}
Output Voltage of Stage 2	150 V_{DC}
Switching Frequency	50 kHz
Output Power	100 Watt

2.4. Duty Cycle Consideration

The output voltages are obtained as below where D_1 and D_2 are duty cycle for stage 1 and stage 2 respectively.

Following equations are valid while determining of the duty cycle.

$$V_{O1} = V_{in}\frac{1}{1-D_1} \tag{7}$$

$$V_O = V_{O1}\frac{1}{1-D_2} \tag{8}$$

$$V_O = \frac{V_{in}}{(1-D)^2} \tag{9}$$

By selecting voltage gain of Stage 1 V_{O1}/V_{in} and voltage gain of Stage 2 V_{O2}/V_{O1}, the duty cycles D_1 and D_2 get equal as below.

$$D_1 = \frac{V_{O1}-V_{in}}{V_{O1}} = 0.71 \tag{10}$$

$$D_2 = \frac{V_O-V_{O1}}{V_O} = 0.71 \tag{11}$$

2.5. Inductor Design

The proposed converter is operated with critical conduction mode. Waveforms are given in Figure 10.

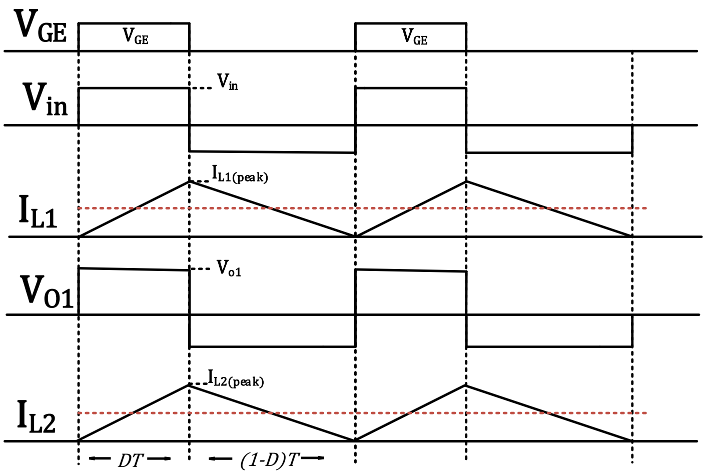


Figure 10:

Inductor voltage – current waveforms when the converter was operating in boundary conduction mode.

Following equations are valid for Stage 1.

$$V_{L1} = L_1 \frac{di}{dt} = L_1 \frac{I_{L1(peak)}}{DT} \quad (12)$$

$$I_{L1(peak)} = 2I_{L1} = 2I_{in} \quad (13)$$

$$V_{L1} = V_{in} \quad (14)$$

$$L_{1(critical)} = \frac{V_{in}DT}{2I_{in}} \quad (15)$$

The boost inductance of Stage 1 $L_{1(critical)}$ is obtained in (15).

Following equations are valid for Stage 2. The boost inductance of Stage 2 $L_{2(critical)}$ is obtained in (19).

$$V_{L2} = L_2 \frac{di}{dt} = L_1 \frac{I_{L2(peak)}}{DT} \quad (16)$$

$$I_{L2(peak)} = 2I_{L2} = 2I_{O1} \quad (17)$$

$$V_{L2} = V_{O1} \quad (18)$$

$$L_{2(critical)} = \frac{V_{O1}DT}{2I_{O1}} \quad (19)$$

Input power is obtained below assuming that the efficiency of Stage 1 and Stage 2 n_1 and n_2 as 0.95.

$$P_{O2} = n_1 x\, n_2 x P_{in} = 100\, Watt \quad (20)$$

$$P_{in} = 110.8\, Watt \quad (21)$$

If $V_{in(min)}$ is chosen as 9 V_{DC}, the maximum input current I_{in} is obtained as below.

$$I_{in} = \frac{P_{in}}{V_{in(min)}} = \frac{110.8}{9} = 6\, Amperes \quad (22)$$

The converter operates with max. duty cycle D when input voltage gets minimum. Thus, max. duty cycle D is calculated as below.

$$D_1 = \frac{V_{O1} - V_{in(min)}}{V_{O1}} = 0.72\, max \quad (23)$$

Ripple current of the inductance is equal to its peak value in critical conduction mode boost converter. Thus, peak value of the inductance for Stage 1 is calculated as below.

$$\Delta I_{L1} = I_{L1(peak)} = 2I_{in} = 12\, Amperes \quad (24)$$

Then, the critical inductance value of Stage 1 $L_{1(critical)}$ is calculated as below.

$$L_{1(critical)} = \frac{V_{in}DT}{2I_{in}} = 14.4\ uH \qquad (25)$$

Using the equations 26-32, stage 2 critical inductance $L_{2(critical)}$ is calculated. First, the power in stage 1 is calculated with equation 26. Using stage 1 output power, I_{o1} current calculated with equation 27. The ripple value of the current is equal to twice the output current of stage 1 in equation 28. Since the control is common, the duty is taken equal in equation 29 and average current of L_2 inductance is equal to stage 1 output current in equation 30. Then the value of, L_2 inductance is given in equation 31.

$$P_{O1} = n_2 x P_{in} = 105.3\ Watts \qquad (26)$$

$$I_{O1} = \frac{P_{O1}}{V_{O1(min)}} = \frac{105.3}{41.9} = 2.5\ Amperes \qquad (27)$$

$$\Delta I_{L2} = 2I_{O1} = 5\ Amperes \qquad (28)$$

$$D_2 = \frac{V_O - V_{O1(min)}}{V_{O1(min)}} = 0.72\ max \qquad (29)$$

$$I_{O1(av)} = I_{L2} \qquad (30)$$

$$L_{2(critical)} = \frac{V_{O1}DT}{2I_{O1}} = 121\ uH \qquad (31)$$

Since DCM operation provides zero soft switching turn on for the switches and soft switching turn-off for the boost diodes and easy control, the prototype is operated in discontinuous conduction mode (DCM (Koc et al., 2022).

2.6. Control Design

In this work, conventional two stage boost converter and proposed two stage boost converter are operated under same conditions and compared with each other. In conventional two stage boost converter, output voltages of the two sateges are controlled separately. The voltage feedback of each stage is measured and substracted from a reference voltage to produce an error voltage. The gate signal is produced by comparing the error voltage with the saw signal. The control structure is shown in Figure 11.

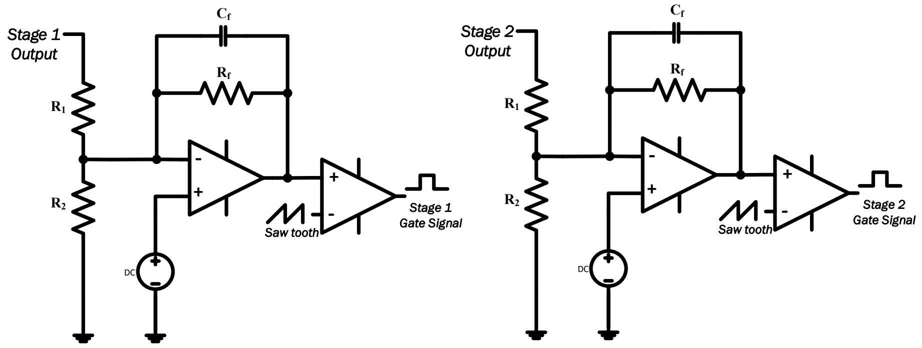


Figure 11:
Separate-stage controlled boost converter control circuit.

Common stage controlled control circuit is given in Figure 12. The voltage feedback received from Stage 2, both stages were controlled with the common gate signal. The voltage feedback sensed from output of the Stage 2 is subtracted from a reference voltage by error amplifier to produce an error and compared with the sawtooth signal to obtain PWM control signals.

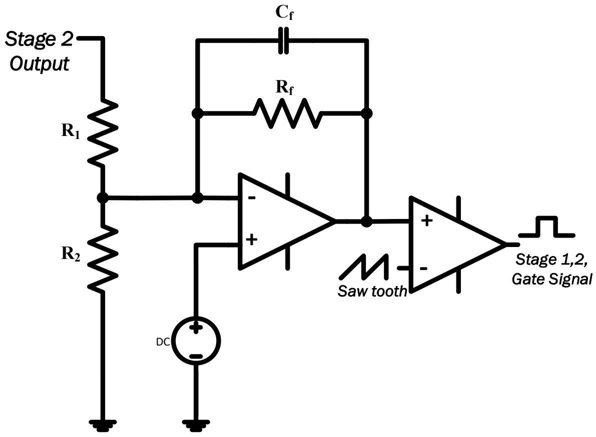


Figure 12:
Common stage controlled boost converter control circuit.

3. PROTOTYPE RESULTS

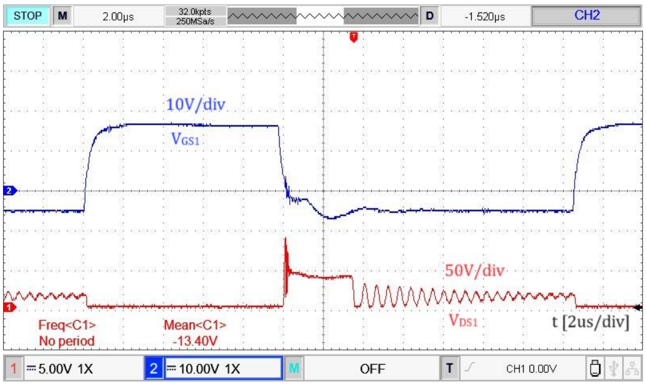
Prototype results of a two stage boost converter with separate and common control are examined in this section. Theoretical analyses have been verified with a DC-DC two stage boost converter application having input voltage of 12 V_{DC}, output voltage of 150 V_{DC}, and output power of 100 W.

Prototype design parameters given in Table 2 below.

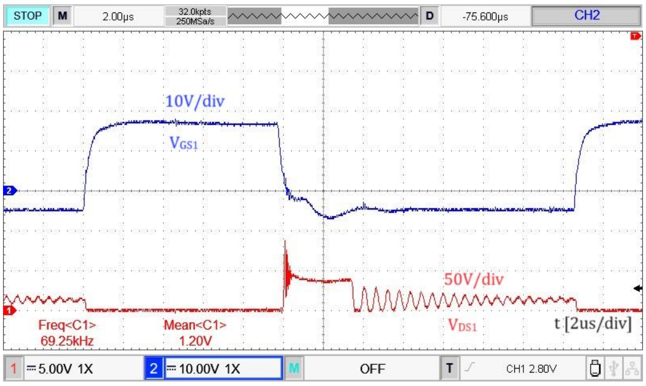
Table 2. Converter Design Parameters.

Parameter	Value
Inductance of Stage 1	3uH
Inductance of Stage 2	50uH
Output Capacitor of Stage 1	2000uF
Output Capacitor of Stage 2	1000uF

Figure 13 a,b, shows the stage 1 gate-source and drain-source voltages of the separately controlled and common controlled two stage boost converter. Channel 1 signal is the drain-source voltage and measured with the probe at 10x. Channel 2 signal is the gate-source voltage and is kept negative when the switch is on. The reason for this is to prevent the switch from uncontrolled turn-on due to miller capacitance.



(a)

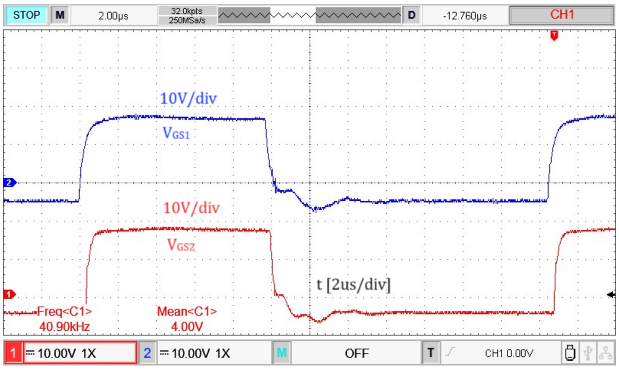


(b)

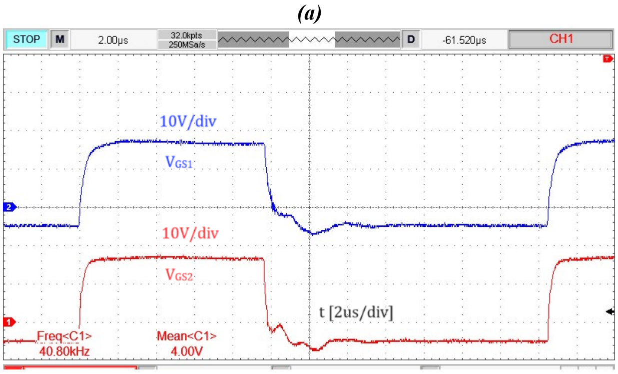
Figure 13:
Gate – Source and Drain – Source voltages of stage 1 of (a) separate controlled (b) common controlled boost converter.

Figure 14 a,b, shows the gate-source signals of the two circuits. Channel 1 is the gate-source voltage of stage 2 and channel 2 is the gate-source voltage of stage 1. It can be observed that the gate-source voltage of Stage 2 is delayed in separate controlled converter.

Figure 14b shows that Stage 1 and stage 2 gate signals of the common controlled boost converter are the same because the control is common. The duty cycles of the stages are equal and the gate signals are applied simultaneously.



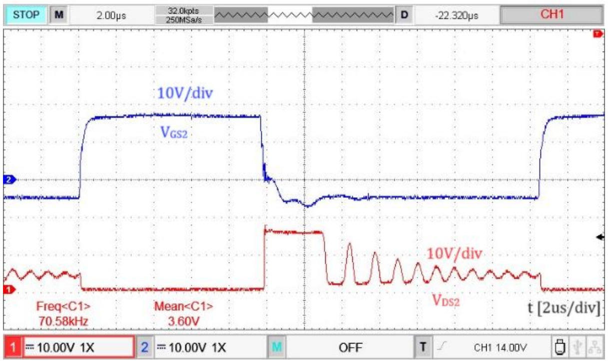
(a)



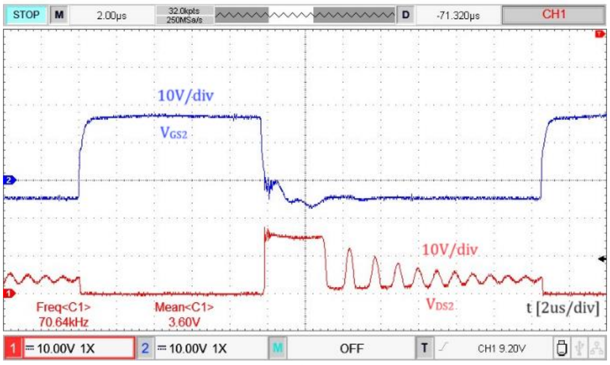
(b)

Figure 14:
Gate – Source voltages of stage 1 and stage 2 of (a) Separate controlled and (b) Common controlled two stage boost converter.

Figure 15 a,b, shows the gate-source and drain-source voltages of stage 2 of the two different controlled circuit.



(a)

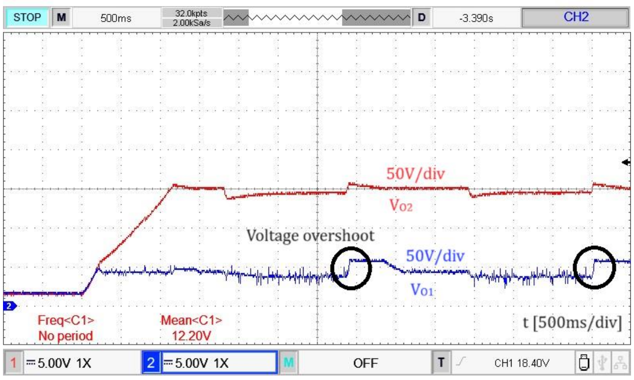


(b)

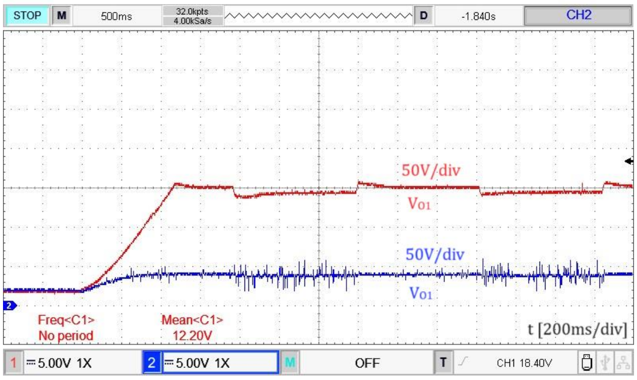
***Figure 15**:*
Gate – Source and Drain – Source voltages of stage 2 of (a) separate and (b) common controlled two stage boost converter.

The output voltage of stage 1 and stage 2 of the two stage boost converter with separate and common control is given in Figure 16 (a) and (b) respectively.

The load is switched on and off. As seen in Figure 16 (a) traditional controlled converter Stage 1 output voltage has voltage overshoot, while the converter using proposed converter doesn't have any voltage overshoot at Stage 1 output voltage. This is the significant advantage of common controlled boost converter. Thus, the lower voltage withstand capacitor can be used at the stage 1 output, resulting in reduced cost and increased power density. When the load is switched off in a separately controlled two stage boost converter, stage 1 tries to regulate itself because the control structure is separate. When the load was switched off, the voltage overshoot is observed in stage 1 voltage since there was no power transfer from stage 1 to stage 2 at this instant. In two-stage control, the feedback signal of stage 2 acts as the feedforward signal for stage 1 and prevents overshoot.



(a)

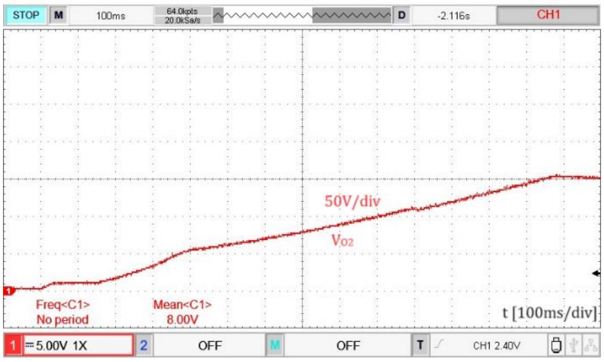


(b)

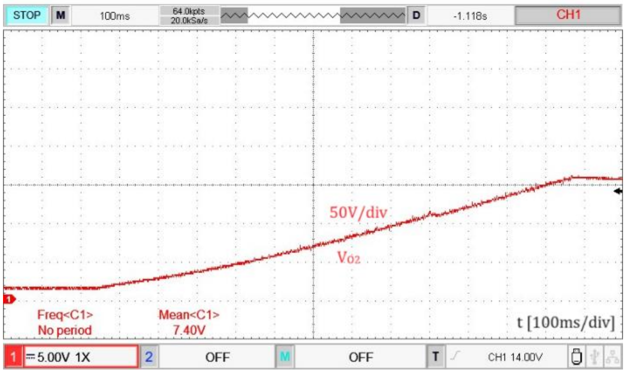
Figure 16:
Output voltages of stage 1 and stage 2 of (a) separate and (b) common controlled boost converter.

The soft start feature in the output voltages of the separate and common controlled boost converter can be seen in Figure 17 (a), (b), respectively.

During soft start, two-stage boost converter with separate control was better regulated.



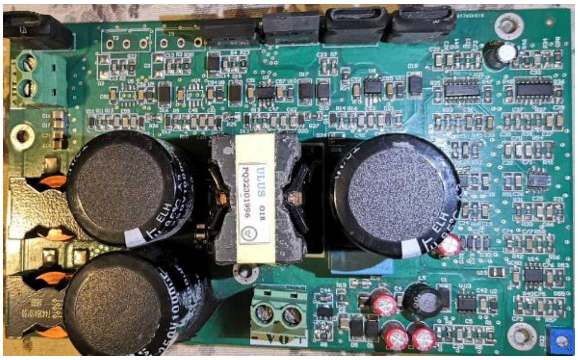
(a)



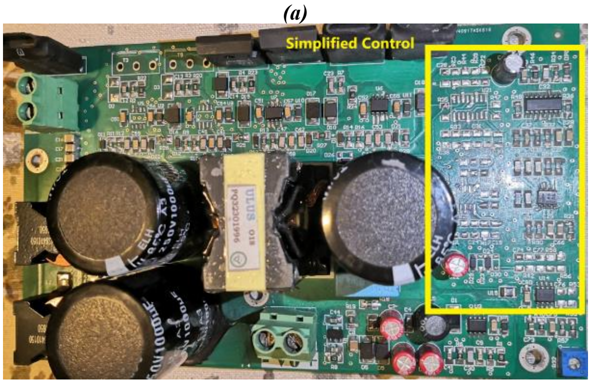
(b)

Figure 17:
Output voltage of (a) separate and (b) common controlled boost converter during soft start process.

The number of components and the cost reduction are shown in Figure 18 (a) and (b) below.



(a)



(b)

Figure 18:

Prototype circuit of (a) separate and (b) common controlled boost converter.

Separate and common stage control compared at below in Table 3. Proposed control has advantages in terms of power density, natural soft-start, regulation quality, transient response and voltage overshoot.

Table 3. Separate and Common Stage Control Comparison

Control Type	Separate Stage Control	Common Stage Control
Power Density	Bad	Good
Cost	Bad	Good
Efficiency	Normal	Normal
Soft-Start	Normal	Good
Regulation Quality	Normal	Good
Transient Response	Normal	Fast
Voltage overshoot of Stage 1 Output Capacitor	Low	High

4. DISCUSSION AND CONCLUSION

A two stage boost converter with improved control is proposed in this paper. Proposed converter uses single controller instead of two separate controllers compared to the conventional two stage boost converters. The proposed control method provides simplified control, reduced cost, fast transient response and higher power density. The voltage overshoot of the output capacitor in stage 1 of the proposed converter reduced compared to the conventional two stage boost converter. The detailed theoretical analysis are carried out and verified with prototype having 12 V_{DC} input voltage, 150 V_{DC} output voltage and 100 W output power. The results are compared with the conventional two stage boost converter.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTION

Mustafa SENTURK: Configuration of paper, Literature Review, Theoretical Analysis, Writing
Huseyin Yesilyurt: Prototype design, Experimental Investigation, Editing,

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