Hybrid Single Phase Buck AC-DC Converter with Improved Power Quality

Golam Sarowar, Md Ashraful Hoque*, and Mohammad Ali Choudhury

***Abstract*—A new topology of single-phase AC-DC converter using Buck conversion with high efficiency at extremely low duty cycle is proposed with low input current total harmonic distortion (THD) and high input power factor. Proposed double stage converter consists of single phase rectifier followed by a switched capacitor buck DC-DC converter. The input current THD is kept low and the input power factor is high with two-loop feedback control. The proposed schemes can be used in the application of new generation LED lighting.**

***Keywords*—AC-DC converters, bridge rectifier circuits, harmonic distortion, passive filters.**

I. Introduction

Single phase AC to DC converters are common in modern day power supplies. The converter forms interface between the utility power supply and electronic equipment connected to them. The process of rectification used to be simple, but recently, rectifiers have become much more sophisticated, and are now systems rather than mere circuits [1] because of the requirement of the power quality.

In practice, conventional rectifiers are harmonic polluters of the AC power distribution systems, because these converters absorb energy from the AC line whereas the rectified line voltage is higher than the DC link voltage. The adverse effects of power system harmonics are: unsafe neutral current in three phase systems, heating and reduction in life in transformers and induction motors, degradation of system voltage waveforms, unsafe current in power factor correction (PFC) capacitors and malfunctioning of certain power system protection elements. In order to solve the harmonic pollutions caused by AC-DC converters, various methods have been proposed. One simple method is to use the input filter, but the size of the inductor and capacitor required in such solution are large. Use of the passive filter keeps THD in tolerable limit but power factor remains low. To overcome the problem, a number of power factor correction AC-DC converters have been proposed and developed [2], [3], [4], [5], [6], [7], [8]. Generally, techniques involving two power-processing stages are used to solve the problems. The input PFC stage improves the power factor as well as maintains a constant DC link voltage. The most common PFC stage employ a Boost converter [4], [5], [9]. Buck, Buck-Boost, uk, SEPIC and ZETA converters are also employed for the same purpose with different input/output voltage gain relationships. In output stage, high frequency DC-DC converter [10], [11] acts as high frequency output current/voltage chopper which is reflected at the input as high frequency chopped AC current. This input current is then filtered by a small filter to obtain near sinusoidal input current with high power factor [12], [13]. This is possible only when the output is full wave pulsed DC.

To obtain quality power, the output voltage is desired to be DC with low ripple. As a result, large output filter capacitor is necessary. This output filter with large capacitance draws pulsed current, and the pulsed ac current is reflected to the input side. Thus additional control is required to maintain sinusoidal shape of the input current. The unidirectional switch used in the DC-DC converters for boost-regulated AC-DC conversion must operate in critical mode [14], [15] that is, the power switch should be turned ON at the instant of zero current in the boost diode. Thus variable switching frequency operation of the DC-DC converter is required due to load or the input voltage changes. Another approach for boost-regulated rectifier involves controlling to a constant level the average current of

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the boost diode. In order to keep the average current constant through the boost diode, the duty cycle must be modulated over the line cycle. Bridge-less configurations [2], [16] and two-diode, two-switch rectifiers are also reported in literatures for AC-DC conversion having the above features of boost-regulated rectifier. The reported bridgeless single phase AC-DC converters use more than one unidirectional switches or one bidirectional switch composed of two unidirectional switches anti-parallel with two diodes.

Recently LEDs draw much attention in the lighting application because LEDs have 30% more efficacy, emits much higher lights in a desired direction, have a longer lifetime [17], [18]. LEDs are operated in very low DC voltage, therefore efficient power electronic circuit is necessary to obtain optimum energy management. Conventionally these applications use a transformer to reduce the voltage and then AC-DC converter is used. Efficiency suffers due to the use of the transformer. Transformerless control techniques suffers from a low input power factor and distorted input current. The conversion efficiency of conventional AC-DC converter varies with the change in duty cycle. The efficiency tends to reduce with extremely low duty cycle [19].

With the widespread development of electronic equipments, harmonics of rectifier have become significant and measurable problem. In addition, conventional single-phase AC-DC converters suffer from problems of low conversion efficiency at extremely low duty cycles and low input power factor [1], [20], [21]. Thus there is a need for quality rectifier which operate with high efficiency, high input power factor and minimum generation of harmonics. In this paper, double stage single phase AC-DC buck converter is designed using switched capacitor circuitry [22] to achieve high efficiency at extremely low duty cycles. A suitable feedback control technique is also used to achieve high input power factor and low THD for input current.

The proposed circuit is discussed in section II and the principle of operation in section III. Open loop simulation of the proposed converter is illustrated in section IV. Due to low input power factor of the proposed converter in open loop simulation, a close loop control is necessary to implement with the converter. The small signal model of the proposed converter with the feedback control is presented in section V. The simulation of close loop converter system is provided in section VI. The paper is ended with concluding remarks in sec VII.

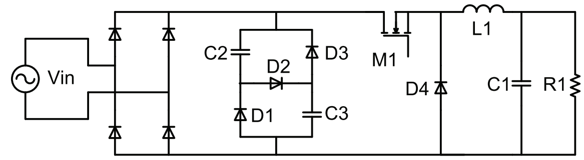


Fig. 1. Proposed circuit for single phase AC-DC Buck converter in two stage.

II. Proposed Circuit Configuration

Modern rectifier technology now incorporates many of the DC-DC converter fundamentals in between the diode bridge configuration and the load to form the double stage converter. The conventional double stage converter suffers from low efficiency at extremely low duty cycles. Fig. 1 illustrates the proposed single phase AC-DC converter using Buck topology in two stage. The first stage is basic single phase rectifier followed by high frequency switched capacitor DC-DC second stage. The value of duty cycle needs to be selected to achieve specific low output voltage from a conventional double stage converter is smaller than that of proposed converter. Addition of the switched capacitor branch helps to obtain same output voltage level with relatively high duty cycle. Thus the efficiency of the proposed converter should be higher than that of conventional double stage converter for same voltage gain. The proposed circuit comprises two inductors (L1 and L2), three capacitors (C1 to C3), eight diodes (D1-D8) and a switch M1. Here L1 work as Buck inductors. The inductor L2 and capacitor C2 are used as input filter. C1 and R1 are the output capacitor and load of the converter respectively. Resistive load has been selected for this investigation because this type of load offers highest harmonic distortion in the input side when output is filtered. On the otherhand R-L or R-C type of load has built-in filter property to reduce the distortion. So in practice the converters are designed with resistive load.

III. Principle of Operation

In single stage converter the input AC chopping at high frequency provides switched AC current. A small input filter makes it nearly sinusoidal. As a result, the input current THD reduces. To increase the input power factor proper feedback is required.

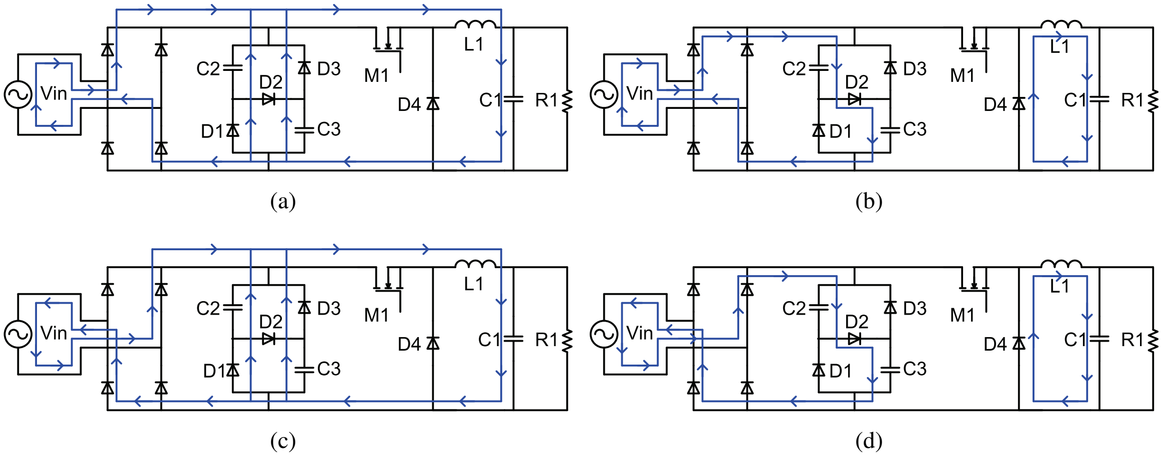


Fig. 2. Four states of operation of proposed double stage single phase AC-DC Buck converter, (a) State A, circuit when the switch is ON during positive half cycle of the AC supply, (b) State B, circuit when the switch is OFF during positive half cycle of the AC supply, (c) State C, circuit when the switch is ON during negative half cycle of the AC supply, (d) State D, circuit when the switch is OFF during negative half cycle of the AC supply.

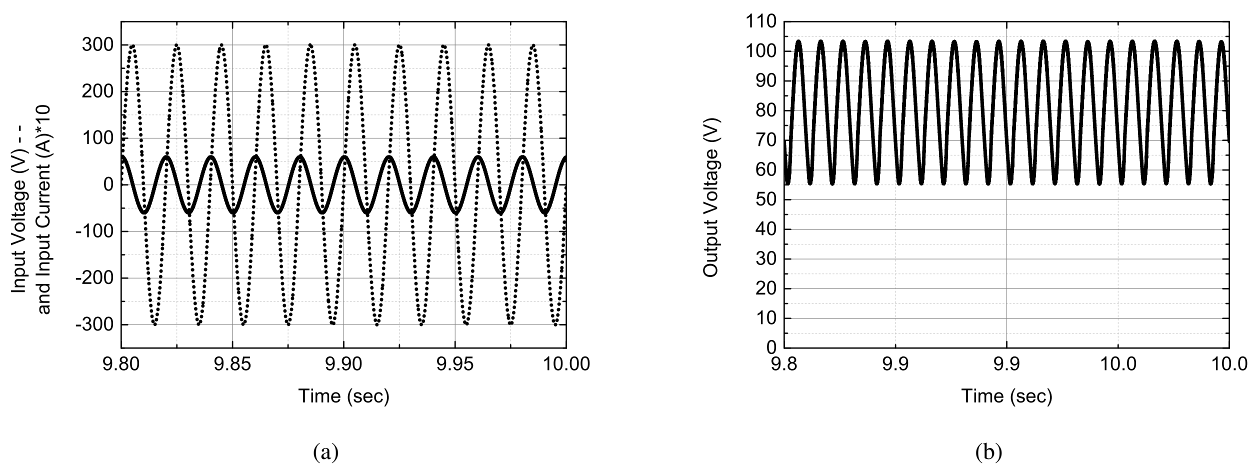


Fig. 3. Input voltage and input current*10 (a) and output voltage waveform (b) of proposed single stage Buck converter at voltage gain of 0.3.

The operating principle of the proposed converters is described below.

The Buck topology in double stage also has four operating states as shown in Fig. 2. State A and B represent the positive half cycle operation with switch ON and OFF positions, whereas, state C and D represent the negative half cycle with switch ON and OFF positions respectively.

IV. Open Loop Simulation Results

The mathematical model of the converter is highly nonlinear and complex. It is usual practice to simulate this type of converters using softwares like PSIM professional version 9.0.3.400 and OrCAD Capture CIS version 9.2. And the control circuit is designed using MATLAB. The results are shown in Fig. 3 to Fig. 7.

1) Circuit Parameters: For the open loop simulation of double stage buck configuration an input ac source of 300V amplitude with frequency of 50 Hz is employed. An MOSFET is used for switching purpose. In double stage topology the inductors L1 and L2 have the values of 400uH and 40mH respectively, the capacitor C1 have the value of 50 F and C2 to C3 have the values of 1F each. A resistor of 100 is used as load. The proposed circuit topologies have been compared with the conventional single phase AC-DC Buck configuration converter.

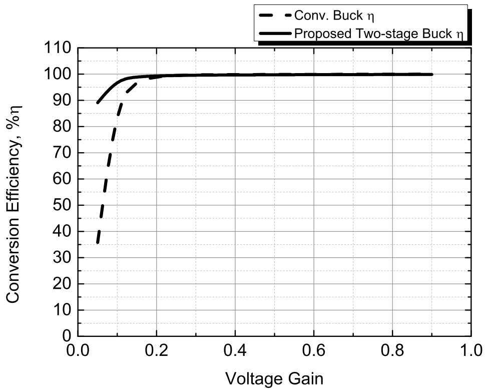


Fig. 4. Comparison of conversion efficiency (%) between conventional and proposed schemes.

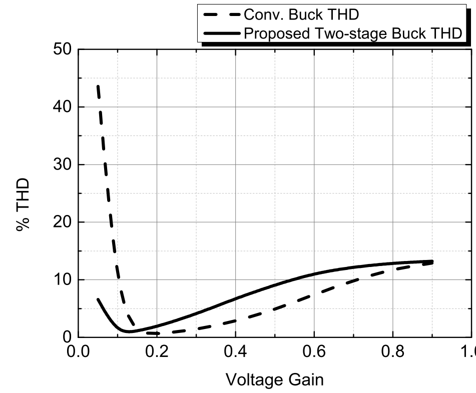


Fig. 5. Comparison of input current THD (%) between conventional and proposed schemes.

2) Results from open loop Simulation: Typical input voltage and current and the output voltage waveforms of the proposed AC-DC double stage Buck converter is given in Fig. 3 for a voltage gain of 0.3.

3) Quantitative Comparison: The input voltage & current of the Fig. 3 (a) clearly shown the THD (%) of the input current of the proposed converter is considerably low, but the input power factor is very low. The input current is almost 90^0 out of phase with the input voltage. The average output voltage of the proposed converter is shown in Fig. 3(b). Average output voltage is approximately 81.2V.

For performance comparison among the proposed and conventional scheme, results are evaluated in terms of efficiency (%) of conversion, THD (%) of input current and input power factor. The outcomes of the investigation are discussed below with diagrams presented in Fig. 4 to Fig. 6.

The performance curve shown in Fig. 4 indicates that the conversion efficiency is reasonable high for the proposed scheme at extremely low duty cycles (0.05-0.15). THD (%) of input current of the proposed converters are reasonably well in extremely low duty cycles compare to the conventional one which is the point of interest (Fig. 5). The proposed converter exhibit low input power factor throughout all the duty cycles as well the conventional one (Fig. 6). The effect of load variation on THD, input power factor and efficiency are shown in Fig. 7. Feedback control scheme needs to adopt to improve the input power factor and to reduce the size of the input filter which will be discussed in the next section.

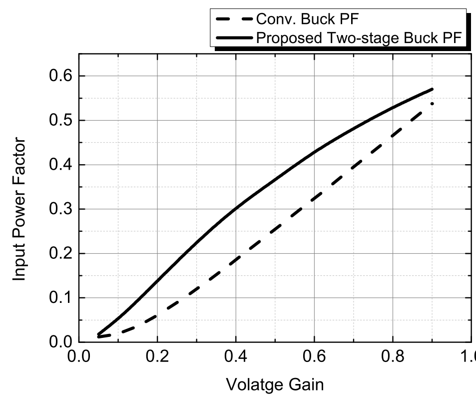


Fig. 6. Comparison of input power factor between conventional and proposed schemes.

V. Feedback Control to Improve Input Power Factor

The input power factor of the proposed converter schemes are very low. Proper feedback control can improve the input power factor of the converters. The PFC feedback control consists of two loop [20]. The inner current loop and the outer voltage loop. Average current mode control is applied to the inner current control loop. The small signal model of the single stage proposed buck converter is given in Fig. 8.

The power stage transfer function for the inner current control loop and outer voltage control loop are derived and shown in equation (1) and (2),

$$G_{PSi}(s) = \frac{\tilde{i}_L(s)}{\tilde{d}(s)} = \frac{1}{(2-D)} \times \frac{\hat{V}_{in} + V_o}{sL} \quad (1)$$

$$G_{PSv}(s) = \frac{\tilde{v}_o(s)}{\tilde{i}_L(s)} = \frac{R}{(sRC+1)} \quad (2)$$

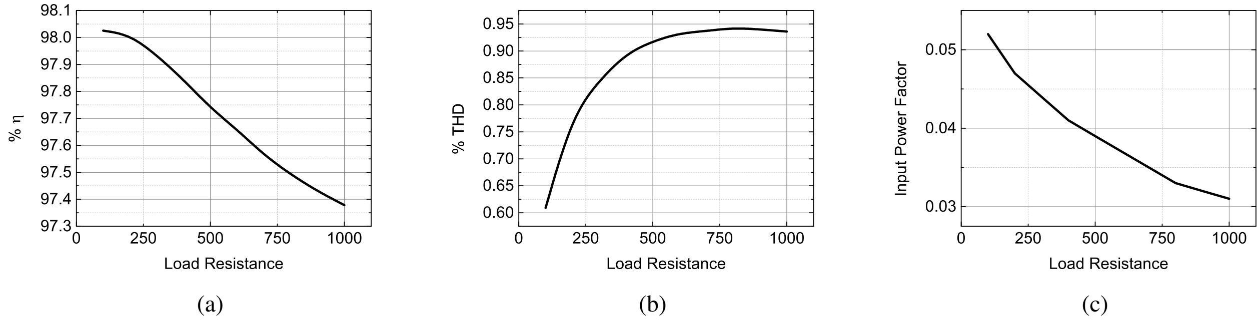


Fig. 7. Effect of variation of load resistance on (a) Efficiency, (b) % THD and (c) Input power factor.

Where,
$G_{PSi}(s)$ = Power stage transfer function of the converter for current control loop,
$G_{PSv}(s)$ = Power stage transfer function of the converter for voltage control loop,
$\hat{V}_{in}$ = Peak input voltage,
V_o = Average output voltage,
$\tilde{i}_L$ = Inductor current perturbation,
$\tilde{d}$ = Duty cycle perturbation,
$\tilde{v}_o$ = Output voltage perturbation,
D = Duty cycle.

The power-stage transfer function for the current control loop in equation (1) is an approximation, valid at high frequencies and not a pure integrator. Therefore to have a high DC loop gain and a zero DC steady state error, the current controller transfer function must have a pole at the origin. In the current control loop the phase due to the pole at the origin of the controller and that of the power stage transfer function of equation (1) add up to -180^0. Hence the current controller in average current mode control introduces a pole-zero pair to provide a phase margin of approximately 60^0 at the loop crossover frequency. The Bode plot of the inner current control loop is shown in Fig. 9. The phase boost of 60^0 is provided at crossover frequency of 10 kHz.

The objective of the outer voltage control loop is to generate the peak of the reference current for the current control loop. In the voltage loop the bandwidth is limited to approximately 15 Hz. The power-stage transfer function for the voltage control loop at these low perturbation frequency is shown in equation (2). Because of such low bandwidth it is perfectly reasonable to assume that the current loop to be ideal at low frequency around 15 Hz. To achieve zero steady state error, the voltage controller should have a pole at the origin. A transfer function is used for the voltage controller, where a pole is placed at the voltage-loop crossover frequency (which is below 15 Hz) is often used for simplicity. The Bode diagram of the voltage control loop is shown in Fig. 10. The PFC controller with the two stage AC-DC buck converter is shown in Fig. 11.

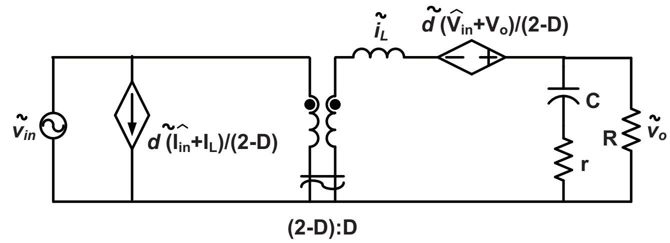


Fig. 8. Small signal model of the proposed double stage AC-DC buck converter.

VI. Closed Loop Simulation Results

The control circuit is designed to achieve an average output voltage of 100V. The comparison of the input power factor with and without the feedback control is shown in Fig. 12 and the data is tabulated in Table I. The simulation result of the input current and voltage are shown in Fig. 13 (a) where input current is multiplied with 100 to show in the same scale with input voltage. The average output voltage is shown in Fig. 13 (b).

The input power factor improved significantly with the adopted feedback controller compared to the uncontrolled converter. Also the inductor and the capacitor of the input filter reduces to 1mH and 1F respectively without affecting converter efficiency and THD (%).The THD of the AC mains current remains

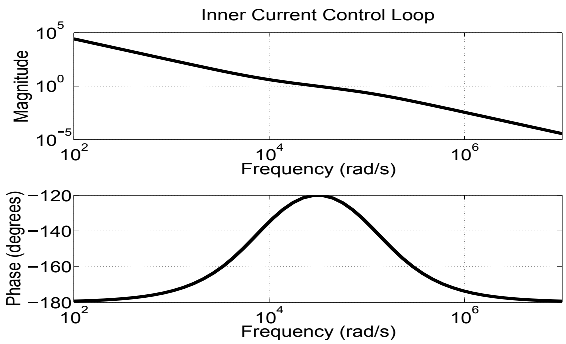


Fig. 9. Compensated Bode plot for the current control loop of the two stage AC-DC buck converter.

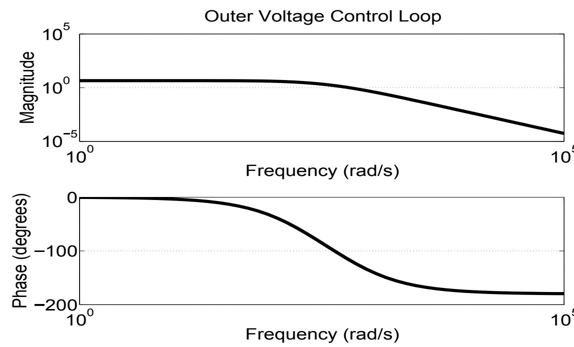


Fig. 10. Compensated Bode plot for the voltage control loop of the two stage AC-DC buck converter.

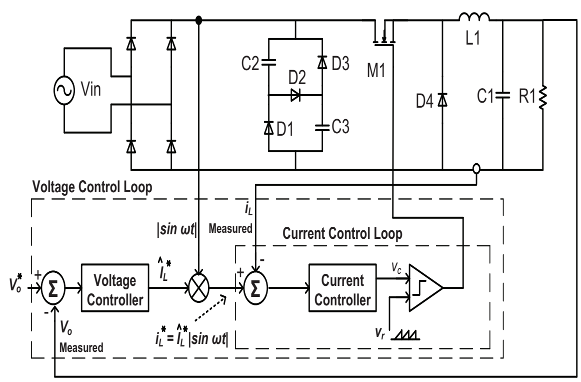


Fig. 11. PFC controlled single phase two-stage AC-DC buck converter.

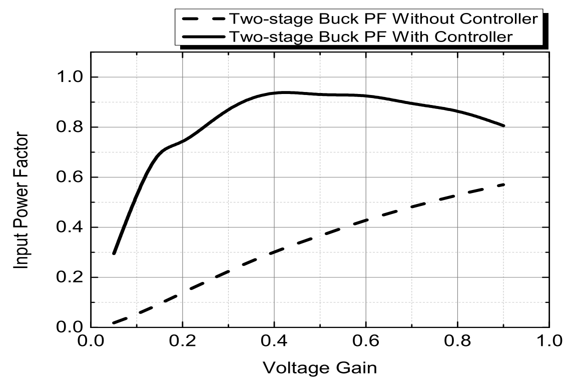
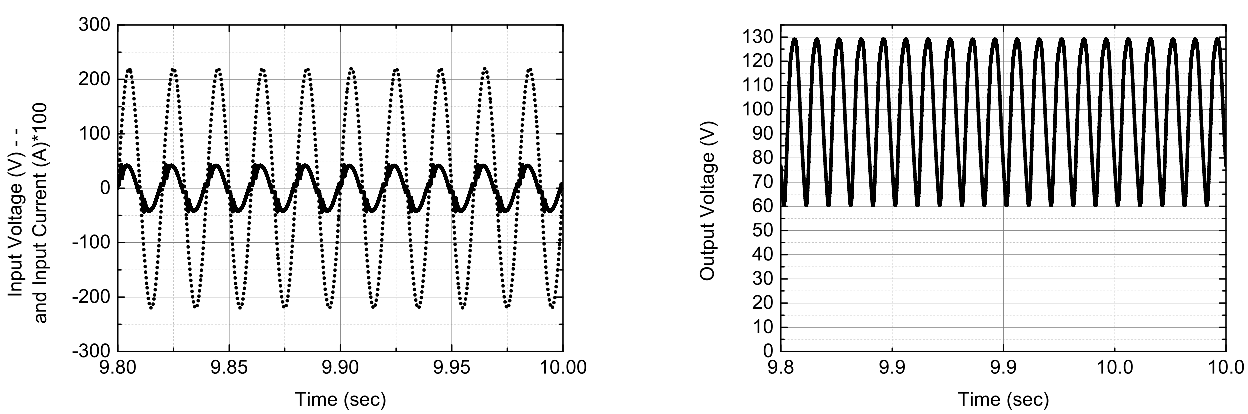


Fig. 12. Comparison of the input power factor of proposed AC-DC buck converter in two-stage with and without the feedback control.



(a)

(b)

Fig. 13. Input voltage and input current*100 (a) and output voltage waveform (b) of proposed single stage Buck converter at voltage gain of 0.3.

around 5% thereby complying with the standard IEC-61000-3-2. The input power factor of the proposed converter is comparable with recent works [7], [23], [24].

VII. CONCLUSION

A new topology for single phase AC-DC Buck converters is proposed in this paper. The conventional double-stage converter is modified to design the

TABLE 1
COMPARISON OF INPUT POWER FACTOR WITH AND WITHOUT FEEDBACK CONTROL

Voltage Gain	Without Controller	With Controller
0.05	0.018	0.295
0.10	0.052	0.536
0.15	0.094	0.726
0.20	0.138	0.724
0.30	0.226	0.886
0.40	0.304	0.951
0.50	0.366	0.925
0.60	0.430	0.933
0.70	0.482	0.891
0.80	0.530	0.871
0.90	0.570	0.806

topology. The proposed converter shows significant improvement in the conversion efficiency at extremely low duty cycles. THD (%) of the input current is kept low but the input power factor was very low. Suitable feedback control is adopted to improve the input power factor. Significant improvement of input power factor is noticed at low duty cycles and achieved maximum input power factor of 0.951 at the voltage gain of 0.4. The conversion efficiency and the THD (%) was not affected by the feedback control. In addition, the feedback control reduced the size of the input filter. High efficiency low voltage can be used for lighting load specifically for new generation LEDs.

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