"ELECO'99 INTERNATIONAL CONFERENCE ON ELECTRICAL AND ELECTRONICS ENGINEERING"

E02.20/A3-11

HIGH PERFORMANCE THREE PHASE CONTROLLED CURRENT PWM CONVERTER UNDER UNBALANCED INPUT VOLTAGE CONDITIONS

D.BEN ATTOUS , *R.ABDESSEMED
Université de biskra
BP 145 BISKRA (07000) ALGERIA
* Université de batna
BATNA (05000) ALGERIA

Abstract

Due to their non-linear nature, static power converters inject harmonics into the ac mains network. This problem is more pronounced in line commutated rectifiers, and it worsens when the ac supply becomes unbalanced. Shunt input filters designed to trap the specific input current harmonics become less effective in reducing the harmonic distortion of the line current when the supply network or the polluting source is modified. Alternate method can be used to eliminate harmonic input current and regulate DC output voltage. This paper describes a simple and effective control technique, suitable for this purpose, which also provide high power factor and small distortion of the supply current under unbalanced input voltage conditions.

1. INTRODUCTION

The low power factor and large harmonics currents generated by controlled and uncontrolled rectifiers are well –known problems that can lead to voltage distortion, increased losses in distribution systems conductors, transformers and shunt capacitors, increased neutral harmonic currents, and excitation of system resonance. Hence, there is a recognised need for high quality rectifiers that present high power factor loads to the ac power system and draw line currents of low harmonic content. The use of power electronics equipment to control power flow with minimum power losses and high efficiency is on the increase. However, such system has non-linear input characteristics. Prominent among these charges, arc welding equipment, and uninterruptible power supplies are being used in industrial applications. They use three phase diode bridge rectifiers as the interface with utility. This leads to degradation in the power quality .As more of these systems are utilised; the problem is getting aggravated. Various standards and recommendations like the IEEE 519 are being revised to limit the harmonics that any system can inject into the utility [1][2][3][4]. Recently, in order to reduce harmonic pollution to meet such standards and to enable the utility to maintain a high power quality, AC/DC converters which make use of pulse width modulation technique (PWM) have been introduced. Both power factor and harmonic improvement can be achieved by forced commutation technique. By using the proper modulation technique for the switches, it is possible to control the output voltage while maintaining nearly sinusoidal input current at unity power factor. A mathematical model of AC/DC PWM converter with proposed control strategy is developed to carry out digital computer simulation under unbalanced utility. A control strategy capable to ensure the desire requirements is described below.

2. CIRCUIT CONFIGURATION

Fig1 shows the schematic of the system under study. It includes a power converter made up of six transistors with inverse parallel diodes is used in the main circuit to achieve bi-directional power flow capability. The left side (input) bridge, connected to the three phase supply through an impedance Z_S composed of R_s, L_s is operated so as to absorb sinusoidal currents, in phase with the lines voltages. The right side (output) bridge, feeding the DC link capacitor and the inductive load, is controlled to produce proper load voltages and currents. In order to obtain fast response of the input converter, an hysteresis current control techniques can be adopted, which ensures that each line currents follows its reference with minimum error (within the hysteresis band) and with minimum delay.

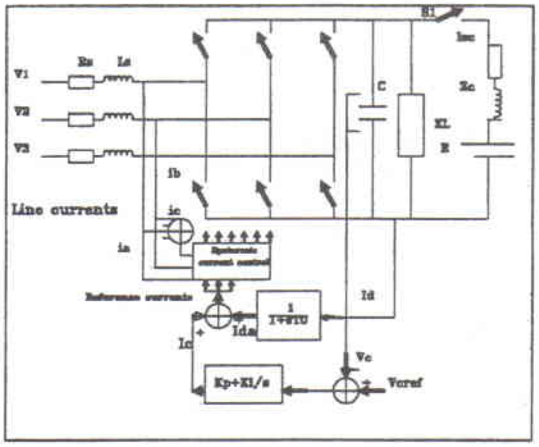

Fig1.Main circuit with proposed control system

In order to maintain constant DC link voltage V_C, irrespective of reference $V_C$ref and load variations a closed loop is introduced. Voltage V_C is compared with the reference $V_C$ref, and the resulting error signal is fed to discrete regulator of type (PI). The discrete regulator is obtained by the discretisation of regulator of voltage which the parameter is calculated in the analogical basis as shown in Fig.2.The output of regulator provides correcting term Ic. The DC component of current (Id) absorbed by the load is low pass filtered to obtain its average value Ida. This term is added to Ic to obtain the amplitude of input current reference Iiref as shown in Fig.3. If a sinusoidal line current is required, the current reference (command) should have sinusoidal waveform, which is kept in phase with the line voltages to ensure power factor unity. In theory, the voltage control loop could work alone. However sensing current Id ensures a feed forward action, which improve the dynamic response to a load variation.

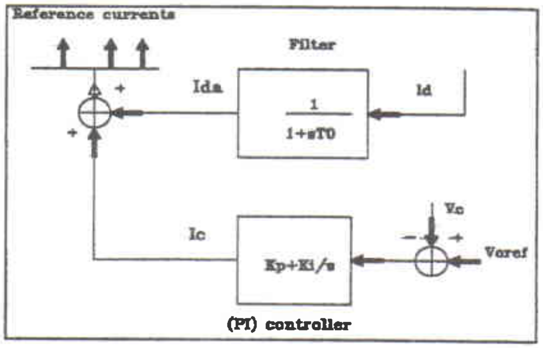

Fig 2.Analogical regulation.

To implement the proposed control system shown in Fig 2, it is required to determine set of various parameters contained in the control system has been carried out based in transients responses of the system. To maintain constant DC link voltage Vc irrespective of reference Vcref and load variations, an outside loop is introduced and a controller type (PI) is used. In order to calculate the parameters of regulator, the block diagram of control shown in Fig 2 can be further simplified and represented as shown in Fig 3, in which all factors can be easily calculated, in considering capacity of filtering only and disregarding the dynamic of the converter.

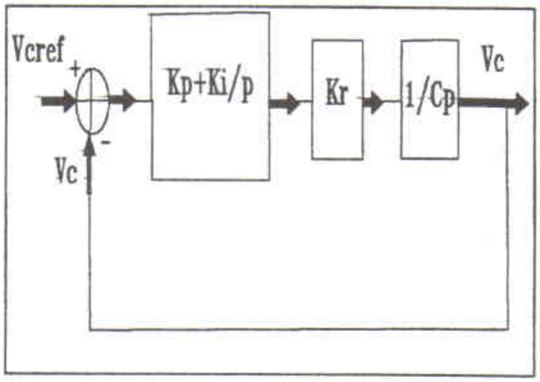

Fig 3.Bloc diagram of voltage control .

The converter is operated in closed loop in order to regulate the output voltage (Vc) to desired level (as shown in Fig3). The output of (PI) controller is used as the amplitude of reference signal. The relation between the DC output current and the reference current is given as follows:

$$Id = Kr(Iref) \qquad (1)$$

Where

Kr: the ratio between the DC and the alternative currents.

Kp, Ki : gains of the (PI) controller.

C : DC link capacitor.

In steady state operation, the DC current results from the power balanced equation [5]:

$$VcId = 3\eta V1I1 \qquad (2)$$

The average current Id delivered by the converter is :

$$Id = \frac{3(V1)(I1)\eta}{Vc} \qquad (3)$$

Where

η: converter efficiency.

V1, I1: RMS values of the line to neutral voltage and input current respectively.

The hysteresis width is assumed to be so small that the input current is equal to the reference current. From equations (1) (3) and with $\eta = 1$, we obtain Kr:

$$Kr = \frac{3V1}{Vc} \qquad (4)$$

For Vc=200V , V1=71V , Kr is 1.065.

The transfer function of (PI) regulator is:

$$Kp + \frac{Ki}{p} = \frac{Ki}{p}(1 + pT1) \qquad (5)$$

With

T1: time constant of the regulator.

The over all transfer function can easily obtained as:

$$\frac{Vc(p)}{Vcref(p)} = \frac{1 + pT1}{\frac{C}{Ki}p^2 + pT1 + 1} \qquad (6)$$

Rewrite (6) in a well –known nominal form of second order.

Where

ω_0: the undamped natural frequency

ξ : damping ratio

With

$$\frac{Ki}{C} = \omega_0^2 \qquad T1 = \frac{2\xi}{\omega_0} \qquad (7)$$

From these equations and with $\xi = 1$, Ki is given by

$$Ki = \frac{4C}{T1^2} \qquad (8)$$

In choosing T1, Ki is calculated for a value of known capacity.

3. STATE FEEDBACK CONTROL STRATEGY

The proposed control system shown in Fig.1 consists of two parts, the DC voltage control and AC line current control [6]:

3.1 DC output Voltage Control System

The transfer from analogical regulation to numerical regulation requires a signal a processing where a sampling period Ts is defined. The transfer function of the analogical regulator is discretised, in using the Euler's implicit approach given by

$$\frac{1}{p} = \frac{Ts}{1 - Z^{-1}} \qquad (9)$$

with

p: laplace operator.

Z^{-1}: delay operator.

The analogical regulator of type (PI) of Fig.2. is discretised as shown in Fig 4, giving the following recurrent equation [5]:

$$s_1(n) = s_1(n-1) + K_i T_S e_1(n) + K_p(e_1(n) - e_1(n-1)) \qquad (10)$$

with:

$s_1(n)$, $s_1(n-1)$: output and past output of the regulator .

$e_1(n)$,$e_1(n-1)$: input and past input of the regulator .

Kp, Ki: gains of the regulator. The output of the PI controller is used as the amplitude I_C of the AC side current reference.

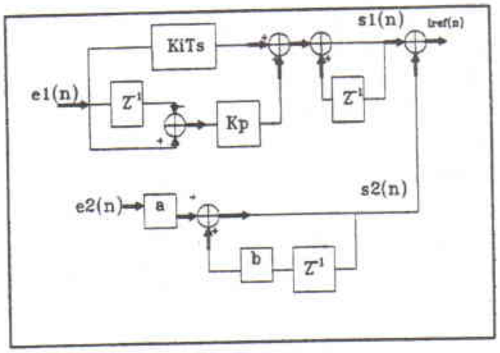

Fig4.Discrete regulator

3.2 AC INPUT CURRENT CONTROL SYSTEM

As mentioned in the preceding section, the output of the PI controller is used as the amplitude of the reference current but will be insufficient to improve the dynamic of the system. Therefore, to speed up the response of the system an additional component Ida of the reference current is added. The output of the filter gives this additional term Ida.
The transfer function of the filter is given by

$$\frac{Ida}{Id}=\frac{1}{1+sT_0} \qquad (11)$$

The filter equation is discretised, giving the following recurrent equation.

$$s_2(n)=ae_2(n)+bs_2(n-1) \qquad (12)$$

with

$$a=\frac{T_s}{T_s+T_0} \quad , \quad b=\frac{T_0}{T_s+T_0} \qquad (13)$$

T0: time constant of the filter.

4. FORMULATION OF DC SIDE VOLTAGE AND AC SIDE CURRENT

In this section, the mathematical formulation of dc voltage and the ac current reference is presented.

4.1 Calculation of DC Voltage

The DC voltage V_C is solved numerically by using the following equations:
For the rectifying mode (S1 is open) as shown in Fig.1.

$$V_C = ZL\,Id \qquad (14)$$

with
ZL: load impedance.
Id: DC output of the converter.
For the regenerating mode (S1 is closed).
DC source whose voltage E is higher than the output voltage V_C of the converter is connected in parallel with the load as shown in Fig.1. The dc voltage is given by:

$$V_C = E - Z_C I_{SC} \qquad (15)$$

with
Z_C: source impedance.
I_{SC}: current of dc source.

4.2 Calculation of Reference Current

The amplitude of the reference current is given by the following equation:

$$Iref(n) = s_1(n) + s_2(n) \qquad (16)$$

If a sinusoidal line current is required, the current command (reference) should have the form

$$I_i ref(n) = Iref(n)\sin(\omega t-(i-1)\frac{2\pi}{3}) \qquad (17)$$

with i =1,2 , or 3 .
In order to obtain a very fast of the input converter, an hysteresis current technique can be adopted, which ensures that each line current follow its reference within the hysteresis band Δi. The ac line current is controlled by the transistors converter in a bang-bang mode. A high switching frequency is given by the following equation

$$f_{max}=\frac{U\max}{8Ls\Delta i} \qquad (18)$$

Where
Umax: max value of line to line supply voltage.
Ls: the ac side inductance.
Δi: hysteresis band.
The achievable bandwidth of the current control loop depends on the switching frequency of the PWM converter

5. INPUT VOLTAGE UNBALANCES

If we assume that the line to neutral supply voltages are V1,V2, V3 , then their corresponding zero, positive and negative sequence voltages can be found as :

$$\begin{bmatrix} Vz \\ Vp \\ Vn \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} \qquad (19)$$

a : is a complex number of unit magnitude with an angle of 120^0 and is defined by :

$$a = 1\angle 120^0 = -0.5 + j0.866 \qquad (20)$$

The ratio of the positive sequence to the negative sequence is defined as the voltage unbalance factor in European standards[ ]

And is used in this paper as an index of degree of unbalance in percentage value , it is expressed as :

$$UBF = \left|\frac{Vn}{Vp}\right| \times 100 \qquad (21)$$

6.PERFORMANCE PARAMETERS OF PWM CONVERTERS WITH THE PROPOSED CONTROL STRATEGY

6.1 Input power factor

The rectifier power factor (PF) shows hot efficiently a rectifier draws real power from the utility at the point of common coupling (PCC). A diode rectifier operates with satisfactory PF. However, in the case of a thyristor rectifier, as the delay angle (α) is increased to control the output voltage, the PF decreases, and PF characteristics are poor. The rectifier input power factor is expressed as:

$$PF = DF \times FPF = \frac{I1}{Irms} \times \cos(V1n, I1) \qquad (22)$$

where:

DF: input current distortion factor.

FPF: fundamental power factor or displacement factor.

I1: RMS rectifier fundamental input current.

Irms: RMS rectifier input current.

V1n: RMS phase1 line to neutral voltage.

The input distortion factor is expressed as:

$$DF = \frac{X1}{\sqrt{X1^2 + \sum_{h=2}^{n} Xh^2}} = \frac{X1}{Xrms} \qquad (23)$$

Where:

Xh: harmonic component.

h: harmonic number 2,3,4 etc.

X1: RMS rectifier fundamental input (current, voltage).

Xrms: RMS rectifier input (current, voltage).

The total harmonic distortion (THD) is defined as the square root of the sum of the squares of the magnitude of the individual of the fundamental component :

$$THD = \frac{\sqrt{\sum_{h=2}^{n} Xh^2}}{X1} \qquad (24)$$

An alternative figure of merit would be to express total harmonic distortion relative to RMS of the entire waveform and not just the fundamental component:

$$\%distortion = \frac{\sqrt{\sum_{h=2}^{n} Xh^2}}{\sqrt{X1^2 + \sum_{h=2}^{n} Xh^2}} = THD1 \qquad (25)$$

From (23) and (24), the input current distortion factor, is given by the following equation:

$$DF = \frac{1}{\sqrt{1 + THD^2}} \qquad (26)$$

6.2 Ripple factor of the load voltage:

The three phase fully controlled bridge rectifier operating under balanced input voltage condition produces an output voltage composed of a DC component and voltage ripples.

The ripple factor (RF) of the load voltage is calculated for the controlled rectifier under balanced and unbalanced input voltages:

$$RF = \sqrt{\left(\frac{Vrms}{Vc}\right)^2 - 1} \qquad (27)$$

To implement the proposed control system in Fig.1, it is required to determine set of various parameters contained in the control system. The parameters given in Table1 have been carried out based on transients responses of the system.

Table 1. Parameters of the system used in simulation

	Voltage (V)	R (Ω)	L (mH)	C (μF)
AC source	71	0.1	5	
DC link				500
Load		20	6	
DC source	230	2	.01	

Gains of the (PI) controller: Kp = 0.4, Ki =80
Time constant of the filter: T0 = 20.E-4s

In this survey, the selection of sampling period is a major concern. Several sampling period T_S were tested and it was found that a sampling period 0.1ms is acceptable.

In order to improve the efficiency of the proposed control configuration , the system is subject to :

1.Balanced network voltage
a step increase in load at t =0.15s

2. Unbalanced input network voltage conditions.

a step increase in load at t = 0.15s.
For UBF =7.5%.
For UBF =62.5%.

The transient behaviour of the system is investigated for the case of a step increase in load at t =0.15s under balanced input voltages.

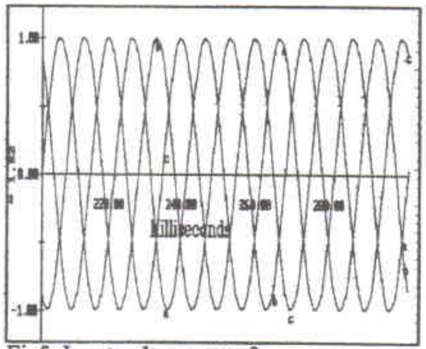

Fig5: Input voltage waveforms.

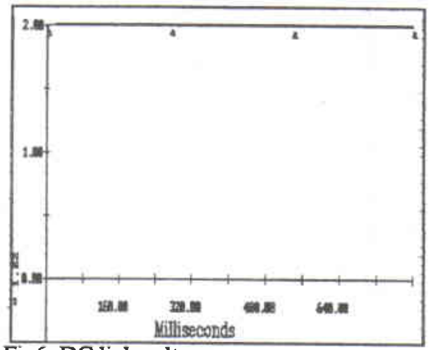

Fig6: DC link voltage.

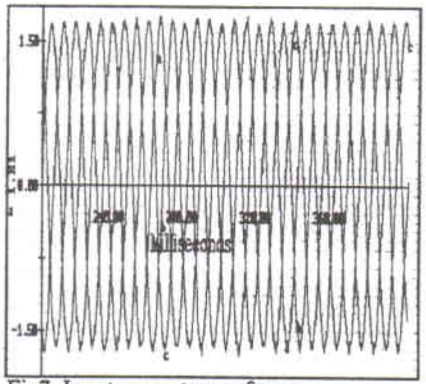

Fig7: Input current waveforms.

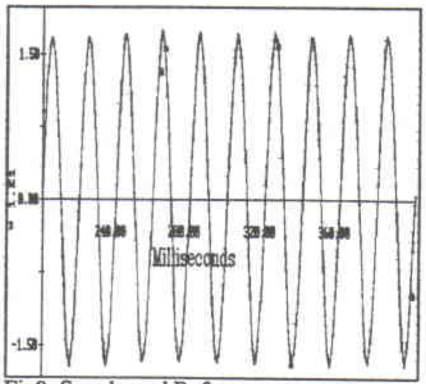

Fig8: Supply and Reference currents.

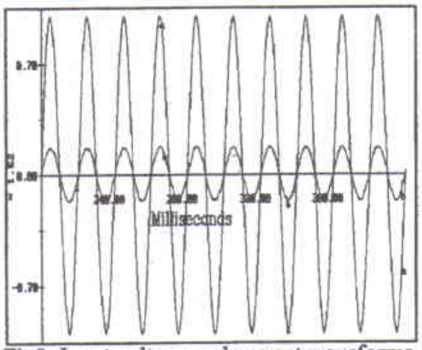

Fig9: Input voltage and current waveforms.

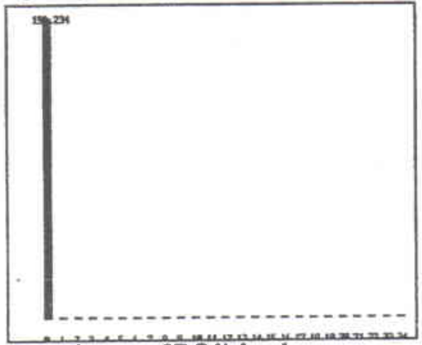

Fig10: Spectra of DC link voltage.

Figs 5 to 10 show the transient waveforms taken during a sudden change in load at t = 0.15s.It is seen that the line current is near sinusoidal with unity power factor .The rapid change of the line current shows that the system has a very good dynamic to load variation and the system keeps an almost constant DC link voltage during the critical load variation The THD in input current waveform is 3.2 % for DC link voltage THD is 1%. The input power factor is 0.999.

The system is subject to a step increase in load for UBF =7.5%.

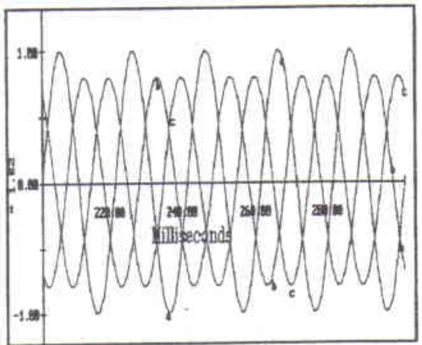

Fig11: Input voltage waveforms.

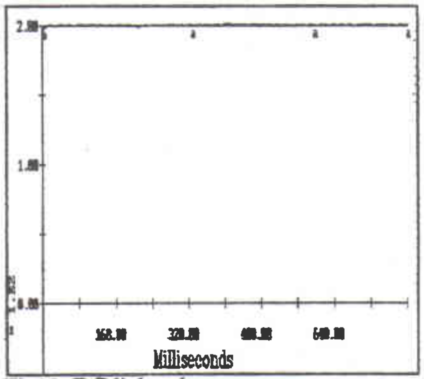

Fig12: DC link voltage.

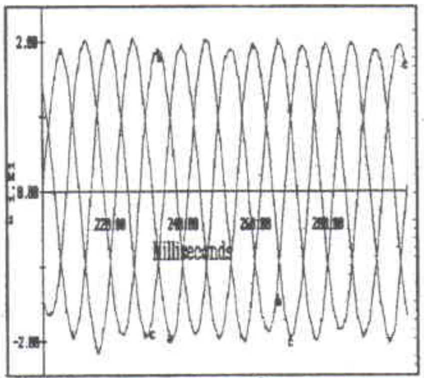

Fig13: Input current waveforms.

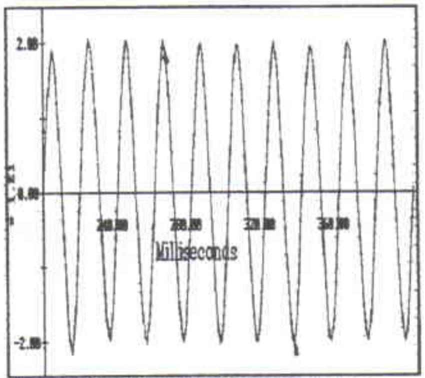

Fig14: Supply and Reference currents.

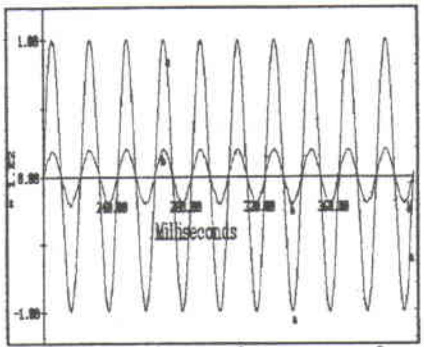

Fig15: Input voltage and current waveforms

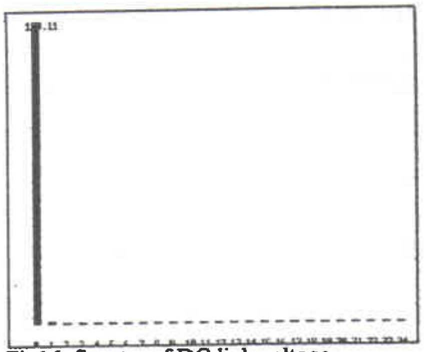

Fig16: Spectra of DC link voltage.

The system is subject to a step increase in load for UBF =62.5%.

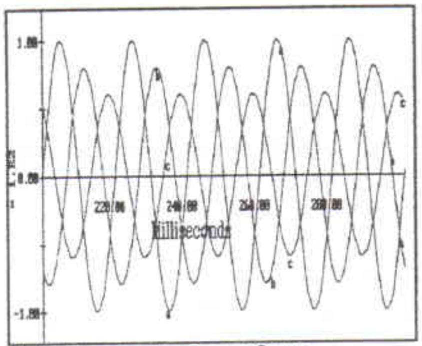

Fig17: Input voltage waveforms.

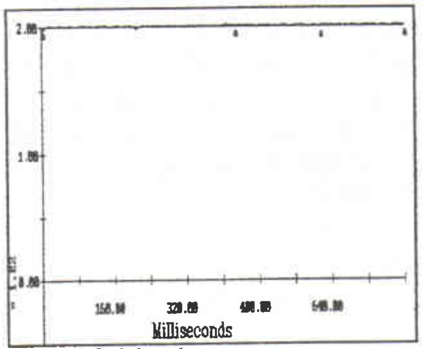

Fig18: DC link voltage.

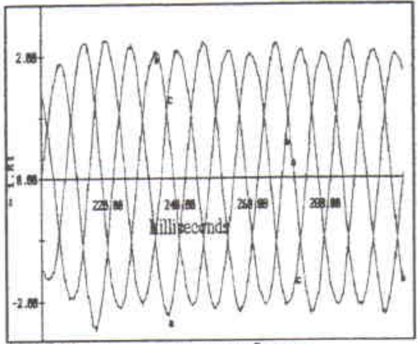

Fig19: Input current waveforms.

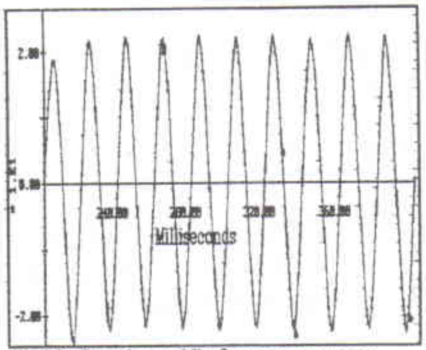

Fig20: Supply and Reference currents.

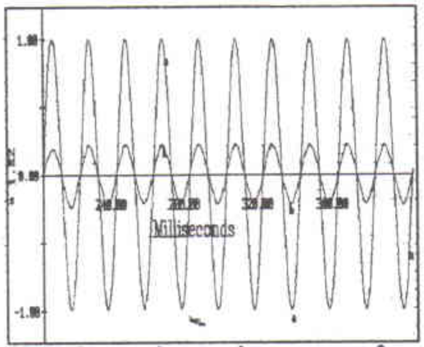

Fig21: Input voltage and current waveforms

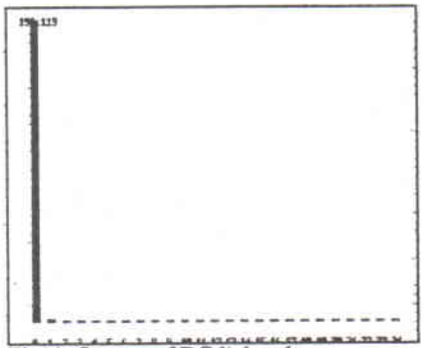

Fig22: Spectra of DC link voltage.

Figs 11 to 16 and Figs 17 to 22 show the simulated transient responses for a typical voltage unbalance of 7.7% and 62.5% respectively. The ac current is sinuoidal with unity power factor. It is evident from the simulation results, the DC link voltage and input current waveforms are the same under unbalanced supply for UBF =7.5% and UBF =62.5%.

The THD in input current waveform is 3.3%. For the DC link, voltage THD is 1.01%. The input power factor is 0.998.

The calculated values of the ripple factors are shown in Table 2.

Table 2: Calculated values of RF.

	BALANCE	UBF= 7.5%	UBF=62.5%
RF	1.3%	1.36%	1.42%

We can conclude that the performance of the system with control strategy is improved even the supply voltage is unbalanced.

7.CONCLUSION

The paper outlines the operation of the proposed circuit configuration and control strategy under balanced and unbalanced input voltage conditions which draws sinusoidal current waveforms at unity power factor and provide a regulated DC link voltage.

The converter has the ability to operate at unity power factor with low current distortion, which is ideal for the power supply system. The simulation results show the transient waveforms of the AC currents, DC link voltage are improved even the system subject to:

Increase in load for (balance and unbalanced input voltages conditions).

8. REFERENCES

[1] S.Manias, P.D.Ziogas, and G.Oliver,"An ac to dc converter with improved input power factor and high power density", IEEE Trans.Ind.App, vol IA-22, no.4, pp.453-459, Apr.1986.

[2] B. -T.Ooi, J.C. Salmon, J.W.Dixon, and A.B, Kalkami,"A three phase controlled – current PWM converter with leading power factor", IEEE Trans.Ind.App. vol. IA-23, no.1, pp78-84, Jan/Feb.1987

[3] J.W.Dixon, A.B.Kulkami, M.Nishmoto, and B.T.Ooi, "Characteristic of a controlled – current PWM rectifier –inverter link", IEEE Trans.Ind.App.vol. IA-23, no.6, pp.1022-1028, Nov/Dec 1987.

[4] J.W.Dixon, and B. -T.Ooi, "Indirect current control of a unity power factor sinusoidal current boost type three-phase rectifier ", IEEE Trans.Ind.Elec.vol. IE-35, no.4, pp508-515, Nov.1988.

[5] D.Ben attous, R Abdessemed, " Digital Voltage Control of AC/DC PWM Converter with improved Power Factor and Supply Current ", accepted for publication in the Electric Machines and Power Systems Journal.

[6] D.Ben attous, R. Abdessemed, " An Ac to DC/DC Converter With Improved Input Waveforms and DC Output Voltage ", International Conference on Power System Technology, Beijing china August 18-21, 1998 pp. 644 –648.