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Hidden Buck Chopper Circuits Topology in a Switch Controlled Singe Phase Rectifier, Size and Cost Analysis

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Abstract

This paper shows hidden buck chopper circuits topology in a single phase switch controlled full wave rectifier. Justification of this realization yields the opportunity to use the single circuit structure for both AC to DC and DC to DC conversion processes. Generally, two diodes out of four diodes are replaced by two switches to offer voltage gain and input power factor regulation in a single phase full wave rectifier. Such modification proves the existence of two buck chopper circuits. Buck circuit is a dc to dc step down converter. This research also includes filter sizing and comparisons of Fast Fourier Transform (FFT) analysis of output voltage for two modes of operations excluding filter stage. To get proper DC output LC filter is used. LC filter size is inversely proportional to switching frequency for a particular output load. The research shows that, size of LC filter for DC-DC conversion process can be chosen flexibly and minimized because the fundamental frequency component of the chopped voltage before filter stage is similar to the switching frequency which can be easily selected to a higher value to reduce the size of filter. In case of controlled AC-DC conversion process the rectified discontinuous voltage before the filter stage naturally includes low frequency components which cannot be eliminated using small filter. So, the size of filter for both of the cases becomes issue of comparisons. It also shows cost analysis.

Keywords: *Rectifier, buck converter, switching frequency, LC filter, filter sizing*

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INTRODUCTION

AC to DC converter termed as rectifier converts bidirectional signal to unidirectional signal [1]. Rectifiers have many uses, such as; components of DC power supplies, DC drives and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power. The main supply system has alternating nature of AC sine wave; the rectification system converts it to a unidirectional signal which is pulsating.

The smoothness of the pulsating wave can be ensured using filters. Many applications, such as; charging mobile phones, laptops and battery require a stepped down DC voltage. To do so chopping action is generally used [2]. Buck converter a dc to dc converter [2–10]. Buck converter provides a lower levelled dc output voltage from input dc voltage. The circuit includes LC filter for smoothing the output voltage and freewheeling diode [2–10].

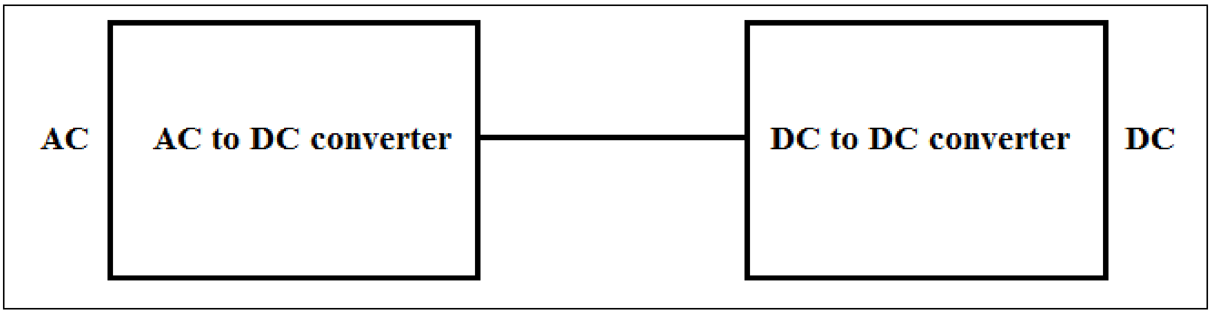


Fig. 1(a): *Traditional AC to DC Step Down Conversion Process-1.*

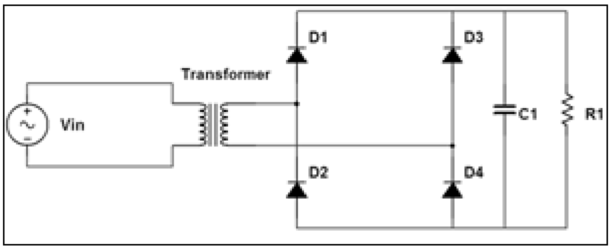


Fig. 2(b): *Traditional AC to DC Step Down Conversion Process-2.*

Generally, the traditional AC to DC step down converter uses two stages, one stage rectifies the input AC then another stage steps down the rectified signal using buck converter [11]. First process is shown in Figure 1(a). Figure 1(b) shows another conversion process which uses transformer to step down the voltage and rectifier stage. Two stages increase the size and reduce the efficiency [11].

Both ac to dc and dc to dc converters use low pass filters to smooth the outputs. Generally the filter includes inductor and capacitor [12–14].

The rectifier circuits are modified with switches to perform the step down action without transformer [1]. Controlled switching can be used for both rectification and step down actions [1].

This paper shows the existence of two buck chopper circuits in a single phase switch controlled full wave rectifier. The realization is explained by analyzing the buck converter circuits and then observing the equivalent circuits of the rectifier circuit in each half cycle of input sinusoidal wave.

In this research, detail of theoretical analysis of the proposed realization in the switch controlled ac to dc converter with mathematical equations has been described. Equation of the converter has been modified from concept of PWM converter [1]. Necessary circuits are simulated by PSIM and output has been observed. A simple switching control circuit has been shown and explained. FFT (Fast Fourier Transform) analysis for both conversion processes for same output power is performed to see the harmonic contents on output voltage. Finally it shows size and cost analysis for the described methods.

ANALYSIS OF THE MODIFIED CONVERTER TO SHOW THE EXISTENCE OF BUCK CHOPPER CIRCUITS

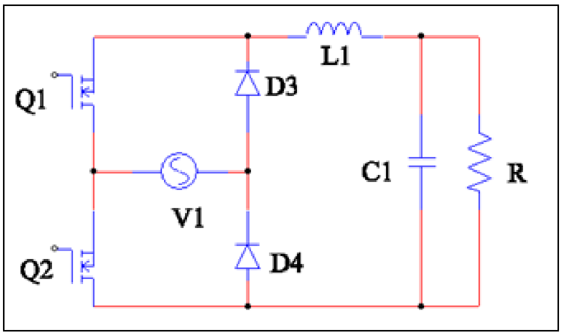


Fig. 2: *Circuit of Analysis to Justify the Proposed Realization.*

The converter has two diodes, two switches and an LC filter [1]. The diodes rectify the input bidirectional signal (sinusoidal wave). Switching controls the magnitude of output unidirectional signal (DC signal) and the filter (LC) reduces the ripple in current and voltage. This process of ac to dc conversion is called rectification. The circuit of Figure 2 will be explained after the explanation of buck converter to justify the proposal.

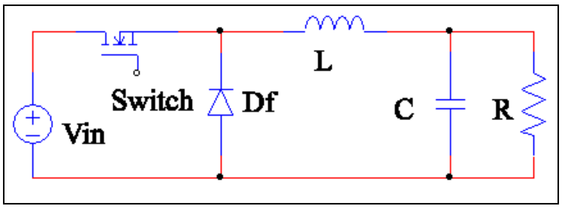


Fig. 3: *Buck Converter.*

Figure 3 shows buck converter which is a dc to dc converter [2–10]. Buck converter provides a lower levelled dc output voltage from input dc voltage. The filter is used to reduce ripple in voltage and current. The buck action is dependent on switching. At ON state of switch, the current flow will be via source (Vin), filter inductance (L), filter capacitor (C) and load (R). In this ON switch state of operation the inductor stores energy from the source. At OFF state switch of operation the stored energy in the inductor will be released and current will circulate among the capacitor, load, freewheeling diode and the inductor itself. The equation of average output voltage for the buck converter which has an input dc voltage Vin is [1]

$$Vo = D * Vin \quad (1)$$

D is the duty cycle (ratio of ON switch time to switching period), TON is the pulse width or ON switch time and Tsw is the switching period. The output voltage is controlled by varying the duty cycle or pulse width of switching pulse which operates the switch.

In the circuit of analysis of Figure 2 the diode D4 operates in positive half cycle of input sinusoidal wave (Mode A). The output in this positive half cycle can be reduced if the switch Q1 operates with a particular duty cycle (D).

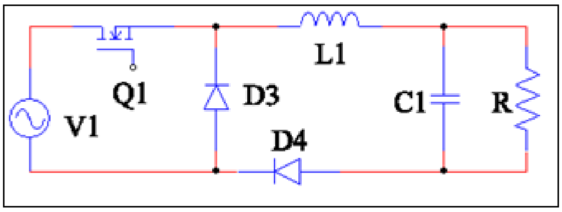


Fig. 4: *Equivalent Buck Circuit of Mode A.*

Figure 4 shows the operation in positive half cycle of input. The equivalent circuit is similar with buck converter of Figure 3 with an extra diode (D4) and the input is half sinusoidal (positive cycle). The extra diode D4 can be equivalently neglected at conduction state because it will be having a very small voltage drop. Here D3 acts as a freewheeling diode. In Mode A the operation is divided into two sectors, one with ON switch mode and another one is with OFF switch.

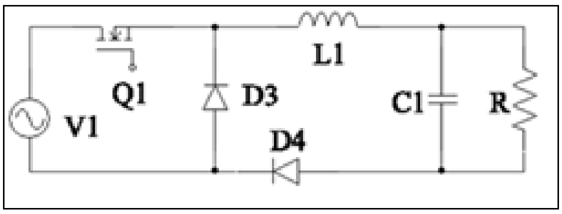


Fig. 5: *Mode A with ON Switch.*

In this case the current flow will be through switch (Q1), filter inductor (L1), filter capacitor (C1), load (R) and diode (D4) as shown in Figure 5. Energy will be stored in the inductor L1 during ON switch mode of operation [2–10].

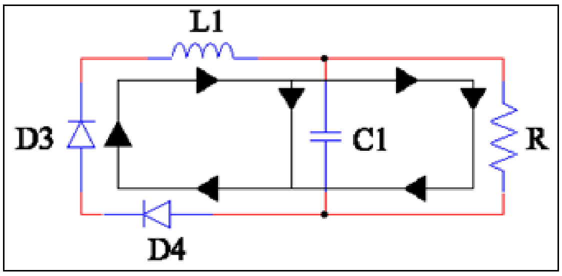


Fig. 6: *Mode A with OFF Switch.*

Energy stored in the inductor during ON switch mode will be transferred to the load (R) in OFF switch mode of operation (Figure 6). The current will circulate through diode (D3), inductor (L1), capacitor (C1), load (R) and diode (D4).

This action is just same as for a buck converter [2–10]. Buck converter is used for dc to dc step down conversion. In case of buck circuit the input is a dc source. So, the average value of output voltage can be controlled by varying the duty cycle. But in the converter of Figure 2 the input is not a pure DC source rather in each half cycle the input is a half sine wave. In the circuit of Figure 2, the voltage wave shape before filter stage will be a rectified discontinuous sine wave due to continuous ON-OFF behavior of switch. Each switch operates in half cycle of input sine wave and the diodes rectify the input sine wave. So, the period of rectified discontinuous sine wave which is shown in Figures 7 and 12 (before filter stage) will be π. The numbers of discontinuous segments (or segments having nonzero values) of the rectified sine wave depend on the numbers of switching pulses (N) in each half cycle of the input sine wave. Point to be focused that, the numbers of discontinuous segments and numbers of segments having nonzero values in each cycle are equal. The average value (dc component) of the signal before filter stage will be filtered out by a suitably sized LC low pass filter to output or it can be stated that the filter practically improves the smoothness of the output voltage taking into account the average value as reference.

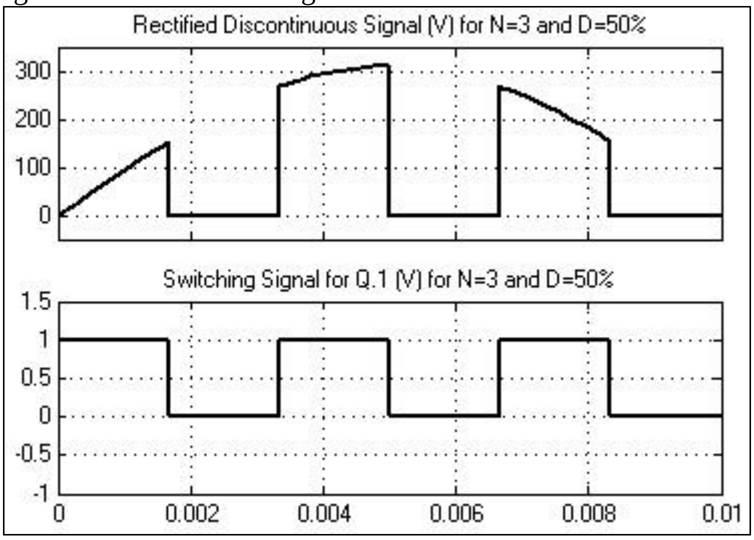


***Fig. 7:** Rectified Discontinuous Sine Wave and Switching Pulses for Q.1.*

Figure 7 represents an example of rectified discontinuous signal and switching pulses. The period of rectified discontinuous signal is π. The switching signal contains N=3 and D=50 %. As mentioned previously, for the specified parameters there will be three intervals of nonzero values and three intervals of zero values in the rectified discontinuous sine wave. For N=3 and D=50 %, each interval will be π/6. The average value of rectified discontinuous voltage will be [1],

$$V(average)=\frac{Vp}{\pi}[\int_{0}^{\frac{\pi}{6}}\mathrm{Sin}(\omega t)d(\omega t)+\int_{\frac{\pi}{3}}^{\frac{\pi}{2}}\mathrm{Sin}(\omega t)d(\omega t)+...+\int_{\frac{2\pi}{3}}^{\frac{5\pi}{6}}\mathrm{Sin}(\omega t)d(\omega t)] \quad (2)$$

Eq. (2) is for N=3 and D=50%. Eq. (2) for any specific N and D can be composed as,

$$V(average)=\frac{Vp}{\pi}[\int_{0}^{\frac{D\pi}{N}}\mathrm{Sin}(\omega t)d(\omega t)+\int_{\frac{\pi}{N}}^{\frac{(1+D)\pi}{N}}\mathrm{Sin}(\omega t)d(\omega t)+...+\int_{\frac{(N-1)\pi}{N}}^{\frac{(N-1+D)\pi}{N}}\mathrm{Sin}(\omega t)d(\omega t)]$$

$$=\frac{Vp}{\pi}\sum_{n=1}^{N}\int_{\frac{(n-1)\pi}{N}}^{\frac{(n-1+D)\pi}{N}}\mathrm{Sin}(\omega t)d(\omega t)$$

Finally,

$$=\frac{Vp}{\pi}\sum_{n=1}^{N}[-\mathrm{Cos}(\omega t)]_{\frac{(n-1)\pi}{N}}^{\frac{(n-1+D)\pi}{N}}$$

$$V(average)=\frac{Vp}{\pi}\sum_{n=1}^{N}[\mathrm{Cos}(\frac{(n-1)\pi}{N})-\mathrm{Cos}(\frac{(n-1+D)\pi}{N})]$$

$$V(average)=\frac{2Vp}{\pi}.\mathrm{Sin}\frac{\pi D}{2N}\sum_{n=1}^{N}\mathrm{Sin}\frac{\pi}{N}(n-1+\frac{D}{2}) \quad (3)$$

Eq. (3) represents the average output voltage or average of voltage before filter stage (considering ideal diodes and switches). In Eq. (3), N is the numbers of switching pulses

in each half cycle, D is the duty cycle, n is the integer and Vp is the peak value of input sine wave. So, the output of the converter with half input sine wave is a function of D, Vp and N.
The period of switching signal,

$$T_{SW} = \frac{T}{2*N} \quad (4)$$

where, T is the period of input sine wave and N is the numbers of switching pulses in each half cycle.

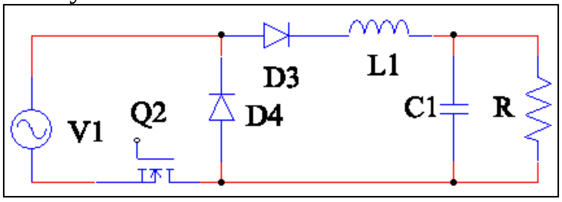


Fig. 8: *Equivalent Buck Circuit of Mode B.*

Figure 8 shows the operation in negative half cycle of input. The equivalent circuit is similar with buck converter of Figure 3 with an extra diode (D3) and the input is half sinusoidal (negative cycle). The extra diode D_3 can be equivalently neglected at conduction state because it will be having a very small voltage drop. Here D_4 acts as a freewheeling diode. In Mode B the operation is divided into two sectors, one with ON switch mode and another one is with OFF switch. Figure 8 shows the equivalent circuit in negative cycle (Mode B). The equivalent circuit is similar to a buck converter with a half sinusoidal input (negative cycle). Here D_4 acts as a freewheeling diode.

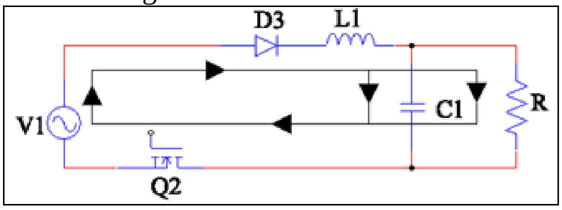


Fig. 9: *Mode B with ON switch.*

In this case the current flow will be through diode (D_3), filter inductor (L_1), filter capacitor (C_1), load (R) and switch (Q_2) as shown in Figure 9. Energy will be stored in the inductor L_1 during ON switch mode of operation.

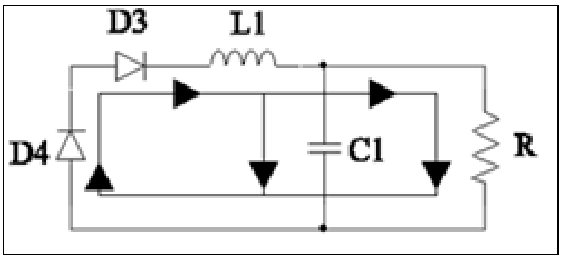


Fig. 10: *Mode B with OFF switch.*

Energy stored in the inductor during ON switch mode will be transferred to the load (R) in OFF switch mode of operation. The current will circulate through diode (D4), diode (D3), inductor (L1), capacitor (C1) and load (R). This process is illustrated in Figure 10. Operation in this mode will be same as described in mode ‘A’ with reversed direction of source. In each mode of operations the existence of buck chopper circuits is visible. So, the proposed realization is justified.

RESULTS AND DISCUSSION

Figure 11 shows the output voltage of the converter. The output has an average value of 12 V. Table 1 summarizes the parameters of the converter. The ripples can be reduced using suitably sized inductor and capacitors. The average value of output voltage (12 V) is less than the input AC (220 Vrms). The whole circuit for simulation is given in Figure 15.

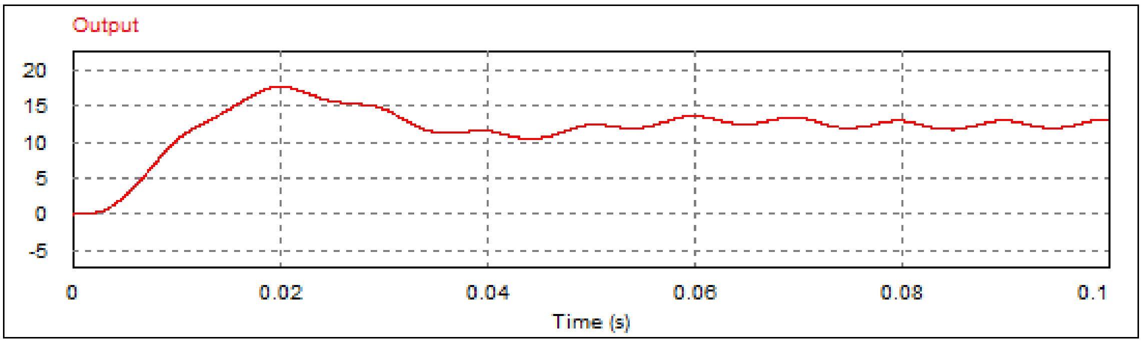


Fig. 11: *Simulated Output Voltage of the Converter.*

Figure 12 shows the input AC voltage and output DC voltage (average 12 V) in the same plot which represents the step down action of the converter. It also shows the unfiltered output voltage. The wave shapes have been traced in same time scale factor.

Figure 13 shows the switching patterns for the converter. Each switch operates for half cycle of the input sine wave. Q1 operates in positive half cycle and Q2 in negative half cycle.

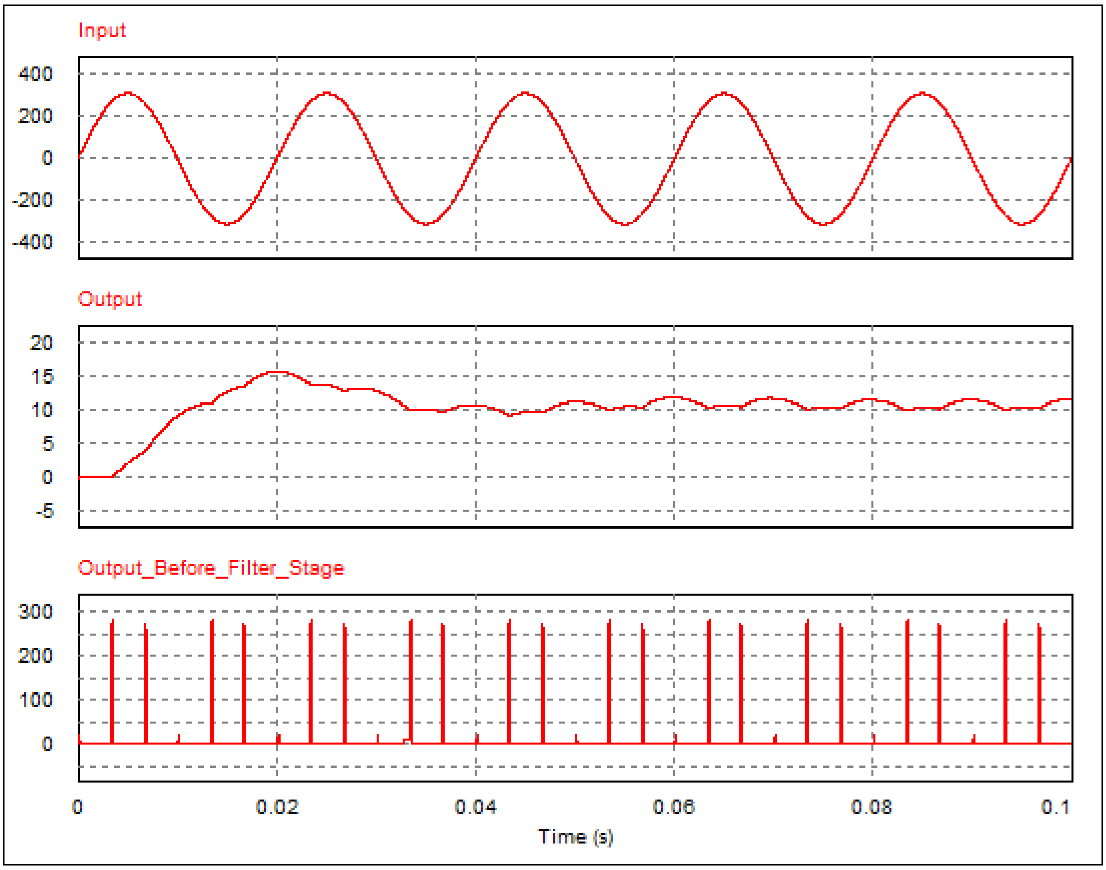


Fig. 12: *Input Sine Wave, Stepped Down Output Voltage and Output Voltage before Filter Stage (Rectified Discontinuous Sine Wave) in Same Plot.*

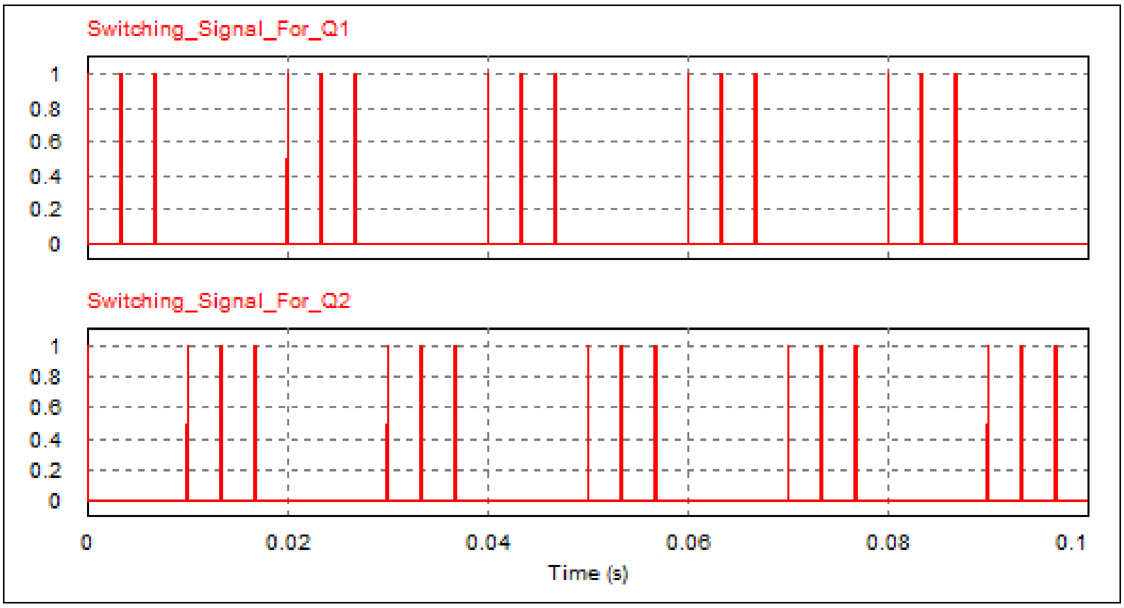


Fig. 13: *Switching Signal Pattern for the Switches Q1 and Q2.*

Switching actually controls the value of output voltage depending upon the variation of pulse width.

The control signals for Q1 and Q2 must be synchronized with input sinusoidal wave which has a period of 20 ms (frequency 50 Hz).

Table 1: *Circuit Components of the Converter.*

Components	Name	Ratings
Filter Inductor	L_1	400 mH
Filter Capacitor	C_1	100 uF
Load Resistance	R	100 Ω
Input	V_1(peak)	311 V
	V_1(rms)	220 V
Output Voltage	V_o(average)	12.09 V

Table 1 shows necessary parameters for simulation. The output voltage has been calculated using Eq. (3). The control signals for half of the input sine wave must operate for 10 ms in which the control signal for Q1 will work and for left half portion of the sine wave another control signal for Q2 will work. In this case each switch will be operated in half of the input sinusoidal wave. So, though there are two switches there is only one switch working equivalently (each switch is working in half cycle of the input sinusoidal wave). The switching patterns are provided in Figure 13. Table 2 specifies the time parameters of the signals (input and switching signals). The simulation is done for N=3 and D=6.6%. Solution of Eq. (3) for Vp=311 V, N=3 and D=6.6% yields, Vo=12.095 V.

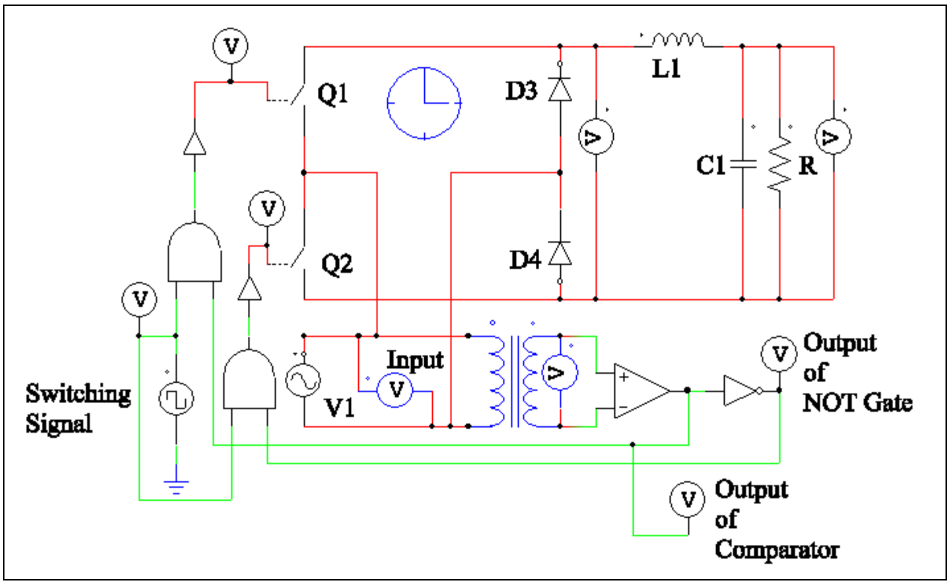


Fig. 14: *Simulation Circuit in PSIM.*

Figure 14 represents the whole circuit for simulation including the control circuit. Switch Q1 is operated in positive half cycle of the input sine wave and Q2 in negative half cycle. In each half cycle the operation will be like a buck converter. The LC filter circuit is used to improve the smoothness of output voltage. Figure 14 also shows a simple control circuit for the switches. The control circuit includes step down transformer, a comparator which is used to generate synchronized pulses with input sinusoidal wave, a NOT gate and two AND gates. Switching pulses are passed with synchronized pulses through the AND gates to the switches Q1 and Q2.

Table 2: *Circuit Components of The Converter.*

Signals	Time/Period
Sinusoidal signal	1/(50 Hz) = 20 ms
Half of Sinusoidal wave	10 ms
Switching signal	3.3333 ms
$D_{\text{Switching signal}}$ (duty cycle)	6.6%
N(number of pulses)	3

Table 2 shows the time parameters for simulations. It also shows the duty cycle and number of applied pulses. The last section will explain the synchronized pulse generation for the switches through the control circuit.

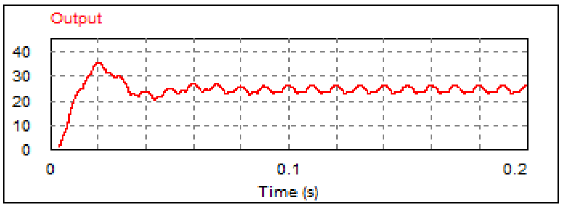


Fig. 15: *Output Voltage for Duty Cycle 0.1332.*

Figure 15 shows the output voltage for D = 0.1332. The output voltage is around 24 V. This is calculation can be justified using Eq. (3).

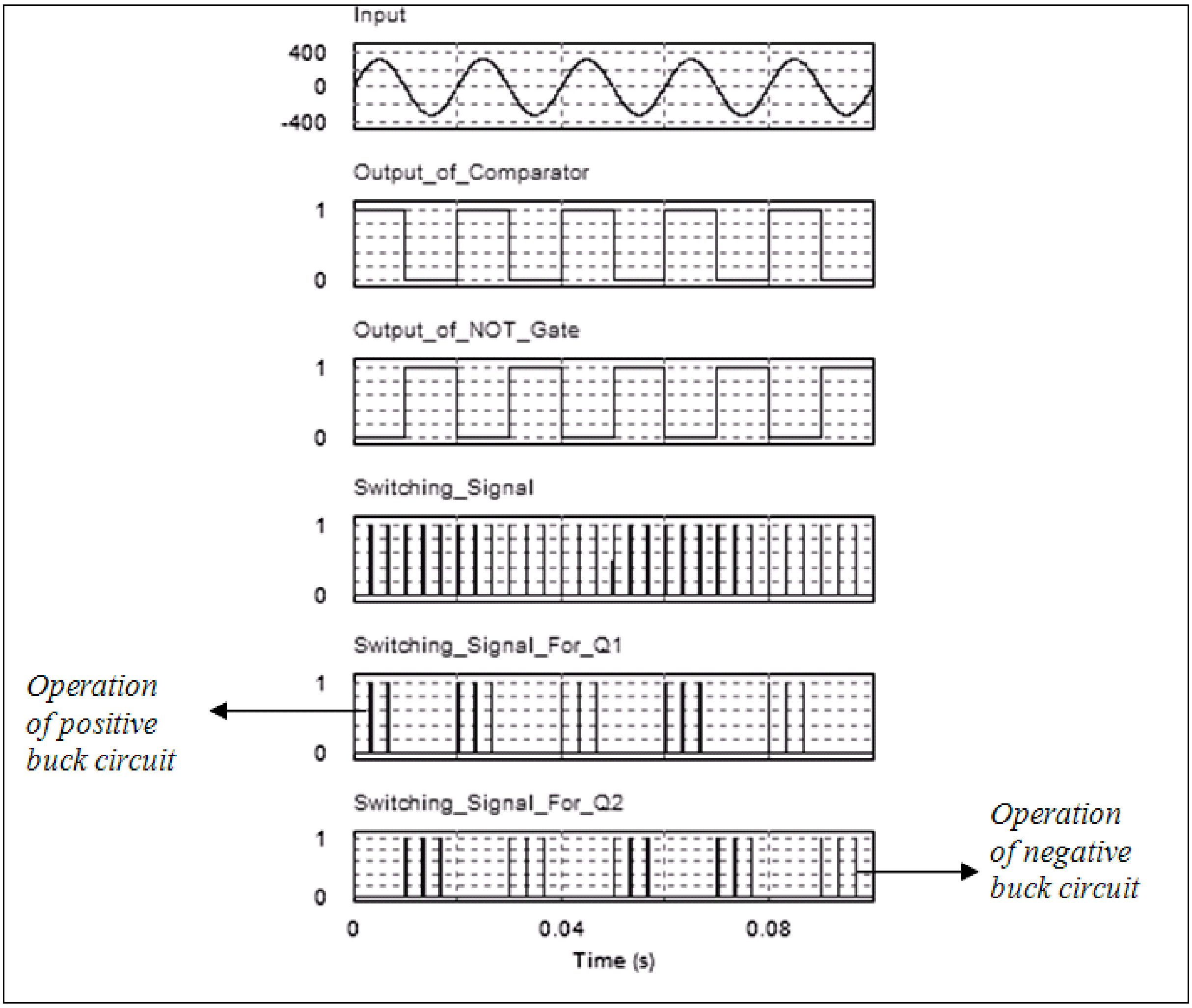


Fig. 16: *Input Voltage, Output of Comparator, Output of NOT Gate, Switching Signal, Pulses for Switch Q1 and Q2.*

Figure 16 shows the wave shapes of control circuit which is used to generate synchronized pulses for the converter. Synchronization of switching pulses with is very important to avoid false operation of the converter. This type of concept is available in research [11]. In this research the control circuit includes a low power transformer to step down the input voltage so that the comparator can perform with it desired operating level of voltage. The comparator compares between the sinusoidal wave and neutral and provides positive pulse in positive portion of sinusoidal wave. The pulse width of output of comparator is half of the period of input sine wave. This pulse and switching signal are passed through an AND gate (2 inputs). The output of AND gate operates switch Q1. The NOT gate inverts the output of comparator and then passed through another AND gate (2 inputs) which has switching pulses into another input terminal. The output of second AND gate operates switch Q2.

SIZE AND COST ANALYSIS FOR SAME OUTPUT POWER

For same output power rating (in this case 1.46 W) the same converter yields different cost and size for two types of conversion methods.

DC to DC Conversion Process

In case of DC to DC conversion the size of converter can be reduced by higher switching frequency selection. Size of converter is totally determined by the size of filter inductor and capacitor. FFT analysis of different outputs for different higher switching frequencies is shown below to observe the harmonics contents of the outputs voltage. To simulate these conditions filter circuit has to be eliminated from the buck chopper circuit (Figure 3). So, circuit of Figure 3 will include only a switch, load resistance (100 Ω) and input voltage (48 V). Output power is 1.46 W.

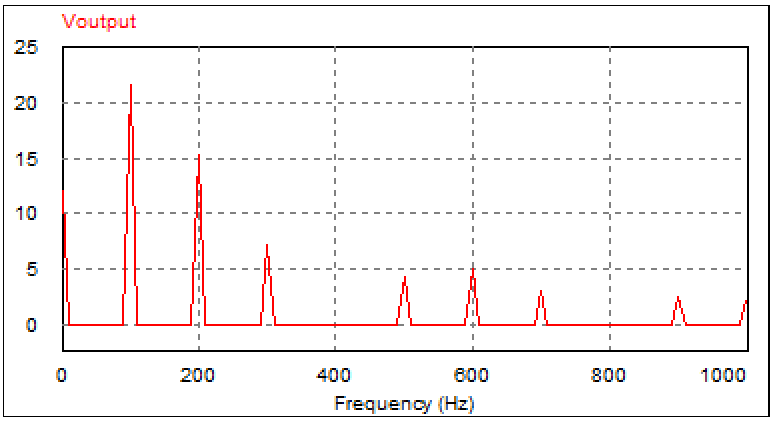


Fig. 17: *FFT Analysis of Output Voltage of Buck Circuit (Excluding Filter) for 100 Hz Switching Frequency.*

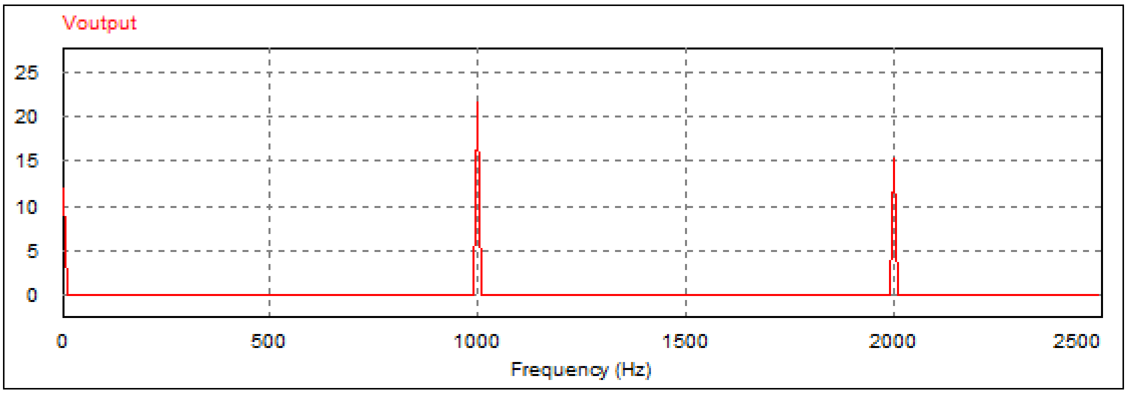


Fig. 18: *FFT Analysis of Output Voltage of Buck Circuit (Excluding Filter) for 1000 Hz Switching Frequency.*

Only the average component (frequency zero) is required as output, so to block the frequency components a low pass filter must be designed. Figures 17 and 18 shows the FFT analysis of output voltages for different switching frequencies. From the analysis it is seen that at higher switching frequencies the output voltage contains higher order harmonics which can be eliminated using small low pass filter. In every case, the average value (at zero frequency) is 12 V.

To design filter, Eqs. (5) and (6) are used [2–10]. From Eqs. (5) and (6), it can be stated that at higher switching frequencies the filter inductance and capacitor becomes smaller. It also justifies the previous discussions.

$$L\min = \frac{R.(1-D)}{2.fs} \quad (5)$$

$$C = \frac{D.Vo}{R.fs.\Delta Vo} \quad (6)$$

where, R is the load resistance, D is the duty cycle, fs is the switching frequency, $Lmin$ is the minimum filter inductance, C is the filter capacitance and $\Delta Vo/Vo$ is the ripple factor of output voltage. So, size of filter can be chosen in a flexible way depending on the higher frequency selection of the switching signals at a particular output load because filter size is inversely proportional to the switching frequency and the dc input has no frequency component. It is also important to mention the range of connected load which is an important issue of filter design [2–10]. Some important issues of filter design can be stated as,

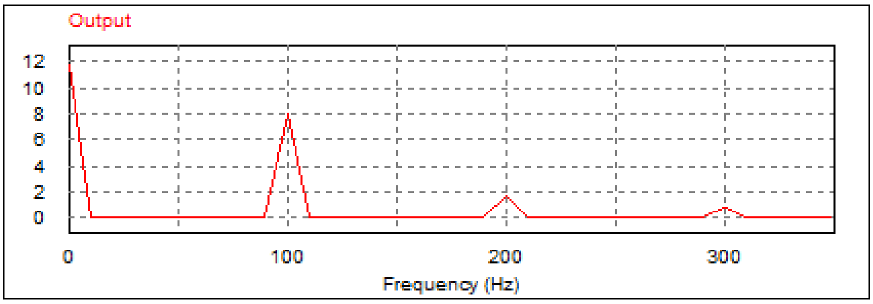
(a) Connected load resistance (R): If the load resistance is low (higher load) then the filter inductor size has to be lower. So, there is a proportional relationship between filter inductance and output load resistance. This statement is justified in Eq. (5).

(b) Switching frequency (fs): For higher switching frequency the filter size will be reduced for a particular output load (R). This is seen from Eqs. (5) and (6).

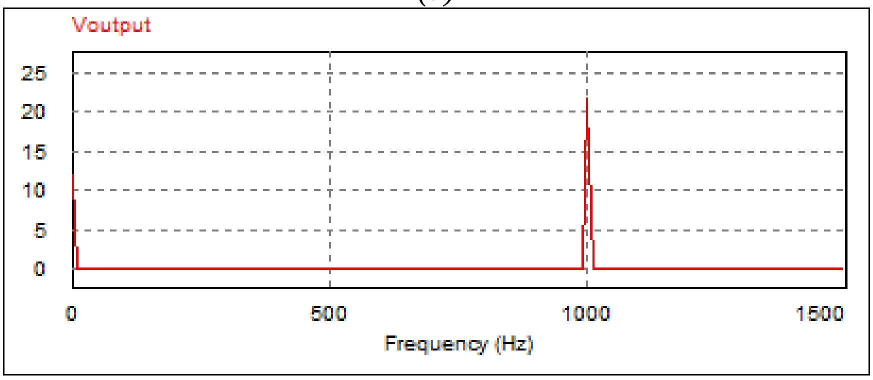
The cost of these inductor and capacitance is almost proportional to their size [11–15]. So, for higher output power the cost of converter will increase.

AC to DC Controlled Rectification Process

In case of AC to DC controlled rectification the output always contains low frequency components (low or fundamental frequency component = supply frequency). It can be visualized from FFT analysis of output voltage.



(a)



(b)

Fig. 19: *(a) FFT Analysis of Output Voltage of ac to dc Controlled Rectification and (b) FFT Analysis of Output Votlage of Buck Circuit for 1000 Hz Switching Frequency (Excluding Filter).*

Figure 19 shows the FFT analysis of output voltages for two different conversion processes for 1000 Hz switching frequency and 1.46 W output power. From the FFT analysis it is seen that in case of ac to dc controlled rectification process the fundamental frequency component is 100 Hz (double of supply frequency, 50 Hz) and 1000 Hz for dc to dc conversion processes. The LPF has to be designed considering fundamental frequency component which is lower in case of controlled ac to dc conversion process. For same output rating (in this case 1.46 W for both cases), the filter design for two different methods will be different and the size will be greater in case of ac to dc controlled rectification due to having very lower fundamental frequency component of 100 Hz at 1000 Hz switching frequency. In case of dc-to-dc conversion process the fundamental frequency component is exactly equal to the switching frequency (in this case 1000 Hz).

In every case the size and cost of the converter will increase with higher output power for same output voltage. The size of filter for ac to dc conversion process will be always greater than the size for dc to dc conversion process (due to naturally existence of low frequency component which is equal to twice of supply frequency and cannot be removed).

Comparison of FFT analysis of output voltages between two conversion methods for same Output power at different switching frequencies has been shown in Figure 19.

It can be stated that the filter size will be greater in case of controlled ac to dc rectification if compared with dc-to-dc conversion process for same output power to get smooth dc output. So, the cost will be higher in case of ac to dc conversion process for same output power.

CONCLUSION

This paper shows two hidden buck converter circuits in a controlled single phase full wave bridge rectifiers. The circuit contains two switches which reduce the output voltage of rectifier circuit. The output shows a dc voltage (12 Vaverage) which contains less ripples. The value of output voltage is dependent on the duty cycle of the switching pulses. The ripple in voltage and current is reduced by an LC filter.

The converter can be used in home appliances and electrical vehicles such as; mobile charger, battery charger, DC power supply and etc. This type of research proves that the same converter can be used for both dc to dc and ac to dc conversion with different switching techniques. Finally, FFT analysis of output voltages at different switching frequencies and filter analysis have been shown to realize the size of the converters. It shows that the filter size for dc to dc conversion process will be smaller than the size of filter used in ac to dc controlled conversion processes. A cost analysis depending on the size has been stated.

REFERENCES

1. Rashid MH. *Power Electronics Circuits, Devices and Applications*, 3rd ed. India: Prentice Hall, 2004.
2. Mithal GK, Gupta M. *Industrial and Power Electronics*, 19th ed. Delhi, India: Khanna Publishers, 2006.
3. Sivanagaraju S, Reddy MB, Prasad AM. *Power Electronics*, 1st ed. India: PHI Learning Private Limited, 2010.
4. Gupta BR. Singhal V. *Power Electronics*, 6th ed. India: S.K. Kataria & Sons, 2010, 246–283p.
5. Moorthi VR. *Power Electronics Devices, Circuits, and Industrial Applications*, 1st ed. India: Oxford University Press, 2005.
6. Jagannathan V. *Power Electronics Devices and Circuits*, 2nd ed. New Delhi, India: PHI Learning Private Limited, 2011.
7. Hart DW. *Power Electronics*, 1st ed. N Y: McGraw-Hill, 2010.
8. Rashid MH. *Power Electronics Handbook*, 3rd ed. Butterworth-Heinemann, Burlington, Massachusetts, 2011.
9. Asghar MSJ. *Power Electronics*, 1st ed. India: PHI Learning Private Limited, 2014.
10. Singh SN. *A Text of Power Electronics*, 3rd ed. India: Dhanpat Rai & Co. 2007.
11. Dwari S, Parsa L. An Efficient AC–DC Step-up Converter for Low-voltage Energy Harvesting, *IEEE T. Power Electron.* August 2010; 25(8): 2188–2199p.
12. Liang TJ, Yang LS, Chen JF. Analysis and Design of a Single Phase ac/dc Step-down Converter for Universal Input Voltage, *IET Electr Power Appl.* September 2007;1(5): 778–784p.
13. Nishimura K, Hirachi K, Komiyama S, *et al.* Two Buck Choppers Built-in Single Phase One Stage PFC Converter with reduced DC Voltage Ripple and its Specific Control Scheme, *in Proc. IEEE Appl. Power Electron. Conf. Expo.*, 2008, 1378–1383p.
14. Bimbhra PS. *Power Electronics*, 5th ed. India: Khanna Publishers, 2012.

15. Prices-Capacitors and Inductors (2015, February 18). (online). Available: http://www.critesspeakers.com/prices-capacitors-and-induc.html

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