An efficient switched-mode power supply using a quadratic boost converter and a new topology of two-switch forward converter

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Resumo

Este trabalho propõe uma topologia de conversor *Forward* a duas chaves associada a um conversor Boost quadrático, que apresenta a característica de ampla elevação da tensão de entrada, ou seja, de 12V para 80V. A combinação destes estágios resulta em uma fonte chaveada em que as tensões de saída são +200V e -200V. A operação dos conversores é analisada e resultados são apresentados para validar a proposta.

Palavras-chave: *Conversor forward a duas chaves. Fontes chaveadas.*

Abstract

This paper presents a topology of two-switch Forward converter associated with a quadratic Boost converter, which provides large voltage step-up (from 12V to 80V). The combination of the stages results in a switched-mode power supply (SMPS) whose output voltages are +200V and -200V. The operation of both converters is analyzed, as some results concerning the proposed SMPS are presented.

Keywords: *Two-switch forward converter. SMPS.*

1 Introduction

In dc/dc conversion applications that demand a large range of input or output voltages, conventional PWM converters must operate at extremely low duty cycle ratios, what limits the operation to lower switching frequencies because of the minimum on-time of the transistor switch (Maksimovic and Cuk, 1991). This problem is eliminated with the proposal of a new class of single-switch PWM converters featuring voltage conversion ratios with quadratic dependence on the duty cycle (Maksimovic and Cuk, 1991). The quadratic Boost converter in Fig. 1 can be used in large voltage step-up applications, since the dc voltage conversion ratio (i.e. static gain) is given by $M(D)=D/(1-D)^2$. However, high EMI levels result, because the switches do not present auxiliary commutation. Although a soft-switched structure has been presented by Barreto *et al* (2002), which is recommended for the replacement of low frequency transformers in cases where the weight and/or volume may be a limitation to the implementation of UPS systems, it employs two additional auxiliary soft commutation cells, causing the number of components and control complexity to increase. In this specific case, the hard-switched topology is perfectly suitable to be employed as a preliminary so-called voltage step-up stage.

To obtain an isolated power supply, two-switch Forward converters are one of the most suitable topologies since the power switches need to block only the supply voltage instead of twice or more times the supply voltage as in flyback or single-ended Forward converters (Jacobson et all, 1989 and Petersen, 2000). This is a particularly interesting benefit for power MOSFET's once that the on-resistance increases exponentially with breakdown voltage. Further, at turning off, there is no leakage inductance spike.

Although there are a number of bipolar transistors and MOSFET's with high voltage ratings which can take that stress, it is a far more reliable design to use the double-ended Forward converter with half the off-voltage stress. Reliability is of overriding importance in a power supply design, and in any weighing of reliability versus initial cost, the best and, in the long run, least expensive choice is reliability. Therefore, two-transistor forward converter is more reliable and attracted attention of great research, but this topology has drawback of hard switching and single quadrant operation of transformer (Ghodke and Muralikrishnan, 2002, and Xu et all, 1999).

A new topology of two-transistor Forward converter, shown in Fig. 2, using two primary windings, is proposed in this paper. It employs an additional switch that operates with twice the switching frequency of the main switches, in order to promote the transformer reset, as a reset winding is not necessary, reducing weight and volume.

Another goal of this work is the development of a switched-mode power supply (SMPS) where the dc input voltage is low and the dc output voltage is quite high. The aforementioned structure can be used in such application, as shown in Fig. 3.

A dissipative snubber, shown in Fig. 4 is added in parallel with switches *S1* and *S2* in order to limit *di/dt* and *dv/dt* rates in the devices, keeping them within their safe operating areas and reducing the switching power losses (Tardiff and Barton, 1989). In this case, conventional RCD snubbers are preferable instead of nondissipative ones, because of the simplicity of design and implementation, once that the high efficiency issue is not the main propose of this work. Since no inductors are employed in the snubber, the weight and volume are reduced and the power density is increased considerably (Finney et all, 1993).

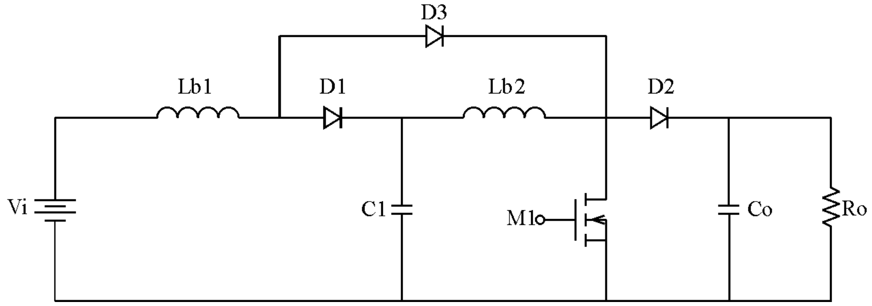


Fig. 1: Quadratic boost converter.

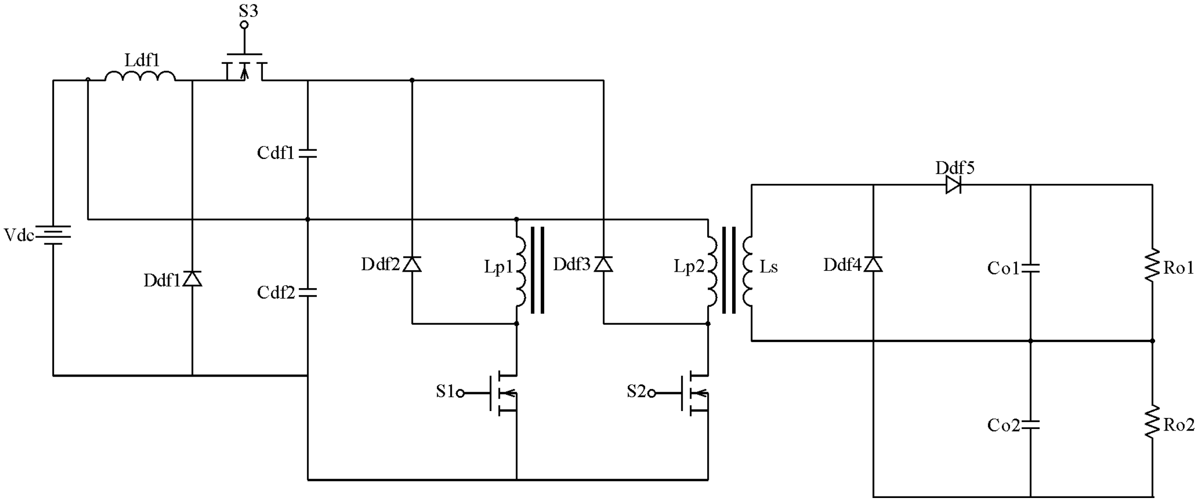


Fig. 2: Two-switch Forward converter.

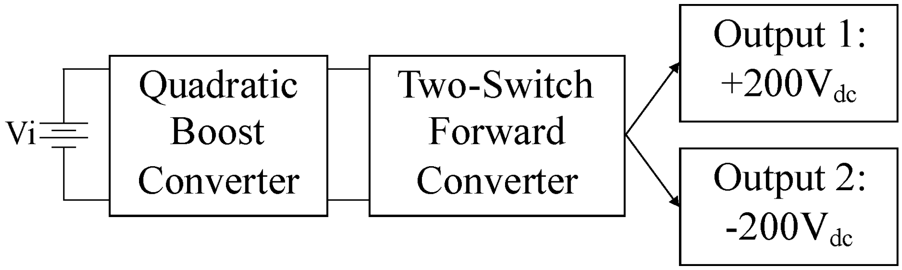


Fig. 3: The proposed SMPS.

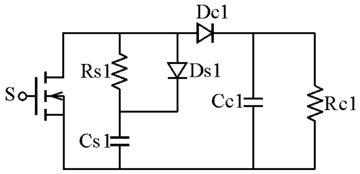


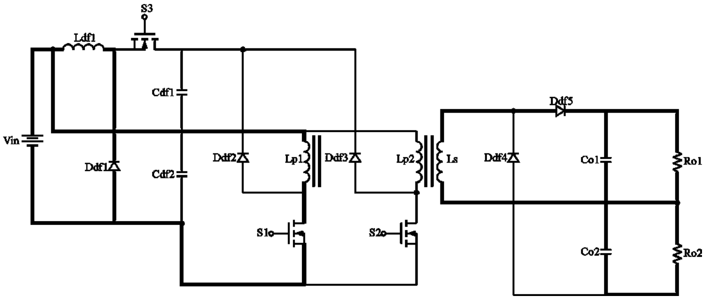
Fig. 4: Snubber employed in switches S1 and S2.

2 Two-Switch Forward Converter

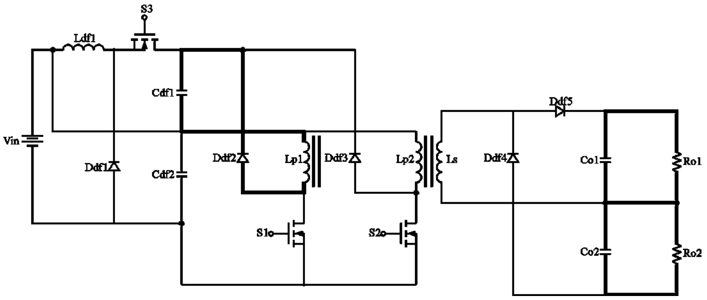
The quadratic Boost converter has been intensively studied by Barreto et al (2002), and it is not necessary to describe its operation once again. Therefore only the analysis of the two-switch Forward converter shown in Fig. 2 is supposed to be presented in this paper. The voltage gain provided by the converter is (Vo/Vi)=2•D•N, where D is the duty cycle and N is the transformer ratio, respectively.

The operation of the Forward converter can be divided in six stages. As the behavior of switches *S1* and *S2* is analogous, only three stages will be analyzed, according to Fig. 5, as Fig. 6 shows the theoretical waveforms.

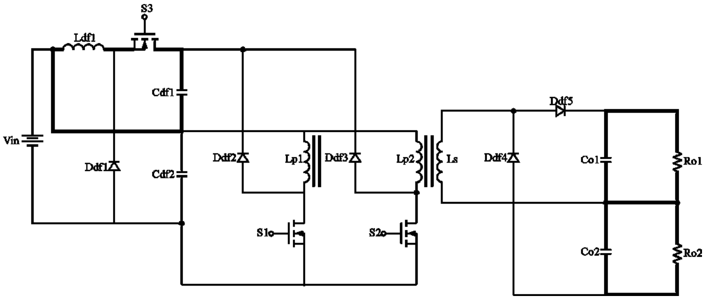
- First stage [t_0, t_1] – switch S1 turning on (Fig. 5 (a)): When switch *S1* is turned on and switch *S3* is turned off, the energy transfer from source to load begins. In this stage, diode *Ddf4* is reversely biased. This interval is determined by the duty cycle imposed to the switch. At the beginning of this stage, capacitor *Cdf1* is charged to the input voltage V_{dc}.
- Second stage [t_1, t_2] – switch S1 turning off (Fig. 5 (b)): When switch *S1* is turned off, the energy stored in the leakage and magnetizing inductances is transferred to capacitor *Cdf1* via diode *Ddf2*.
- Third stage [t_2, t_3] – switch S3 turning on (Fig. 5 (c)): Switch S1 remains turned off, and switch S3 must be turned on until the whole energy stored in capacitor *Cdf1* is transferred to inductor *Ldf1*.



(a) First stage



(b) Second stage



(c) Third stage

Fig. 5: Operating stages of the two-switch Forward converter.

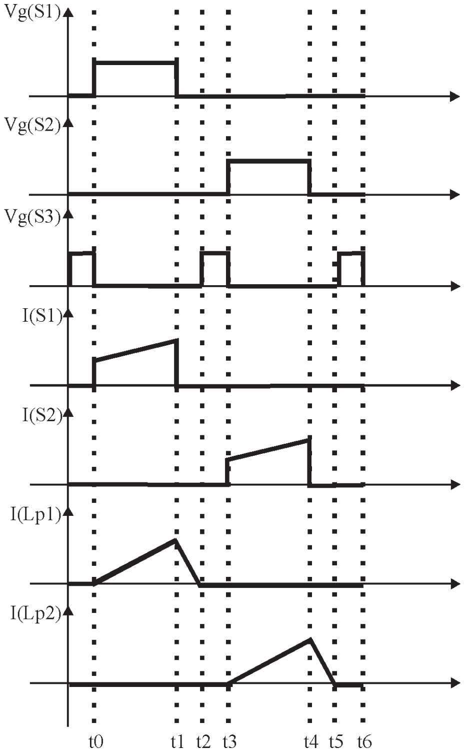


Fig. 6: Main theoretical waveforms.

3 Simulation and experimental results

Simulation tests have been carried out on the quadratic Boost converter shown in Fig. 1, using the parameters set presented in Table 1. In this case, a battery is used as the supply voltage *Vi*, instead of the utility voltage rectified by a diode bridge. Fig. 7 shows some simulation results regarding the operation of the converter under the conditions stated below.

Experimental results were also obtained for a prototype built with the same parameter set. Diodes *D1*, *D2* and *D3* are HFA08TB60 and switch *M1* is IRFP260, as the waveforms are represented in Fig. 8.

The parameter specifications of the two-switch Forward converter shown in Fig. 2, using the RCD snubber presented in Fig. 4, are summarized in Table 2.

Fig. 9 shows some simulation results regarding the operation of the converter under the conditions stated below. Fig. 9 (a) presents the relevant waveforms for switch *S1*. Fig. 9 (b) represents the output voltages, which are obtained considering balanced loads.

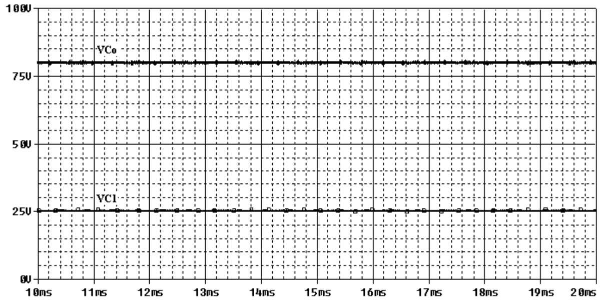
Experimental results from a laboratory prototype were obtained for the two-switch forward converter. Diodes are HFA08TB60 and switches *M1* are IRFP260. Fig. 10 shows the switching detail with and without the use of the RCD snubber, where it can be seen in Fig. 10 (a) that the power dissipation area corresponding to the switching losses is much greater than that in Fig. 10 (b).

Fig. 11 illustrates soft-commutation in switch *S1*. As it can be noticed, it is turned on and off in ZCS and ZVS modes, respectively. Fig. 12 depicts the output voltages obtained with the proposed Forward topology.

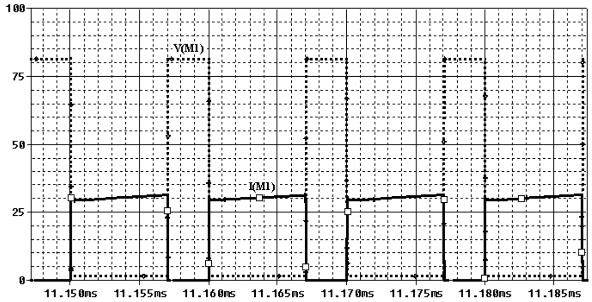
Finally, Fig. 13 represents the efficiency of the SMPS as a function of the output power, which is about 86% at rated power.

Table 1: Parameters set employed in the quadratic Boost converter

Parameter	Value
Lb1, Lb2	100µH
C1, Co	100µF
Diodes D1, D2, D3	Ideal
Switch M1	Ideal
Switching frequency	100kHz
Input voltage	12V
Output voltage	80V
Output power	300W

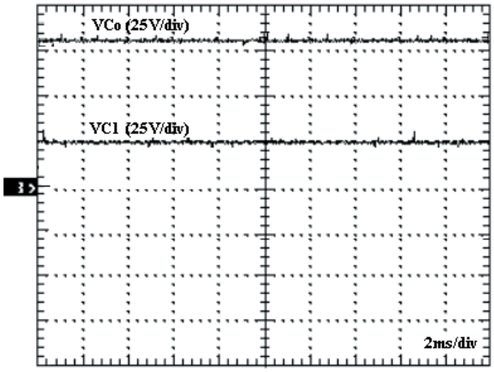


(a) Voltage across capacitor C1 and output voltage

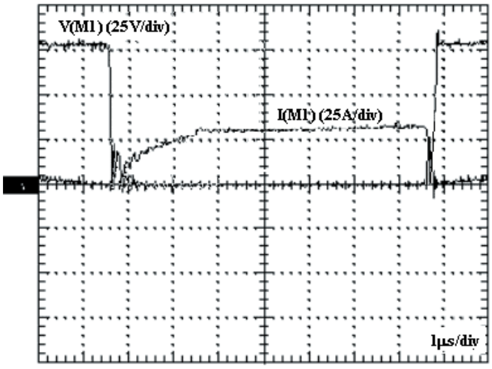


(b) Current and voltage waveforms regarding switch *M1*

Fig. 7: Simulation results obtained for the quadratic Boost converter.



(a) Voltage across capacitor C1 and output voltage



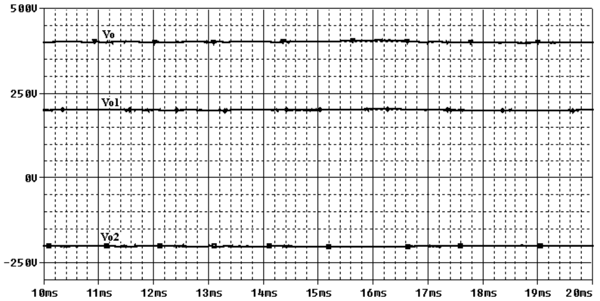
(b) Current and voltage waveforms regarding switch *M1*

Fig. 8: Experimental results obtained for the quadratic Boost converter.

Table 2: Parameters set employed in the two-switch forward converter

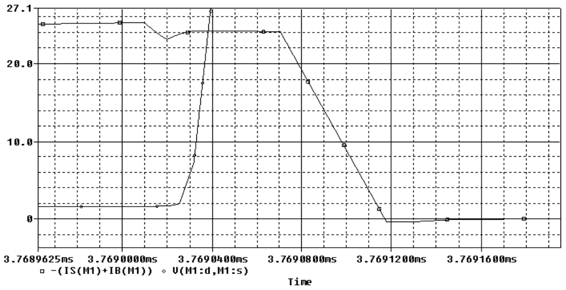
Parameter	Value
Ldf1	100μH
Lp1, *Lp2*	80μH
Ls	1mH
Cdf1	1μF
Cdf2	100μF
Co1, *Co2*	30μH
Diodes *Ddf1*, *Ddf2*, *Ddf3*, *Ddf4*, *Ddf5*	Ideal
Switches *S1*, *S2*, *S3*	Ideal
Switching frequency – *S1* and *S2*	50kHz
Switching frequency – *S3*	100kHz
Input voltage	80V
Output voltages	+200V, -200V
Output power	300W

(a) Current and voltage waveforms regarding switch *S1*

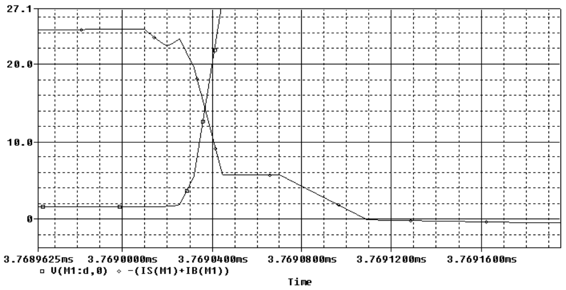


(b) Output voltages

Fig. 9: Simulation results obtained for the two-switch Forward converter.



(a) Without snubber



(b) With snubber

Fig. 10: Switching detail in switch *S1*.

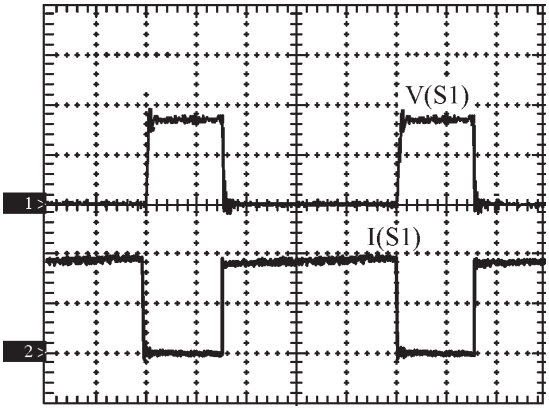


Fig. 11: Current and voltage waveforms regarding switch *S1*.
Scales: *V(S1)*=100V/div.; *I(S1)*=2A/div.; time 1µs/div.

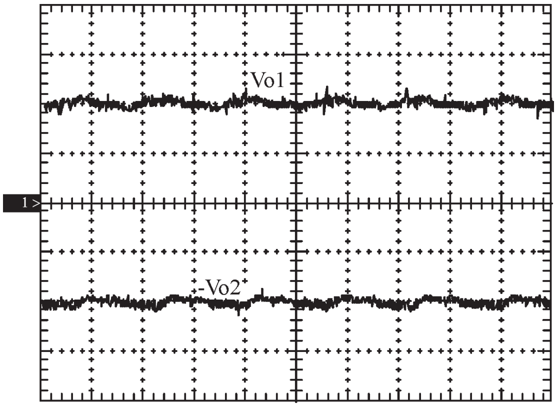


Fig. 12: Output voltages.
Scales: *Vo1*, -*Vo2*=100V/div.; time 5ms/div.

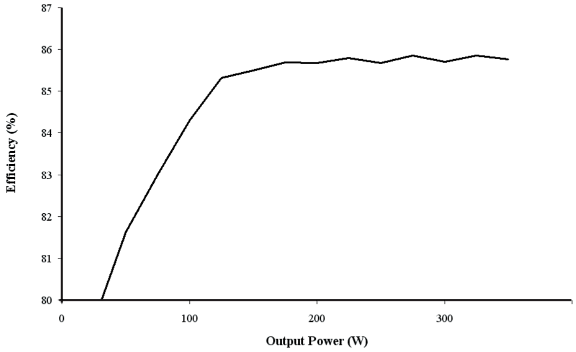


Fig. 13: Efficiency curve of the proposed SMPS.

4 Conclusion

This paper has reported some results regarding a switched-mode power supply with reduced weight, size and complexity. Both structures presented here have been studied, and the operating principles of the Forward topology have been analyzed theoretically. Some relevant data are presented, validating this proposal.

The quadratic Boost converter is an adequate choice as a step-up stage because it provides a significantly high dc/dc conversion ratio. Considering that this converter operates in high switching frequencies, and it presents reduced weight and size, its application becomes feasible in cases where single-stage boost converters are inadequate.

In isolated power supplies, two-switch Forward converters are preferred instead of flyback or single-ended Forward converters because the power switches are submitted to the supply voltage instead of twice or more times the supply voltage.

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