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A new topology single-phase single switch non-isolated Buck-Boost converter with improved performance

***Abstract**. A new topology of single–phase AC-DC Buck-Boost converter is presented in this paper. The proposed converter provides conversion efficiency as high as 99.29% for open loop operation. Proposed converter with feedback controller can provide quality power factor (0.98) and reduced input current THD (16%) for average 1000V DC output voltage. Dynamic response of the proposed converter has also been observed for sudden changes of load. Analysis and simulation results of the circuit are obtained using software simulation.*

Streszczenie.** Zaproponowana nową topologię jednofazowego przekształtnika DC-DC typu buck-boost. W stanie jałowym konwersja jest rzędu 99,29%. Zaproponowany konwerter ma dużą skuteczność, małe zniekształcenia prądu I dobrą dynamikę. **Nowa topologia jednofazowego przekształtnika typu buck-boost

Keywords: AC-DC power conversion, Power factor correction controller, Buck-Boost converter.
Słowa kluczowe: przekształtnik DC-DC, przekształtnik typu bucjk-boost

Introduction

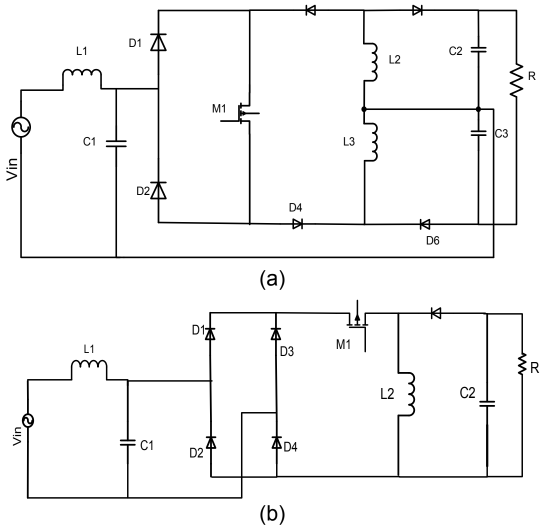
Single-phase full wave rectifiers with bridge configuration form have the problem of non-sinusoidal input current and low input power factor. Numerous methods have been proposed to solve these drawbacks. The use of filter in input side comes as a solution but filter inductor and capacitor required in such solution are large. The THD (Total Harmonic Distortion) is improved but power factor remains low. To overcome the problems, switch mode converters have been introduced. A conventional single-phase AC-DC switch mode converter comprises of a bridge rectifier followed by a DC-DC converter [1,2]. The most common of these topologies is a single-phase rectifier followed by a boost DC-DC converter. Buck, Buck-Boost, Cûk and SEPIC converters may be engaged for the same purpose with divergent input/output voltage gain relationships [2,3,4]. Transformerless high volatge step up DC-DC topology presented in [5] used multiple stage voltage lift cells for high boosting operation. A two-stage AC-DC Buck-Boost converter was proposed in [6,7], where the first stage acts as a step-up converter, while the second stage acts as a step-down converter. The main drawback is that control is difficult during transitions between Buck and Boost modes. Another form of single stage AC-DC Buck-Boost converter was introduced in [8] wherein the converter works in Continuous conduction mode (CCM).It requires a dedicated controller for power factor correction. Due to the high peak values of discontinuous input capacitor current its switching devices are exposed to high voltage stresses [9].

Some recent topologies of AC-DC Buck-Boost converters are designed to provide low input current THD and high input power factor. One of them is the input switched single phase Buck-Boost AC-DC Converter. The circuit has low input current THD and high input power factor throughout the variation of duty cycle in open-loop analysis. But conversion efficiency of the circuit is low for lower duty cycles. For the operation in buck mode, the circuit can at best achieve 36% lower voltage than the input signal [10]. Another work that has been done on AC-DC up-down operation, achieves very low input current THD in open loop analysis. It has the disadvantage that, the circuit shows very poor input power factor for lower and higher duty ratios [2]. A work on AC-DC Buck Boost converter was done that achieved extremely low voltage gain. The converter was actually designed for microprocessor operations that require very low DC voltages. The input power factor of the circuit is extremely low. Another disadvantage of the circuit is the input current THD is extremely high [11] . Different control techniques are used for closed loop feedback operation to enhance converter performances [12,13] .

In this paper, a new topology of single-phase non isolated AC-DC Buck-Boost converter has been proposed. The proposed circuit has a visible difference from the conventional full-bridge rectifiers or the mentioned DC-DC converter regulated rectifiers. There is no isolating instrument between source and the load. The proposed converter provides better conversion efficiency than the conventional converter throughout the variation of duty cycle. The proposed converter with PFC controller provides very high input power factor (0.98) which is close to unity. It keeps the input current THD around 16%, which is within the IEEE standards (20%) [14]. The proposed circuit has a variable voltage gain which means it can implement both the Buck and Boost mode operation.

Proposed Circuit Configuration

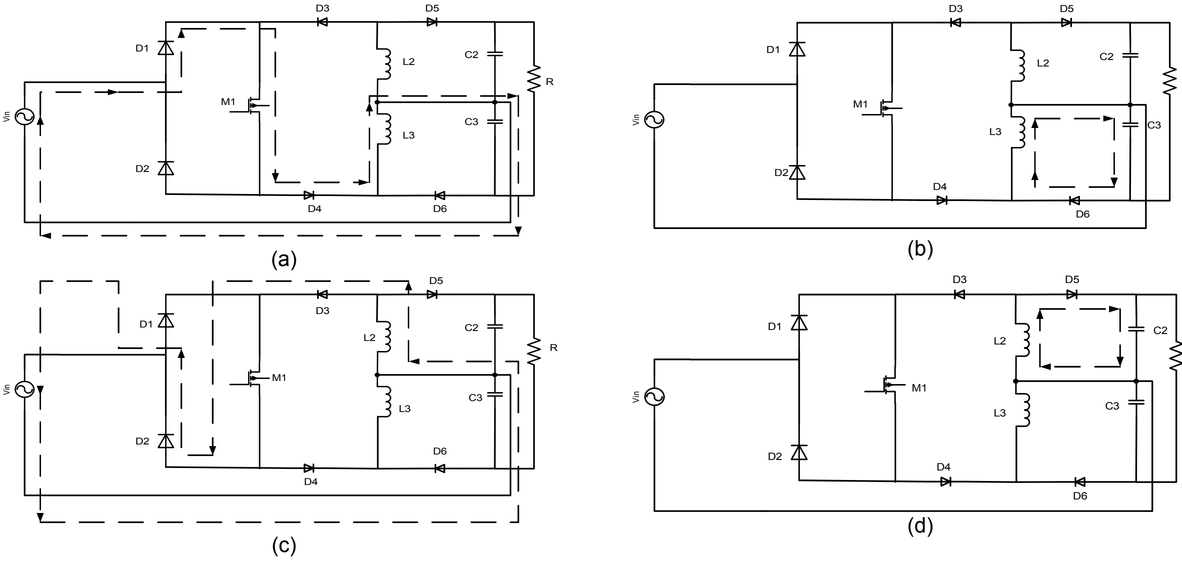
The proposed single-phase non-isolated AC-DC Buck Boost converter is shown in Figure 1.The proposed converter provides output voltage that is in the same polarity of the input signal. There are three inductors (L1 to L3), three capacitors (C1 to C3), six diodes (D1 to D6) and a switch M1.The inductor L1 and the capacitor C1 form the input filter. Inductors L2 and L3 act as Buck-Boost inductors. Capacitors C2 and C3 are used as output capacitors and resistor R is used as load.



(a)

(b)

Fig.1. (a) Proposed Single-Phase AC-DC Buck Boost Converter
(b) Conventional Single-Phase AC-DC Buck Boost Converter



(a) (b) (c) (d)

Fig.2. Four Modes of Operation of Proposed AC-DC Buck-Boost Converter
(a) Mode 1: positive half cycle when M1 is ON (b) Mode 2: positive half cycle when M1 is OFF
(c) Mode 3: negative half cycle when M1 is ON (d) Mode 4: negative half cycle when M1 is OFF

Principle of Operation

The proposed AC-DC Buck Boost converter has four modes of operation. In positive half cycle there are two modes of operation with switch ON and OFF position. Similarly, in negative half cycle there are another two modes with switch ON and OFF position.

Mode 1: When the switch (M1) is ON during positive half cycle of the input signal, inductor L3 charges from the source. Current flows through D1, M1, D4 and L3 as shown in Fig.2(a).
Mode 2: In the positive half cycle of the input signal when the switch (M1) is OFF, the source is isolated from the rest of the circuit as shown in Fig.2(b). The diode D6 is forward biased and C3 is charged through inductor L3.
Mode 3: When the switch (M1) is ON during negative half cycle of the input signal inductor L2 charges from the source. Current flows through D2, M1, D3 and L2 as shown in Fig.2(c). Diodes D1, D4, D5 and D6 remain off.
Mode 4: In the negative half cycle of the input signal when the switch (M1) is OFF, the source is isolated from the rest of the circuit as shown in Fig.2(d). The volatge of inductor L2 forward biases the output diode (D5) and charges the output capacitor (C2).

Ideal Voltage Gain Equation of the Proposed Converter

When the switch is on, the voltage across inductor L3 is

(1) $v_{L3} = v_{in}$

When the switch is off,

(2) $v_{L3} = -v_{C3} = -0.5v_o$

Here, v_{L3}, v_{C3} and v_o are voltage across inductor L3,capacitor C3 and output resistor R respectively. Volt-sec balance over one switching cycle will not be equal to zero since the input is sinusoidal. The volt-sec balance over a line frequency period will be zero. For full supply cycle of N switching per period for inductor L3,

(3)

$$\sum_{n=1}^{N}\int_{t_i}^{t_i+T_{Sw}} v_{L3}dt = \sum_{n=1}^{N}\int_{t_i}^{t_i+DT_{Sw}} v_{in}dt + \sum_{n=1}^{N}\int_{t_i+DT_{sw}}^{t_i+T_{Sw}} -\frac{1}{2}v_o dt = 0$$

Here, T_{sw} is total switching period, DT_{sw} is ON period of switch and D is the duty cycle. Let us assume,

(4) $v_{in} = v_{in\,\max}\sin(\omega t-\theta_{in})$

(5) $v_o = v_{o\,\max}\sin(\omega t-\theta_o)$

Then equation (3) can be expressed as

(6)

$$\sum_{n=1}^{N}\int_{t_i}^{t_i+T_{Sw}} v_{in\,\max}\sin(\omega t-\theta_{in})dt = \sum_{n=1}^{N}\int_{t_i+DT_{Sw}}^{t_i+T_{Sw}} 0.5v_{o\,\max}\sin(\omega t-\theta_o)dt$$

Now after integration, from equation (6)

(7) $$\sum_{n=1}^{N} v_{o\,\max}\sin(\omega t_i-\theta_o) = \frac{2D}{1-D}\sum_{n=1}^{N} v_{in\,\max}\sin(\omega t_i-\theta_{in})$$

Then the average value of output volatge is

(8) $$v_{oavg} = \frac{1}{\pi}\int_0^{\pi} v_{o\,\max}\sin\theta d\theta$$

(9) $$v_{oavg} = \frac{2D}{1-D}\times\frac{2v_{in\,\max}}{\pi}$$

The relation of input and output voltage in equation (9) shows that the converter can work in both Buck mode and Boost mode. Simulated output voltage and theoretical voltage is compared in Table 1.

Table 1: Output voltage for theoretical and simulation results

Duty Cycle	Voavg (Theoritical)	Voavg (Simualtion)
0.1	43V	51V
0.2	96V	107V
0.3	164V	181V
0.4	255V	288V
0.5	382V	441V
0.6	573V	637V
0.7	892V	879V
0.8	1528V	1128V
0.9	3438V	852V

It can be seen from Table 1 that the simulation results match with theoretical results for most of the duty ratios. It is expected that there should some deviation for extremely high duty ratios.

Simulation and Results

Simulation of the proposed circuit is performed with PSIM software. For simulation of Buck-Boost configuration an input ac source of 300V amplitude and with frequency of 50 Hz is employed. Here MOSFET is used as the switching device and the switching frequency is set at 10 kHz. Inductor L1 and capacitor C1 act as input filter with

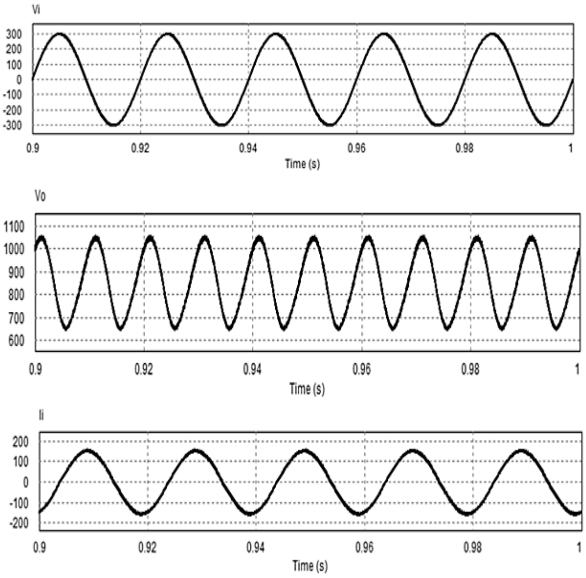


Fig.3. Typical input voltage, output voltage and input current wave shapes of the proposed converter

corresponding values of L1 = 5mH and C1 = 1μF.The values of other inductors and capacitors for the circuit are L2 = 1mH, L3 = 1mH, C2 = 110 μF and C3 = 110 μF. A resistor R = 100 Ω is used as the load in the circuit.

Typical input current, input voltage and output voltage waveforms are shown in fig.3 for the proposed single phase non-isolated AC-DC Buck Boost converter. Detailed numerical results from simulation is shown in table 2.

Table 2. Open loop result of proposed converter under duty cycle variation

Duty cycle	Efficiency (%)	Power factor	THD (%)	Voltage gain
0.1	97.59	0.71	40.29	0.24
0.2	99.06	0.77	57.15	0.55
0.3	99.29	0.75	61.19	0.85
0.4	99.28	0.81	50.79	1.35
0.5	99.16	0.90	37.72	2.08
0.6	99.05	0.97	25.65	3.01
0.7	98.72	0.97	15.75	4.15
0.8	98.03	0.82	7.33	5.32
0.9	95.29	0.34	1.54	4.02

The propsed AC-DC Buck-Boost converter shows good conversion efficiency for all duty raios. Power factor is also good for some duty ratios in open loop analysis.

Performance analysis under duty cycle variation

The performance analysis of proposed converter in comparison with the conventional converter is done with the variation of duty cycle. The data used for conventional converter in fig.1(b) are L1=5mH, L2=1mH, C1=1uF, C2=220uF.The same switching frequency (10 kHz) is maintained for both the circuits with the same load (R = 100Ω). The proposed converter shows better efficiency over the conventional one as seen from fig.4 except for duty ratio of 0.8 and 0.9. The proposed converter presents higher voltage gain than the conventional one throughout the variation of duty cycle except for duty ratio of 0.9 as illustrated on fig.5. The total harmonic distortion(THD) of input current shows better performance in case of proposed converter for higher duty cycles.

Performance analysis under load variation

Both conventional and proposed single phase AC-DC Buck-Boost converter circuits are subjected to load variation at constant switching frequency and duty cycle. The switching frequency is set to 10 kHz and duty cycle is maintained at 60%.The load resistance is varied from 50Ω to 150Ω. The proposed converter shows higher power factor over the conventional one throughout most of the variation of load. The power factor of the proposed converter remains almost close to unity. The proposed converter has much higher efficiency than the conventional one over the variation of load as seen in fig.8. The efficiency of the proposed converter is as high as 99% for most load variations.

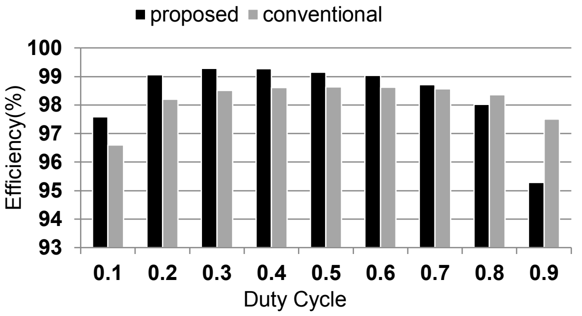


Fig.4. Comaprison of efficiency between proposed and conventional converter under D variation (R=100Ω, Fs=10 kHz)

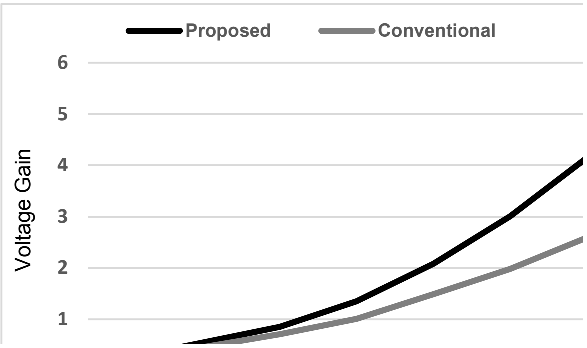


Fig.5. Comparison of gain between proposed and conventional Buck-Boost converter under D variation (R=100 Ω, Fs=10 kHz)

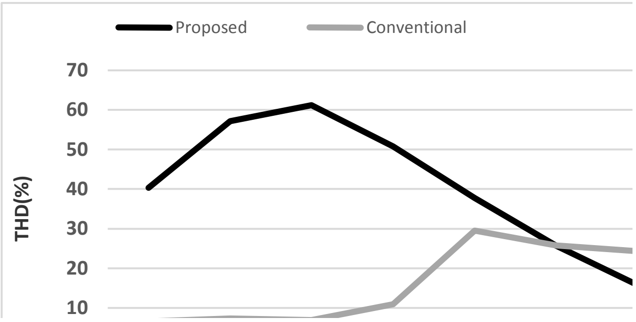


Fig.6. Comparison of THD between proposed and conventional Buck-Boost converter under D variation (R=100 Ω, Fs=10 kHz)

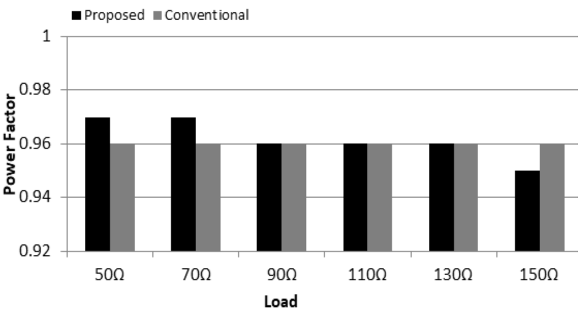


Fig.7. Comparison of power factor between proposed and conventional Buck-Boost converter under load variation (D=0.6, Fs=10 kHz)

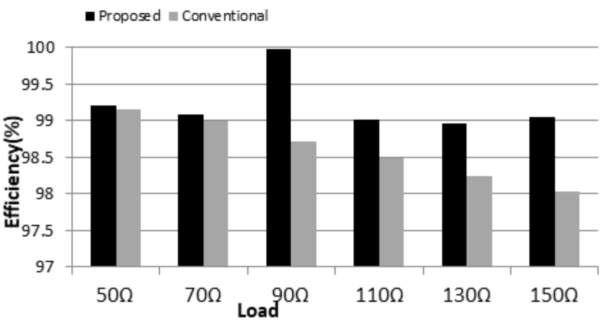


Fig.8. Comparison of efficiency between proposed and conventional converter under load variation (D=0.6, Fs=10 kHz)

Performance analysis under frequency variation

Both proposed and conventional single phase AC-DC Buck-Boost converter circuits are subjected to frequency variation at constant duty cycle and for the same load. The switching frequency is varied from 10 kHz to 100 kHz. The proposed converter has better power factor than the conventional one throughout the variation of switching frequency. Retaining good PF in high switching frequency is a great attribute for a converter. Fig.9 depicts the comparison between conventional and proposed converter under Fs variation.

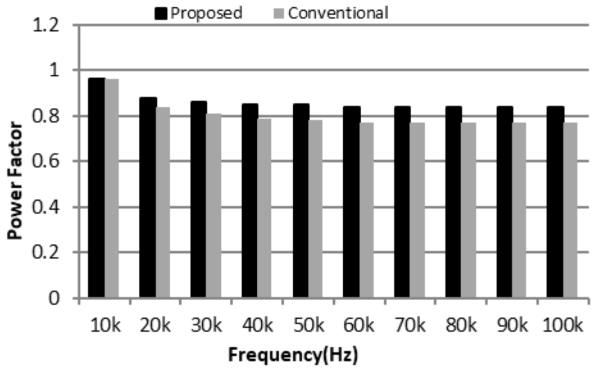


Fig.9. Comparison of power factor between proposed and conventional converter under frequency variation (D=0.6, R=100 Ω)

Feedback Controller with Proposed Converter

In general, the input power factor of conventional AC-DC converters is very low in open loop operation. These results in many problems in overall power system. Proper feedback controller design can overcome such troubles by improving the input power factor of the converters. Generally, PFC control consists of two loops. One is inner current control loop and the other is the outer voltage control loop. Feedback controller is designed for the proposed single phase non-isolated AC-DC Buck Boost converter as shown in Fig.10.

The average inner current control loop ensures the form of i_L^* based on the template |sin ωt| provided by assessing the rectifier output voltage $|v_S(t)|$. Based on the output voltage feedback, the outer voltage control loop determines the amplitude of $\hat{I}_L$ of i_L^*.The output voltage will drop below its preselected reference value V_0^* if the inductor current is inadequate for a given load supplied by the PFC. The output voltage is measured and is taken as the feedback signal. By utilizing this feedback signal, the voltage control loop adjusts the inductor current amplitude to fetch the output voltage to its reference value. The voltage feedback control functions to control the output voltage of the PFC to the pre-selected dc voltage.

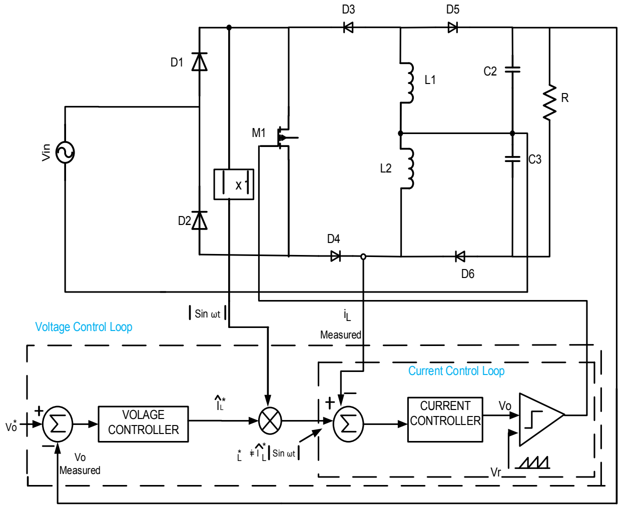


Fig.10: Proposed converter with feedback controller

The current and voltage controller is realized with a PI controller as shown in Fig.11. The transfer function is given as follows

$$G_c = -\frac{R_2}{R_1}\frac{(s+\frac{1}{R_2 C})}{s} \tag{10}$$

The selected values of proportioanl and intergral gains are K_p=-22 and K_i= - 4545.45 by trial and error method.Then Gc is

$$G_c = -22 - \frac{4545.45}{s} \tag{11}$$

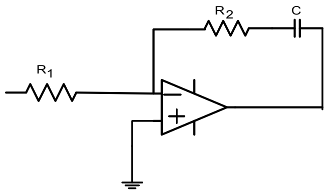


Fig.11. PI controller for feedback operation

Simulation with Designed Controller

Simulation has been done for the proposed converter with feedback controller.The PFC Controller is designed to obtain an average output voltage of 1000 V. From Fig.12 it is evident that the input volatge and current is nearly in phase so that the PFC controller can achieve high power factor. The THD of input current is around 16%. The details comparison is shown in Table 3.

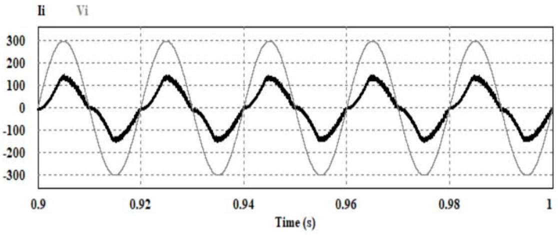


Fig.12. Wave shape of Input voltage and Input current of proposed converter with feedback

Table 3 Results of Feedback controller for 1000 Vdc

Performance Parameters	Conventional Buck-Boost	Proposed Buck-Boost Without Feedback	Proposed Buck-Boost With Feedback
Efficiency	97%	97.5%	98%
Input PF	0.627	0.823	0.98

Dynamic Response of Proposed Converter

Dynamic response observation is a very crucial part in AC-DC converter design. Many converters can't maintain a desired level of voltage with sudden changes in load. Thus it is important to design such converters that can maintain desired level of output voltage with changes in load .The proposed converter exhibits dynamically stable voltage level with sudden changes in load. To evaluate the voltage regulation and the dynamic response of the proposed converter with feedback control, the controller was set with the reference voltage to provide 1000 Vdc output with a resistive load of 200 Ω. Simulation of the circuit is carried out with sudden load changes which is given in Table 4.The simulation result showing the output voltage is given in Fig.13. It is evident from the resultant waveform that, due to feedback control the output voltage of the converter remains almost constant with the change of load.

Table 4 Changes in load for proposed converter

Time (ms)	Load(Ω)
0-300	200
300-500	66.6
500-750	100
750-1000	150

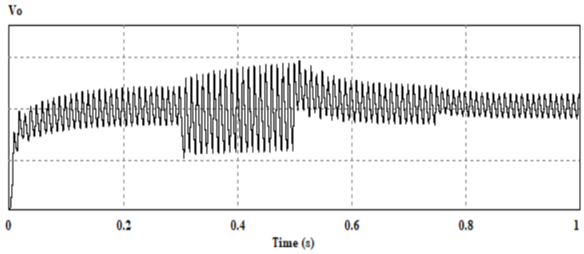


Figure 13: Typical waveform of output voltage for load change using feedback controller

Conclusion

From the open loop analysis, it is evident that, the proposed converter provides better conversion efficiency than the conventional converter throughout the variation of duty cycle. The proposed converter has some deficiency in terms of input power factor which is less than the conventional converter for lower and higher duty cycles. By using suitable feedback control in closed loop system, the problem of low input power factor has been corrected. The proposed converter with PFC controller provides very high input power factor (0.98) which is close to unity. The proposed converter has lesser total harmonic distortion (THD) of input current in comparison with the conventional one for higher duty cycles but for lower duty cycles the conventional converter shows better performance Again, using the feedback controller, the THD of input current is kept within IEEE Standards for the proposed converter. In terms of voltage gain, two converters provide similar performance in buck mode but the proposed converter has higher boost voltage than the conventional converter. Shortly we can say that, the proposed converter has some lacking in terms of input power factor and THD in open loop analysis but the introduction of feedback controller has eliminated these shortcomings. The proposed converter with feedback controller provides higher conversion efficiency, reduced total harmonic distortion (THD) of input current and quality power factor.

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