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A THREE-PHASE HIGH POWER FACTOR TWO-SWITCH BUCK-TYPE CONVERTER

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Abstract: The paper proposes a three phase, two switch buck type converter with high power factor. The key feature of the proposed converter is that a switch in the converter has a lower peak voltage stress than a switch in a conventional three-phase, single-switch buck-converter. A switch in the converter sees a line to neutral voltage across it rather than a line to line voltage which is the case for the switch in the conventional converter. The voltage stress in the proposed converter is limited to the peak value of the phase voltage of the input capacitors rather than the peak value of the line-to-line voltage, as is the case in the conventional converter. Since a switch in the proposed converter sees a line to neutral voltage instead of a line to line voltage the peak voltage stress is almost half than that of the switch in the conventional converter as this stress is reduced by a factor of $\sqrt{3}$. This reduces switching losses and allows lower rated standard devices to be used in converters. In the paper, the operation of the proposed converter is given and general considerations that should be taken into account when trying to design it are discussed. The feasibility of the converter is confirmed with results obtained from computer simulation and from an experimental prototype.

Keywords: Buck Converter, Power Factor, Harmonics, Switching Losses

1. INTRODUCTION

Low power factor and high line current harmonics have received scrutiny from both power system and power electronics applications. This is due to the increased installation of rectifiers in applications such as machine drives, electronic lighting ballasts, uninterruptible power supply, HVDC systems, battery energy storage systems, inprocess technologies such as electroplating, welding units, battery charging for electric vehicles. In most of these power electronic applications ac input power needs to be first converted to a dc voltage. Such a conversion is usually accomplished by a rectifier. Diode rectifiers cause low power factor and high harmonic distortion. Still diode rectifiers are used as they are cheap and simple. Three-phase ac-dc converters operating from the ac utility mains can generate current harmonics that may cause the mains voltage to become distorted. To prevent this from happening power factor correction (PFC) techniques are used. These harmonics can be significantly reduced if the input power factor is corrected by shaping the input current in each of the three phases so that it is sinusoidal and in phase with the phase voltage.

The simplest and least expensive method of PFC for three-phase ac-dc converters is to add a passive inductive-capacitive (LC) three-phase filter to the converter [1] (i.e.), either in series or parallel to the line. But this approach has several drawbacks. One of these is that the filter components are large and very bulky. Active methods of PFC are therefore preferred as they result in smaller, less bulky converters. Single phase ac-dc PFC converters use one main power switch to perform PFC, while a six switch converter

is typically used to perform three phase active PFC by processing the bulk of the power fed to the load or just a fraction of it as an active filter. Using a six-switch converter, however, is costly and complicated given the number of active switches that must be used and the sophisticated control needed to ensure a good power factor.

For ac-dc power converters operating at a power level just high enough for three phase converters to be considered a better option than single phase converters, cheaper and simpler methods of performing three-phase active input PFC have been developed using converters with less than six switches [2]- [4].

Most three-phase ac-dc single-switch converters are boost converters. One such converter, first proposed in [5], is the single-switch boost converter shown in Fig.1.(a). This converter is operated with constant duty cycle throughout the line cycle. Many three phase ac-dc single switch converters that perform PFC with a reduced number of switches are variations of converter shown in Fig. 1.

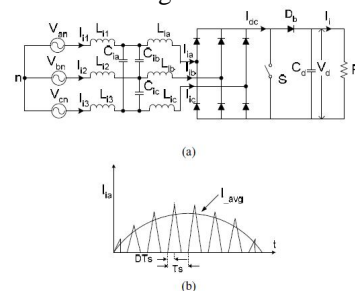


Fig. 1. (a) Conventional three-phase, single-switch ac-dc single boost converter. (b) Typical input inductor current waveform.

It is also possible to use a buck version of three phase single-switch boost converter such as the one shown in Fig. 3. This converter is attractive because it can perform three phase PFC using very simple control methods without the need for additional bulky components on the ac side of the diode bridge. It can also produce smooth, continuous input currents that do not have the high frequency noise that the single switch boost converter has. This converter and other buck-type converters like it, however, have a drawback that has restricted their use to a limited number of applications - the switch has a very large peak voltage stress due to the high peaks of the discontinuous input capacitor voltages even though the output voltage can be made to be lower than the input voltage. The excessive peak voltage can be reduced if variable switching frequency control techniques are used but this causes the converter to have the drawbacks that converters operating with such techniques have, such as the need for converter magnetic to be designed to work over a large range of switching frequencies which results in the need for them to be relatively bulky.

In order to overcome the limitations of the conventional single-switch buck-type converter and other topologies that are based on it, the three-phase, two-switch ac-dc PFC buck converter shown in Fig. 4 will be proposed in the paper. The converter can operate with non excessive peak switch voltage stresses even if it is operated with fixed switching frequency. In the paper, the operation of the conventional three-phase single-switch converter will be reviewed. The operation of the proposed converter as well as its features will then be explained in detail.

2. CONVENTIONAL BUCK CONVERTER OPERATION

The conventional three-phase single-switch buck converter shown in Fig. 3(a) can be operated with a constant duty cycle throughout the line cycle. It can be designed so that the phase voltages are discontinuous, as shown in Fig. 3(b).

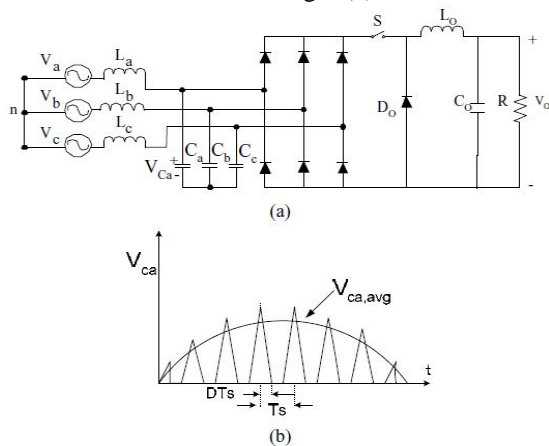


Fig.3. (a) Conventional three-phase, single-switch ac-dc single buck converter. (b) Typical input capacitor voltage waveform.

The converter typically goes through three main modes during a switching cycle. If phase input voltage V_{an} is positive and at its peak value and phase voltages V_{bn} and V_{cn} are both negative and equal in magnitude to one-half of V_{an} , then these modes are as follows:

Mode 1(t0-t1): At time $t = t_0$, the switch is turned on and the input capacitors C_a , C_b and C_c start to discharge to supply load current. The output diode D_o is completely off. The current through switch S is $I_s = I_o$.

Mode 2(t1-t2): At time $t = t_1$, input capacitors C_a , C_b and C_c are completely discharged and the voltage across each capacitor is zero. Current continues to flow through the switch and the output diode conducts $I_o - I_s$ current.

Mode 3(t2-TS): At time $t = t_2$, The switch is turned off, the input capacitors C_a , C_b and C_c start to charge up with the voltages proportional to their respective phase currents and input phase voltages. On the dc output side, the output diode turns on and the load current freewheels through it. If the output current is discontinuous, then current will stop flowing through the diode some time before the start of the next switching cycle.

The general operating principle of the converter is that line-to-line voltage is placed across the input capacitors when the switch is off, then the capacitors are made to fully discharge when the switch is on. The current in each input inductor rises when the switch is turned off and the voltage across each capacitor is initially zero.

The current in each inductor falls when the voltage across the capacitors is greater than the input voltage and there is negative voltage across each inductor. Since it is line-to-line voltages that are placed across the capacitors, these line-to-line voltages must be greater than the input voltages so that the converter can function properly. This results in high peak voltage stress as the voltage stress across the switch is dependent on the peak input capacitor voltage. While the input capacitors are being charged and discharged, the output section of the converter operates in the exact similar manner as a standard dc-dc buck converter. An excellent input power factor can be achieved if the converter is made to operate with discontinuous input capacitor voltages.

Doing so makes these voltages to be ideally sinusoidal with high frequency components that are blocked by the input inductors so that the input phase currents are ideally sinusoidal with few if any high frequency components.

3. PROPOSED CONVERTER OPERATION

The peak voltage stress of the switches in conventional buck converters can be reduced if the switches are exposed to phase voltages instead of line voltages. This is the main operating principle behind the proposed converter. The proposed converter goes through six main modes during a switching cycle. Fig. 5 shows the equivalent circuits of the various operating modes during a switching cycle for the case when phase input voltage V_{an} is at its peak value and phase voltages V_{bn} and V_{cn} are both negative and equal in magnitude to one-half of V_{an} .

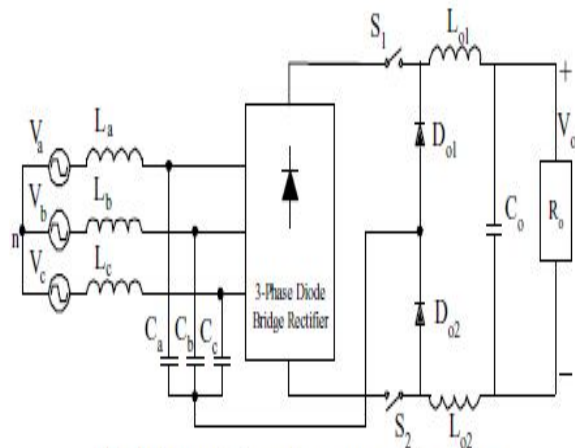


Fig. 4. Proposed three-phase, two-switch rectifier.

3.1 Circuit Operation for $D > 0.5$

Mode 1 (t_0-t_1): Fig. 5(a): At time $t = t_0$, the switch S_1 is turned on. On the ac side, the input capacitor C_a starts to discharge through output diode Do_2 . The output diode Do_1 is completely off. The switch S_2 is conducting from the previous mode and its current is $I_{S2} = I_b + I_c$. The voltage of input capacitors C_b and C_c is already zero. The current through switch S_1 is $I_{S1} = I_o$. At the end of this mode, the input capacitor C_a completely discharges and V_{Ca} is zero.

Mode 2 (t_1-t_2) Fig. 5(b): At time $t = t_1$, all the input capacitors, C_a , C_b and C_c , are completely discharged. The bridge diodes D_1 , D_2 and D_6 are conducting. Both switches S_1 and S_2 are conducting such that $I_{S1} = I_a$ and $I_{S2} = I_b + I_c$. Both output diodes Do_1 and Do_2 are also conducting and their respective currents are $I_{Do1} = I_o - I_a$ and $I_{Do2} = I_o - (I_b + I_c)$.

Mode 3 (t_2-t_3) Fig. 5(c): At time $t = t_2$, the switch S_2 is turned off, the input capacitors C_b and C_c start to charge up and the voltage across each capacitor starts to increase. The bridge diodes D_2 and D_6 turn off. The output current is supplied by the switch S_1 and through Do_1 . The current through output diode Do_2 is $I_{Do2} = I_o$.

Mode 4 (t_3-t_4) Fig. 5(d): At time $t = t_3$, switch S_2 is turned on and the current through it is $I_{S2} = I_o$. The bridge diodes D_2 and D_6 start to conduct. At the end of this mode, input capacitors C_b and C_c

completely discharge and voltages V_{Cb} and V_{Cc} are zero.

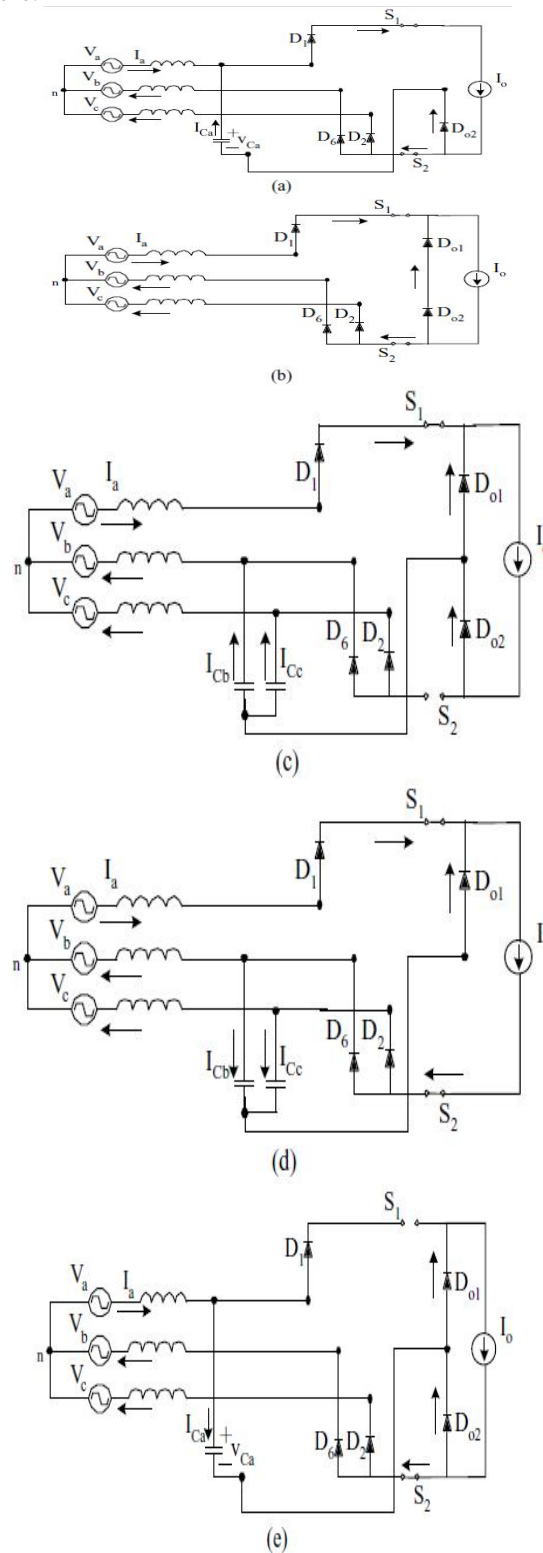


Fig. 5. Converter operating modes (a) Mode 1: $[t_0-t_1]$, (b) Mode 2: $[t_1-t_2]$ and Mode 5: $[t_4-t_5]$, (c) Mode 3: $[t_2-t_3]$, (d) Mode 4: $[t_3-t_4]$, (e) Mode 6: $[t_5-t_6]$.

Mode 5 (t_4-t_5) Fig. 5(b): This mode is similar to Mode 2. All the input capacitors, C_a , C_b and C_c , are

completely discharged. The bridge diodes D1, D2 and D6 are conducting.

Both switches S1 and S2 and both output diodes Do1 and Do2 are conducting to provide the output current.

Mode 6 (t5-Ts) Fig. 5(e): At time $t = t_5$, switch S1 is turned off, input capacitor Ca starts to charge up and the voltage across capacitor Ca starts to increase. The bridge diode D1 turns off. The output current flows through output diode Do1, switch S1 and through Do1. The current through output diode Do2 is $I_{Do2} = I_o$.

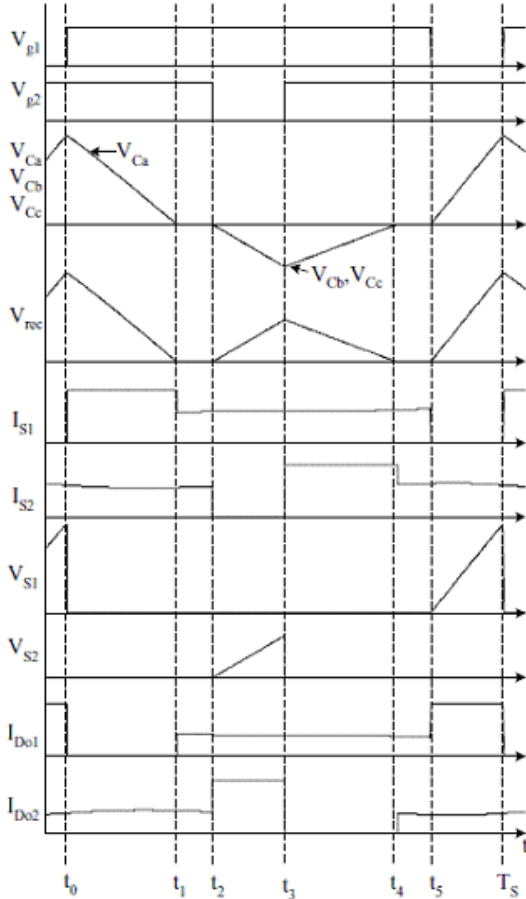


Fig. 6. Key waveforms for the operating modes of the converter during one switching cycle for $D > 0.5$.

3.2 Circuit Operation for $D < 0.5$

The duty cycle of the converter decreases with the reduction in load. When it becomes less than 0.5, there are intervals when none of the switches is on, these intervals are (t_2-t_3) and (t_5-T_s) as shown in Fig. 7. During these modes the load current freewheels through the output diodes Do1 and Do2 while on the ac side, the input capacitors continue to charge up with the currents proportional to their respective input voltages.

4. COMPARISON OF SWITCH VOLTAGE STRESSES

To compare the switch voltage stresses of the conventional and the proposed converter, input

capacitor voltage waveforms must be taken into account. Consider the operation during a switching cycle for the case when phase input voltage V_{an} is at its peak value and phase voltages V_{bn} and V_{cn} are both negative and magnitude of $V_{bn} > V_{cn}$. Fig. 8(a) shows the input capacitor voltages V_{Ca} , which is positive, while V_{Cb} and V_{Cc} are negative and instantaneous value of V_{Cb} is higher than that of V_{Cc} . The switch voltage stress in this converter is determined by the peak line-to-line voltage across input capacitors. For this case, the switch voltage stress will be difference of positive and negative voltage (largest of V_{Cb} or V_{Cc}) and i.e. $V_{Ca} - V_{Cb}$.

Generalizing the switch voltage stress by considering phase 'a', maximum voltage across input capacitor Ca is given as

$$V_{Ca, pk} = \frac{I_{an, pk}}{C_a} (1-D)T_s \quad (1)$$

and the peak voltage of diode bridge rectifier is

$$V_{rec, pk} = \sqrt{3} V_{Ca, pk} \quad (2)$$

The maximum voltage across the switch is therefore given as

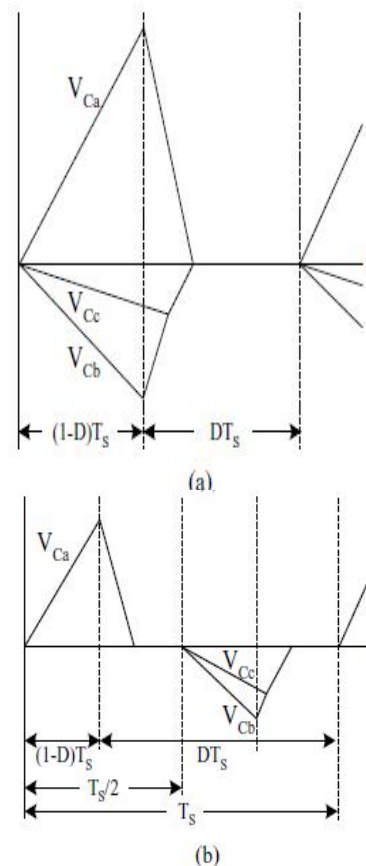


Fig. 8. Voltages across input capacitors Ca, Cb and Cc (a) Single-switch buck converter (b) Proposed two-switch buck converter.

$$V_{S, pk} = \sqrt{3} V_{Ca, pk} \quad (3)$$

Now consider the proposed converter in Fig. 4. For the same time duration as described above. The

operation of the two-switch buck converter is briefly described here. During the first half of the switching cycle, when the switch S1 is off, the input capacitor Ca charges up with the voltage proportional to voltage of phase 'a' and when this switch is turned on, Ca discharges till VCa reduces to zero. During the second half of the switching cycle, the operation is repeated for switch S2. The input capacitor voltage waveforms are shown in Fig. 8(b) For this converter the voltage stress across switch S1 is peak value of VCa and voltage stress across switch S2 is peak value of VCb (largest of VCb or VCc).

Generalizing, the maximum voltage across the switch becomes

$$V_{S, pk} = V_{Ca, pk} \quad (4)$$

The voltage stress in the proposed converter is limited to the peak value of respective phase voltage of input capacitors, instead of peak value of line-to-line voltage in the conventional converter.

5. CONVERTER FEATURES

The proposed converter has the following features:

- (i) The peak voltage stress of the switches in the proposed converter is almost half that of a switch in a conventional single-switch converter so that the need for higher rated, less optimal devices is avoided.
- (iii) Since there are two switches, the proposed converter can operate over a wider load range with high power factor than the conventional single-switch converter. The converter can therefore operate in heavy load applications without compromising power quality.
- (iv) The converter is still considerably simpler than a six switch or even three- and four-switch reduced switch rectifiers. The control of the converter can also be simple and a technique where the converter's duty cycle is relatively constant over the line cycle can be used. If desired, however, more sophisticated techniques can be used.

6. DESIGN CONSIDERATIONS

In order to design the converter, a systematic procedure must be developed. The design of the converter should ensure a good power factor over the complete range of line and load conditions while trying to keep the peak voltage stress of the switches as small as possible. The procedure [6] should consist of the following steps:

- (i) Design the input capacitors so that they operate with a highly discontinuous voltage, if possible, over the whole input voltage range. The input power factor should be high and the input current harmonic content should comply with the appropriate standard.

- (ii) Design the input inductors to achieve the desired harmonic content.
- (iii) Design the dc side inductors Lo so that they contain a small amount of current ripple.
- (iv) Design the dc side capacitor Co so that they contain a small amount of voltage ripple.

Therefore, in order to design the converter, the following design considerations should be taken into account:

- (i) *Input Capacitors:* The input capacitor value directly affects the power factor and the operating range of the converter. The input capacitors Ca, Cb, Cc should be small enough so that the voltages across them are discontinuous to achieve high input power factor and minimum THD. Under light load conditions, as the duty cycle tends to get smaller, the input capacitors have less time to discharge completely and hence the operation can shift to continuous voltage mode (CVM), which is undesirable. It is therefore important to consider light load conditions when designing the input capacitors.
- (ii) *Switch Voltage Stress:* The switch voltage stress for this converter is inversely proportional to the value of input capacitors as stated by equations (1) and (4). Larger input capacitor values will result in the capacitors being charged to lower voltages and thus lower switch voltage stress.
- (iii) *Switching Frequency:* Operation at higher converter switching frequencies will decrease the values of the input and output inductors and thus the size of the overall converter. Higher switching frequency operation also means that the input capacitors will have less time to discharge. This will create a need for smaller input capacitor values, which can increase the voltage stress of the switches.

7. SIMULATION RESULTS

An experimental prototype of the proposed converter was built to confirm its feasibility. The converter was implemented with main circuit components La=Lb=Lc=μH, Ca=Cb=Cc= nF, Lo= mH and Co=μF, switching frequency of fs = 25 kHz. Fig. 9 shows experimental waveforms obtained with the converter operating with input voltage Vin=415VLLrms, output voltage Vo=200 V, output power Po=2 kW.

It can be seen from Fig. 9(a) that a nearly sinusoidal input current waveform can be obtained. Fig. 9(c) shows the converter switch current and voltage waveforms. It should be noted that the voltage across the switch is triangular, which is characteristic of three-phase, buck converters operating in DCM as the voltage across each input ac side capacitor drops to zero due to the charging and discharging of these

capacitors. It should also be noted that the switch current dips and becomes equivalent to the Phase A

current a short time after the switch is turned on. This is a natural phenomenon of the converter.

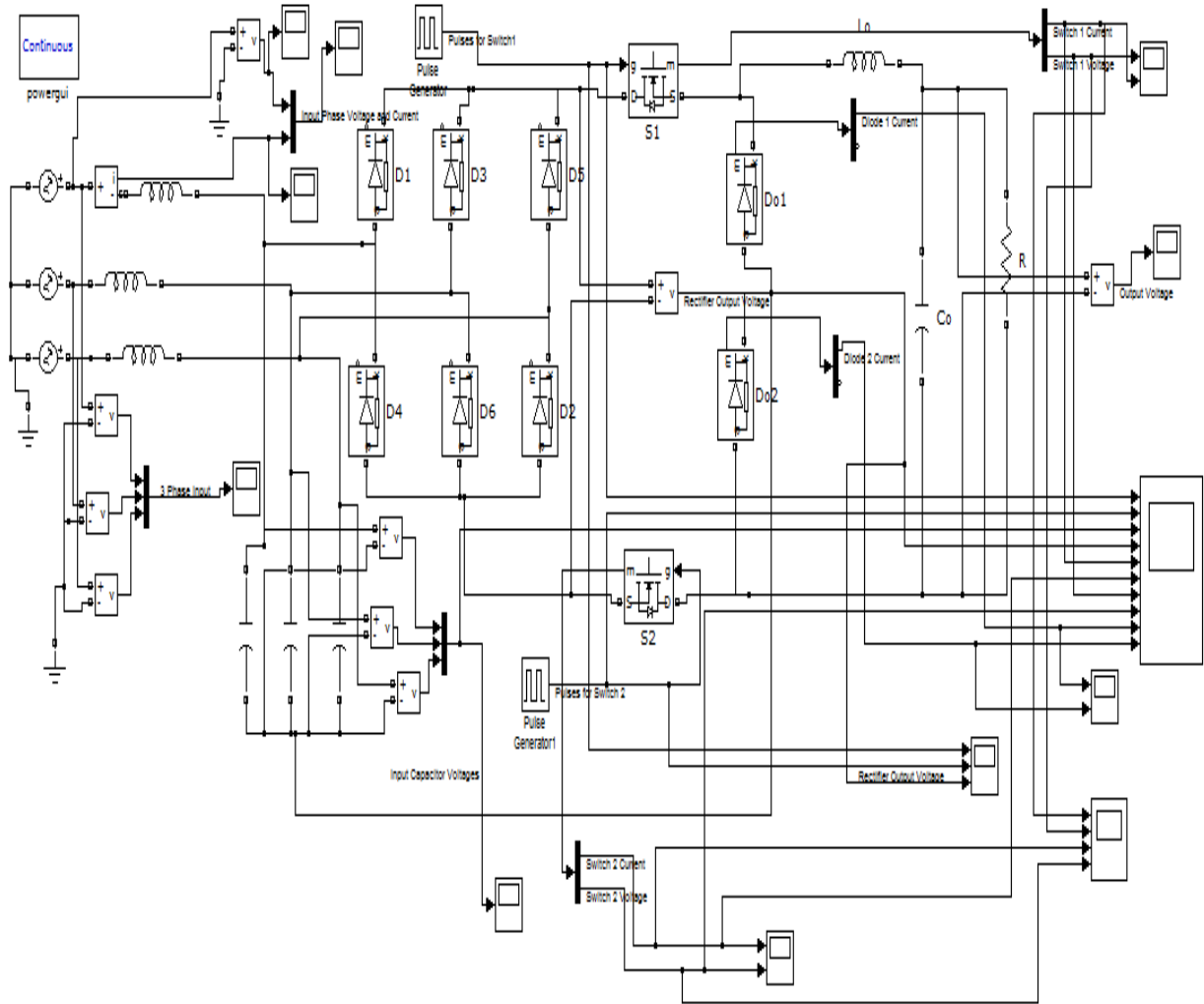


Fig.9.Proposed three phase two-switch rectifier

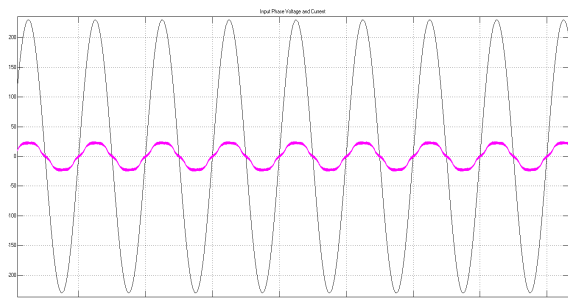


Fig.9 (a).Input Phase Voltage and Current

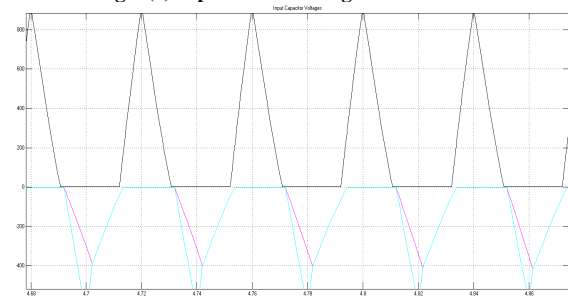


Fig.9 (b).Input Capacitor Voltage

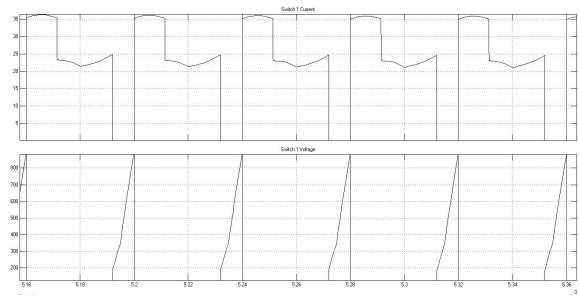


Fig.9 (c).Switch Current and Voltage

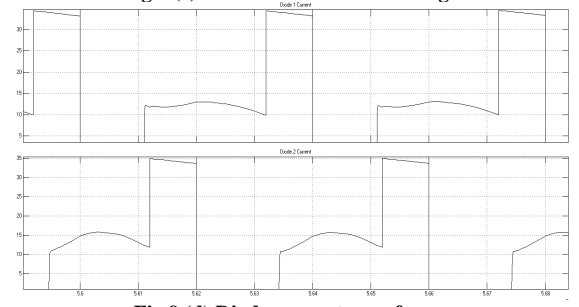


Fig.9 (d).Diode current waveforms

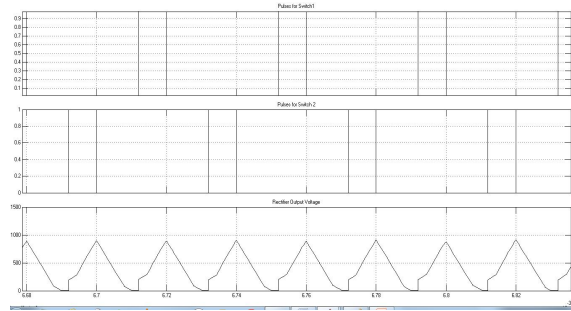


Fig.9 (e).Rectifier Output waveform

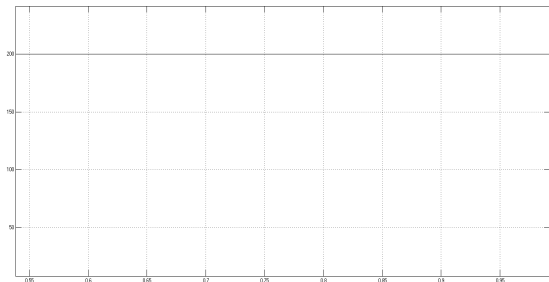


Fig 9(g).Controlled Output Voltage

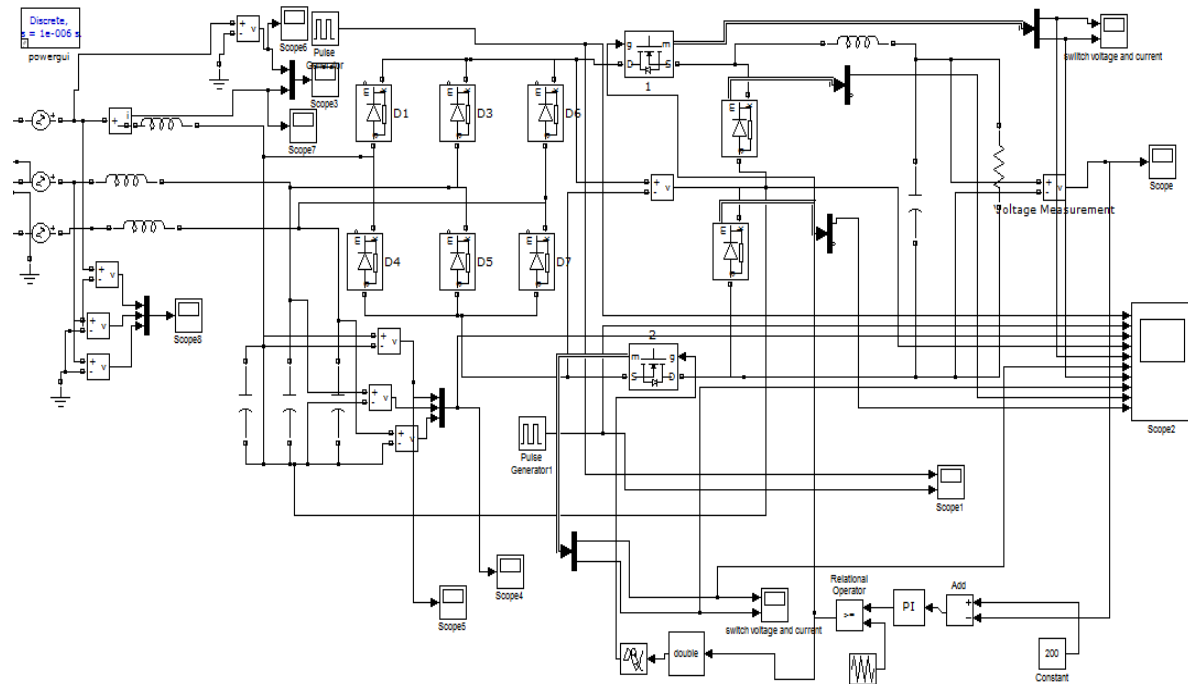


Fig.9 (f).Controlled Output Circuit

8. CONCLUSION

A new three-phase, two-switch buck converter was proposed in this paper to address the switch voltage stress issue of the conventional converter. The voltage stress in the proposed converter, in a switching cycle is limited to the peak value of respective phase voltage of input capacitors, rather than peak value of line to-line voltage in the conventional converter. The peak voltage switch stress is almost half as compared to that of traditional converter.

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