A two-stage chopper with isolation for renewable energy applications

V.P. Sandhya

Assistant Professor, Department of Medical Electronics, SRM Valliammai Engineering College, SRM Nagar, Kattankulathur -603203, Kanchipuram district, Tamilnadu, India

ABSTRACT

In this work, the design and development of a Chopper using a two stage buck–boost operation is discussed. This converter is suitable for low power application such as a matrix LED lighting system. The advantage of this converter is that instead of using two controlled switches as in case of a conventional converter, this circuit uses one MOSFET as a switch. The circuit uses two inductors and two capacitors as energy transferring elements that are able to provide a good quality, high efficiency power supply to the load. In this paper the design of TSBB converter is analyzed with closed loop control using a PI controller circuit. Even with smaller values of inductor and capacitor a highly efficient power supply can be made. The main feature of this circuit compared to the other circuits proposed is, comparing with the circuits designed previously with the same concept is that, in this work a galvanic isolation between the load and the source is provided. Thus, by a suitable controller and galvanic isolation the ripple magnitude in the output is reduced considerably. A simulation model of the TSBB converter with results is presented.

Keywords:Two Stage buck–boost (TSBB), LED Matrix, Duty cycle (α), galvanic isolation, discontinuous conduction mode (DCM), continuous conduction mode (CCM).

INTRODUCTION

Energy efficient lighting is the need of the day and is becoming an area of continuous research. Illumination engineers and architects require an efficient and aesthetic lighting. In this way the LED lighting system using Matrix type of LED arrangement is becoming more popular. But the problem with such type of lighting is the power supply. Even the recent types of power supplies used for led illumination system are poor in efficiency and they are unreliable. The tungsten lamps provide only 8-10 lm/ W and very inefficient, they are then replaced by fluorescent lamps now with the efficacies of an LED is as high as 100 lm/W[3] they are mostly preferred. The problem with the LED lighting is that they cannot be supplied directly from the DC or ac voltage. Therefore there should be some kind a device to regulate the power fed to the lighting system all these mean a power supply should be developed to act as a driver circuit to the LED matrix lamp[6]. With the double buck boost converter, two converters are cascaded with a single switch and it includes two low value inductors and capacitors and suitably placed diodes thus the LED lamp can be supplied with low current low ripple and high efficiency power. In Section II, the working of TSBB converter [1] is presented. In Section III, the analysis and design of the TSBB converter [1] in various modes is detailed. In Section IV, Simulation results of TSBB converter is discussed. Section V discusses on the laboratory prototype made and in the section VI results and conclusions are discussed.
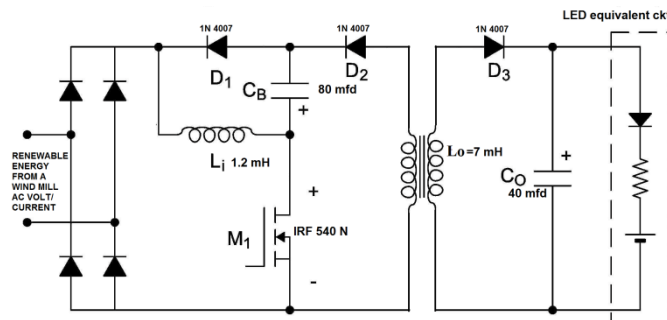

Fig. 1 Schematic circuit of a TSBB converter with isolation

TWO STAGE BUCK BOOST CONVERTER

Fig. 1 shows the schematic circuit of the TSBB converter. The Chopper acts as two buck–boost converters which are electrically isolated and connected to the load. The input buck–boost converter is made up by Li, D1, CB, and M1, and the output buck–boost converter here acts as a fly wheel converter due to addition of galvanic isolation and comprises of LO, D3, CO. The first converter produces a reverse output across the capacitor CB which is corrected by the second converter and a positive output voltage with respect to ground, thereby simplifying the measurement of the load current, in the closed-loop operation, also reducing the sensing circuitry and hence the cost.

By operating the input inductor Li in discontinuous conduction mode (DCM), the average current through the line will be almost in phase with the line voltage, which results in a line power factor near-unity, this is important if the converter operates from mains voltage in a grid. Also, the output inductance LO can be operated either in continuous conduction mode(CCM) or Discontinuous Conduction Mode. DCM results in a bus voltage across CB that is independent of duty cycle and output power. But there is a drawback in above said DCM since it requires a higher value of capacitance to be connected across the output in order to achieve reduced current ripple in the output of the TSBB converter. So to avoid high current ripple in the output and to reduce the value of the output capacitance, CCM operation is preferred. In addition to above, to reduce the ripple voltage occurring at low frequencies, the second stage of the TSBB is operated with α =50% (duty cycle), since the duty cycle is multiplied by the buck–boost converter voltage ratio. In this way, it will be possible even to use a film capacitor to implement the output capacitance; this gives the TSBB converter longer life rating and improved efficiency over the use of electrolytic capacitors.

Moreover, with a careful design of the converter, the bus capacitor can also be made low enough to be implemented with film technology, thus avoiding the low-life-rating electrolytic capacitors in the whole converter. This implies the design of the converter so that it operates with a α lower than 0.5. In this manner, the output converter voltage ratio will be lower than one, thus reducing the low-frequency voltage ripple in the same amount.

A. *Need for Isolation*
Among the regulators non-isolated switching regulators are very common, or Point of Load (POL) converters. Although low cost and simple, these converters suffer from one disadvantage in that there is an electrical connection between the input and output. Many safety agency bodies require a separation from the applied input voltage and the output voltage which is often user accessible. An isolated DC-DC converter will have a high frequency transformer providing that barrier. This barrier can withstand anything from a few hundred volts to several thousand volts, as is required for medical application. A second advantage of an isolated converter is that the output can be configured to be either positive or negative. Where many users get confused concerns how to connect the input up, particularly with the differences between a data com system where the input negative is connected to chassis and a telecom system input positive is connected to chassis.

ANALYSIS OF TSBB CONVERTER

The input voltage is thus given as

$$vp(t) = Vm\sin \omega t.$$

A. *Line Current*
The input current ipcorresponds to the current through the inductance Li during the time interval $0 - \alpha TS$, where α is the transistor duty cycle and TS is the transistor switching period. This current is modulated by the rectified line voltage [1], as. Thus, the value of the input current averaged at line frequency can be calculated as follows [1]

$$\langle i_p \rangle = \frac{\alpha^2 Vp}{2L_i f_s} \sin\omega t$$

….1

where ip_peakis the instantaneous peak current in each switching period, fSis the switching frequency, Vp is the peak line voltage, and ω is the line angular frequency. The mean input power Pi can now be calculated as [1]

$$P_i = \frac{\alpha^2 V_p^2}{4L_i f_s}$$

….2

B. *Output and Bus Voltages*
The output voltage VO for the ideal converter can be obtained by equalling input and output powers. The output power is obtained as follows:

$$P_o = \frac{V_o^2}{R}$$

….3

with R being the static equivalent resistance[5] of the LED load,which can be obtained by the ratio between the dc values ofLED voltage (VLED) and current (ILED) at each operating point[7]

$$R = \frac{V_\gamma}{I_{LED}} + R_\gamma$$

…..4

where Vγand Rγare the voltage and resistance parameters ofthe LED lamp equivalent circuit [8] Then, assuming 100% efficiency, by equalling (2) and (3),the output voltage is finally obtained

$$V_o = \frac{\alpha V_p}{2\sqrt{D}}$$

…5

Where D is a non-dimensional factor given by

$$D = \frac{f_s L_i}{R}$$

…6

Since the output stage corresponds to a buck–boost converter (flywheel converter) operating in CCM, the bus voltage VB can be calculated by using the voltage conversion ratio for this converter [2]

$$V_B = \frac{1 - \alpha}{\alpha} V_0 = \frac{(1 - \alpha)V_g}{2\sqrt{D}}$$

(7)

As can be seen from (5) and (7), when operating the input stage in DCM and the output stage in CCM, the bus and output voltages are reversely dependent on the duty cycleα.

For example, if the α increases, the output voltage increases, and the bus voltage decreases in the same amount. The sum of both voltages does not depend on theduty cycle, being only proportional to the line peak voltage, as given by the following:

$$V_B + V_0 = \frac{V_g}{2\sqrt{D}}$$

…8

It must be noted that the input stage must be operated in DCM under any load the limit duty cycle αlimit can be obtained from the voltage conversion ratio in the DCM–CCM boundary

$$\alpha_{limit} = \frac{1}{1 + V_p/V_B}$$

…9

Till the actual duty cycle is lower than the limit value given by (9), the first stage will operate in DCM mode only.

C. *Energy transferring components*

The value of the energy transferring element at the input which is Li is calculated based on the output power and assuming 100% efficiency the value of inductance is so obtained to be

$$L_i = \frac{\alpha^2 V_p^2}{4P_0 f_S}$$

…10

Similarly, the value of the capacitor which is another energy transferring element called as bus capacitor CB is calculated so as to limit the low-frequency ripple of the bus voltage, this bus voltage is what applied to the second stage of the TSBB converter. The current through this capacitor is also the currents through diodes D1 and D2. In these diodes, only the current through D1 is modulated by a rectified line frequency. In order to calculate the bus ripple, the low-frequency component of the current through D1 must be obtained. The average current through D1 can be calculated as follows:

$$\langle i_{D1} \rangle = \frac{1}{T_s} \frac{i_{D1\_peak}\, t_1}{2}$$

$$\dots (11)$$

Where iD1_peak is the peak current through D1 in each switching period and t1 is the time needed by this current to reach zero. Both values are changing after double the line frequency and have the following values:

$$i_{D1\_peak} = \frac{V_p}{L_i} \alpha T_s$$

$$\dots (12)$$

$$t_1 = \frac{\alpha V_p T_S}{V_B}$$

$$\dots (13)$$

Using (12) and (13) in (11), the D1 average current is given as follows

$$\langle i_{D1} \rangle = \frac{\alpha^2}{2 V_B f_s \alpha T_s\, 2\, L_i} L_i 2 i_{D1\_peak}{}^2$$

$$\dots (14)$$

Equation (14) can also be expressed as follows:

$$\langle i_{D1} \rangle = \frac{\alpha^2 V_p^2}{2 V_B f_s L_i}$$

$$\dots (15)$$

Then, the low-frequency ac component circulating throughD1 and CB is given by

$$\langle i_{D1} \rangle_{ac} = \frac{\alpha^2 V_p^2}{4 V_B f_s L_i}$$

$$\dots (16)$$

Now, the low-frequency peak-to-peak ripple voltage acrosscapacitor CB,ΔVB_LF can be obtained as

$$\Delta V_{B\_LF} = \frac{\alpha^2 V_p^2}{8 \pi V_B L_i C_B f_s f_L}$$

$$\dots (17)$$

current through diode D1, obtained from (16), and fL is the line frequency. The necessary bus capacitance for a given peak-to-peak ripple in the bus voltage is then calculated from (17) as follows:

$$C_B = \frac{\alpha^2 V_g^2}{8 \pi V_B L_i \Delta V_{B\_LF} f_s f_L}$$

$$\dots (18)$$

Note that, as long as the output buck–boost converter operates in CCM, the LED current ripple at low frequency depends only on the bus voltage ripple and, thus, on the bus capacitance CB. The output capacitance CO has no effect on this low frequency ripple. Finally, the output inductance and capacitance LO and CO are obtained using the well-known expressions for a buck–boost converter operating in CCM

$$L_O = \frac{\alpha V_B}{0.5 \Delta I_{Lo\_HF} f_S}$$

$$\dots (19)$$

$$C_O = \frac{\alpha I_O}{\Delta V_{O\_HF} f_s}$$

$$\dots (20)$$

where ΔILo_HF is the LO high-frequency peak-to-peak currentripple, ΔVO_HF is the high-frequency peak-to-peak output voltage ripple, and IO is the dc current through the LED load.[4]

SIMULATION RESULTS

Simulation of the TSBB converter was done using PSim Software. It was found that Psim was easier to use and the results can be obtained quicker as the time taken for the simulation was less.

The circuit configuration shown in fig 2 shows, TSBB converter in closed loop mode using a PI controller. The values of the PI controller elements are so chosen to give a reduced steady state error. Instead of going in for standardised tuning methods, it was found that manual tuning gave satisfactory results. So the tuning of the PI controller was done based on trial and error method manually.

The Proportional gain (Kp) is given by the equation (21) where the values of R1 and R2 are determined by manual tuning method [9]

$$Kp = \frac{R_2}{R_1}$$

(21)

Similarly, the integral gain (Ki) is given by the equation (22) where the values of R1 and R2 are determined by manual tuning method [9]
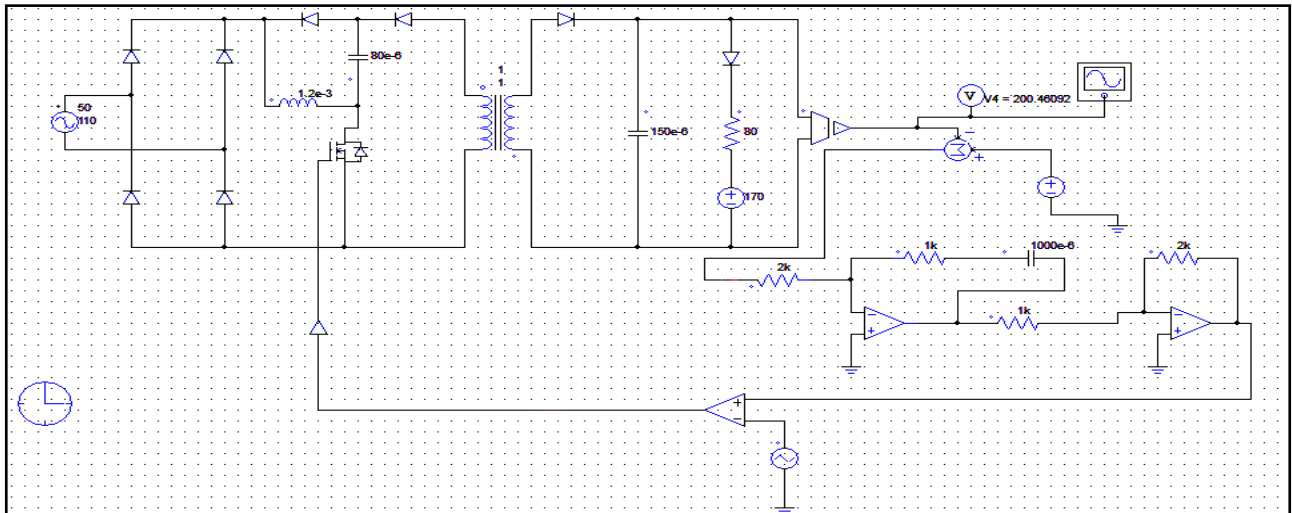
$$Ki = \frac{1}{R_2 C}$$

(22)

Fig. 2 Simulation circuit of the DBB converter in closed loop

CONCLUSION

Atwo stage buck boost converter (TSBB) has been successfully simulated in this paper there by a circuit configuration is discussed for providing quality power supply for low power applications.In closed loop mode suitable controller namely the PI controller was used.

It is evident from the results discussed in the previous sections that the configurations of TSBB converter in closed loop is efficient compared to the converters using more than one control switch.

The added advantage of this converter is that this is suitable for power converters used for medical applications where isolation is essential. Though Isolation may end up in increase of cost,it is a safety aspect that cannot be neglected in certain applications.

Thus, it can be concluded that the configuration of a TSBB converter in closed loop mode is more efficient, safe and reliable for any low power loads.

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