A NEW BUCK-BOOST CONVERTER WITH SINUSOIDAL SUPPLY CURRENT

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ABSTRACT

This paper presents a new single-phase single-way AC-to-DC converter using two switching device. Continuous and sinusoidally shaped line current which is placed in phase with the bus voltage is achieved for buck or boost operation. The converter power can be varied over a wide range by controlling only one switching device. Theoretical analysis, simulation and experimental results using a 500 W converter are presented, to demonstrate the superiority of the proposed converter.

1-INTRODUCTION

The conversion of AC power to DC power has been carried out by using a diode bridge and a large DC capacitor connected at the rectifier output. This approach has many disadvantages, such as high input current harmonic components, a maximum input power factor of approximately 0.5, and fixed output DC voltage. The AC-DC converter using a thyristor bridge has the advantage of simple configuration and variable DC output. However, it has the characteristics of lower input power factor and injection of lower-order harmonics into the supply.

With the development of power semiconductor devices, several single-phase schemes for shaping the line current have been proposed and analyzed [1-8]. For small output power applications, AC-DC buck-boost converters with only one switching device can be used [1-3]. The most popular methods used in the industry today incorporate the boost converter [4-5]. This converter is adequate to operate in the continuous load current mode for high power applications or in the discontinuous load current mode for lower output power. The buck regulator can also be used for similar applications. However, the drawback of the buck regulator is the noticeable sharp turn-off power conversion as the instantaneous line voltage falls below the output voltage

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which degrades the power factor and generates higher order harmonics. A converter circuit which combines the buck and boost modes in one power stage has achieved nearly unity power factor [6-7], but a harmonic filter is required to absorb high frequency components in order to achieve continuous supply current [3,6,7].

This paper presents a new buck-boost converter in a single power stage. The proposed converter uses two power switches with simple control circuits. However, input current wave-shaping using bang-bang hysteresis technique is used to achieve nearly unity supply power factor. Input current control is carried out by controlling one switch for buck or boost operation. However, the second switch controls the capacitor voltage and the power flow to the load. A discussion on the principle of operation is followed by detailed analysis showing the characteristics of the proposed converter. Experimental and predicted results confirm that the tested converter is useful as a buck-boost rectifier with satisfactory input and output performance.

2-THE PROPOSED CIRCUIT CONFIGURATION

Fig.1 shows the circuit configuration of the proposed buck-boost converter including the two control switches S_1 and S_2. As in the step-up converter, the capacitor voltage V_c will always be greater than the input DC voltage (V_{sd}). When the switch S_1 is on, the diode D_M is reverse biased, thus isolating the output stage from the main supply and the input current rises through L_1. When S_1 is off, D_M conducts and so the output stage receives energy from the inductor L_1 as well as from the supply. However, the flow of energy to the load is controlled via S_2 such that the capacitor voltage should always be higher than the instantaneous value of the input DC voltage (V_{sd}). Accordingly, the operation of the input power control and waveshaping of the supply current is based on the firing control of S_1. The main components of this control is shown in Fig.1. However, the control of S_2 includes a hysteresis comparator to maintain the capacitor voltage higher than certain value(V_{cr}).

3-ANALYSIS OF THE PROPOSED CIRCUIT

3-1- Modes of Operation.

The various switching states of the two switches give several operation modes,the equivalent circuits of which are shown in Fig.2. During mode-I, S_1 is on and S_2 is off (Fig.2(a)). The inductor L_1 is connected to the source via both the main-switch S_1 and the diode bridge. Therefore, the inductor current i_1 flows through the source via the diode bridge. The current i_1 and accordingly the energy stored in the inductor increases. Meanwhile, the current of switch S_2 remains zero and the load current i_L freewheels through the diode D_f. Mode-I ends when the main-switch S_1 is turned off and the circuit operation changes to mode-II (Fig.2(b)). In this mode, the inductor current i_1 circulates through the capacitor C via the main diode D_M. As a result, i_1 decreases giving rise to the capacitor voltage. Mode-III starts when S_2 is turned on (Fig.2(c)). In this mode, the freewheeling diode D_f is turned off while the load is being connected to the capacitor terminals and to the supply through the inductor L_1. During the action of S_2, if S_1 is turned on , the circuit operation changes to mode-IV (Fig.2(d)). In this mode, D_M becomes reverse biased. The inductor current i_l increases and meanwhile, the capacitor discharges through the load. The circuit modes of operation described above, are determined by the operating conditions. The switching pattern for S_1 and S_2 is accordingly generated.

3-2- Sequence of Operating Modes.

Four conditions describing the buck-boost operation modes are shown in Fig.2. If switch S_1 is on and S_2 is off mode-I starts, Fig.2(a), and the supply current i_1 flows through the loop V_s-L_1-S_1, such that:

$$V_{sd} = i_l \quad R_l + L_l \quad di_l/dt \tag{1}$$

Meanwhile, the load current I_L freewheels via D_f. From the equivalent circuit of mode-I,

$$0.0 = i_L \quad R_L + L_L \quad di_L/dt \tag{2}$$

The inductor current rises and when it exceeds a preset upper limit i_u, the switch S_1 is turned off and the system changes to mode-II. The upper limit i_u is given by,

$i_u = i_{lr} + H_i$

where,

i_{lr} : reference sinusoidal current in phase with the supply voltage.

H_i : current hysteresis band.

In this mode (mode-II), the current i_L continues circulating via the diode D_f. It follows that equation 2 above is still applicable but equation 1 becomes,

$$V_{sd} = i_l \quad R_l + L_l \quad di_l/dt \quad +V_c \tag{3}$$

The capacitor voltage rises and when it exceeds an upper limit V_u the switch S_2 is turned on and mode-III starts. Vu is defined as,

$V_u = V_{cr} + H_c$

where,

V_{cr} : reference dc voltage.

H_c : voltage hysteresis band.

Considering mode-III and the equivalent circuit shown in Fig.2(c), equation 3 is still applicable, however, equation 2 becomes,

$$V_c = i_L \quad R_L + L_L \quad di_L/dt \tag{4}$$

If the inductor current i_l becomes smaller than a lower limit i_{lr}, the switch S_1 is turned on and the system changed to mode-IV. In this mode, the inductor current increases according to equation 1. However, the capacitor voltage V_c decreases following equation 4 . When V_c becomes smaller than lower limit V_{cr}, the switch S_2 is turned off starting mode-I and the sequence of operation is repeated.

Consider equations 1 and 3, the rate of change of i_1 is determined by L_1 and C. Therefor, L_1 and C are chosen according to the range of the switching frequency. However, for safe operation the resonant condition should not be reached and so, the switching frequency should be much higher than $f_r = [1/2\pi \sqrt{(L_1 C)}]$ to prevent resonant phenomenon in the LC circuit.

4- SYSTEM MODELING

The following main assumptions are taken into consideration for simplicity:

. During the conduction states, losses in the fast recovery diodes and the IGBT switches are taken as constant voltage drops (one volt for the diode and two volts for the IGBT). However, losses in the inductor cores and snubber circuits as well as switching losses are neglected.

MATLAB software is used for simulation studies and also for selection of proper hysteresis levels and switching device ratings. Equations 1-to-4 which describe operation modes of the converter circuit are solved using Runge-Kutta algorithm. However, circuit parameters and operating conditions of the experimental setup are listed in Appendix A. Nevertheless, performance characteristics at the supply terminals are obtained by application of the formulas given below;

The distortion factor DF is given as:

$$DF = \sqrt{[(\sum_{n=2}^{n=\infty} I_{sn}^2) / I_{s1}]}$$

I_{s1} is the fundamental component of supply current .

The input power factor PF :

$$PF = \cos \varphi_1 / \sqrt{[1+(DF)^2]}$$

φ_1 is the angle between I_{s1} and V_s.

5- SIMULATION AND EXPERIMENTAL RESULTS

To confirm the validity and superiority of the proposed converter, test results have been carried out using a 500w experimental setup. The tests were performed considering both buck and boost modes where nearly unity power factor operation has been achieved. In Fig.3, simulation results showing the supply current waveform at various levels are presented. The source-current i_s is nearly sinusoidal and in phase with the supply voltage. The continuous supply current is confined between the two references (i_u and i_{1r}) for both buck (Fig.3(a,b)) and boost (Fig.3(c)) operation. Fig.3(d) shows the input current harmonic spectrum at I_s 3.5A rms. AT this condition, the calculated DF is 0.08 and the input PF is 0.997. Simulation results of the capacitor voltage, output voltage and load current for both buck and boost modes are shown in Fig. 4. The capacitor voltage is always higher than the reference voltage V_{cr}, (V_{cr}=125v). However, the load voltage is controlled such that the capacitor voltage is kept higher than V_{cr}. Nevertheless, the load current i_L is continuous due to the effect of load inductance. The experimental results shown in Figs.5and6 confirm the simulation results shown in Figs.3and4. Fig.7 shows the performance characteristic of the proposed converter. Both the input power factor (PF) and the input-current distortion factor (DF) are satisfactory over a wide range of load power variation. Efficiency (η) is higher than 80% over the whole range of variation.

Comparison of the results obtained for bucking and boosting operation of the proposed converter show that, the supply current is continuous, therefore, the control system is simpler than the conventional cascade buck-boost converter. Also, output voltage of the proposed circuit can be varied over a wide range while maintaining a nearly unity power factor operation for both bucking and boosting.

6- CONCLUSION

A developed single-phase step-up/ step-down converter has been presented. From the reported results, it could be seen that the supply current is sinusoidally wave-shaped with nearly unity power factor; The source current is continuous and the load power is controlled using only one switch, accordingly, the control circuit is simple. A wide range of the output voltage variation has been achieved. Simulation and experimental results have been shown to be in good agreement. The single-phase AC-to-DC converter presented in this paper provides a system with good quality AC current and can be designed for low and medium power applications, such as power supplies and DC drives.

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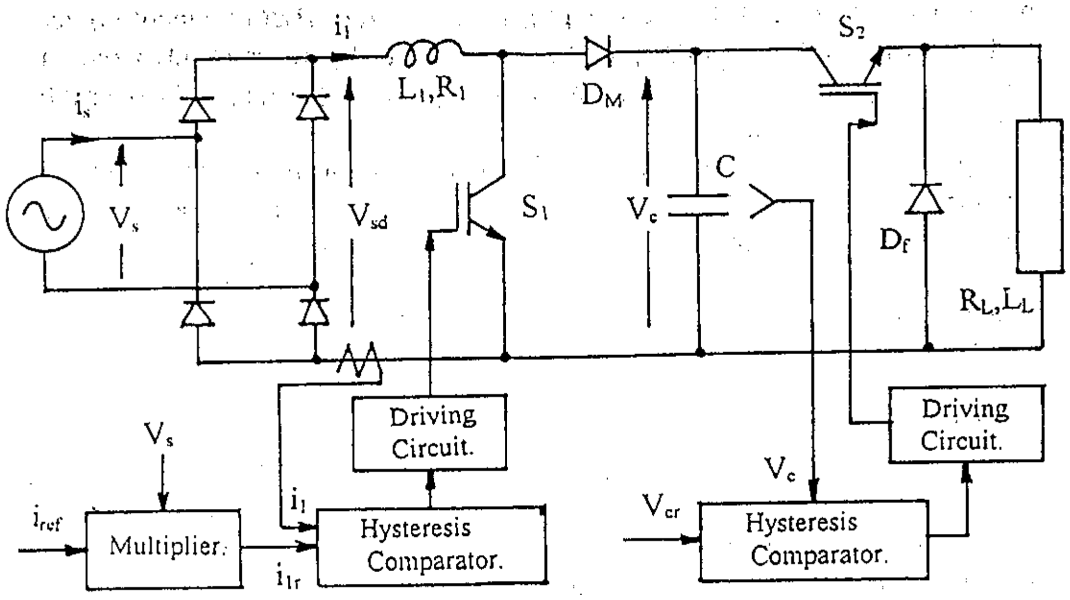
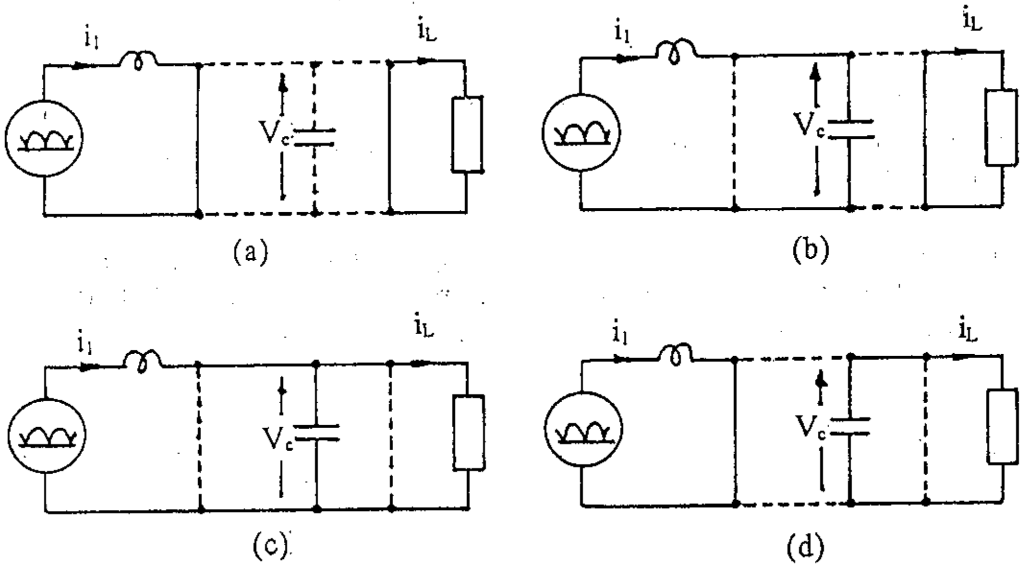


Fig. 1. Proposed buck-boost converter system.



(a) (b)

(c) (d)

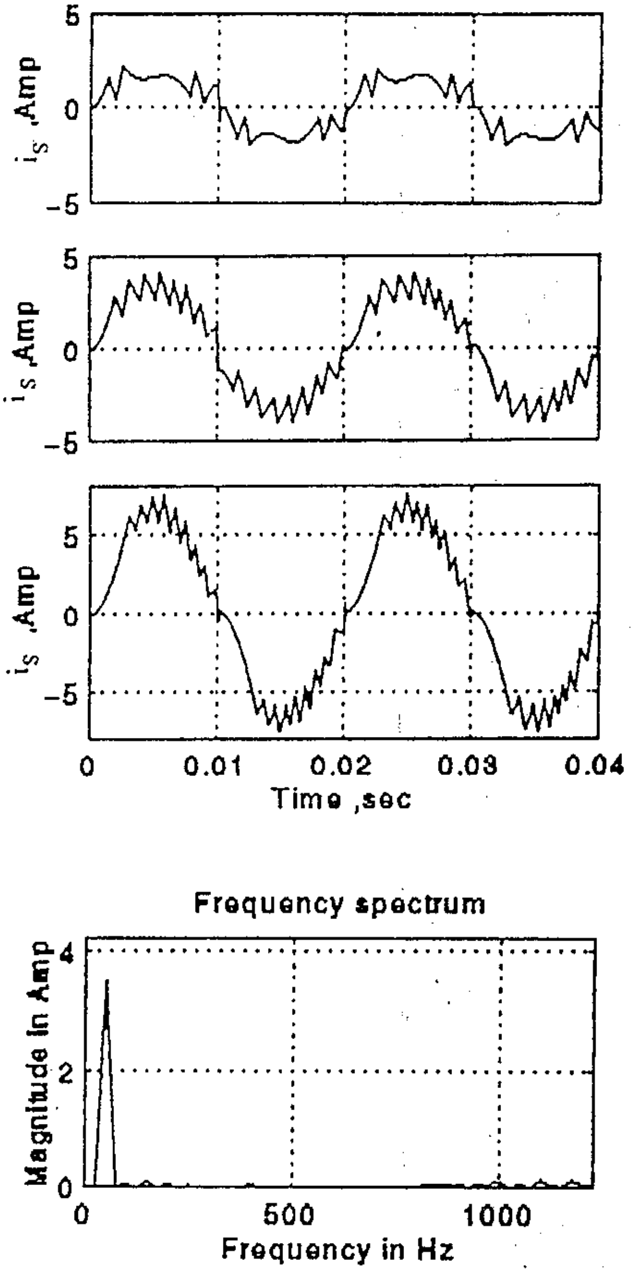
Fig.2. Equivalent circuit of the proposed converter.

(a)Mode-I S_1 on, S_2 off, $i_1 < i_{1r}+H_i$, $V_c < V_{cr}+H_c$.

(b)Mode-II S_1 off, S_2 off, $i_1 > i_{1r}$, $V_c < V_{cr}+H_c$.

(c)Mode-III S_1 off, S_2 on, $i_1 > i_{1r}$, $V_c > V_{cr}$.

(d)Mode-IV S_1 on, S_2 on, $i_1 < i_{1r}+H_i$, $V_c > V_{cr}$.



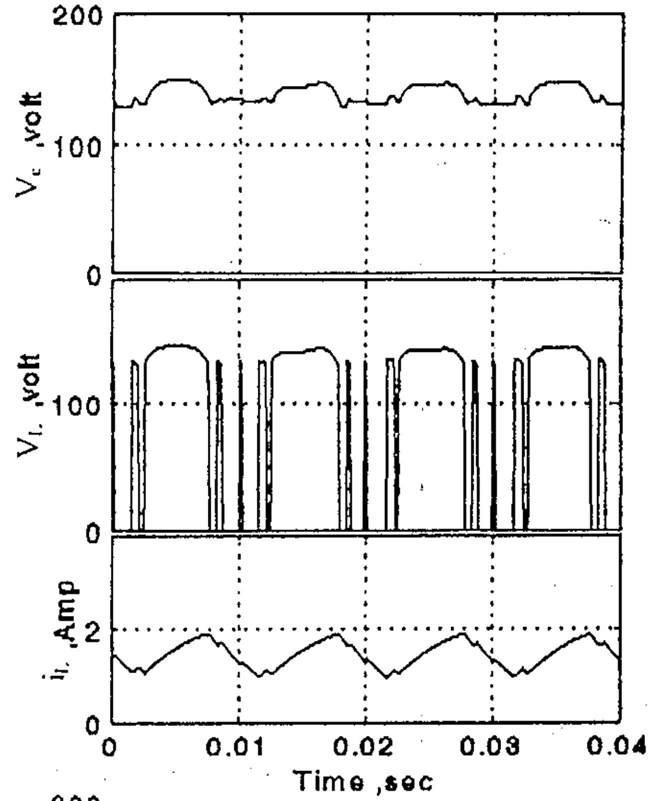
(a) i_s waveform at I_s=1.3A.

(b) i_s waveform at I_s=2.5A.

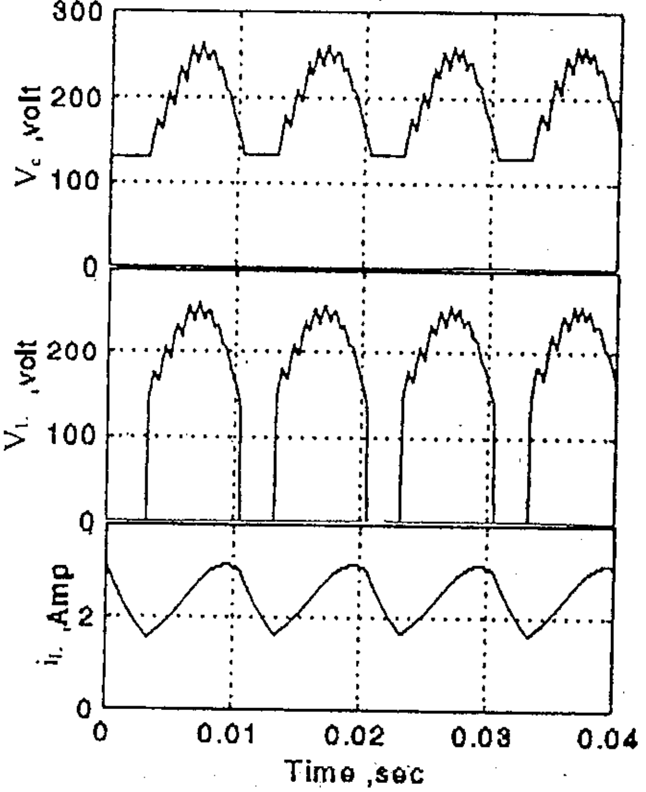
(c) i_s waveform at I_s= 4A.

(d) i_s spectrum at I_s=3.5A.

Fig.3. Supply current waveform and spectrum (Simulation results).

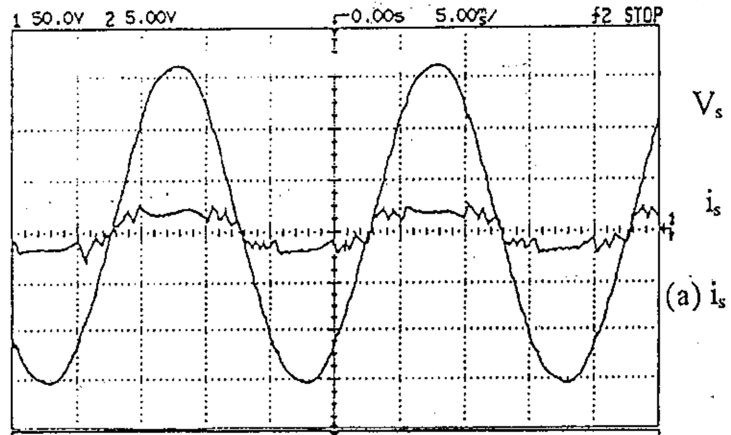


(a) Buck mode (Is=1.3A).

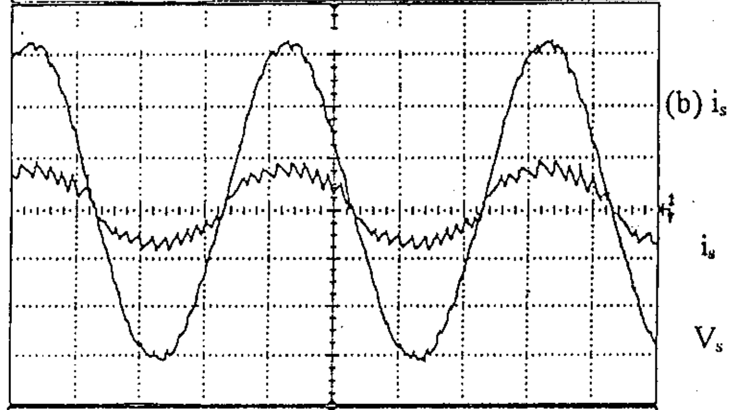


(b) Boost mode (Is= 4A).

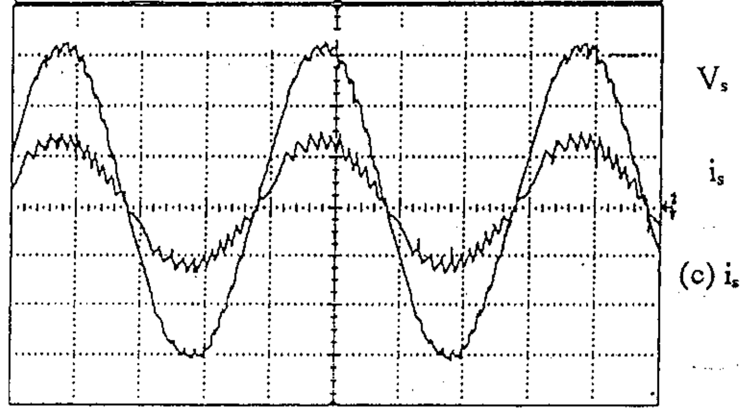
Fig.4. Capacitor voltage, output voltage and load current (Simulation results).



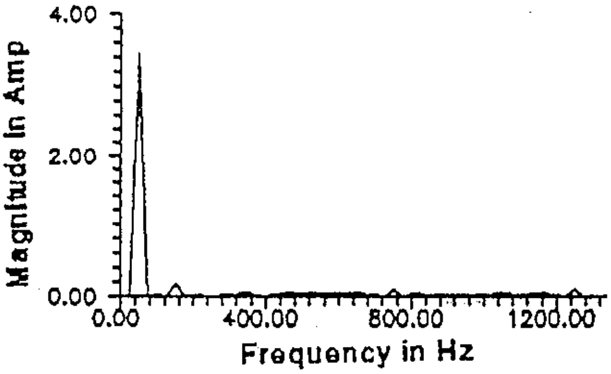
(a) i_s waveform at I_s=1.3A.
5A/div .



(b) i_s waveform at I_s=2.5A.
5A/div



(c) i_s waveform at I_s= 4A.
5A/div



(d) i_s spectrum at I_s=3.5A.

Fig. 5. Supply current waveform and spectrum (Experimental results).

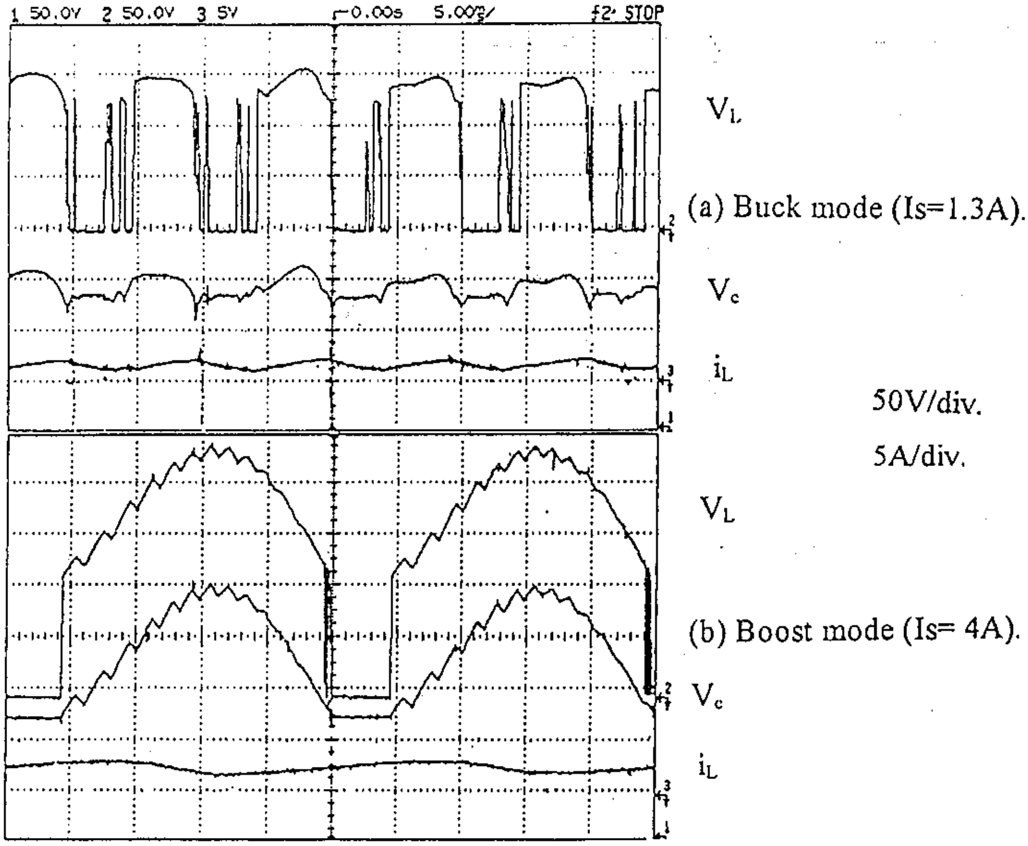


Fig.6. Capacitor voltage, output voltage and load current (Experimental results).

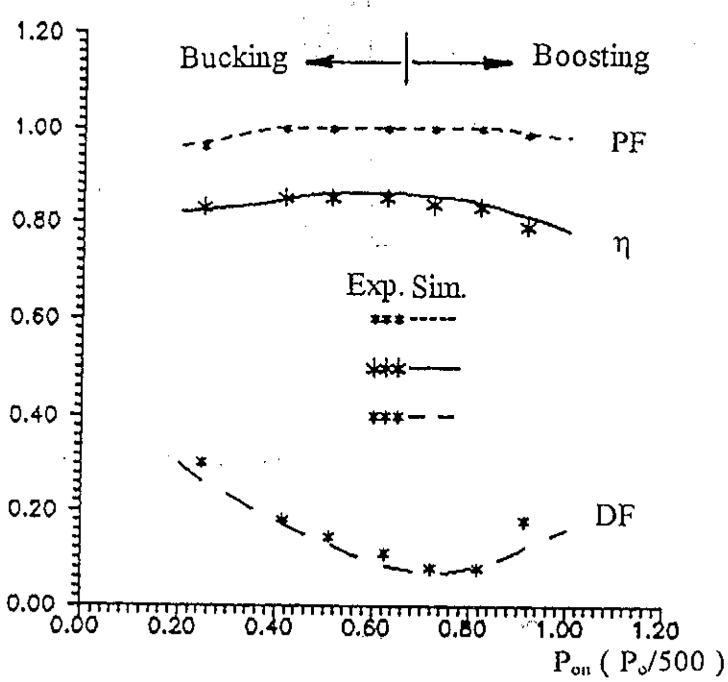


Fig.7. Power factor, efficiency and distortion factor versus normalized output power.

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APPENDIX (A)

Data and parameters of the experimental set-up:

V_s=110 volt , H_i=0.7 A , H_c=3 volt , L_1=24 mH , R_1=1.4 Ω , C=50 μF , L_L=290 mH , R_L=62 Ω .

بسم الله الرحمن الرحيم

ملخص البحث

مغير جديد للتعضيد أو التوهين له تيار مصدر ذو موجه جيبية

يقدم هذا البحث مغيراً جديداً ذو وجه واحد لتحويل الجهد المتردد إلى جهد موحد بإستخدام قنطرة توحيد ومفتاحين الكترونيين . وقد أمكن عن طريق هذا المغير التحكم فى كل من الشكل الموجى لتيار المصدر بجعله ذو شكل جيبى غير متقطع وفى نفس الوجه مع جهد المصدر وكذلك التحكم فى الجهد الموحد للحمل .

أمكن الحصول على الشكل الجيبى لتيار المصدر بمقارنته بموجه جيبية متزامنة مع جهد المصدر وتشغيل أحد المفتاحين (توصيل أو فصل) بحيث يتأرجح تيار المصدر حول موجة جيبية وفى نطاق ضيق . استخدم المفتاح الآخر للتحكم فى تدفق القدرة إلى الحمل بإستخدام مكثف تخزين .

لإبراز تميز المغير المقترح تم بناء دائرة بقدرة ٥٠٠ وات وإختبارها حيث أمكن تغيير جهد الخرج على مدى واسع بالتعضيد أو التوهين مع الإحتفاظ بتيار المصدر تقريباً جيبى وفى نفس الوجه مع الجهد مما جعل معامل القدرة مقارب للوحدة عند المصدر .

وقد تم تحليل أداء المغير نظرياً وقورنت النتائج النظرية بالمعملية حيث حققت تطابقاً مرضياً .

يمكن تصميم المغير المقترح للتطبيقات ذات القدرات المنخفضة والمتوسطة مثل مصادر القدرة المستمرة أو نظم التسيير الكهربى بالتيار المستمر .