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Analysis of Symmetrical & Asymmetrical PWM Based Single Phase AC to AC Converter for Power Quality Improvement

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ABSTRACT: A single phase bidirectional AC to AC buck converter circuit using power MOSFET operating in high frequency chopping mode is simulated and analyzed for electrical parameters such as output voltage, input current, input power factor, harmonic profile and efficiency using MATLAB/simulink software package. The various PWM techniques such as symmetrical ramp-DC PWM (SRDPWM), asymmetrical ramp-triangular PWM (ARTPWM), asymmetrical sinusoidal PWM type-1 [ASPWM1] and asymmetrical sinusoidal PWM type-2 [ASPWM2] techniques are adopted to analyze the harmonic profile, input power factor and efficiency of the converter. The rms value of the output voltage, output current and source current can be significantly increased by varying the duty ratio K in case of symmetrical PWM control strategy and modulation index MI in case of asymmetrical PWM control strategies independent of variation in switching frequency. It is observed from the simulation results that, the ASPWM1 switching strategy gives more output voltage, input power factor, efficiency by increasing modulation index MI and reduced low order harmonics of output voltage and source current by increasing the number of pulses per half cycle P compared to other PWM techniques rendering easy and economical filteration.

KEYWORDS: AC chopper, symmetrical ramp-DC PWM, asymmetrical ramp-triangular PWM, asymmetrical sinusoidal PWM technique, harmonic profile, power factor, efficiency.

I. INTRODUCTION

Industrial loads such as heaters, illumination control, furnaces, AC motor speed control and also theatre dimmers uses AC voltage controllers. Such voltage regulators, however, have slow response, poor input power factor, and high magnitude of low order harmonic at both input and output sides. These converters need large input-output filters to reduce low order harmonics in the line current. These drawbacks have been overcome by designing various topologies of AC chopper [1-8]. In most standard AC choppers, the commutation causes high voltage spikes and an alternative current path has to be provided when current paths are changed. This alternative current path is implemented using additional bidirectional switches [3]. Such topologies are difficult and expensive to realize and the voltage stress of the switch is also high, resulting in reduced reliability. The harmonic analysis and power factor improvement are the two important parameters to be considered in AC to AC converter circuits [9]. It is required to select the modern PWM technique which gives best performance of the converter with respect to improved input power factor and reduced harmonic content in both input current & output voltages.

In this paper, a single phase bidirectional AC buck converter is proposed and analyzed for RL load using symmetrical ramp-DC PWM (SRDPWM), asymmetrical ramp-triangular PWM (ARTPWM), asymmetrical sinusoidal PWM type-1 [ASPWM1] and asymmetrical sinusoidal PWM type-2 [ASPWM2] techniques. In case of SRDPWM technique, duty ratio K is varied in order to vary the power flow, better harmonic profile and efficiency of the converter. Whereas in case of ARTPWM, ASPWM1 and ASPWM2 technique, the modulation index MI is varied in order to change the power flow, harmonic profile, power factor and efficiency of the convert. But the number of pulses per half cycle (P) is increased in both symmetrical and asymmetrical PWM techniques in order to change the entire harmonic profile of the output voltage and input source current. The change in switching frequency has no effect on output voltage, current and source current variation in both symmetrical and asymmetrical control strategies.

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II. OPERATION OF THE CONVERTER TOPOLOGY

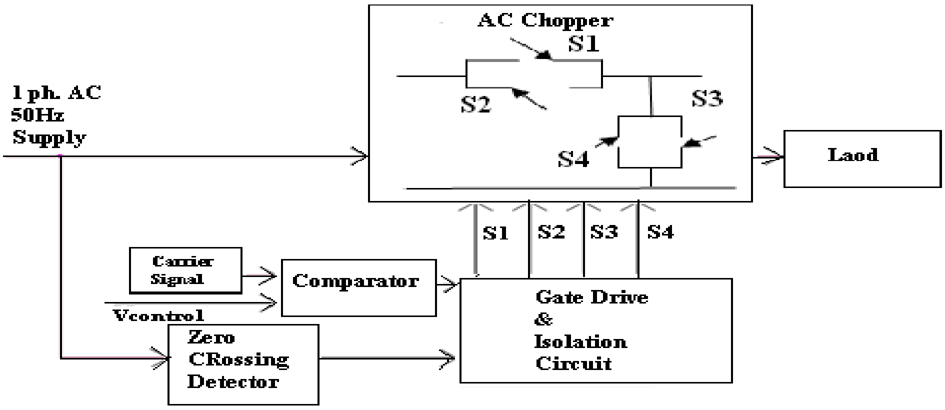


Fig. 1 Block diagram of single phase AC to AC converter

Fig.1 shows the block diagram of single phase AC to AC buck converter with control circuit to generate pulses to power MOSFET embedded four quadrant switches operating in high frequency chopping mode. The control circuit comprises of comparator that compares carrier signals such as ramp or triangular signal with control or reference signals such as DC, negative ramp and sine wave signals. The logical operation takes place between PWM pulses and zero crossing detector pulses in order to generate switching pulses to trigger the particular set of switches during positive and negative half cycles respectively. The duty ratio K can be increased in order to vary all the electrical parameters including harmonic profile. Whereas P can be varied in order to vary the harmonic profile of the converter. The technique continues to evoke interest with respect to variation of P and K [8]. The chopped output voltage waveform is analyzed for harmonic content for various values of P & K. This technique can be adopted for the harmonic content reduction at the high frequency chopping mode facilitating easy filtration at lower cost.

Fig. 2 shows Buck AC chopper derived from the DC buck chopper, where the normal unidirectional switches are replaced with four quadrant bidirectional switches. The combination of switches M1 with series diode D1 and M2 with series diode D2 forms one set of four quadrant switch for modulating purpose. Similarly the switch combination M3 with series diode D3 and M4 with series diode D4 forms another four quadrant set of switches for freewheeling operation with RL loads.

The control of the switches is based on the different modern PWM techniques. In practical realizations of the converter, stray inductances increase the voltage stress of the bidirectional switches and may destroy the switches. This situation requires the converter using AC snubber comprising RC combination (Rs and Cs).

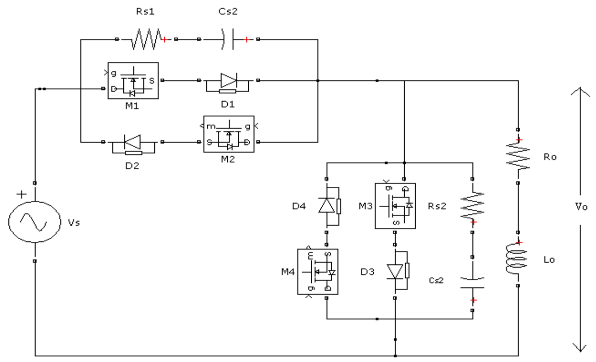


Fig2. Single phase AC to AC converter for RL loads

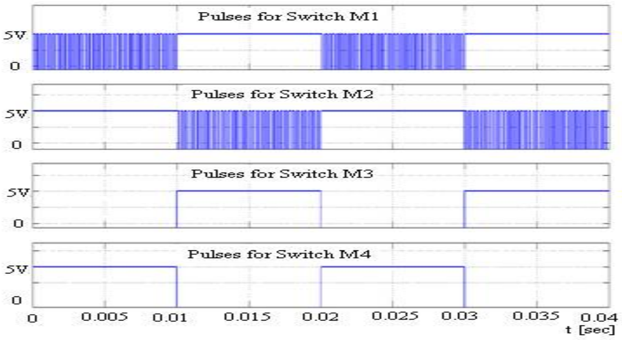


Fig3. Switching pattern for the MOSFET switches of converter

In the configuration of the buck ac chopper, the commutation policy is that the switches M2 and M4 for Vs > 0 are additionally turned on during which switch M1 is modulated. During negative half cycle, for Vs < 0, the switches M1 and M3 are turned on additionally during which switch M2 is modulated according to the duty ratio determined from the control strategy. If the load inductor current iL is positive, the inductor current is bypassed through output side using M4 and diode D4. If the load inductor current is negative, then it bypasses through the input side using M2 and diode D2. The enhancement type MOFSETs are used in converters as switching devices due to their high switching frequency greater than 1MHz, and is available with forward blocking voltage and current of 1000V and 40A respectively. The operation of power switching devices at higher frequencies results in decreased size of inductors and filter capacitors that facilitates compact and economical power electronic systems. Fig. 3 shows the switching pattern for the four forced commutated switches of the single phase buck AC chopper. The dead-time is requisite to avoid current spikes of practical non-ideal switches and at the same time a current path of the inductive load has to be provided to avoid voltage spikes. The modulating signals are logically multiplied (using AND gates) with zero crossing detector signals and given to switches M1 and M2. The switching pulse to switches M3 and M4 are the output of zero crossing detectors itself. The modulating pulses can be symmetrical or asymmetrical which depends on the type of PWM technique. But the logical operation remains same for all the PWM techniques.

III. MERITS OF AC TO AC CONVERTER CIRCUITS

The merits of AC to AC converter circuit are the reduced lower order harmonics at both input and output side. Sinusoidal input currents with nearly unity input power factor can be achieved with the help of input filters. Sinusoidal output currents with RL loads without filters. The higher switching frequency selection results in reduction of filter size. AC chopper does not require gating signals synchronous with the line voltage. Faster dynamic response with respect to sag and swell correction and high efficiency of the converter can be achieved.

IV. VARIOUS PWM SWITCHING PATTERNS

The various PWM switching techniques selected for AC chopper are analyzed for input power factor, harmonic profile and efficiency of the converter circuit.

A. Symmetrical ramp-DC PWM (SRDPWM),

In the SRDPWM control strategy of a single phase ac chopper as shown in Fig.4, the switching pulses are generated by comparing ramp with DC voltage. The high frequency components are easy to be cancelled by using simple filters. The carrier signal Ramp having peak value of 10V is varied for different switching frequencies such as 4.2 KHz, 4.8 KHz, 5.4 KHZ and 6 KHz. The reference or control signal is varied from 4V to 9V in order to get duty ratio from 0.4 to 0.9. The number of pulses per half cycle P can be calculated as

$$P = \frac{F_s}{2F} \qquad (1)$$

The duty ratio is defined as

$$K = \frac{t_{on}}{T_s} \qquad (2)$$

Where

Fs : Switching frequency in Hz.
F : Fundamental or supply frequency in Hz
ton: On time of switching pulses in secs.
Ts : Total Switching time in secs.

B. Asymmetrical ramp-triangular PWM (ARTPWM)

In the ARTPWM control strategy of a single phase ac chopper, the switching pulses are generated by comparing negative slope ramp with triangular signal as shown in Fig.5. The peak to peak value of triangular waveform is 20V. The triangular waveform is varied for different switching frequencies such as 4.2 KHz, 4.8 KHz, 5.4 KHZ and 6 KHz. The negative ramp signal peak value is varied from 4V to 9V with different slopes in order to vary the MI in linear region from 0.4 to 0.9. The ratio of peak value of ramp to the peak value of triangular signal is named as modulation index MI. The definition of modulation index is

$$\mathrm{MI} = \frac{V_{\mathrm{ramp-peak}}}{V_{\mathrm{tri-peak}}} \qquad (3)$$

C. Asymmetrical sinusoidal PWM type-1 [ASPWM1]

In the ASPWM1 control strategy of a single phase ac chopper, the switching pulses are generated by comparing unidirectional AC signal with triangular signal as shown in Fig.6. The peak to peak value of triangular waveform is 20V. The triangular waveform is varied for different switching frequencies such as 4.2 KHz, 4.8 KHz, 5.4 KHZ and 6 KHz. The control signal sine wave peak value is varied from 4V to 9V in order to vary the MI in linear region from 0.4 to 0.9. The ratio of peak value of sine wave to the peak value of triangular signal is named as modulation index MI. The definition of modulation index is

$$MI = \frac{V_{sine-peak}}{V_{tri-peak}} \qquad (4)$$

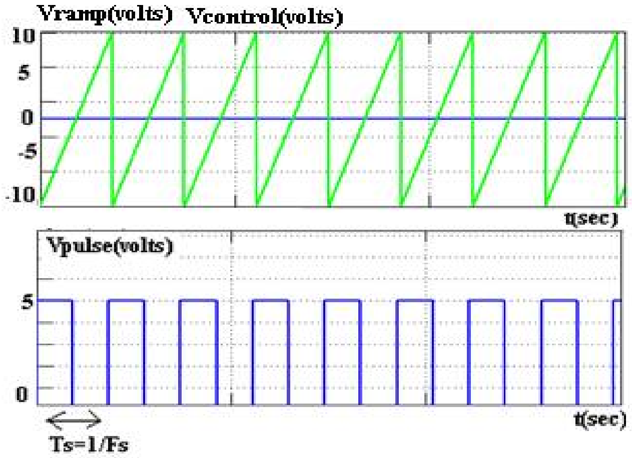


Fig.4 SRDPWM technique and the corresponding switching pulses pulses

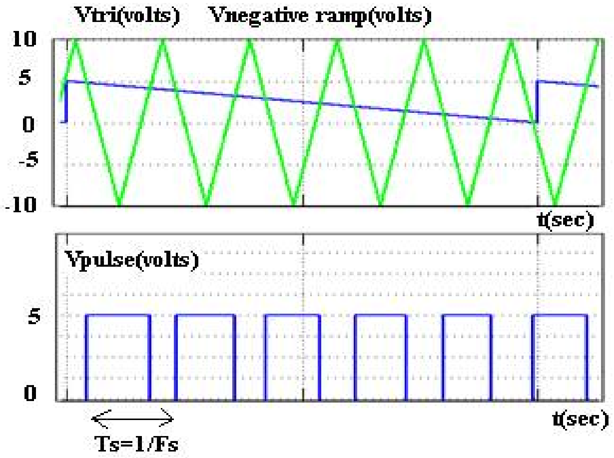


Fig.5 ARTPWM technique and the corresponding switching

D. Asymmetrical sinusoidal PWM type-2 [ASPWM2]

In the ASPWM2 control strategy of a single phase ac chopper, the switching pulses are generated by comparing unidirectional AC signal with positive triangular signal whose peak value is 10V as shown in Fig.7. The peak value of control signal which is unidirectional sine wave is varied from 4V to 9V in order to vary MI in linear region from 0.4 to 0.9. The ratio of peak value of sine wave to the triangular signal is named as modulation index MI. The definition of modulation index is

$$MI = \frac{V_{sine-peak}}{V_{tri-peak}} \qquad (5)$$

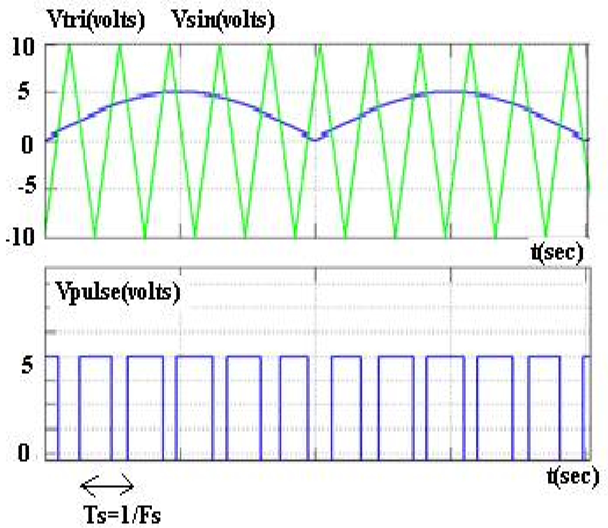


Fig.6 ASPWM1 technique and the corresponding switching pulses

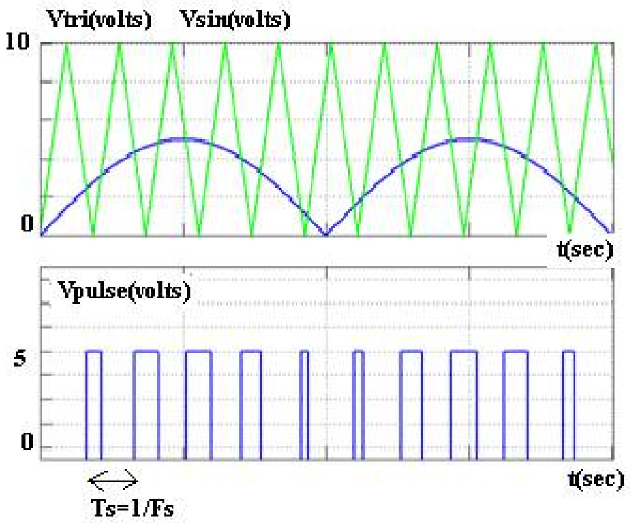


Fig.7 ASPWM2 technique and the corresponding switching
pulses

V. SIMULATION OF AC TO AC CONVERTER CIRCUIT

The Harmonic profile, input power factor and efficiency of the converter are investigated using MATLAB/simulink. The single phase buck AC chopper with AC snubber simulation model is as shown in Fig. 8. The system characteristics are input voltage Vs= 230 V, 50Hz supply, semiconductor element MOSFET IRFPE40, snubber elements Rs=5.4KΩ & Cs=3nF, load parameters are Ro=529Ω Lo=0.9H. The Switching frequency is varied from 4.2 KHz to 6 KHz and corresponding P is varied from 42 to 60 pulses per half cycle which is related as given in equation (1). The harmonic order up to 100th order is considered in the analysis. The harmonic components present in the source current and output voltage are dependent on P as nP ±1. Where n is an even number. For instance, if P=42, then the order of the harmonics present are 2P ±1, 4P ±1 etc [harmonic order 83, 85, 167, 169]. In this way selective harmonic elimination can be done by selecting the proper value of P. Therefore for P=42, harmonic order up to 82nd order can be eliminated in the output voltage and source current.

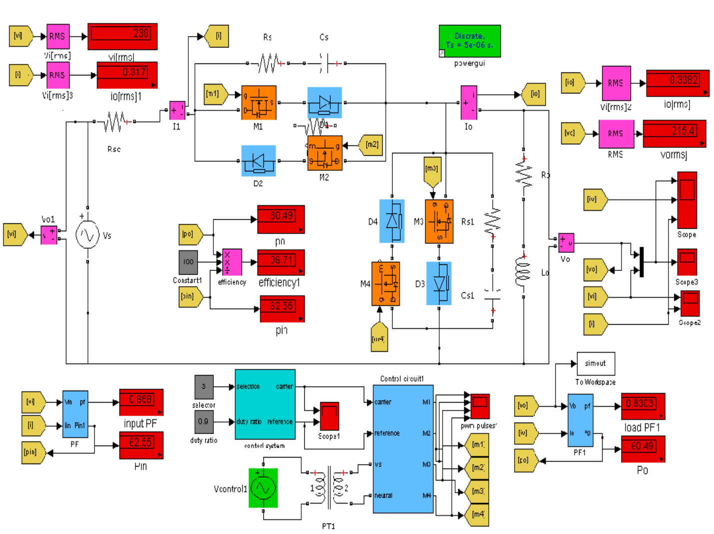


Fig. 8 Simulation circuit of single phase AC to AC converter built

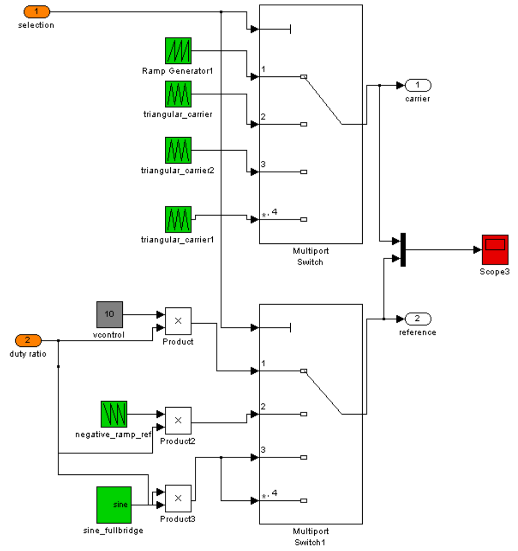


Fig.9 PWM selector module
using MATLAB/simulink software package.

The input side parameters like input voltage, source current are sensed to calculate input side rms values, input power factor and input power using sub models. Similarly output side parameters like output voltage and current are sensed to calculate their rms values, output power and power factor by using sub models. Hence, the power factor PF is modeled using the general definition as given in equation (6).

Using all these parameters, the efficiency of the converter can be calculated as per equation (7) using sub models and displayed using numeric displays.

$$PF = \frac{P_s}{s} = \frac{P_s}{V_{rms} I_{rms}}$$

$$PF = \frac{\frac{1}{T}\int_0^T v_s(t) i_s(t)dt}{\sqrt{\frac{1}{T}\int_0^T v^2{}_s(t)dt}\sqrt{\frac{1}{T}\int_0^T i^2{}_s(t)dt}} \qquad (6)$$

The efficiency can be calculated as

$$\eta = \frac{P_o}{P_s} = \frac{\frac{1}{T}\int_0^T v_o(t) i_o(t)dt}{\frac{1}{T}\int_0^T v_s(t) i_s(t)dt} \qquad (7)$$

The PWM selector is modeled in MATLAB simulink in order to select the various types of switching patterns by giving selection number. This subsystem is modeled using two number multiport switch blocks that works like a digital multiplexer [many into one]. Four ports are chosen in order to consider four different PWM techniques. First multiport switch is connected with carrier signals like Ramp, Triangular and the second multiport switch is having reference signals. Fig.10 shows the waveforms of output voltage Vo, output current Io and source current Is for P=42. The output current is almost a sine wave without ripple content due to freewheeling operation of inductive load. For Vs >0, the positive inductive load current passes through freewheeling bidirectional switches and negative inductive load current passes through the source.

Fig.11 indicates the plot of output voltage with respect to the variation of duty ratio K. It is observed that the output voltage remains same irrespective of the switching frequency variation. The harmonic profile changes with the increase in duty ratio as shown in Fig. 12. The THD(Vo) predominantly reduces with respect to increase in number of pulses per half cycle P or switching frequency Fs. For instance, selecting P=60 or Fs=6 KHz, up to 119th harmonic order are eliminated and hence the THD(Vo) at K=0.9 is 1.65%. But as the switching frequency is increased, the efficiency of the converter decreases due to switching losses as shown in Fig.13. The characteristics of these plots are similar in all the PWM techniques.

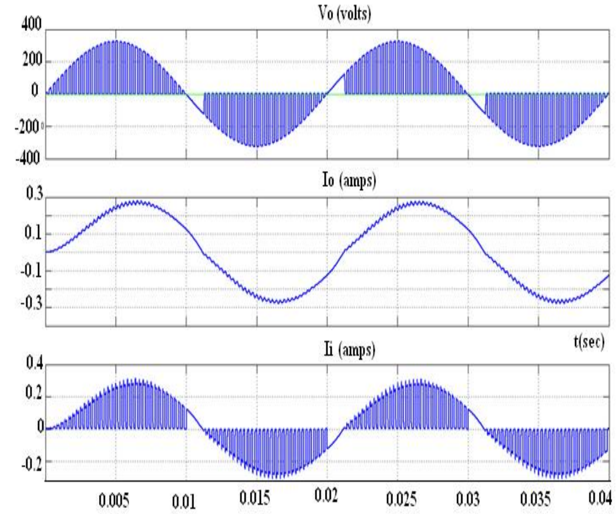


Fig.10 Waveforms of V_o, I_o and I_s of the converter for P=42 [F_s=4.2KHz] switching

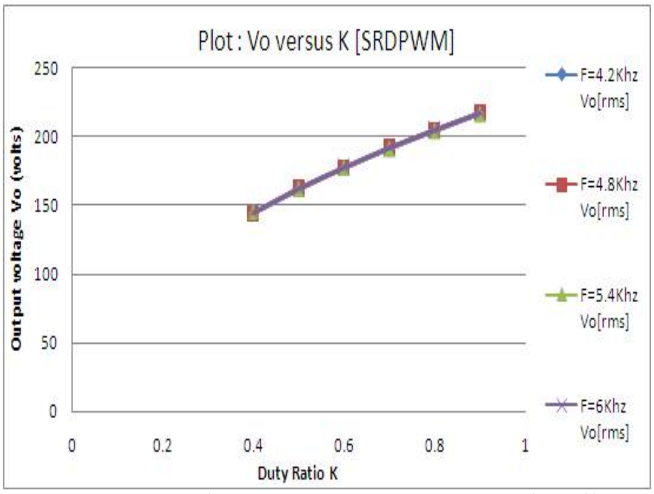


Fig.11 Plot of output voltage versus duty ratio for different frequency using SRDPWM technique

Fig.14 & Fig.15 indicates the harmonic profile of various PWM switching patterns at switching frequency Fs=6 KHz. The THD of the output voltage is maximum in case of ASPMW2 type [THD (Vo) = 20.5% for K=0.4 to 18.5% for K=0.9] and minimum in case of SRDPWM technique [THD(Vo)=11.01% for K=0.4 to 2.47% for K=0.9]. Similarly The THD of the source current is maximum in case of ASPMW2 type [THD(Is)=26.93% for K=0.4 to 29.3% for K=0.9] and minimum in case of SRDPWM technique [THD(Is)=13.5% for K=0.4 to 4.97% for K=0.9]. The ARTPWM and ASPMW1 techniques are better than the ASPMW2 technique with respect to THD of output voltage and source current variation. These techniques have better harmonic profile from K=0.4 to 0.6. But there is almost constant or slight increase in THD values with respect to variation of MI in these cases. Hence SRDPWM technique is better with respect to harmonic profile than other techniques with respect to variation of duty cycle K=0.6 onwards.

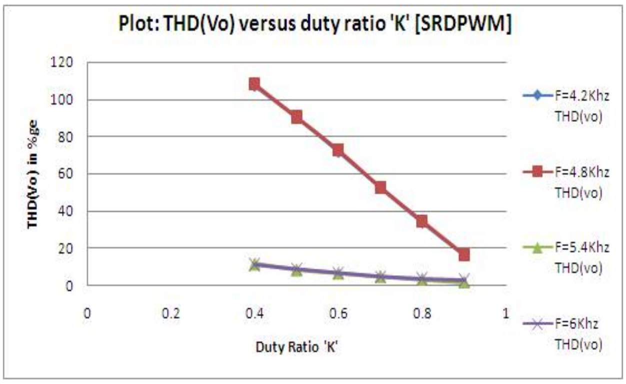


Fig.12 Plot of THD(Vo) versus duty ratio for different switching frequency using SRDPWM technique

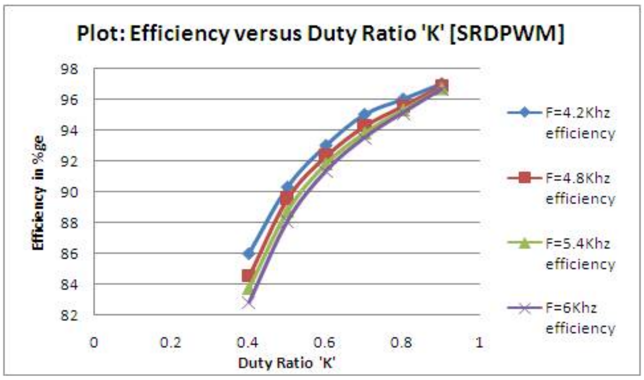


Fig.13 Plot of efficiency versus duty ratio for different switching frequency using SRDPWM technique

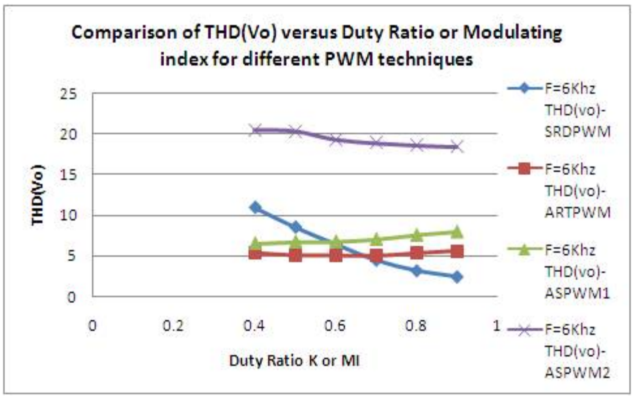


Fig.14 Plot of THD(Vo) versus duty ratio for different PWM technique with constant switching frequency of 6 KHz.

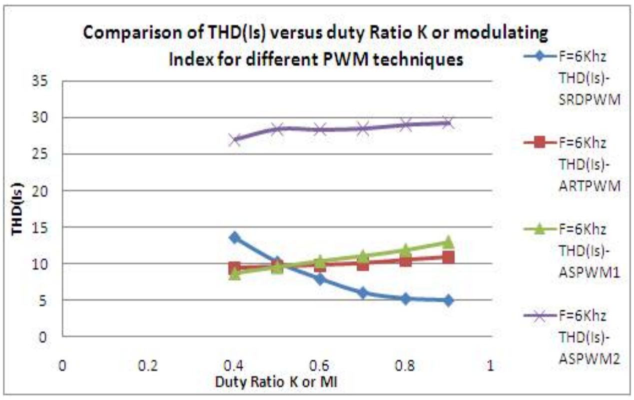
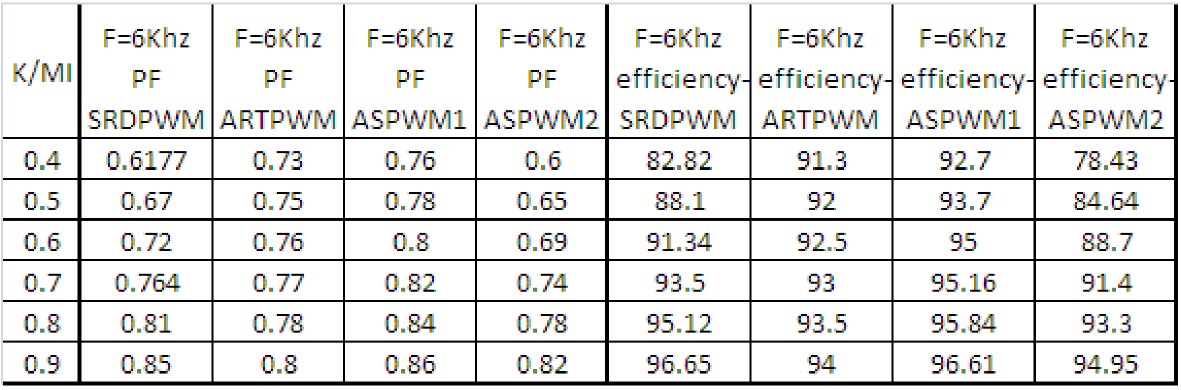


Fig.15 Plot of THD(Is) versus duty ratio for different technique with constant switching frequency of 6 KHz.

Table-1 indicates that the input power factor of the converter is more in case of ASPMW1 technique for the variation of MI from 0.4 to 0.9. Even though harmonic profile is better in case of SRDPWM technique, since the input power factor is more in case of ASPMW1 technique, the overall efficiency of the converter is better using this technique. Therefore it is required to consider both harmonic profile and power factor in order to observe the overall efficiency of the converter. Hence ASPWM1 technique is being recommended for this converter.

Table-1 Analysis of power factor and efficiency with respect to duty ratio/MI for different PWM techniques



K/MI	F=6Khz PF SRDPWM	F=6Khz PF ARTPWM	F=6Khz PF ASPWM1	F=6Khz PF ASPWM2	F=6Khz efficiency-SRDPWM	F=6Khz efficiency-ARTPWM	F=6Khz efficiency-ASPWM1	F=6Khz efficiency-ASPWM2
0.4	0.6177	0.73	0.76	0.6	82.82	91.3	92.7	78.43
0.5	0.67	0.75	0.78	0.65	88.1	92	93.7	84.64
0.6	0.72	0.76	0.8	0.69	91.34	92.5	95	88.7
0.7	0.764	0.77	0.82	0.74	93.5	93	95.16	91.4
0.8	0.81	0.78	0.84	0.78	95.12	93.5	95.84	93.3
0.9	0.85	0.8	0.86	0.82	96.65	94	96.61	94.95

VI. CONCLUSION

A single phase bidirectional AC to AC buck converter is simulated and analyzed for electrical parameters like output voltage, input current, input power factor, harmonic profile and efficiency using MATLAB/simulink software package. The various PWM techniques like SRDPWM, ARTPWM, ASPWM1 and ASPWM2 techniques are adopted to analyze the converter behaviour. The rms value of the output voltage, output current and source current can be significantly increased by varying the duty ratio K in case of symmetrical PWM control strategy and modulation index MI in case of asymmetrical PWM control strategies independent of variation in switching frequency. It is observed from the simulation results that the ASPWM1 switching strategy gives more output voltage, input power factor, efficiency by increasing MI and reduced low order harmonics of output voltage and source current by increasing the number of pulses per half cycle P or switching frequency than other PWM techniques rendering easy and economical filteration.

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