

# THREE PHASE AC-DC CONVERTER FOR UTILITY POWER FACTOR IMPROVEMENT AND PEAK VOLTAGE STRESS REDUCTION

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**Abstract:** *Three phase, reduced-switch, ac-dc buck-boost type converter is a simple and low cost topology that can operate with input-power-factor correction. In this paper, the design and steady state operation of the proposed converter is analyzed and compared with the performance of conventional three phase single switch buck boost converter in detail. From the analysis, the observed special features of the proposed converter are better power factor correction at input side and lower peak switch voltage stress. The converter is found to be suitable to operate in wide span of output voltages (buck and boost) for an ac input voltage.*

**Key words:** *3 $\phi$  diode rectifier, power factor improvement*

## I. INTRODUCTION

POWER electronic converters that operate from the utility mains, are the reason for generation of current harmonics which will be fed into the mains. It is necessary to restrict these harmonics to satisfy regulative standard values. This could be achieved by power factor issue correction (PFC). Three-phase PFC is usually performed by employing a six-switch converter either to allow the bulk amount of power given to load or to be an active filter that processes solely a little of the power fed to the load.

Use of conventional six-switch rectifier to achieve good power factor needs smooth control, which is costly and complex. To obtain a cheaper control, the number of switches used for the converter should be reduced [1]-[6].

In [7], one such type of converter (single switch buck boost converter) is designed and analyzed with less number of switches to get good power factor. Generally, in boost type of converters, the output is always higher than the input voltage. Due to this

reason, this converter is not suitable for applications which require wide range of AC voltages.

To achieve the DC regulation for the wide range of AC voltages, buck boost converter based topologies are found to be better as discussed in [8]. The power factor improvement technique for the single switch three phase buck boost converter is explained in [9]. To improve the power factor, the converter is designed to be operating its input line currents in discontinuous conduction mode. In this topology, the input power factor was improved but the peak voltage across the switch is very high. Hence this topology became impractical due to this peak switch voltage stress.

To reduce the peak voltage stress of the switch, a new topology is proposed in [10]. In this topology instead of using a single switch, two switches are used and neutral point connected capacitive type filter is placed at the input side. Hence the peak voltage stress of each switch is reduced.

In this paper, the performance of the topology proposed in [10] is analyzed and compared with the conventional three phase single switch buck boost converter. The design procedure of the converter is explained elaborately and the results in terms of better power factor correction and lower switch voltage stress are discussed.

## II. STANDARD CONVERTER OPERATION

The three phase AC-DC single switch buck-boost converter is shown in Fig-1.

When the value of duty cycle value is less than 0.5, the standard converter is operated in buck mode. If duty cycle value is greater than 0.5 then the converter is operated in boost mode.

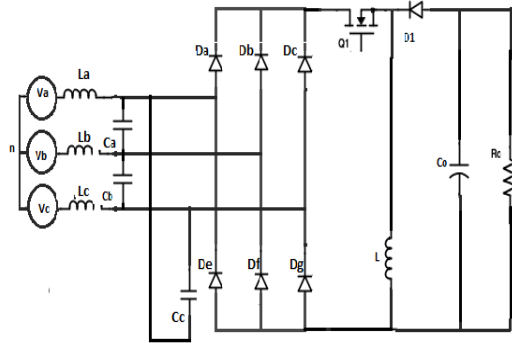


Fig 1: Schematic of standard 3 phase single switch buck boost converter

The principle of operation of standard converter is explained as follows.

#### i. Buck mode operation:

##### Mode-1

Whenever, the switch  $Q_1$  is turn ON, the three capacitors  $C_a$ ,  $C_b$  and  $C_c$  starts discharging. The line current and the discharging current will flow through the diode  $D_a$ ,  $Q_1$  and  $L$ . the output inductor starts charging. Finally the current will return to the AC side through the diode  $D_g$ . the output capacitor  $C_0$  will discharge and this voltage will appear as the output voltage across the load  $R_0$ . If the three input side capacitors discharged completely, then the switch will be turned off.

##### Mode-2

Whenever, the switch  $Q_1$  is turn OFF, the three capacitors  $C_a$ ,  $C_b$  and  $C_c$  starts charging. The output inductor current will freewheels through the  $D_0$ . If all the three input side capacitors charged completely, then the switch will be turn ON. The corresponding waveforms for buck mode are shown in Fig.2.

#### ii. Boost mode operation MODE:

##### Mode-1

Whenever, the switch  $Q_1$  is turn ON, the three capacitors  $C_a$ ,  $C_b$  and  $C_c$  starts discharging. The line current and the discharging current will flow through the diode  $D_a$ ,  $Q_1$  and  $L$ . the output inductor starts charging. Finally the current will return to the AC side through the diode  $D_g$ . the output capacitor  $C_0$  will discharge and this voltage will appear as the output voltage across the load  $R_0$ . If the three input side capacitors discharged completely, this mode of operation will be ended.

##### Mode-2

The switch will be in ON condition, but the three capacitors discharged completely. Here the capacitor voltage will be zero. This is said to be discontinuous voltage mode of the capacitor. The output inductor  $L$  current will freewheels through the  $D_0$ .

##### Mode-3

When the switch will OFF, the three input capacitors  $C_a$ ,  $C_b$  and  $C_c$  start charging. The output inductor starts discharging and this discharging current will flow through the capacitor  $C_0$  and  $D_0$ . The corresponding waveforms for the boost mode are shown Fig.4

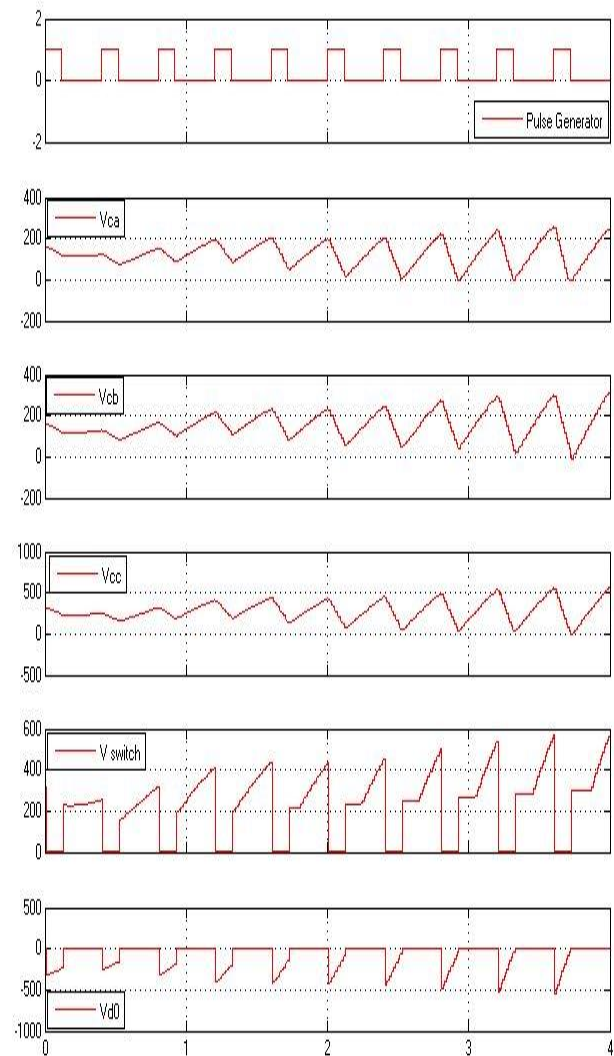


Fig 2. Waveforms related to buck mode of operation

Fig: 2- 1) Gate pulse for the switch 2) Voltage across the capacitor  $C_a$  3) Voltage across the capacitor  $C_b$  4) Voltage across the capacitor  $C_c$  5) Voltage across the switch 6) Voltage across the output diode  $D_0$

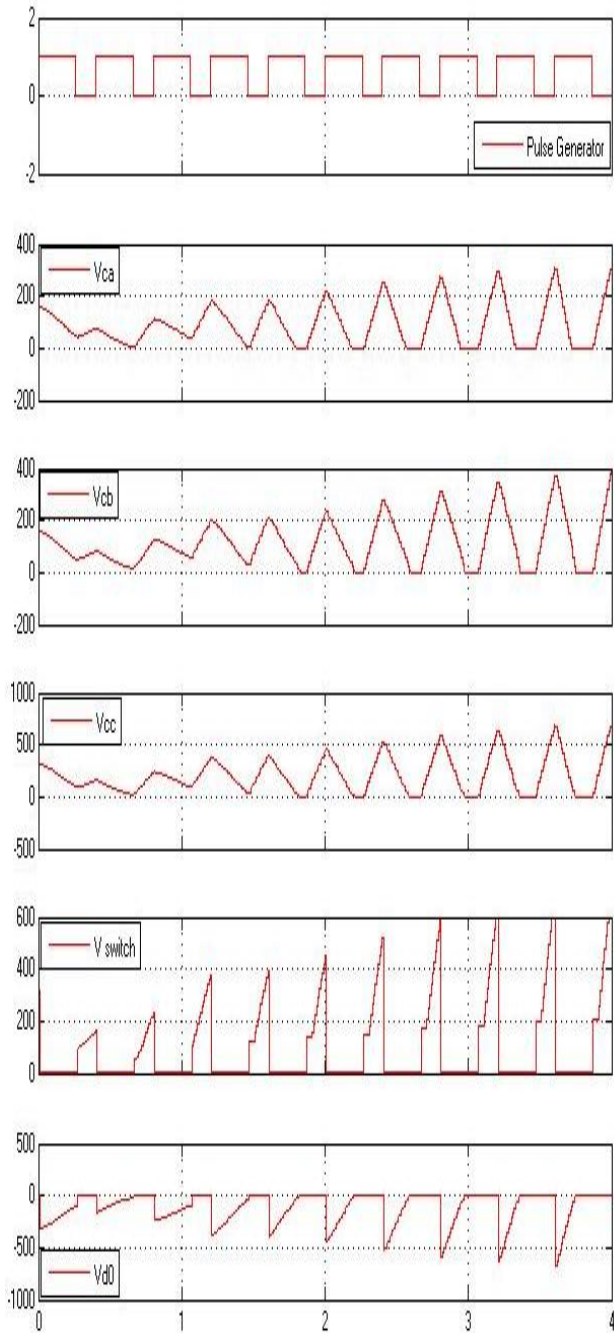


Fig-3. Waveforms related to boost mode of operation

Fig.3 – 1) Gate pulse for the switch 2) Voltage across the capacitor  $C_a$  3) Voltage across the capacitor  $C_b$  4) Voltage across the capacitor  $C_c$  5) Voltage across the switch 6) Voltage across the output diode  $D_0$

### III. PROPOSED CONVERTER

The three-phase reduced switch buck–boost converter is shown in Fig.4 (which is taken from [10]). The converter is very similar to the standard converter shown in Fig.1(which is taken from [9])

because the input portion is same and input section PFC is achieved by the charging and discharging of the input capacitors.

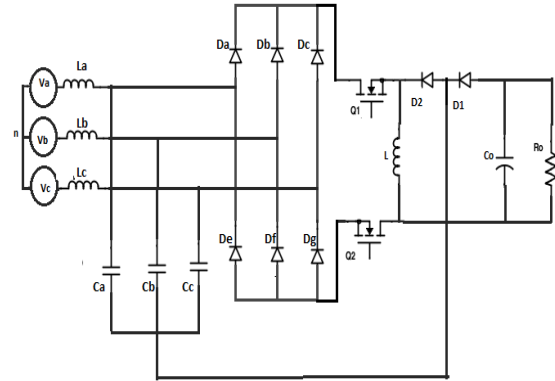


Fig: 4 Proposed converter

The most distinctive feature between the recommended converter (Fig.2) and the standard typical converter (Fig.1) is that, each and every of the switches within the recommended converter sees a line-to-neutral voltage (the voltage across one among the 3 input capacitors) across it instead of a line-to-line voltage (the potential difference across 2 input capacitors), which is the case for the switch within the standard typical converter. Since a switch in Fig.2 experiences line-to-neutral voltage instead of a line-to-line voltage, its extreme switch voltage stress is 1.732 (i.e  $\sqrt{3}$ ) times less than that of the switch in the standard converter. As a result of diminishing the high voltage stress value, lower rated elements may be used rather than what rating devices can be utilized in the standard converter for the exact converter ratings of power.

### IV. PERFORMANCE ANALYSIS

The proposed circuit is analyzed based on the following assumptions.

For steady state performance analysis of the proposed converter the following assumptions are made [7]:

a) The switching frequency  $f_s$  is large with respect to the line frequency  $f_l$ ; hence, during a switching period ( $T_s$ ) the input side voltages, currents and resistances are constants.

b) The three input filter capacitor values  $C_a$ ,  $C_b$  and  $C_c$  are considered to be equal. In a same way, the input filter inductors  $L_a$ ,  $L_b$  and  $L_c$  are of equal values.

c) To operate input capacitor in DVM throughout the line cycle, the capacitor value assumed is small.

d) Consider the DC voltage source  $V_2$  as a combination of the load resistance  $R$  and output capacitor  $C_0$ .

e)  $\pi/6$  of line cycle is considered by a reason of the uniformity of the three phase system.

Fig.5 shown represents the equivalent single switch buck boost converter. LC filter is added to input side of the normal buck boost converter. The performance analysis of this converter under steady state is described in the following subintervals.

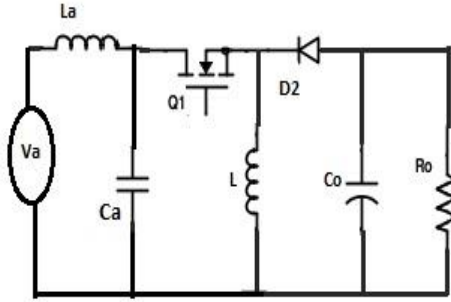


Fig.5 DC-DC buck boost regulator with input LC filter

*Subinterval 1:*

The switch will turn ON when time  $t=0$ . Capacitor discharging current is  $I_2 - I_1$  where  $I_2$  is the switch current and  $I_1$  is the input section current. Output section diode  $D_0$  is reverse biased. Hence, the voltage drop across the diode is equal to  $V_c + V_2$ . At the end of this mode, i.e when  $t=t_1$ ,  $V_c$  becomes zero and capacitor starts to charge in opposite direction.

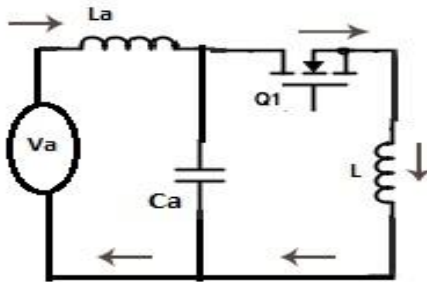


Fig.5a Subinterval 1

*Subinterval 2:*

At  $t=t_1$ , the input capacitor voltage is equal to the negative of output voltage  $V_2$  i.e  $V_c = -V_2$ . The current will flows through the switch and  $L_0$ . Diode  $D_0$  is forward biased and its current is equal to  $I_2 - I_1$ .

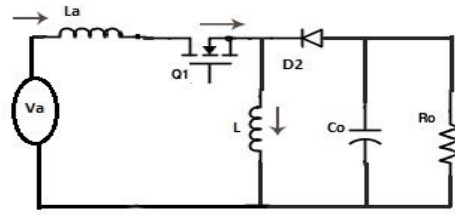


Fig.5b Subinterval 2

*Subinterval 3:*

The switch will turned off when  $t=DT_s$ . Therefore  $C$  starts charging by  $I_1$  and current flowing through the diode  $D_0$  is  $I_2$ . The capacitor charges to its peak value  $V_{CM}$  at  $t=T_s$ .

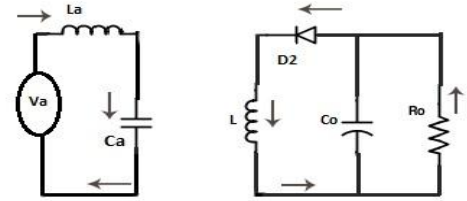


Fig.5c Subinterval 3

## V. DESIGN PROCEDURE

The design of the proposed converter is discussed in the following steps

a. Conversion ratio ( $M$ ):

It is the ratio between output voltage ( $V_2$ ) to the peak line to line input voltage ( $V_1$ ).

$$M = V_2 / (\sqrt{3} * V_1)$$

Fig.4 shows the plot between the values of voltage conversion ratio ( $M$ ) and the values of duty cycle of the proposed converter ( $K < 0.5$  i.e buck mode). This plot is given in [10] to choose the input capacitor value.

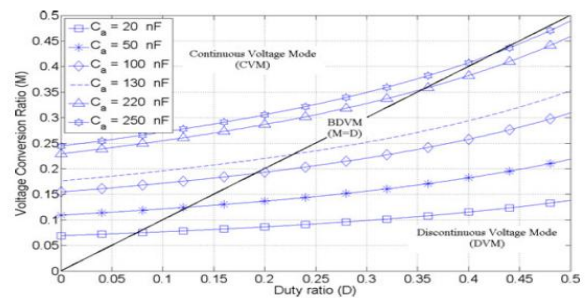


Fig 4. Voltage conversion ratio VS duty ratio [[10]]

Based on this plot, for a particular conversion ratio, for selected duty ratio, choose the input capacitor value which is operated in DVM. In boost mode of operation of the proposed converter, the current is so small to fully discharge the input capacitors during switching cycle which gives the distorted input line currents. So the selected capacitors should be small. But the small capacitors results the high switch voltage stress. So selection of capacitors should satisfy both the conditions.

#### b. Specifications

1. Line to Line input rms voltage ( $V_1$ ) = 230V.
2. Output Voltage ( $V_2$ ) = 150V ( $K < 0.5$ ) and  $V_2 = 500V$  ( $K > 0.5$ ).
3. Output power ( $P_0$ ) in terms of wattage = 2000W
4. Switching frequency ( $f_s$ ) = 25 kHz.

#### c. Design calculations

5.  $M = (150)/(\sqrt{3} \cdot 187) = 0.46$
6.  $L_0 \text{ (Critical)} = \{(1-D)R\}/2f_s = 0.9\text{mH}$   
(from [11])
7.  $C_0 \text{ (Critical)} = D/(2f_s R) = 99.2\text{nF}$
8.  $L_a = L_b = L_c \text{ (Critical)} = V_{ph-ph}/(4\pi \cdot f_s \cdot n \cdot I_{pk})$   
Where  $n$  = ripple current in %.

## VI. RESULTS FROM THE SIMULATION

The simulation of the standard three phase AC-DC single switch buck boost converter is done by using Matlab-Simulink. The simulation is done by taking  $L_a = L_b = L_c = 1.3\text{mH}$ ,  $C_a = C_b = C_c = 220\text{nF}$ ,  $L_0 = 1.3\text{mH}$  and  $C_0 = 1500\mu\text{F}$ .

### a) Standard Converter

#### i) Buck mode simulation results

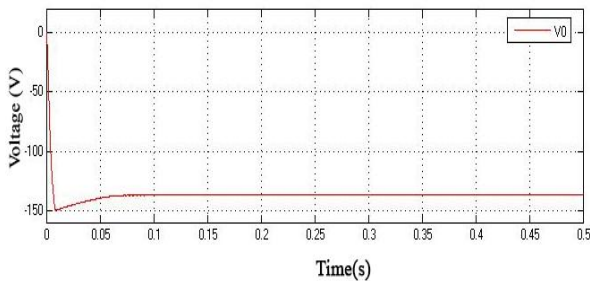


Fig.5a output voltage of standard converter in buck mode of operation

Fig 5a represents the output voltage obtained in buck mode operation of standard converter, which is 146V.

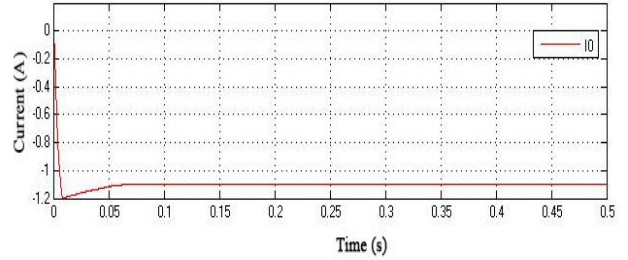


Fig.5b Output current of standard converter in buck mode of operation

The above Fig 5b represents the output current obtained in buck mode of operation of standard converter, which is 1.1A.

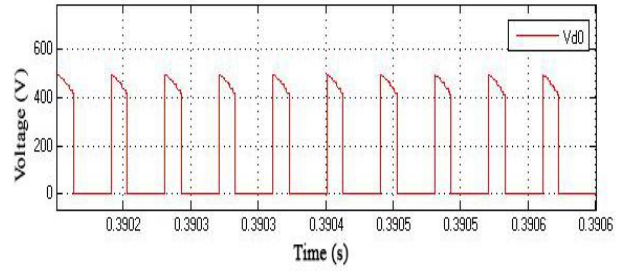


Fig.5c Voltage across the switch of standard converter in buck mode of operation

Fig 5c represents the voltage across the single switch in buck mode operation of standard converter, which is 500V.

#### ii) Boost mode simulation results

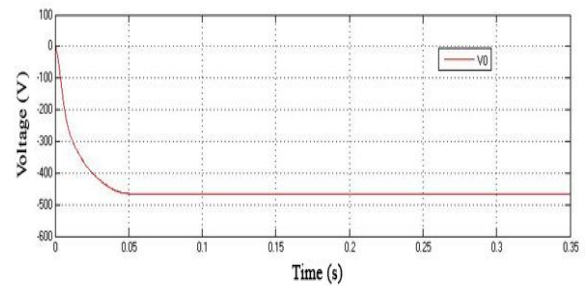


Fig.5d Output voltage of the standard converter in boost mode of operation

The Fig 5d represents the output voltage obtained in boost mode operation of standard converter, which is 465V.



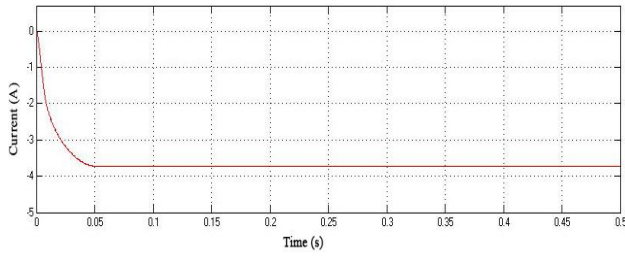


Fig.5e Output current of the standard converter in boost mode of operation

Fig 5e represents the output current obtained in boost mode operation of standard converter, which is 3.8A.

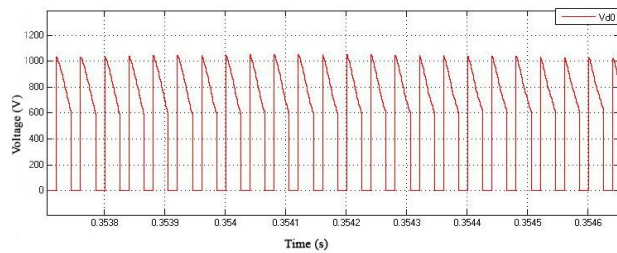


Fig.5f Voltage across the switch of standard converter in boost mode of operation

The above Fig.5f represents the voltage across the single switch in boost mode operation of standard converter, which is 1050V.

Compared to theoretical and simulation analysis for the standard converter, the values obtained are approximately same. In buck mode, the output voltage according to simulation is 146V and current is 1.1A, whereas, in boost mode the output voltage is 465V and current is 3.8A. the peak voltage stress in buck mode is approximately 500V and in boost mode approximately 1050V.

Table I provides power factor obtained from simulation for standard converter with and without filter.

Table-I

Mode of operation	Pf without filter	Pf with filter
Buck	0.83	0.95
Boost	0.84	0.96

## b) Proposed converter results

The simulation of the recommended three phase AC-DC reduced switch buck boost converter is done by using Matlab-Simulink. The simulation is done by taking  $L_a=L_b=L_c= 1.3\text{mH}$ ,  $C_a=C_b=C_c= 220\text{nF}$ ,  $L_0 = 1.3\text{mH}$  and  $C_0 = 1500\mu\text{F}$ .

### i. Buck mode simulation results

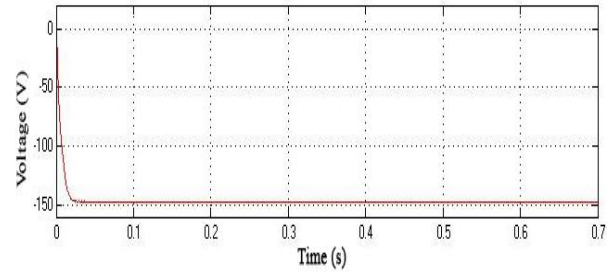


Fig.6a Output voltage of the proposed converter in buck mode of operation

The Fig 6a represents the output voltage obtained in buck mode operation of proposed converter, which is 147V.

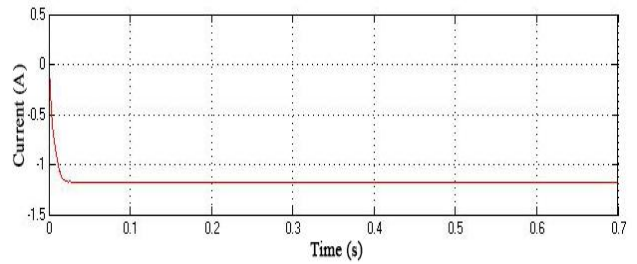


Fig.6b Output current of the proposed converter in buck mode of operation

The Fig 6b represents the output current obtained in buck mode operation of proposed converter, which is 1.17A.

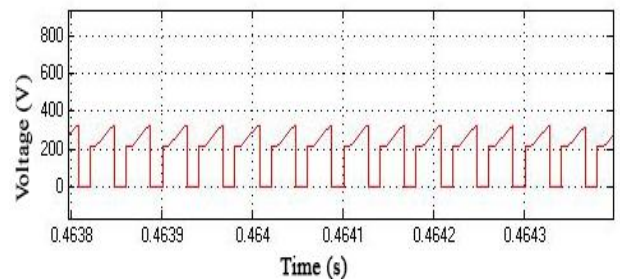


Fig.6c Voltage across the switch of proposed converter in buck mode of operation

The above Fig.6c represents the voltage across each switch in buck mode operation of proposed converter, which is 326V.

## ii.Boost mode simulation results:

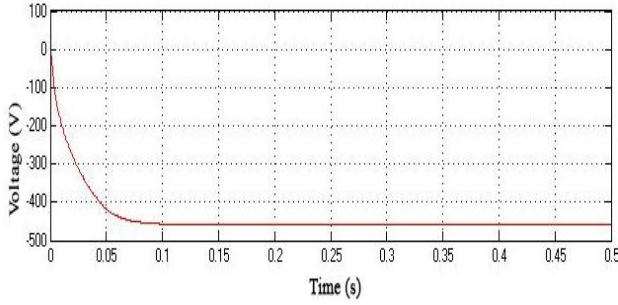


Fig.6d Output voltage of the proposed converter in boost mode of operation

The Fig 6d represents the output voltage obtained in boost mode operation of proposed converter, which is 467V.

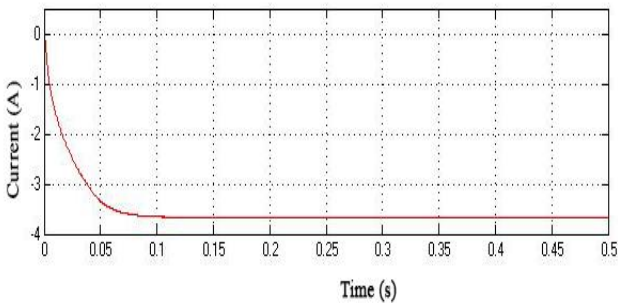


Fig.6e Output current of the proposed converter in boost mode of operation

The Fig 6e represents the output current obtained in buck mode operation of proposed converter, which is 3.7A.

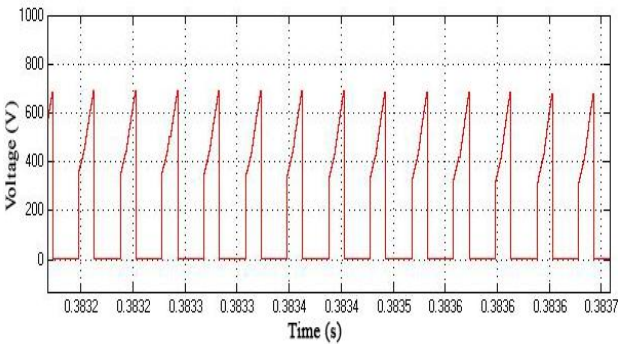


Fig.6f Voltage across each switch of proposed converter in boost mode of operation

The above Fig 6f represents the voltage across each switch in boost mode operation of proposed converter, which is 690V.

Compared to theoretical and simulation analysis for the proposed converter, the values obtained are approximately same. In buck mode, the output voltage according to simulation is 147V and current is 1.17A, whereas, in boost mode the output voltage is 467V and current is 3.7A. the peak voltage stress in buck mode is approximately 326V and in boost mode approximately 690V.

Table II provides power factor obtained from simulation for proposed converter with and without filter.

Table: II

Modes of operation	Pf without filter	Pf with filter
Buck	0.83	0.99
Boost	0.86	0.99

## VII. COMPARISION BETWEEN THE STANDARD AND PROPOSED CONVERTERS

From the above results, the comparison between the various parameters of standard and proposed converters is tabulated.

### BUCK MODE OF OPERATION:

Table-III provides the various parameters of the buck mode of operation for standard and proposed converter for same power rating.

Table: III

Parameter	Standard converter	Proposed converter
Output Voltage	146V	147V
Output Current	1.1A	1.17A
Switch Voltage	500V	326V
Power Factor	0.94	0.99

## BOOST MODE OF OPERATION RESULTS:

Table-IV provides the various parameters of the boost mode of operation for standard and proposed converter for same power rating.

Table: IV

Parameter	Standard converter	Proposed converter
Output Voltage	465V	467V
Output Current	3.8A	3.7A
Switch Voltage	1050V	690V
Power Factor	0.96	0.99

From the above comparison, it is observed that there is improvement in P.F by 0.04 and the voltage across the switch is reduced by  $\sqrt{3}$  times in proposed converter than in the standard converter in both buck and boost modes. Hence the ratings of the switch will be reduced so that the cost is also reduced.

## VIII. CONCLUSION

In this paper, three phase ac- dc buck boost converters that can improve the input power factor and can reduce the peak voltage stress is analyzed. From the results, it is found that the conventional converter is impractical due to its high potential gradient stress across the switch. The input capacitors voltages have dc component that does not alter the input PFC. Considering these features of the proposed converter, this converter is expected to be feasible alternative solution for improving the power factor at utility mains.

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