# A INDUCTOR AVERAGE CURRENT MODE CONTROLLER plus PROPORTIONAL INTEGRAL CONTROLLER FOR A BI-DIRECTIONAL AC-DC POWER CONVERTER isWITH POWER FACTOR CORRECTION FOR DC MICRO GRID

**Submitted by**
**Vikas PN**
**Lecturer in Electrical engineering**
**Government Polytechnic college Meenangadi Wayanad**

## ABSTRACT

In existing power converters and motor drive systems draw non-sinusoidal currents from the power supply. Non-sinusoidal currents contain harmonics that disturb the power supply, which is of serious concern. Other equipments that use the same power supply are adversely affected. This article investigates the operation and performance of a new AC-DC converter that allows bi-directional power flow, provides improved input power factor, and reduces harmonic magnitude and disturbance to the power supply by system. The bi-directional feature allows recovery of regenerative energy of loads, back to the power supply and hence the converters increase overall energy efficiency. The proposed converter has high potential for industrial applications, dc micro grid, such as electronically controlled robots, lifts and general industrial motor drive systems.

## 1. Introduction

In current days, design of sophisticated static frequency conversion techniques has gained increasing attention from many researchers owing to the growing demand for industrial motor drives with power conditioning and power factor management. Many existing power converter and motor drives system draw the non–sinusoidal input current from the mains. The classical AC/DC rectification approach of using a full wave bridge followed by a bulk capacitor is not suitable due to the undesirable input current harmonics. These harmonics need to be controlled using passive filtering or active filtering with power factor correction. A common problem associated in drive system with frequent regeneration is the size of the dc link capacitor is often very large to limit the link voltage [1-8]. Normally, a large capacitor bank of thousands of microfarad is required. The large value of capacitor not only increases the size and weight of converter equipment, but also equipment cost. In order to reduce the link capacitor, a bidirectional converter can be used so that regenerative energy can be fed to the supply instead of being stored in large capacitor. The controller analysis of various systems has been reported [9-13]. This article presents a modified thyristor based AC/DC power converter circuit with reduced harmonics and improved power factor. The inductor average current control method of the converter provides improved power factor in both power flow direction. The input current is sinusoidally shaped to follow the input voltage either in phase with the input voltage in motoring mode or 180 degree out of phase with the input voltage in the regenerating mode. Thus, the power factor approaches unity reduces harmonics and disturbance on the power supply. The bidirectional converter is attractive for industrial motor drive with regeneration capability. This converter has the following advantages,

- Operates with unity power factor and reduced harmonics for bi-directional power flow.
- Low cost and robust.
- Uses reduced dc link capacitor and hence costs effective.
- Uses simple control technique and same inductor current for both motoring and regeneration mode.

Hence this article proposes to study the converter operation through simulation and implementation and also verify the characteristics of the converter. Also, validate the design of

- Circuit element parameters
- Current mode controller
- PI controller
- Synchronizing and triggering circuit

The design and performance of the converters is validated through computer simulation using MATLAB/Simulink and implementation of proposed converter is validated.

## 2. Operation of Bi-Directional AC-DC Power Converter

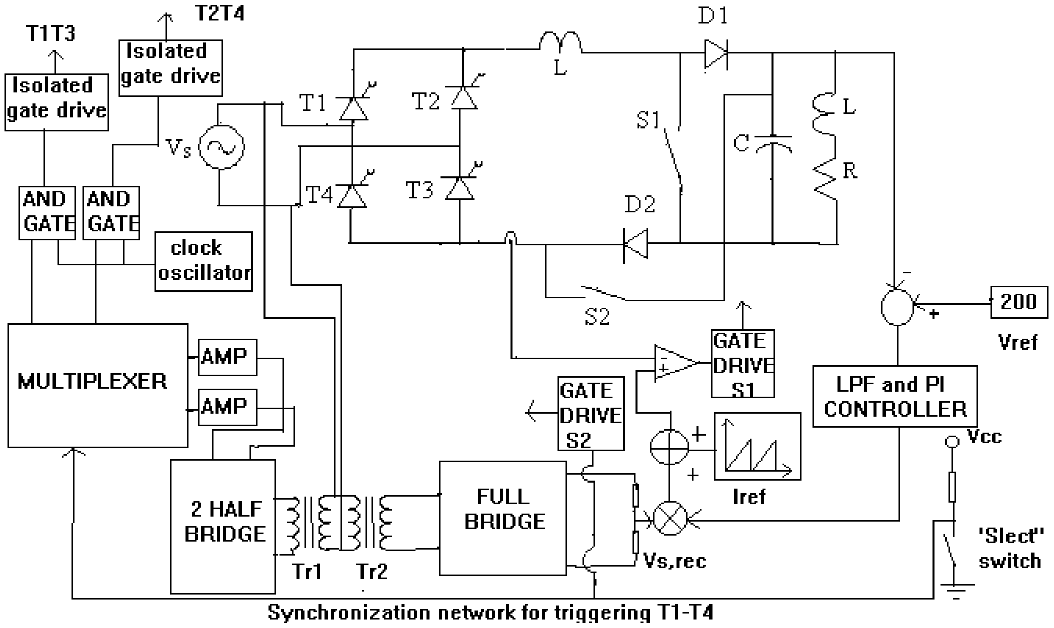

**Fig.1** Proposed bidirectional ac-dc power converter

Fig.1 shows the circuit configuration of proposed high power factor ac-dc bi-directional converter [4]-[7]. It consists of three main components. They are the power conversion stage and inductor average current controller and the synchronization circuit for triggering the thyristor. Power conversion stage consists of four low cost, highly robust thyristors (T1-T4), two fully controlled switches (S1 & S2 such as power mosfets), two diode (D1 & D2), one inductor L and one capacitor C. The operating mode of converter either in motoring mode or in regenerating mode is controlled by the conduction state of S2, which is determined by sensing the dc link voltage. For motoring operation the converter is operated as a boost converter and S2 is kept in the blocking state. For regeneration S2 is turn on and the converter is operated as a buck converter. For both motoring and regeneration operation S1 is used to shape the current to follow a sinusoidal waveform. Under the normal operation the “select” signal controls S2 and changes the triggering signal applied to T1-T4 through the synchronization network. The synchronization network synchronizes the conduction for the rectifying thyristors (T1-T4) with line voltage. The bidirectional converter has been tested under motoring mode and regenerating mode conditions. During motoring test the converter was loaded with electronic load and the regenerative test was carried out by connecting a dc voltage source to the converter output.

### 2.1 Motoring mode operation

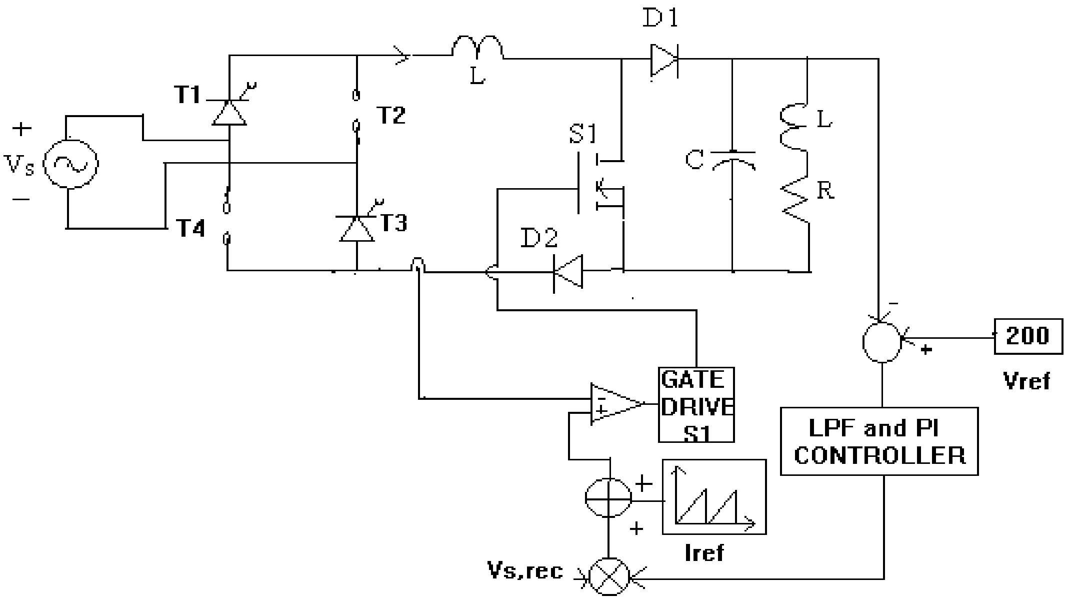

**Fig.2** Operation of the converter in the motoring mode + ve half cycle of power source

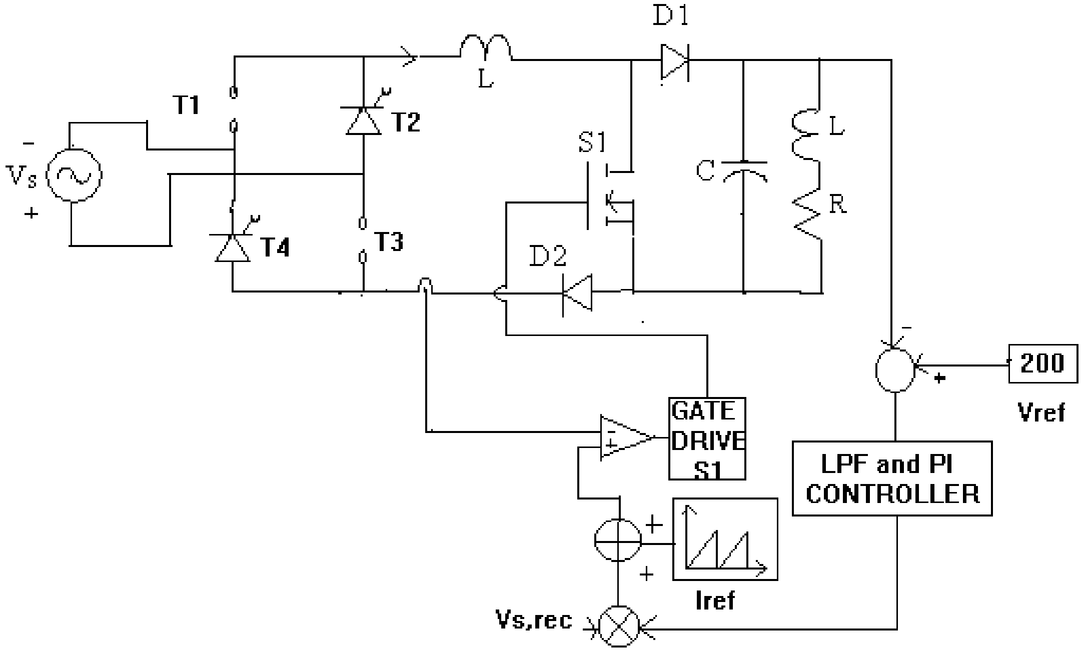

**Fig.3** Operation of the converter in the motoring mode - ve half cycle of power source

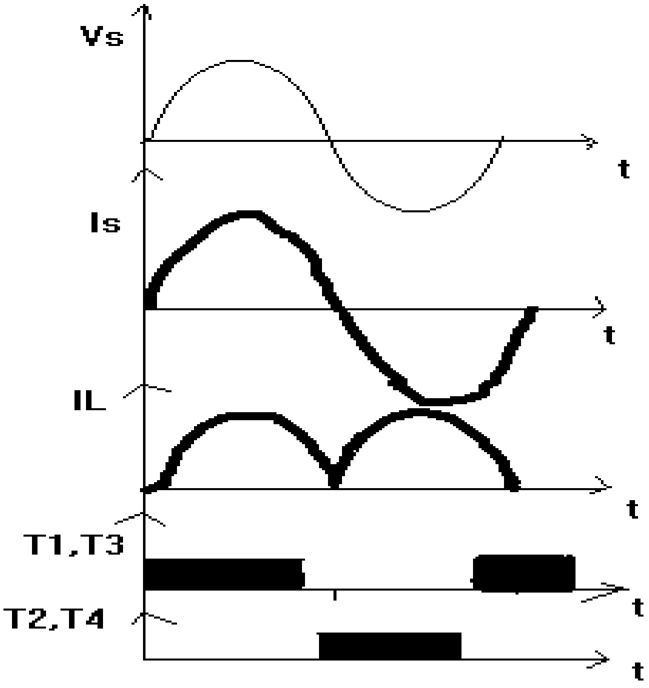

**Fig.4** Timing diagram

The triggering signals of T1-T4 are synchronized with the line voltage Vs by the synchronization network shown in fig.1 and the operation of power conversion stage and timing diagrams shown in fig.2&3&4. In motoring mode the thyristor T1and T3 is fired at an angle 345 degree in the +ve half cycle of Vs and T2 and T4 are fired at an angle 165 degree, which gives an input voltage for the chopper circuit, similar to that the diode rectifier. S2 is turned off for the entire motoring mode period and the chopper circuit acts as a boost converter and a boost converter is formed by L, S1, D1and C and diode D2 is forward biased. When the switch S1 is conducting the current flowing in the inductor will rise. Once the switch is turned off the current in the inductor will start fall as the diode D1 conducts and the energy will transferred to the output load. In order to maintain the control of the dc link voltage, it must always be higher than the input voltage. By varying the duty cycle of the switch S1 to control the output voltage. The inductor current $i_L$ is controlled to follow the rectified waveform of Vs,rect by a PWM signal generated from the current mode controller. As in fig.11 the feedback current $i_{fb}$ is compared with reference sinusoidal waveform $i_{ref}$ and is forced to remain between the maximum and the minimum values of $i_{ref}$. Fig.4 shows the operations of motoring mode. It consists of topology AI and topology AII in the one switching cycle of period Ts. ”AI” is operated for a time interval of dTs (where d is duty cycle of S1) and “AII” is operated for a time interval of (1-d)Ts.

- Topology AI-fig.4(a): iL is defined as

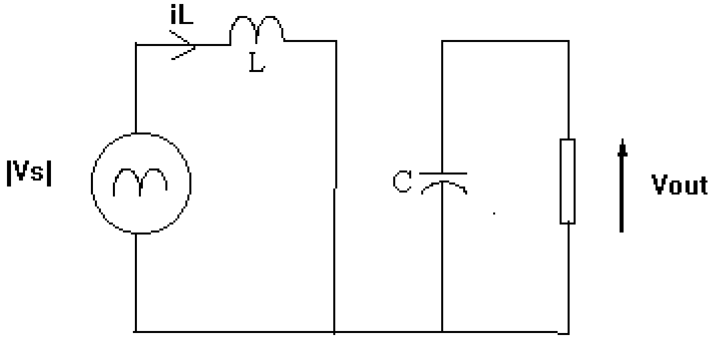

**Fig. 4(a)** Operation boost converter-I

$$i_L(t)=i_{L,0}+\frac{Vs}{L}t \qquad (1)$$

iL,0 is the initial value of iL at the beginning of a switching cycle. At the end of this interval dTs

$$i_L, dTs=i_{L,0}+\frac{VsdTs}{L} \qquad (2)$$

- Topology AII-fig.4(b)&(c):
-

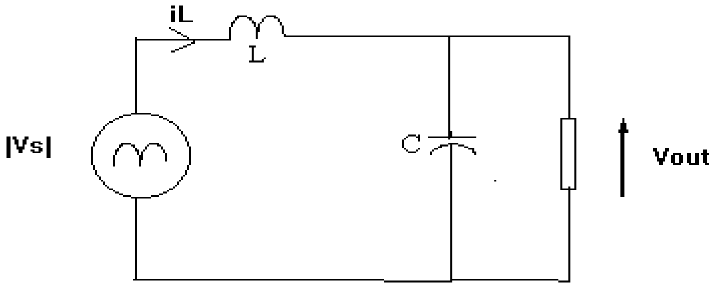

**Fig. 4(b)** Operation of boost converter-II

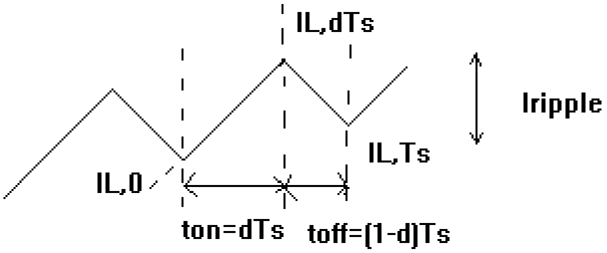

**Fig. 4(c)** Inductor current

$$i_L(t)=i_{L,dTs}+\frac{Vs-Vout}{L}t$$

$$i_L(t)=i_{L,0}+\frac{VsdTs}{L}+\frac{Vs-Vout}{L}t \qquad (3)$$

At the end of the half cycle

$$i_L,Ts=i_{L,0}+\frac{VsTs}{L}-\frac{Vout}{L}(1-d)Ts \qquad (4)$$

By using equation (4), the ideal quasi steady state conversion characteristics is given by

$$|Vs|=Vout\ (1-d) \qquad (5)$$

As, $|Vs| = Vm|Sin\,\omega t|$

$$d(t) = 1 - \frac{Vm}{Vout}|Sin\,\omega t| = 1 - \frac{1}{M1}|Sin\,\omega t| \qquad (6)$$

Where

M1=Vout/Vm

## 2.2 Regenerating mode operation

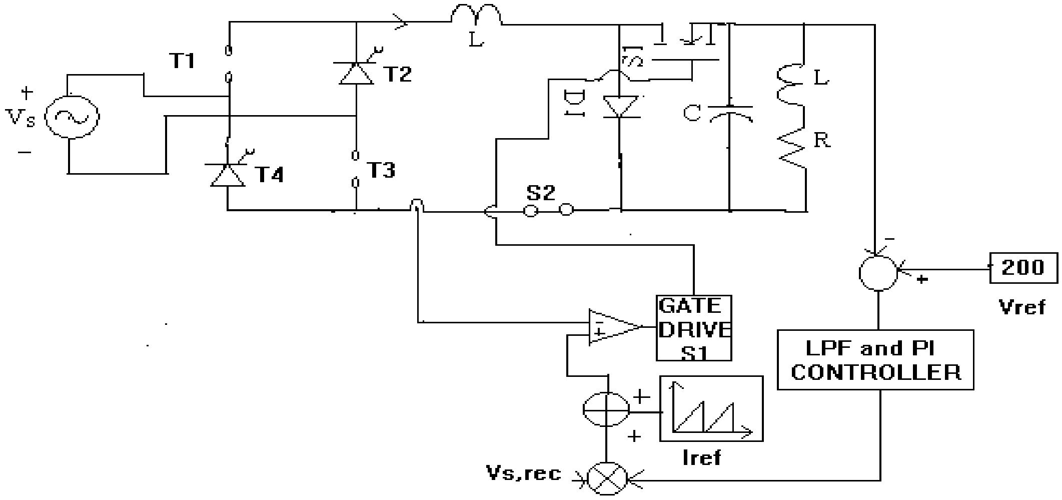

**Fig.5** Operation of the converter in the regenerating mode + ve half cycle of power source

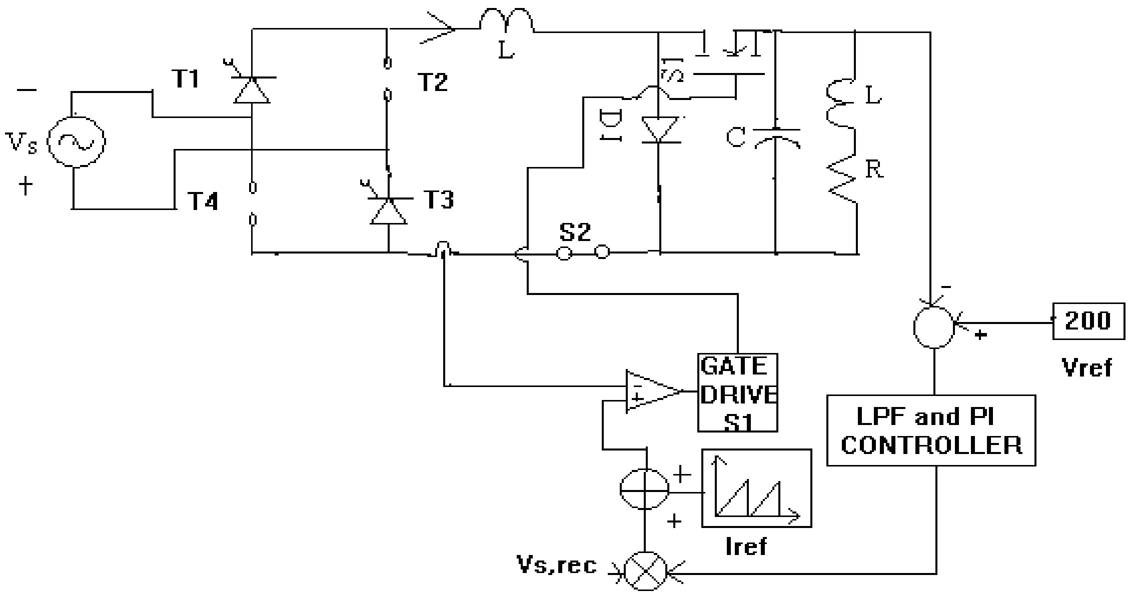

**Fig.6** Operation of the converter in the regenerating mode - ve half cycle of power source

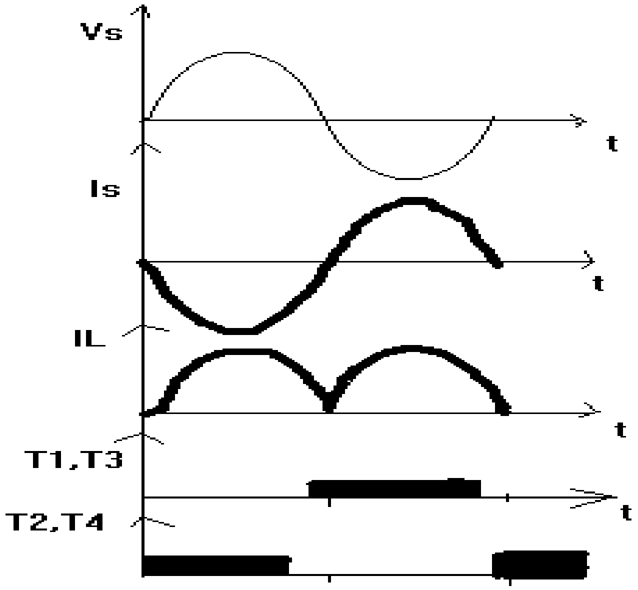

**Fig.7** Timing diagram

During the regenerating mode S2 is turned on and D2 is reverse biased. In this mode T1-T4 are operated in anti-phase with the operation in motoring mode, which gives the reverse input voltage.

The converter now acts as a buck converter with voltage across the bulk capacitor as the input voltage. In regenerating mode when the switch S1 is closed the inductor current will rise and the current will flow from the load to supply through the thyristor. When the switch is open the inductor current will fall as the current flows through diode D1, so that power can fed back to the ac power supply. As shown in fig. 5 & 6 &7, T2 and T4 are turned on in positive half cycle while T1 and T3 are turned on in negative half cycle. The operation is simply achieved by triggering the "select "switch to exchange the synchronization signals applied to T1-T4 (open the select switch for regenerating mode and closed it for motoring mode). The thyristor are pre-triggered in their half cycle with an advance angle of about 15 degrees. For example if the supply source is in the positive half cycle and T2 and T4 are in the ON state,T1 and T3 will be pre-triggered at about 15 degrees before the voltage supply source goes to negative half cycle. Pre-triggering the incoming thyristor T1 and T3 enables the outgoing thyristor T2 and T4 to naturally commutate without using extra commutation circuit. In this operating mode the converter is operated as a buck converter, feeding the power from the regenerative load to supply source. The phase current $i_s$ is 180 degree out of phase with the supply voltage. The operation of the current mode controller is still applicable since the inductor current is flowing in the same direction as that in the motoring mode. Both the motoring mode and regenerating mode have a similar inductor current. It consists of topology AI and topology AII in the one switching cycle of period Ts. ”BI” is operated for a time interval of dTs (where d is duty cycle of S1) and “BII” is operated for a time interval of (1-d)Ts.

- Topology BI-fig.7(a): In one switching cycle, IL is given by

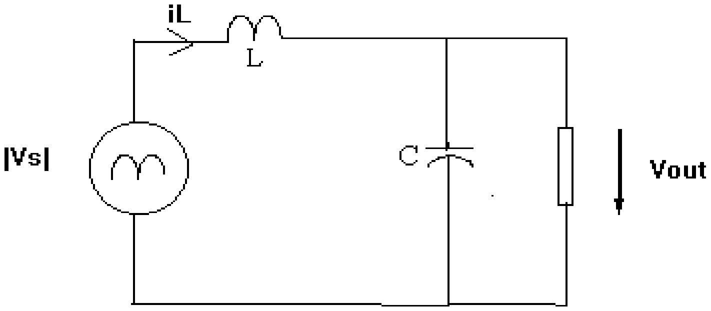

**Fig.7(a)** Operation of buck converter-I

$$i_L(t)=i_{L,0}+\frac{Vout-Vs}{L}t \tag{7}$$

iL,0 is the initial value of iL at the beginning of a switching cycle. This stage is defined by the ON time of S1 (dTs). At the end of this stage

$$i_{L,dTs}=i_{L,0}+\frac{Vout-Vs}{L}dTs \tag{8}$$

- Topology BII-fig.7(b)&(c): iL is given by

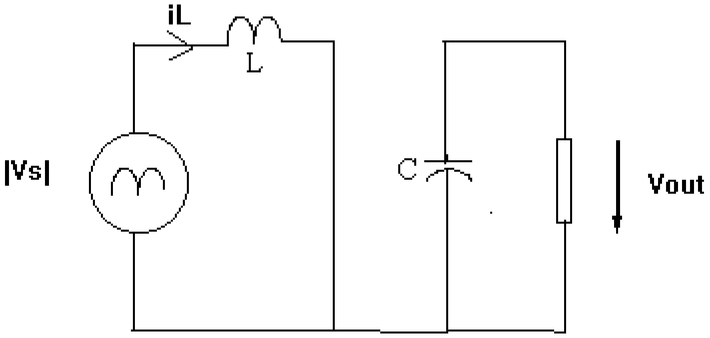

**Fig.7(b)** Operation of buck converter-II

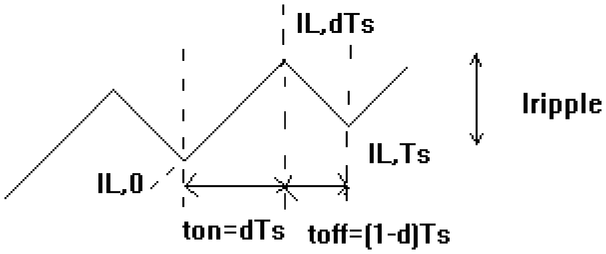

**Fig. 7(c)** Inductor current

$$i_L(t)=i_{L,dTs}-\frac{Vs}{L}t \qquad (9)$$

This stage is defined for period of Toff = (1-d) Ts. Therefore

$$i_{L,Ts}=i_{L,0}-\frac{Vout-Vs}{L}dTs-\frac{Vs}{L}(1-d)Ts \qquad (10)$$

By using equation (10), the ideal quasi steady state conversion characteristics is given by

$$|Vs|=d\ Vout \qquad (11)$$

As $|Vs|=Vm|Sin\,\omega t|$,

$$d=\frac{Vm}{Vout}|Sin\,\omega t|=\frac{1}{M2}|Sin\,\omega t| \qquad (12)$$

Where

M2=Vout/Vm

### 2.3 Average output current

**Motoring mode:** If the input current of the converter is assumed to be perfectly sinusoidal and the conversion efficiency is assumed to be 100%

$$i_S=i_m|Sin\,\omega t|$$

$$\frac{1}{\pi}\int_{0}^{\pi} Vs\,i_S\,d\omega t = i^2_{out,avg}\,R_L$$

$$\frac{1}{2}Vm\,\mathrm{Im} = i^2_{out,avg}\,R_L$$

$$iout,avg=\sqrt{\mathrm{Im}\,Vm/2}\,R_L \qquad (13)$$

Where

Im is the peak value of supply current

As Im is controlled by the current controller, the output voltage can be varied by changing the Iref.

**Regenerative mode:** Again if supply current is assumed to be sinusoidal and conversion efficiency is 100%

$$i_S=-i_m|Sin\,\omega t|$$

$$\frac{1}{\pi}\int_{0}^{\pi} Vs\,i_S\,d\omega t=-iout,avgVout$$

$$\frac{1}{2}Vm\,\mathrm{Im}=iout,avgVout$$

$$iout,avg=\frac{\mathrm{Im}}{2M2} \qquad (14)$$

As iout,avg is determined by Im, the reversible power from the load to the supply side can be controlled by adjusting the Iref.

## 2.4 Design the value of inductance (L)

**Motoring mode:** The value of L is determined by the desired ripple in supply current. Considering the input current in fig.8 it’s peak to peak value $i_{ripple}$ is given as

$$i_{ripple}=\frac{VsdTs}{L}=\frac{VmTs}{L}|Sin\,\omega t|\left(1-\frac{1}{M1}|Sin\,\omega t|\right) \qquad (15)$$

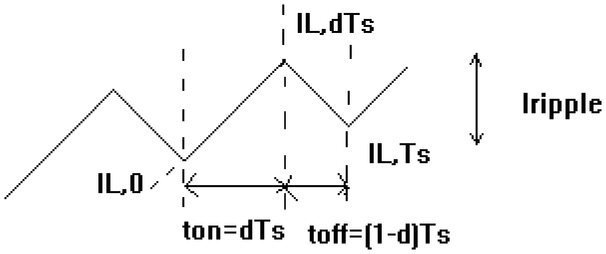

**Fig. 8** Inductor current

Differentiating $i_{ripple}$ with respect to Sinwt and equating the expression to zero gives

$$1-\frac{2}{M2}|Sin\,\omega t|=0 \tag{16}$$

For maximum value of $i_{ripple}$. The minimum value of L that limits the maximum ripple current to a value $i_{ripple,max}$ is,

$$i_{ripple}=\frac{VmM1Ts}{4L\min} \tag{18}$$

Lmin=VmM1Ts/4 $i_{ripple}$

**Regenerative mode:** As in fig.8 the ripple current flowing through the inductor is

$$i_{ripple}=\frac{(Vout-Vs)}{L}dTs$$

$$=\frac{(Vout-Vm|Sin\,\omega t|)d|Sin\,\omega t|}{L}Ts$$

$$=\frac{VoutTs}{L}\left(1-\frac{1}{M2}|Sin\,\omega t|\right)\frac{1}{M2}|Sin\,\omega t|$$

$$=\frac{VmTs}{L}|Sin\,\omega t|\left(1-\frac{1}{M2}|Sin\,\omega t|\right) \tag{19}$$

It gives the same expression as (19). Therefore, the minimum inductor Lmin that limits ripple current to a value is

$$i_{ripple} = \frac{VmM\,2\,Ts}{4\,L\min} \qquad 2.20$$

$$Lmin=VmM2Ts/4\ i_{ripple}$$

In the above mathematical derivations, the output voltage is assumed to be constant

## 2.5 Design of output capacitor C

The value of C is determined by considering the maximum ripple voltage on the Vdc.Fig.9 shows the equivalent circuit in motoring mode.

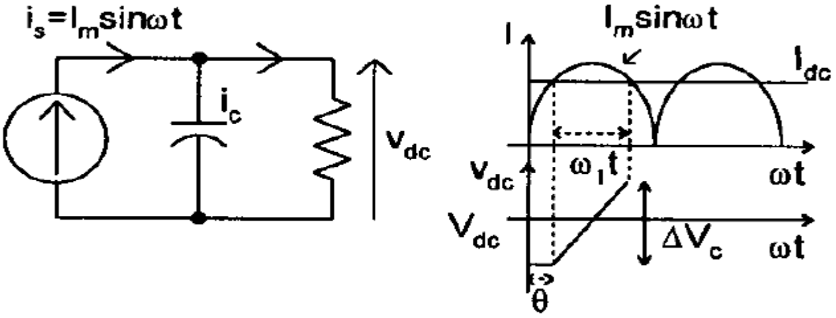

**Fig. 9** Equivalent circuit in motoring mode

$$i_C(t)= i_S(t)-Idc$$

$$i_S = \mathrm{Im}\,Sin\,\omega t \qquad (21)$$

Where Im is the peak input current, $\omega$ is the angular frequency of the ac main, and Idc is the dc link current.

In steady state, the average value of is equals Idc. Thus

$$\mathrm{Im} = \frac{\pi}{2} Idc \qquad (22)$$

and

$$C \geq \frac{Idc}{\omega \Delta Vdc,\max}(\pi Cos\,\theta - \pi + 2\theta)$$

$$\theta = Sin^{-1}\frac{2}{\pi}$$

$$C\frac{dVdc}{dt} = i_C(t)$$

## 2.6 Modelling of Dc-Dc Converters

By using the state-space averaging model of boost converter can be written as

$$A = A_{on}\,d + A_{off}\,(1-d)$$

$$B = B_{on}\,d + B_{off}\,(1-d)$$

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{d-1}{L} \\ \frac{1-d}{L} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} E \tag{23}$$

## 3. Design of PI controller

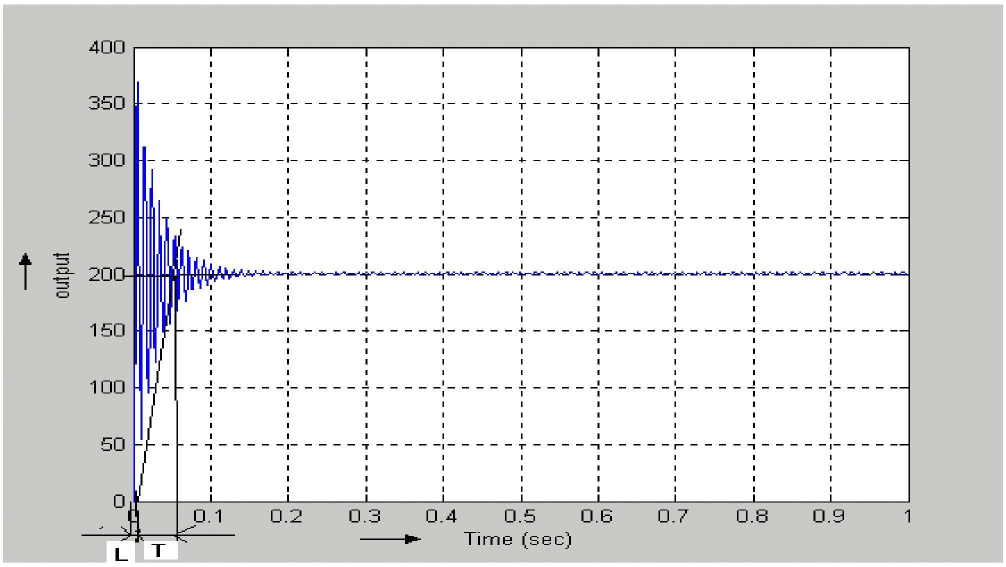

Fig. 10 PI response

Kp = 0.9 T/L

Ti = L/0.3

Where

T is time constant

L is dead time

From the response

T=0.0165 sec

L=0.0015 sec

Then,

Kp = 0.9 * 0.0165/0.0015=10.5

Ti = 0.0015/0.3=0.005sec

Transfer function =Kp(1+1/TiS)=10.5(1+1/.005S)

After tuning the Kp and Ti

Now,

T.F=.4(S+600)/S

**3.1 Design of low pass filter**

Transfer Function=1/(1+SRC)

Choose cut-off frequency=fc=79Hz

Capacitor range from 0.1µf to .001µf

Choose capacitor=.01µf

$$f_c = \frac{1}{2\pi RC}$$

$$R = \frac{1}{2\pi * 79 * .01\mu} = 200\,K\Omega$$

T.F=0.002/(s+500)

### 3.2 Design of inductor average current controller

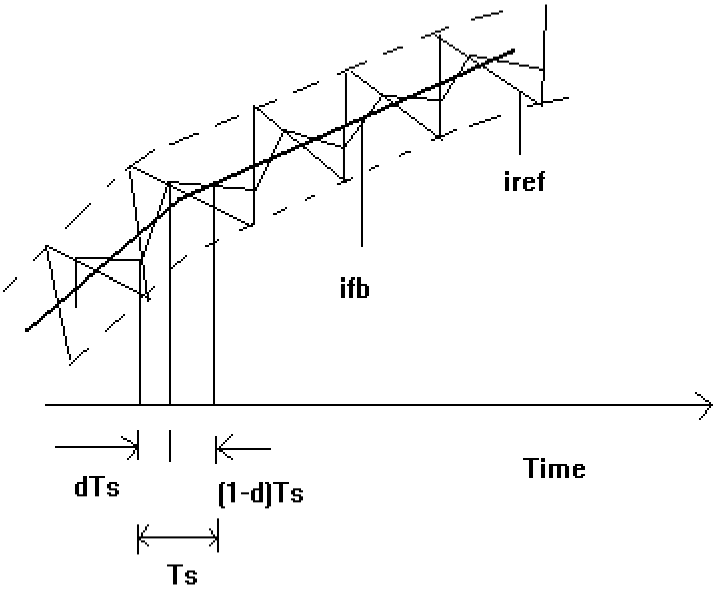

Fig.11 Waveforms of ifb and iref

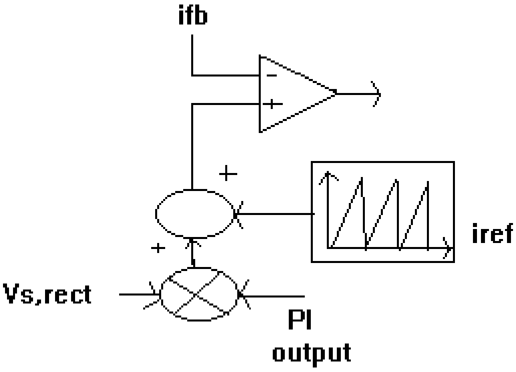

Fig.12 Inductor average current controller

In Fig.12 the PI controller output and full bridge diode rectifier output are applied to multiplier. Now, multiplier multiply the both signal to form the modulating signal. This modulating signal and ramp function are applied to summer. It's sums the both signal to form reference current. Then reference current is compared to feedback current to form pwm pulse to control the switch S1.The duty cycle of the switch S1 can be varied by changing the ramp function magnitude. In Fig.11 the feedback current is compared with reference sinusoidal waveform and is forced to remain between the maximum and minimum values of iref.

Advantages:

- Average current tracks the reference current with high degree of accuracy. This is especially important in high power factor converters.
- Slope compensation is not required, but there is a limit to loop gain at switching frequency in order to achieve stability.
- Noise immunity is excellent.
- The average current mode control can be used to sense and control the current in any circuit branch.
- Switching frequency is fixed.
- Speed of the response is fastest.
- Ripple current is fixed.
- Filter size is usually small.

Ramp function magnitude: 4.2A

Reference current magnitude: 10A

Fed back current magnitude: 8A

### 3.3 Synchronization and triggering circuit

As in Fig.13, switch on the ac supply to the circuit. Now, 141V is applied to the input of the step down transformer and 141V is step down to 5V. This 5V is applied to input of the two half bridge which gives two rectified +ve sine waveforms (i.e. one for +ve half cycle and other for –ve half cycle). Then this signal is amplified and applied to zero crossing detectors. Then the zero crossing detectors produces two pulse of same period of half cycle of ac voltage input. Simultaneously the function generators produce two square pulses. One at 0 to 8.6ms period of one half cycle and other at 10ms to 18.6ms of another half cycle of input. Both zero crossing detector output and function generator output are fed to the AND gates. Then output of AND gates are applied to multiplexer. Either motoring mode or regenerative modes are decided by multiplerxer. Now the outputs of multiplerxer are applied to AND gates and simultaneously 555 IC in astable produces the pulse train of very high frequency 10 kHz. Both AND gates output and pulse train are fed to the AND gates. In which the two inputs are logically ANDed or pulse train is superimpose on the ZCD output. Output of AND gates are fed to delay circuit(for example T1and T3 are pre-triggered before 15 degree for +ve half cycle and T2 and T4 are pre-triggered before 15 degree for –ve half cycle. The pre triggering of incoming thyristors T1and T3 enables the outgoing thyristors T2and T4 to naturally commutate without using extra commutation circuit). The output of delay circuit is applied to drive the thyristor.

## 5. Conclusions

The proposed bidirectional ac-dc power converter was studied and the designs and performance is validated through the computer simulation using mat-lab simulink and power system block set. The control scheme used in this converter is simple and commonly used in current controlled power converter. The designed controller has produced excellent performance.

## REFERENCES

1. S.Y.Hui, Henry shu hung Chung,”A bidirectional ac-dc power converter with power factor correction,”IEEE.power electronics, vol.15, no.5, September 2000.

2. J.T.Boys and A.W.Green,”Current forced single phase reversible rectifier,”IEE proc. Vol.136, no.5, 1989.

3. M.Morimoto, K.Sumito,”New single phase unity power factor PWM converter inverter system,” in proc.IEEE PESC’89.

4. F.Rahman, L.Zhong,”A single phase regenerative variable speed induction motor drive, “in EPE’95.

5. R.M.Davis and C.G.Alexander,”A bidiectional ac-dc power converter for fixed polarity dc loads,” in proc, IEE PEVD’88.

6. R.Itoh and Ishizaka,”Single phase sinusoidal rectifier with step up-step down characteristics,”IEE proc. Nov.1991.

7. M.H.Rashid, Power Electronics: circuit, device, and application, 2nded. Englewood cliffs, NJ: prentice hall-1993.

8. W.M.Grandy, M.J.Samotyi,"Survey of active power line conditioning methodologies," IEEE Trans. Power delivery. July 1990.

9. Arunkumar, T.S. Sivakumaran, K. Ramash Kumar, "Improved performance of linear quadratic regulator plus fuzzy logic controller for positive output super lift Luo-converter", *Journal of Electrical Engineering*, Vol. 16, No. 3, pp. 397-408, 2016.
10. K. Ramash Kumar, D.Kalyankumar, DR.V.Kirbakaran "An hybrid multi level inverter based DSTATCOM control", *Majlesi Journal of Electrical Engineering*, Vol. 5. No. 2, pp. 17-22, 2011.
11. K. Ramash Kumar, S. Jeevananthan, "PI control for positive output elementary super lift Luo converter", *World Academy of Science, Engineering and Technology*, Vol. 3, No. 3, pp. 130-135, 2010.
12. S. Padma, Dr. R. Lakshmipathi, K. Ramash Kumar and C. P. Nandagopal, "A PI controller for enhancing the transient stability of multi pulse inverter based Static Synchronous Series Compensator (SSSC) with Superconducting Magnetic Energy Storage (SMES)", *World Academy of Science, Engineering and Technology*, Vol. 3, No. 3, pp. 136-142, 2010.
13. 13. P. Sivakumar, V. Rajasekaran, K. Ramash Kumar, "Investigation of intelligent controllers for varibale speeed PFC buck-boost rectifier fed BLDC motor drive", *Journal of Electrical Engineering*, Vol. 17, No. 4, pp. 459-471, 2017