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Analysis, Synthesis and Simulation of Compact Two-channel Boost Converter for Portable Equipments Operating with a Battery or Solar Cell

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Abstract

This paper is intended to help engineers and designers of high power industrial application such as engineers of power systems as well as control engineers and designers of very low power industrial applications such as designers of computer motherboards and other microcomputer circuits supplied from alternative energy sources or battery via boost converters.

Alternative energy source systems such as solar-cells or photovoltaic systems (PV) are progressively becoming more popular. In these applications, it is often required to convert the generated low DC voltage to a higher variable voltage prior to converting it into an AC to be compatible with the electric grid and common appliances. Usually a boost converter is used to step up the d.c. voltage generated at the outputs of such systems [1]. The basic configuration of boost converters usually used for this purpose suffers from some drawbacks just like high ripple in their output

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currents and voltages which increases the losses of the system and makes their control complicated and their response to the variation in the input voltage and load parameters unstable.

To eliminate these drawbacks, this paper introduces a two-channel boost regulator with uncoupled smoothing reactors. Detailed analysis, design, control strategy and simulation have been proposed in this paper to investigate the advantages of using the two-channel connection with uncoupled smoothing reactors.

It has been proved throughout this paper that two-channel configuration of boost converter helps increasing the output power of the converter, filtering out the harmonic content from its output and input, making their control easier and more efficient, increasing the operating frequency of the converter and thus decreasing the size of the components and filters used in the circuit.

Moreover, the paper deals with voltage control strategy that usually used for such systems thus to regulate the boost converter to obtain a robust output current and voltage. Simulation results show that voltage mode control technique provides good current and voltage regulation of boost converters and is more feasible for the chopper up conversion technique of these converters.

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Keywords: Boost converter, uncoupled smoothing reactors, Two-channel and fundamental configuration, voltage mode control.

1. Introduction

The rapidly expanding application and demand for alternative energy resources has increased for last several years. With the development of different efficient technologies associated with the benefits of energy use, the demand for power electronic converters and switching regulators which nearly all of commercial and consumer energy products require has also dramatically increased [2].

One of the most common methods used to increase their efficiency and output power is to use two-channel series or parallel connection of these modules. However, due to the shading that may cover the area, the voltage of these modules falls down and the power is then insufficient. Furthermore, the size of solar cells, the area required for their implementation and the economical cost of such modules, all these parameters increase with the two-channel connection of these cells.

To overcome the drawbacks of PV systems, power electronic converters known as boost converters are often employed. Using DC-DC boost converter with smoothing inductors helps to store energy for longer periods of time and thus to increase the efficiency of the overall system as well as to remove the bad effect of the absence of sunlight and increases the area of usage of solar energy systems with a wide variety of load types [2].

However, the periodic switching of such systems generates harmonic contents in the input and output currents and voltages which increases the losses and makes their control more sophisticated and complex.

In this paper a boost converter with several channels connected in parallel is discussed. This solution may completely remove the ripple generated at the output, increases the power from the converter, improves efficiency and the overall dynamic behaviour as well as increasing the switching frequency and consequently lower the size of reactors. The outputs of the two-channel boost converter are combined through uncoupled smoothing reactors [3].

The equal division of the currents into the individual channels is achieved using voltage mode control which is developed in such a way just to yield a dynamic accuracy in the model and robustness in the load. Control algorithms of such converter are mainly used to determine the duty ratio and triggering PWM signals required to operate the converter switches adequately in its both regimes, uninterrupted and interrupted regimes.

Nomenclature

V_s	Converter supply voltage
V_o	Average value of the converter output voltage across the load
i_l	inductor current
i_s	Source input current
k	switching duty ratio of the converter
T	Operating period of the converter
f	Switching frequency
V_{oref}	Desired value of converter output voltage
$k_{feedback}$	Gain of feedback sensor

2. Conventional two-channel boost converter with uncoupled smoothing inductors

A circuit diagram for a conventional two-channel connection of boost converter with uncoupled reactors L_1 and L_2 is shown in Figure 1. Such converter has two legs connected in parallel, S_1, D_1 and S_2, D_2. They are supplied from solar cells represented by a dc supply V_s and they are turned on differently with a shifting time of T/2. The load is represented by an inductance L_a and resistor R_a. The capacitive filter C is used for filtering of the undesirable ripple in the load voltage v_o and for making it as smooth as possible, V_o [1].

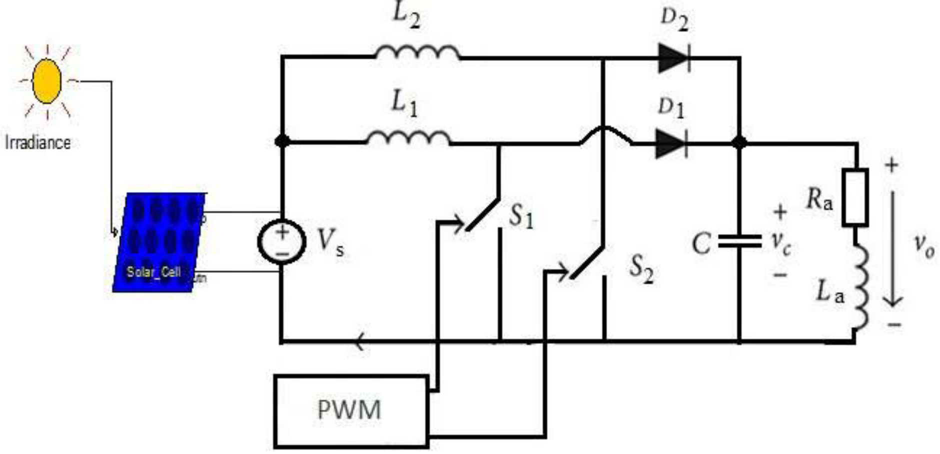


Fig. 1. Double-channel boost converter with uncoupled reactors, (L_1 and L_2).

2.1. Boost Converter Switching Analysis in dc steady state – Fundamental Converter

In order to study dynamic and steady state behaviour of the boost converter, the convertor was simulated and controlled. In this paper, the simulation was conducted using the following technical parameters: switching frequency of 200Hz, reactor's inductance value of 10mH and load resistance of 1Ω. The supply voltage of the converter is about 50V and it operates on a duty time ratio of $k=0.5$. Hence, the mathematical model describing the fundamental configuration behaviour of this converter, which has the switching function waveform as shown in figure 2a, is given for the on-state of its active switch as:

Under steady state conditions and a very small value of the load inductance, the current instantaneous ripple of a channel current Δi_1 is determined from the steep rise respective from the fall down of the reactor current during the on-time respective the off-time of switch S_1. This ripple is obtained as follows [4]:

$$i_1(t)=i_1(0)+\frac{1}{L_1}V_s\,t_{on} \tag{1}$$

In the Off-state of switch S_1, the converter voltages and the reactor current in this channel are related as:

$$-V_s-L_1\frac{di_1}{dt}+V_o=0 \quad\Rightarrow\quad t_{off}=T-t_{on}=\frac{L_1\,\Delta i_1}{V_o-V_s} \tag{2}$$

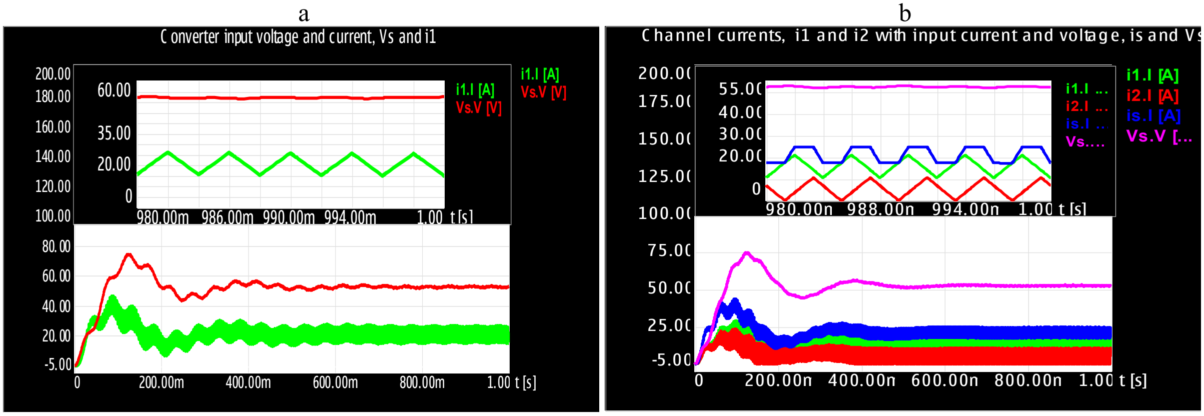
Under steady state conditions, the current instantaneous ripple of a channel current Δi_1 is determined from the steep rise respective from the fall down of the reactor current during the on-time respective the off-time of switch S_1. This ripple is obtained as follows:

$$T=t_{on}+t_{off}=\frac{L_1\,\Delta i_1}{V_s}+\frac{L_1\,\Delta i_1}{V_o-V_s}\Rightarrow\Delta i_1=\frac{V_s\left(V_o-V_s\right)}{fL_1\,V_o}=\frac{k\left(1-k\right)V_o}{fL_1}=\frac{k\,V_s}{f\,L_1} \tag{3}$$

Eq. 3 indicates that the average load voltage V_o should be greater than the supply voltage V_s, otherwise the reactor current would increase indefinitely and the system would be unstable.

2.2. Boost Converter Switching Analysis in dc steady state – Two-channel Converter

Provided that all reactors of two-channel converter have identical inductance values whereas $L_1 = L_2 = L_3 = L$, then the converter input current, i_s, is given as the sum of its channel currents, i_1, i_2 and i_3. Therefore, the instantaneous ripple of the source current i_s of n-channel converter, may be determined again from the steep rise of this current during on-state of one switch and off-state of the remaining (n-1) switches as shown in Figure 2b [4-5].



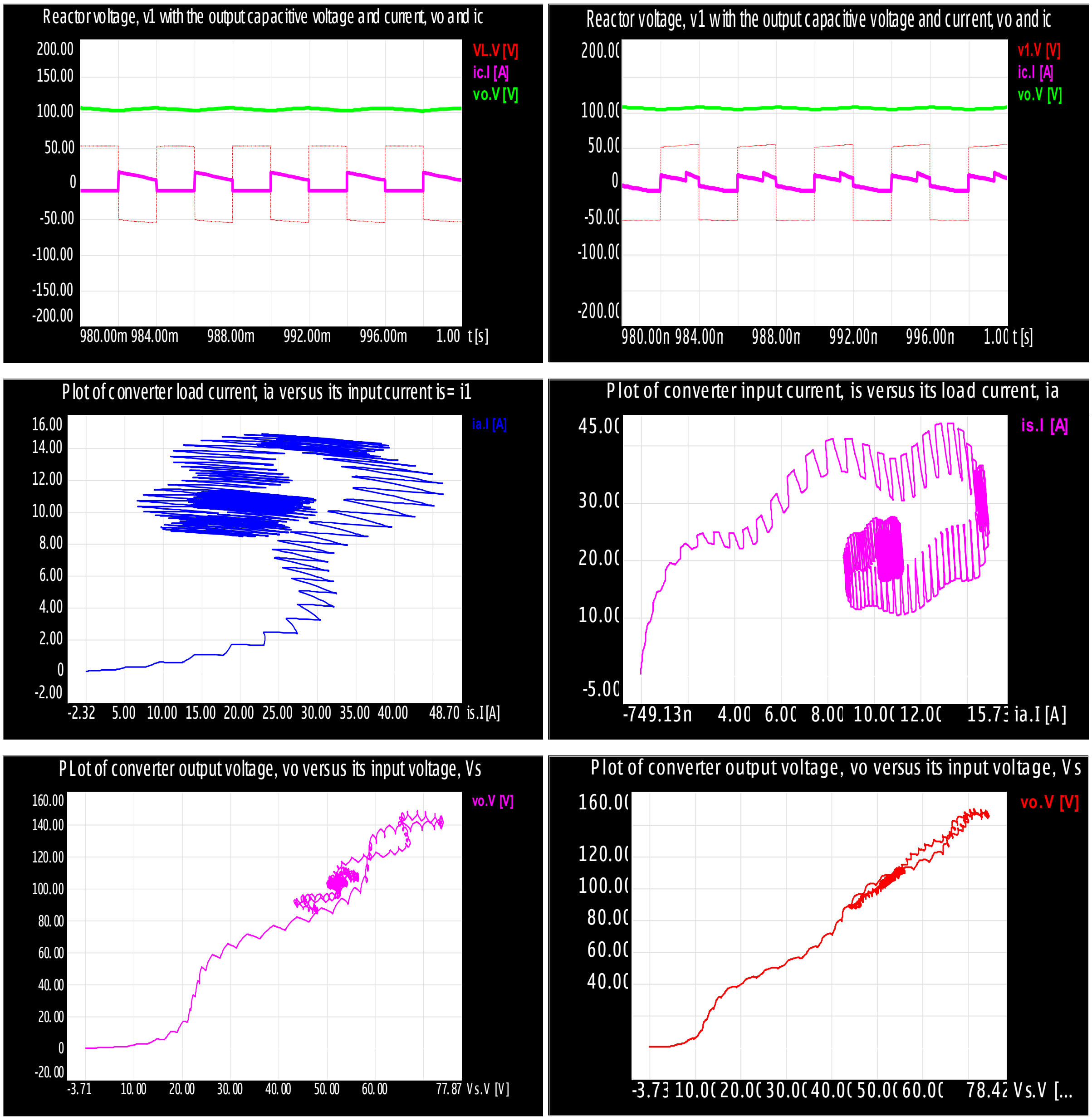


Fig. 2. Current and voltage steady state and transient waveforms of boost converter for k =1/2: (a) fundamental connection; (b) two-channel connection.

Thus, for $0 \le k < 1/2$, the instantaneous ripple of the source current is given as:

$$\Delta i_s = \frac{V_s}{f\,L\left(1-k^2\right)}\left[\left(1-k-2k^2\right)k\right] \tag{4}$$

And for $1/2 \le k < 1$, it yields:

$$\Delta i_s = \frac{V_s}{f\,L\left(1-k^2\right)}\left[1+4k+k^2-2k^3\right] \tag{5}$$

3. Voltage Mode Control Strategy of Boost Converter

Voltage mode control with PWM PI-controller used in this paper comprises a single voltage loop used to adjust the duty ratio which directly depends on the output voltage variations. Application of KVL and KCL to the circuit of the converter, its state-space model will be given as follows:

$$\frac{d}{dt}\begin{bmatrix} i \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{R_a\,C} \end{bmatrix}\begin{bmatrix} i \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{v_o}{L} & \frac{1}{L} \\ -\frac{i}{C} & 0 \end{bmatrix}\begin{bmatrix} k \\ V_s \end{bmatrix} \tag{6}$$

Therefore, the converter input and output transfer functions may be formed as:

$$\frac{k(s)}{i(s)} = \frac{LCs^2 + \frac{L}{R}s + (1-k)^2}{(CV_o)s - 2(1-k)I} \;,\; \frac{v_o(s)}{k(s)} = \frac{(1-k)V_o - (L\,I)s}{LCs^2 + \frac{L}{R}s + (1-k)^2} \tag{7}$$

Regulation of the output voltage is achieved by comparing the actual output voltage of the converter with a reference value of the desired output voltage. The actuating error signal generated from this comparison is then compared with a high frequency triangular signal generated by means of an integrator. The result of this comparison is then fed to the PWM comparator to produce gating signals for the active switches of the converter. The controller parameters are chosen using the trial and error method during the calculation. Figure 3 shows the structure of block diagram of this converter [5-8].

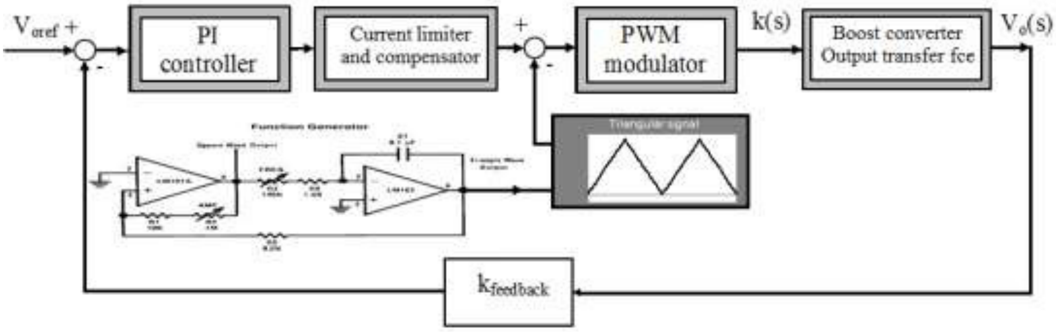


Fig. 3. Structure of voltage mode control of boost converter in steady state case.

4. Simulation Results

The analytical results are verified using the simulation in the environment of Matlab, Simplorer 7, and Excel. The components of the converter were replaced by prototype models that meet the requirement of simulations and do not adversely affect the function of the system. All the components of the regulator including BJTs, diodes, coupled damping filters are assumed to be ideal. Dynamic properties of the switches and diodes were neglected. It does not have a significant effect on the main converter operation, especially when the converter operating frequency is not closed to the cutoff frequency of the transistors.

The converter input current instantaneous ripple of the fundamental and the double-channel converter are illustrated as a function of duty ratio, k, in Figure 4. It can be seen that the overall current ripple of the double-channel converter is greatly reduced as compared to that of its basic configuration.

Concerning the control block diagram of the converter shown in Figure 3, in order to get a stable closed loop system, it is necessary to consider the bode plot of the loop gain or just the control-to-output gain of the converter. As depicted in Figure 5, the phase Margin introduced by the open loop resp. output transfer functions of this system passes 0db at a phase angle equal or less than -90° resp. than -180° which is the required condition for making the system stable during parameter changes and other variations [9-10].

The compensation network is designed as a simple first order network under the condition of a unity open loop gain. Voltage and current variation were simulated, designed and compensated just to make the system stable under load and source variations. These are limited by smoothing inductors as well as by PI controllers.

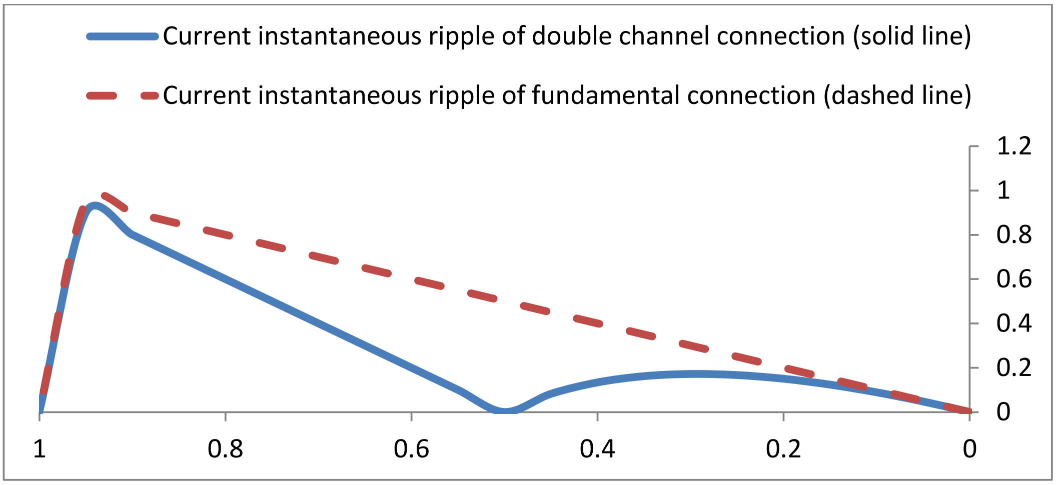


Fig. 4. Plot of current instantaneous ripple of fundamental and two-channel boost converter versus duty time ratio, *k* as it varies from zero to unity (Excel).

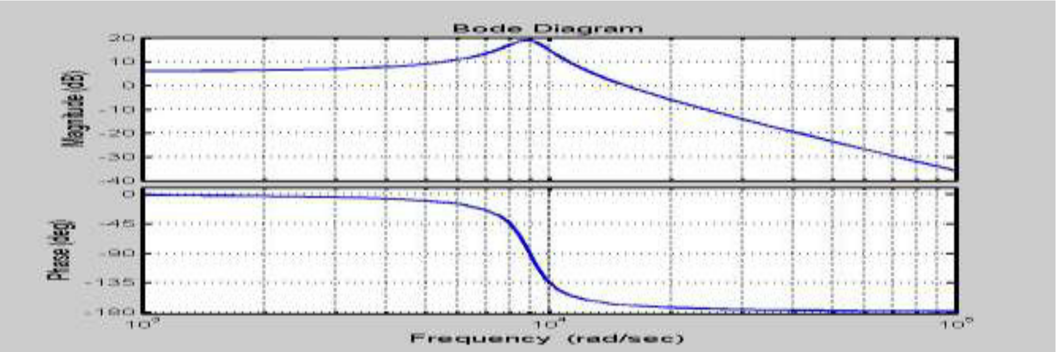


Fig. 5. Bode plots of Control to output transfer function (red - Simplorer) and Open loop transfer function (blue - Matlab).

5. Conclusion

Two-channel boost converter with uncoupled smoothing reactors used in increasing the voltage produced from alternative energy sources has been briefly proposed and analyzed. Moreover, the mathematical analysis and simulation results obtained in this paper objectively lead to the following conclusion: By using smoothing reactors with two-channel boost converter, the overall current and voltage ripple in the converter could be effectively reduced, compared to that of the fundamental connection [11, 13].

Using two-channel connection results in increasing the operating frequency of the converter and thus in decreasing the demands to the material and the economical costs required for designing the reactors. PWM based PI voltage mode controller shows that the converter dynamic performance and the non-linearity and un-stability of this converter due to its parameters variation are improved [3, 12].

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