March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

A Inductor Average Current Mode Controller Plus Proportional Integral Controller for a Bi-Directional AC-DC Power Converter with Power Factor Correction for DC Micro Grid

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Article Info
Volume 83
Page Number: 2529 - 2544
Publication Issue:
March - April 2020

Article History
Article Received*: 24 July 2019*
Revised*: 12 September 2019*
Accepted*: 15 February 2020*
Publication*: 19 March 2020*

Abstract:
This paper presents the current mode controller for two-directional ac-dc power converter with power factor correction for dc micro grid. The performance of the designed model is justified with help of MATLAB/Simulink software. The results are presented to show the proficient of the developed model.

1. Introduction

In current scenario, the power factor correction converters are plays a major role in many applications. Most of the power converters fed non-linear load draws the non-disturbed input current waveform from the mains. The conventional methods of AC-DC power with filter has major problems [1-8]. The current controllers for various power factor correction converters have been reported [9-13]. Therefore, in this paper, it is propose a SCR based AC-DC bidirectional power converter with proficient power factor. The main benefits of this designed model has minimal cost, small capacitor size, good power factor and output voltage regulation.

1. Operation of Bi-Directional AC-DC Power Converter

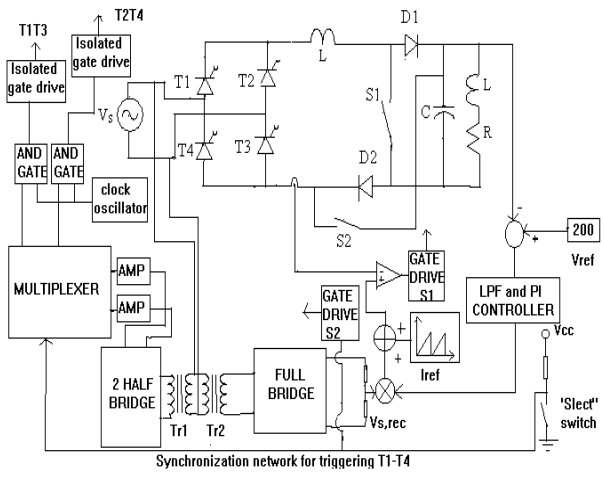


Fig.1 Proposed bidirectional ac-dc power converter

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

Fig.1 shows the ac-dc bi-directional converter. It consists of power circuit and inductor average current controller and the synchronization circuit for triggering the thyristor. Power conversion stage consists of four low cost, SCRs T1-T4, switches (S1 & S2), D1 & D2, L and C.

2.1 Motoring mode operation

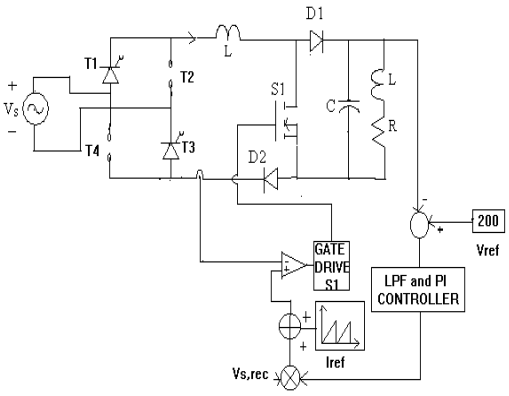


Fig.2 Motoring mode operation during positive half cycle of supply

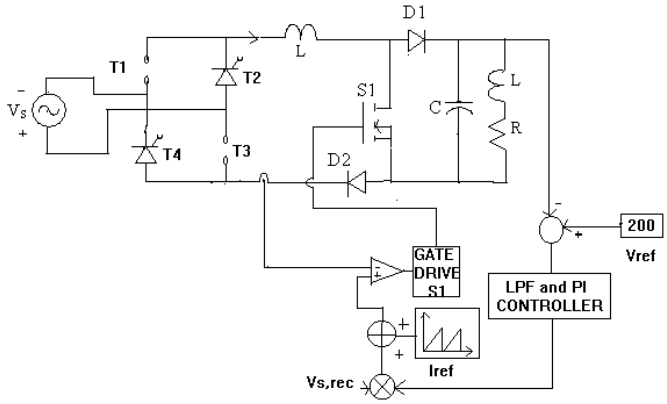


Fig.3 Motoring mode operation during negative half cycle of supply

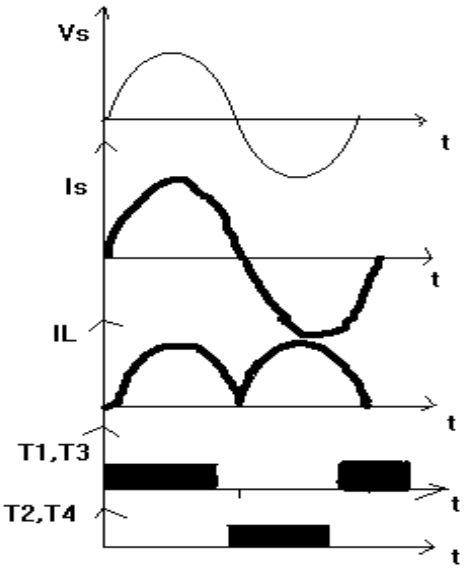


Fig.4 Timing diagram

The firing of T1-T4 are synchronized with the supply voltage in fig.1 and its switching diagram in figs 2,3, and 4. In motoring mode, T1and T3 is turn on at an angle 345 degree in the positive half cycle of supply voltage whereas T2 and T4 are turn on at an angle 165 degree that gives an input voltage for the chopper circuit, similar to that the diode rectifier. S2 is open for the whole motoring mode 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}. Topology AI-fig.4(a): iL is defined as

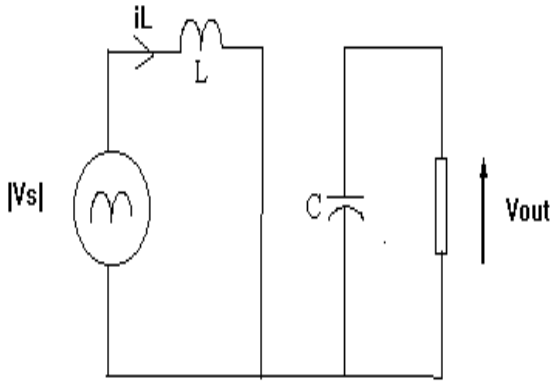


Fig. 4(a) Operation boost converter-I

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

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

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

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

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

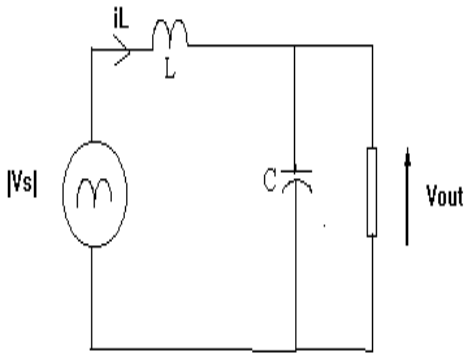


Fig. 4(b) Operation of boost converter-II

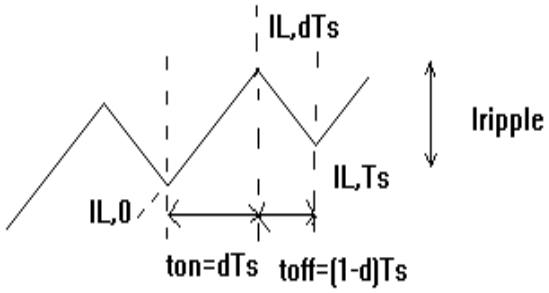


Fig. 4(c) Inductor current

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

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

At the end of the half cycle

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

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

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

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

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

Where

M1=Vout/Vm

2.2 Regenerating mode operation

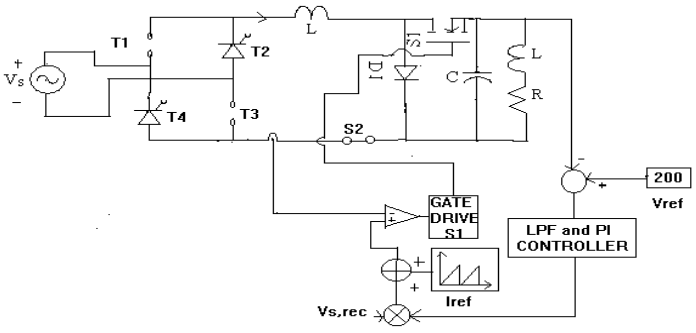


Fig.5 Regenerating mode + ve half cycle of power source

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

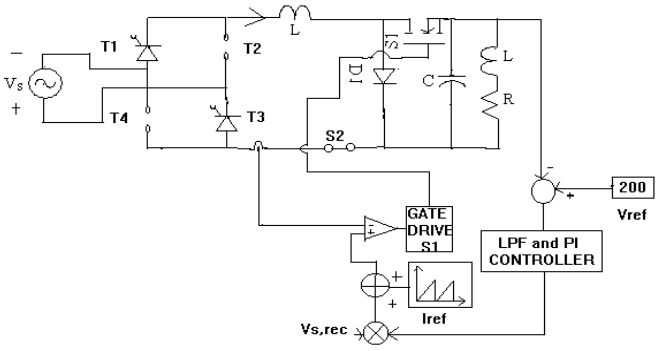


Fig.6 Regenerating mode - ve half cycle of power source

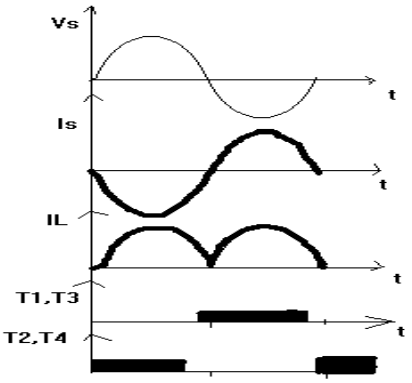


Fig.7 Timing diagram

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. Fig.7(a): In one switching cycle, IL is given by

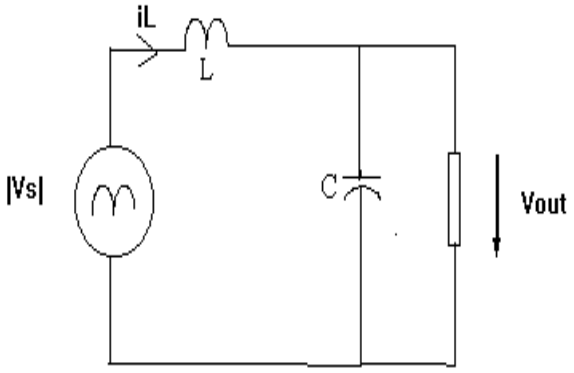


Fig.7(a) Operation of buck converter-I

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

(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

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

(8)

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

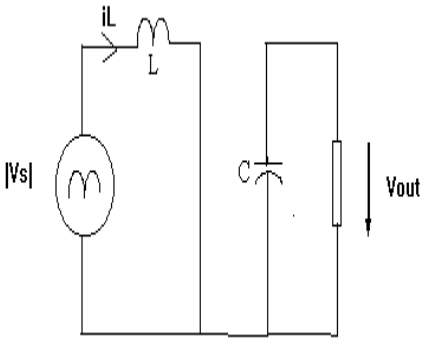


Fig.7(b) Operation of buck converter-II

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

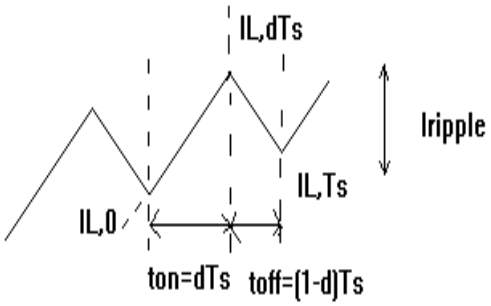


Fig. 7(c) Inductor current

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

(9)

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

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

(10)

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

$$|Vs| = d\ Vout$$

(11)

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

$$d = \frac{Vm}{Vout}|Sin\omega t| = \frac{1}{M2}|Sin\omega t|$$

(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%

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

$$\frac{1}{\pi}\int_0^{\pi} Vsi_S d\omega t = \text{i}^2\text{out,avg R}_\text{L}$$

$$\frac{1}{2}Vm\,\text{Im} = \text{i}^2\text{out,avg R}_\text{L}$$

$$iout,avg = \sqrt{\text{Im}Vm/2}\ \text{R}_\text{L}$$

(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%

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

$$\frac{1}{\pi}\int_0^{\pi} Vsi_S d\omega t = -iout,avgVout$$

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

$$iout,avg = \frac{\text{Im}}{2M2}$$

(14)

2.4 Design the value of inductance (L)

Motoring mode: Considering the input current in fig.8 it's peak to peak value i_{ripple} is given as

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

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

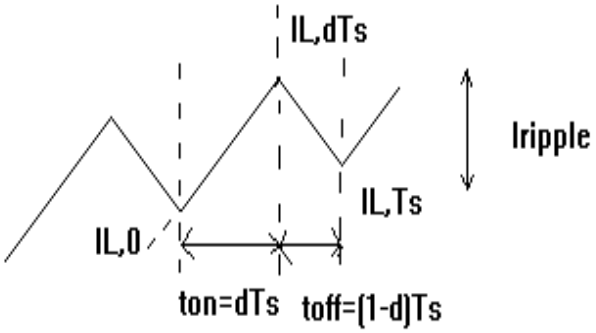


Fig. 8 Inductor current

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

$$1-\frac{2}{M2}|Sin\omega t| = 0 \quad (16)$$

$$i_{ripple} = \frac{VmM1Ts}{4L\min} \quad (18)$$

Lmin=VmM1Ts/4 i_{ripple}

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

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

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

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

$$= \frac{VmTs}{L}|Sin\omega t|(1-\frac{1}{M2}|Sin\omega t|) \quad (19)$$

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

$$i_{ripple} = \frac{VmM2Ts}{4L\min}$$

2.20

Lmin=VmM2Ts/4 i_{ripple}

2.5 Design of output capacitor C

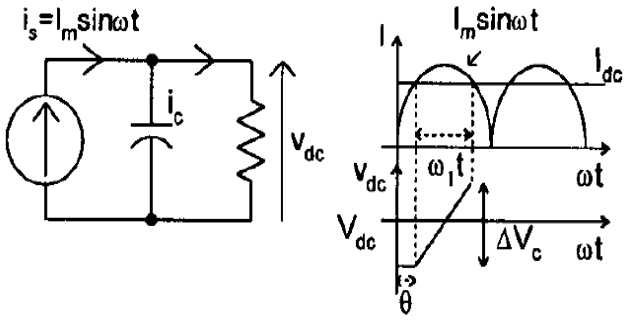


Fig. 9 Equivalent circuit in motoring mode

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

$$i_S = Im\,Sin\omega t \quad (21)$$

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

Where Im is the peak input current, ω 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

$$\text{Im} = \frac{\pi}{2} Idc \quad (22)$$

and

$$C\frac{dVdc}{dt} = \text{i}_C(t)$$

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

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

2.6 Modelling of Dc-Dc Converters

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

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

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

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

3. Design of PI controller

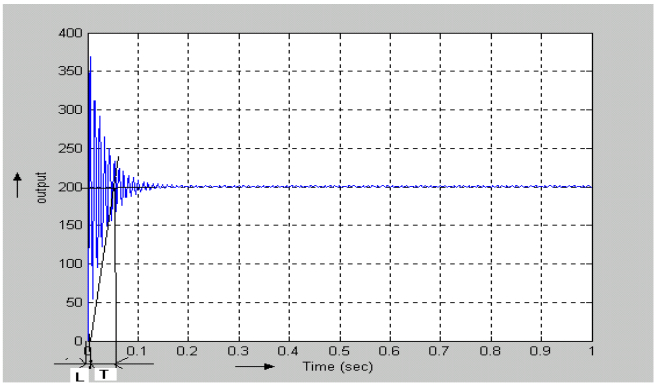


Fig. 10 PI response

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

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

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

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

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

T.F=0.002/(s+500)

3.2 Design of inductor average current controller

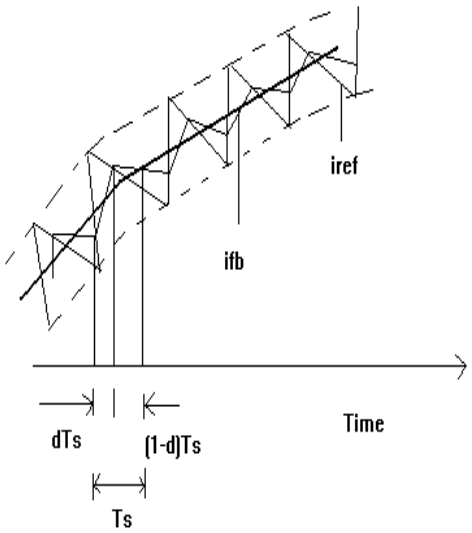


Fig.11 Waveforms of ifb and iref

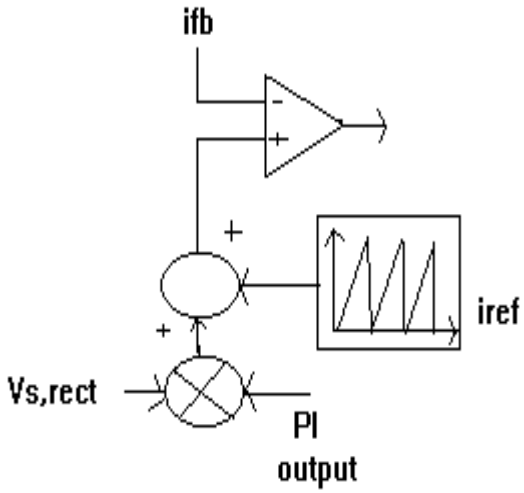


Fig.12 Inductor average current controller

In Fig.12 the PI controller output and full bridge diode rectifier output are applied to multiplier. Now, multiplier multiplies 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.

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

3.3 Synchronization and triggering circuit

Fig. 13 show Simulink diagram of synchronization circuit.

$$C \geq \frac{Idc}{\omega \Delta Vdc,\max}(\pi Cos\theta - \pi + 2\theta) \geq \frac{2.5}{2*\pi*50*5}(\pi * Cos\theta - \pi + 2\theta) \geq 200\mu F$$

$$\Delta Vdc,\max = 5V$$

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

$$Vs Is = Po$$

$$Is = \frac{500}{100} = 5A$$

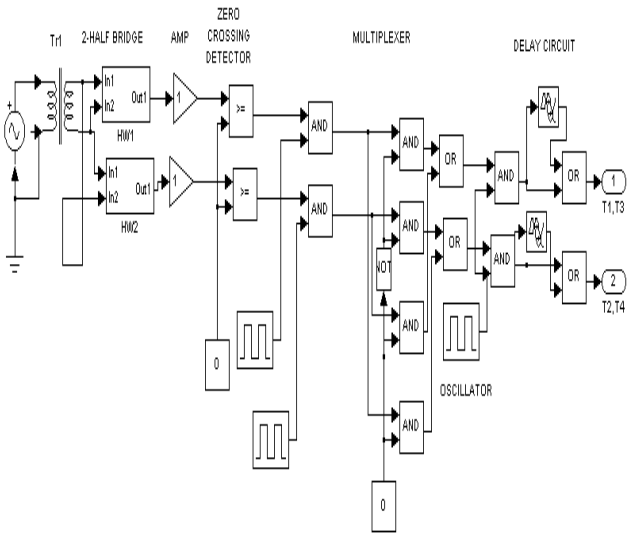


Fig. 13 Synchronization and triggering circuit

3.4 Design specification of proposed converter

$$Vs = VmSin\omega t = 100*\sqrt{2}Sin2*\pi*50*t$$

$$Vm = 141V$$

$$Vs = 100V$$

$$Switching\ frequency = 40KHz$$

$$Ts = 25\mu\sec$$

Choose, Iripple=10% of Is

Output voltage is assumed to be constant,

$$Vout = 200$$

$$M1 = M2 = M = \frac{Vout}{Vm} = \frac{200}{141.41} = 1.42$$

The conversion efficiency is assumed to be 100%

Input power=Output power

Load resistance

$$R = \frac{Vout^2}{Po} = \frac{(200)^2}{500} = 80\Omega$$

$$Iripple,\max = 0.1*\frac{P*2}{Vm} = 0.1*\frac{500*2}{141} = 0.714A$$

$$L\min = \frac{VmMTs}{4Iripple,\max} = \frac{141.14*1.42*25*10^{-6}}{4*.71} = 1.76mH$$

$$Iref = \frac{\sqrt{2}*2*P}{\eta*Vrms} = \frac{\sqrt{2}*2*500}{1*100} = 10A$$

Motoring mode:

$$\frac{|Vs|}{Vout} = 1-d$$

$$|Vs| = \frac{2Vm}{\pi}Cos\alpha = \frac{2*141}{\pi}Cos345 = 88.9V$$

$$1-d = \frac{88.9}{200}$$

$$d = 0.5667$$

$$Ton = dTs = 0.5667*25*10^{-6} = 14.16\mu\sec$$

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

Regenerating mode:

$$\frac{|Vs|}{Vout} = d$$

$$|Vs| = \frac{2Vm}{\pi} Cos\alpha = \left|\frac{2*141}{\pi} Cos165\right| = 88.9V$$

$$d = \frac{88.9}{200}$$

$$d = 0.4335$$

$$Ton = dTs = 0.4335*25*10^{-6} = 10.68\mu\sec$$

4. Simulation results and discussion

In this part, the simulation results for both closed loop motoring mode and regenerating mode is presented.

4.1 Motoring mode (closed loop)

Figs. 14 to 21 show the simulated responses of proposed converter during motoring mode. From these results, it is clearly found that designed converter with controller has produced unity power factor and excellent output voltage regulation.

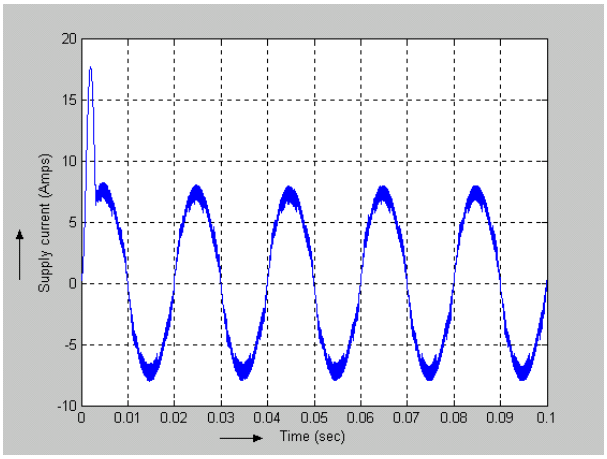


Fig. 14. Simulated supply current of proposed converter with controller

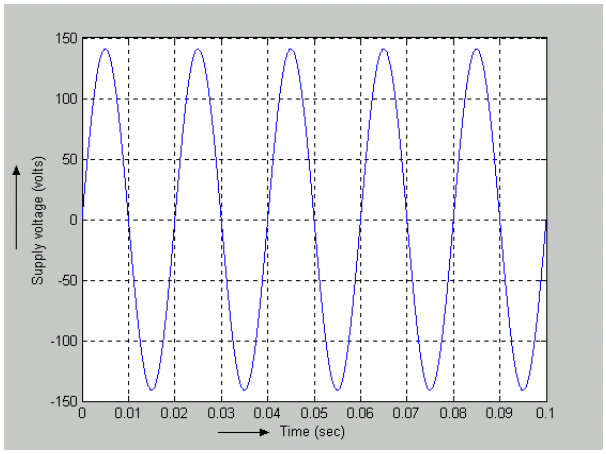


Fig. 15. Simulated supply voltage of proposed converter with controller

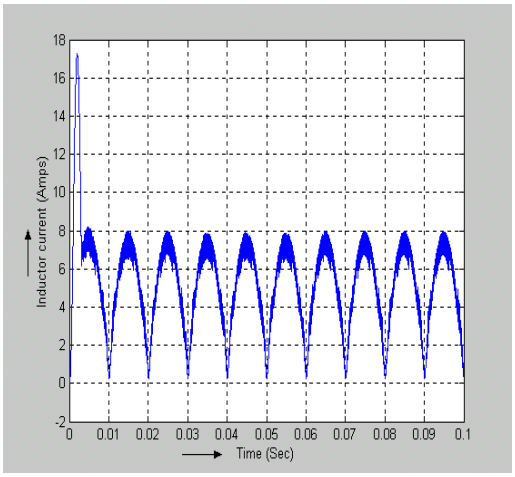


Fig.16. Simulated inductor current of proposed converter with controller

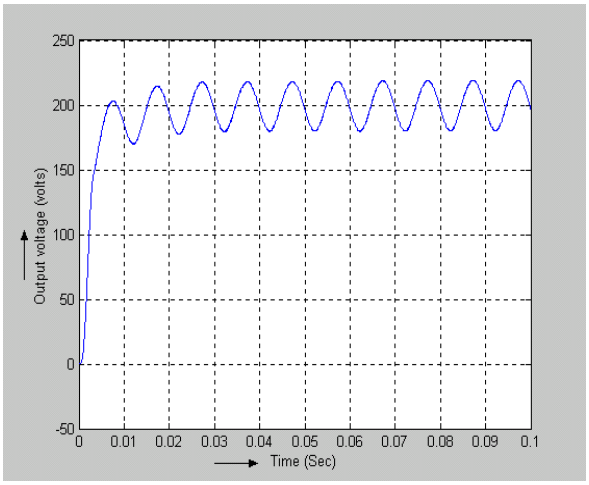


Fig. 17. Simulated output voltage of proposed converter with controller

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

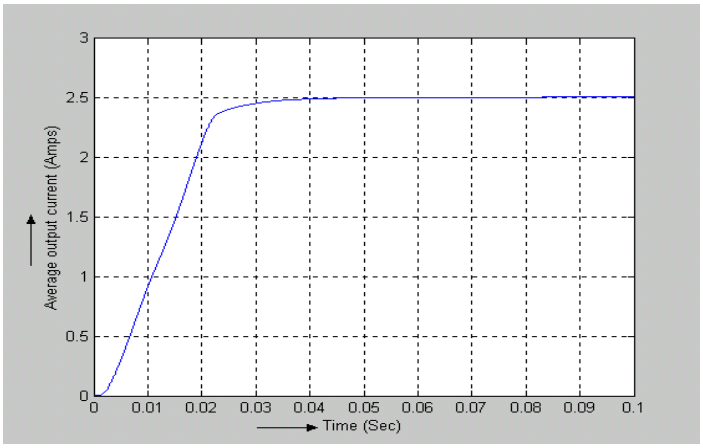


Fig. 18. Simulated average output current of proposed converter with controller

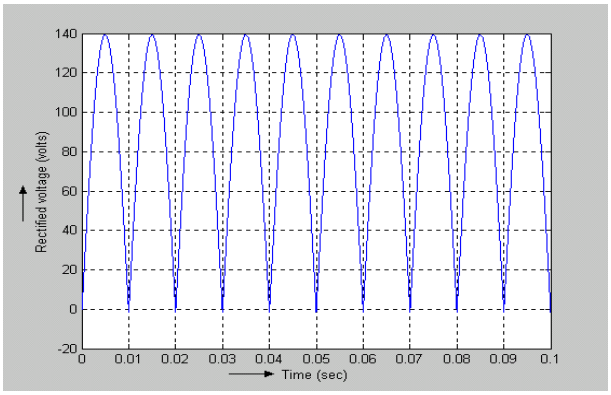
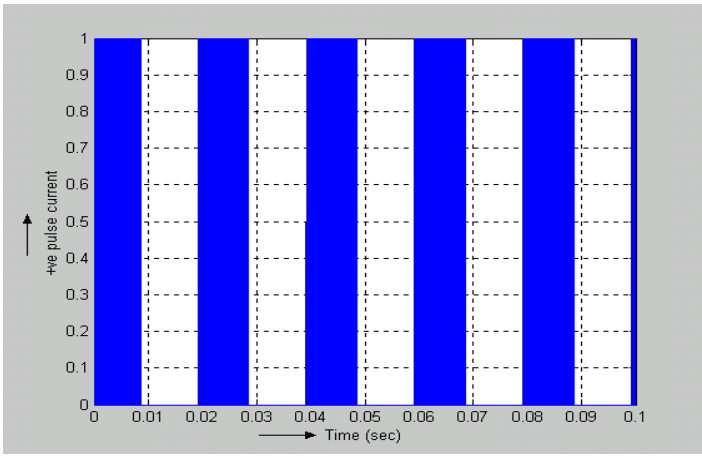
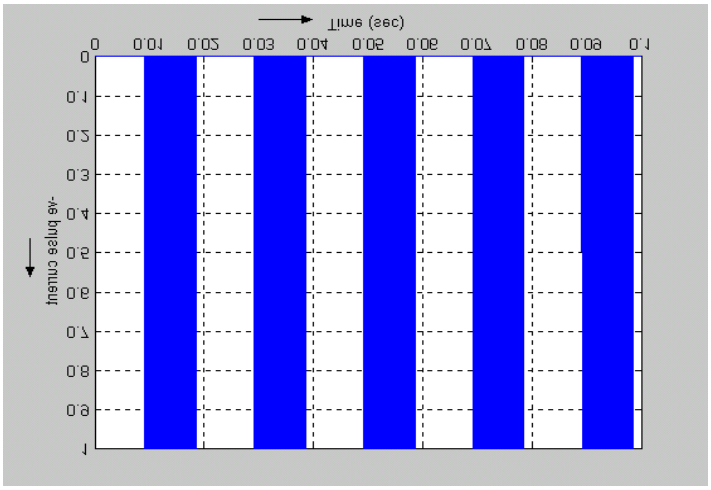


Fig. 19. Simulated thyristor rectified voltage of proposed converter with controller



(a)



(b)

Fig. 20. (a) and (b) Simulated thyristor firing pulse of proposed converter with controller

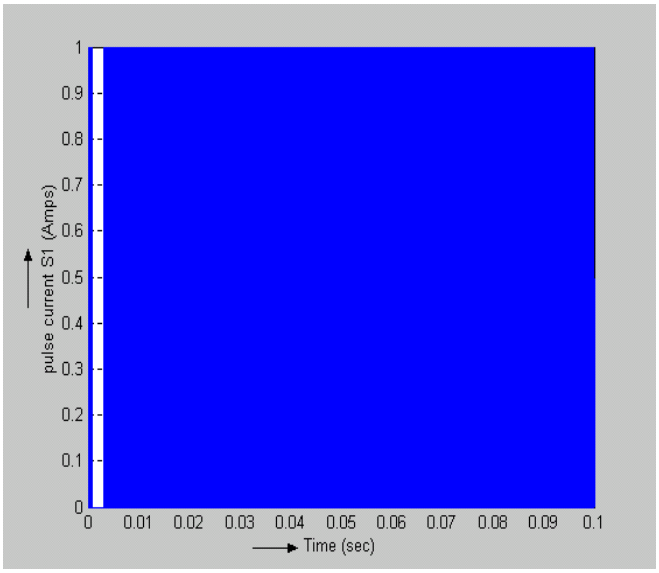


Fig. 21. Simulated PWM pulse for switch S1

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

4.2 Regenerating mode (closed loop)

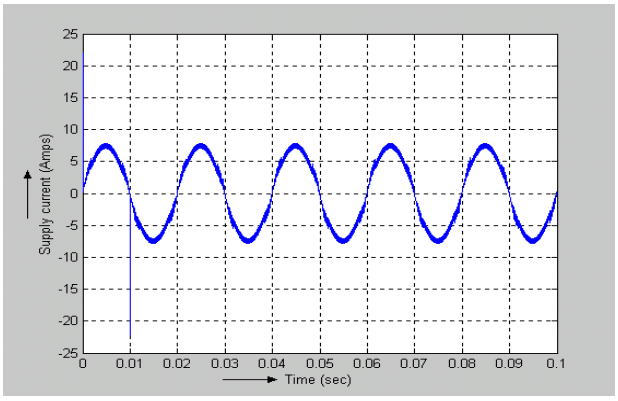


Fig.22. Simulated supply current of proposed converter with controller in regenerating mode

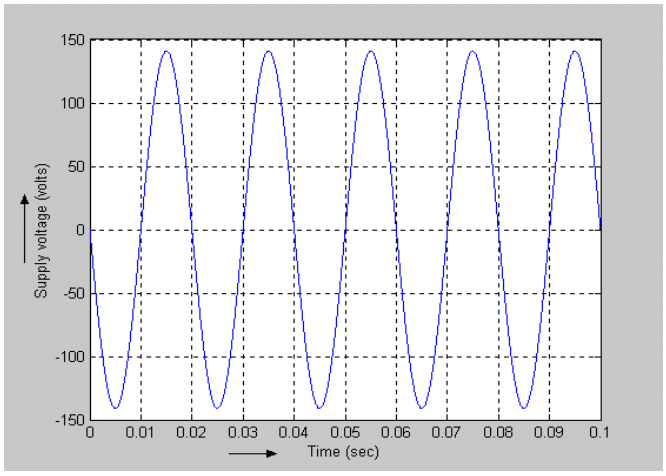


Fig. 23. Simulated source voltage of proposed converter with controller in regenerating mode.

Figs. 22 to 28 show the simulated responses of proposed converter during regenerating mode. From these results, it is clearly found that designed converter with controller has produced unity power factor and excellent output voltage regulation.

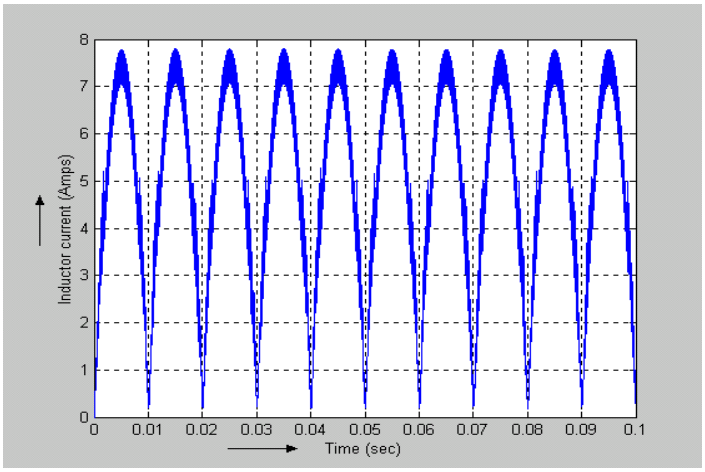


Fig. 24. Simulated inductor current of proposed converter with controller in regenerating mode.

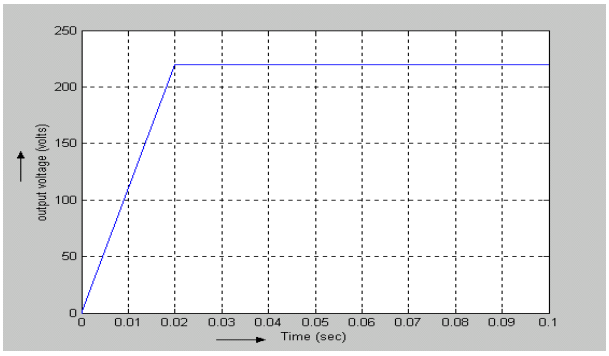


Fig. 25. Simulated average output voltage of proposed converter with controller in regenerating mode

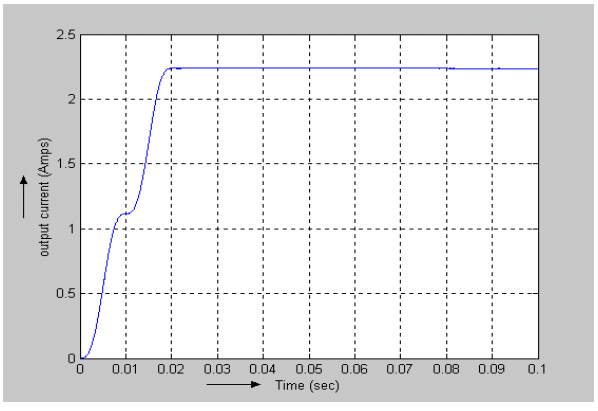


Fig. 26. Simulated average output of proposed converter with controller in regenerating mode.

March - April 2020
ISSN: 0193-4120 Page No. 2529 - 2544

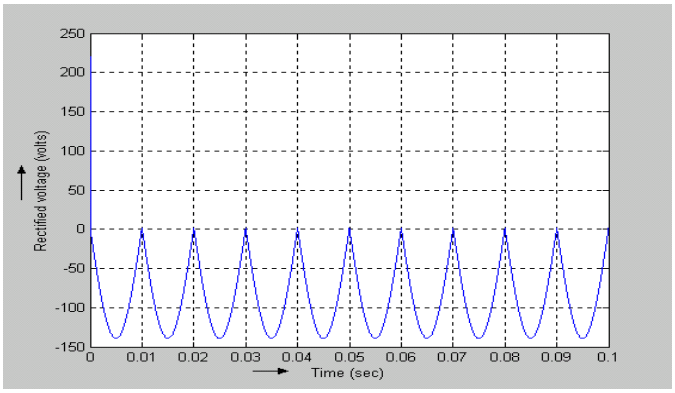


Fig. 27. Simulated rectifier output voltage of proposed converter with controller in regenerating mode.

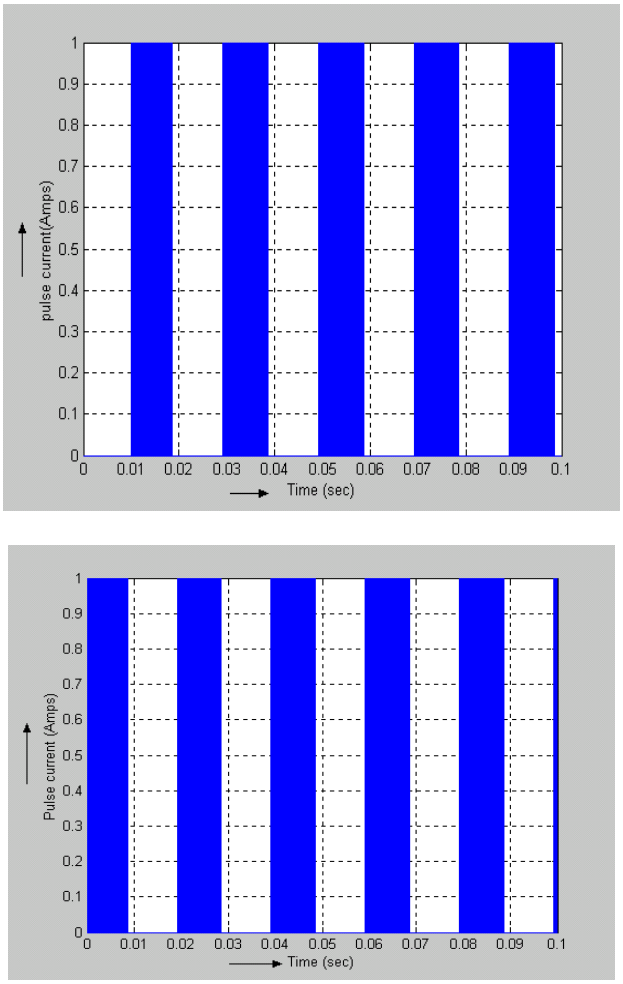


Fig. 28. Simulated thyristor firing pulse

5. Conclusions

The proposed bidirectional ac-dc power converter was studied and the designs and performance is validated through the MATLAB/Simulink. The control scheme used in this converter is simple and commonly used in current controlled power converter. The designed controller has produced excellent performance.

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