ANALOGE CONTROL OF CUK CONVERTER WITH HIGH QUALITY PERFORMANCE

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ABSTRACT:

The paper presents a novel analoge control of single-phase singl-way current and / or voltage-source rectifier based on the cascade-combination of diode bridge and cuk converter. It is shown that the supply current can be sinusoidally waveshaped with nearly ripple-free output voltage. Operation at high power factor can be achieved by forcing the source current to be in phase with the source voltage. State-space analysis are employed to predict steady-state and dynamic behaviour of the rectifier with an analoge PI voltage and / or current controller. Theoritical and experimental results are shown to be in good agreement.

1. INTRODUCTION:

With the development of power semiconductor devices, switching at high frequency of AC-to-DC converters have been employed with conventional DC sources and front-end convertors of rectifier-inverter systems. To meet the performance requirements, active current wave-shaping techniques have been developed to provide nearly sinusoidal source current [1,2,5].

Active current wave-shaping at the a.c. source is usually referred to as power factor correction (PFC). To do so, an active switch is conntrolled in such a manner that the input current is forced to follow a sinusoidal reference [1,2]. In such an application a diode bridge followed by a suitable converter circuit, is usually employed [2-4].

A PWM signal, which is sinusoidally distributed, can be achieved by an off-line computer, but this approach cannot suppress the resonance [5]. The reason for this is that the supply current is not directly controlled

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because AC filter capacitors are always connected across the supply terminals to bypass the commutating energy and to absorb the high-frequency harmonics due to switching operation.

In this paper, an analoge control to obtain a single-phase current and / or voltage source rectifier with suppressed resonance in the AC supply circuit, is presented. Current wave-shaping technique using bang-bang hysteresis is used to achieve nearly unity supply power factor. A cascade combination of a diode bridge and cuk converter is considered. The proposed system is suitable for source current control due to the action of an inductor connected in series with the supply. The analoge control circuit is used to achieve unity supply power factor with ripple-free output. The control circuit of the PFC schemes considered so far [1-5] employs an expensive precision multiplier in order to adjust the amplitude of the sinusoidal reference signal. In this paper, an analoge circuit is used to convert a d.c. level to sinusoidal reference. This permits simple and low cost control, but on the expense of a delay time of about 60 ms which is acceptable for many applications. The proposed control is examined under variations in both output DC current / voltage reference and load resistance.

Experimental and predicted results show that the proposed system is useful as a rectifier with sinusoidal supply current and satisfactory control range for the output current and voltage.

2. SYSTEM CONFIGURATION:

Fig.1 shows the rectifier system with the proposed control. The power circuit consists of a single-phase diode bridge (D_1 to D_4) , and Cuk converter [6]. The capacitor C acts as the energy storage / transfer element. Accordingly, step-up or step-down of the output voltage can be obtained by appropriate switching of the IGBT switch SW. Also, the inductance L_2 and the capacitor C_0 are used as a d.c. filter to improve quality of the DC output.

The control circuit consists of a PI controller, a DC-to-AC converter, a hysteresis comparator with hysteresis width H and a driving circuit. The action of this control circuit determines the switching pattern of the IGBT which in turn acts to regulate the output current and / or voltage and to achieve nearly sinusoidal supply current.

3. POWER CIRCUIT OPERATION:

The action of the switch SW. and that of the diode D result in several operaion modes. Equivalent circuits of those modes are shown in Fig.2. Consider the switch SW. was off. Then the charged capacitor C will be of polarity as shown in Fig.2a. If the switch SW is then turned on (mode 1),

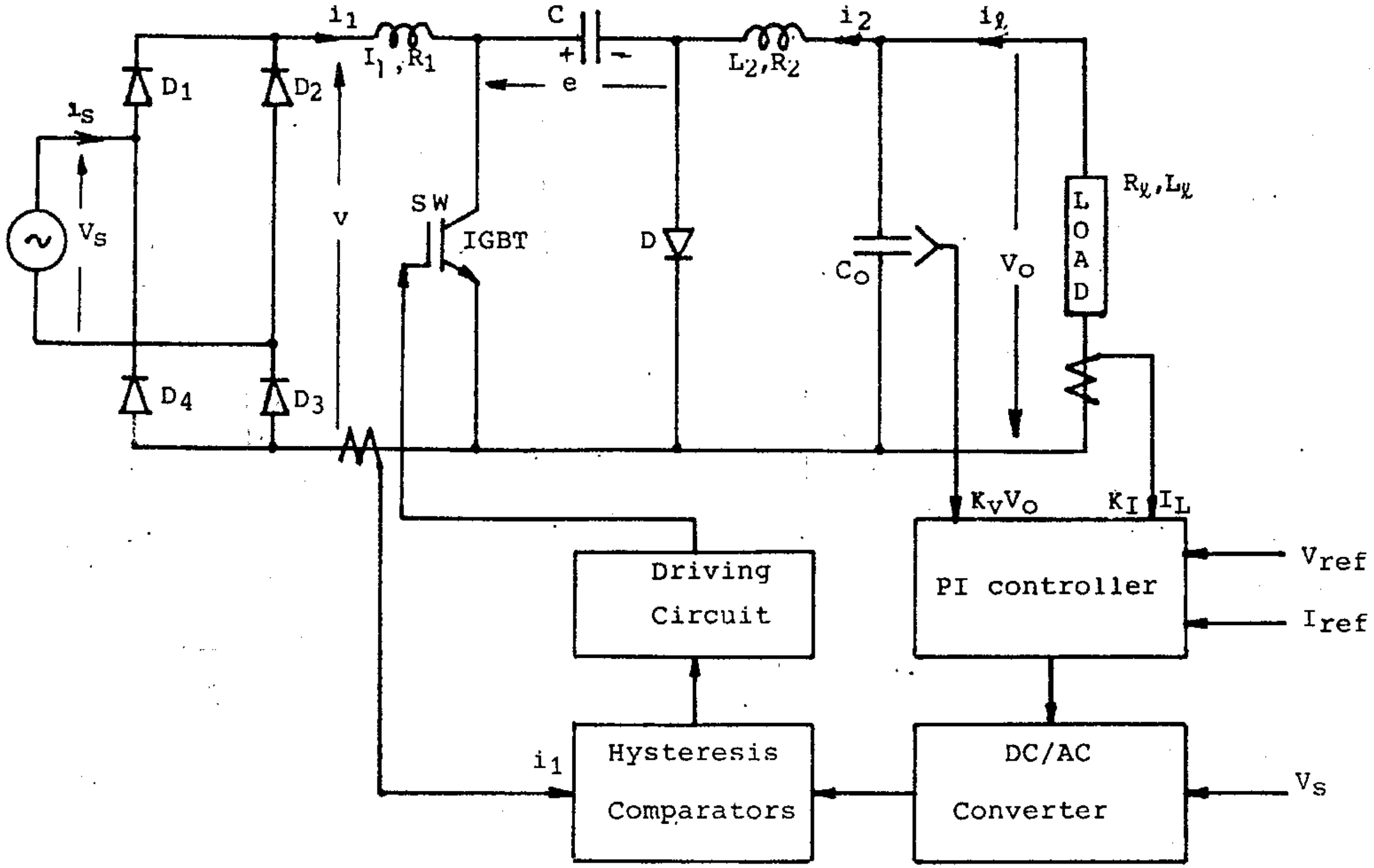


Fig.1. Block diagrame of the Rectifier circuit.

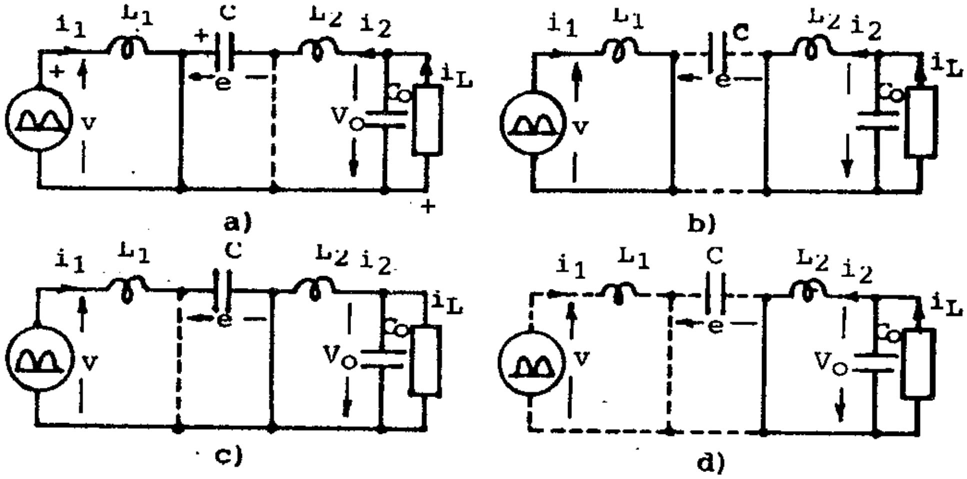


Fig.2. Modes of operation for cuk converter
a) Mode 1 SW on, $e > o$, $i_1 > o$).
b) Mode 2 SW on, $e = o$, $i_1 > o$).
c) Mode 3 SW off, $e > o$, $i_1 > o$).
d) Mode 4 SW off, $e > o$, $i_1 = o$).

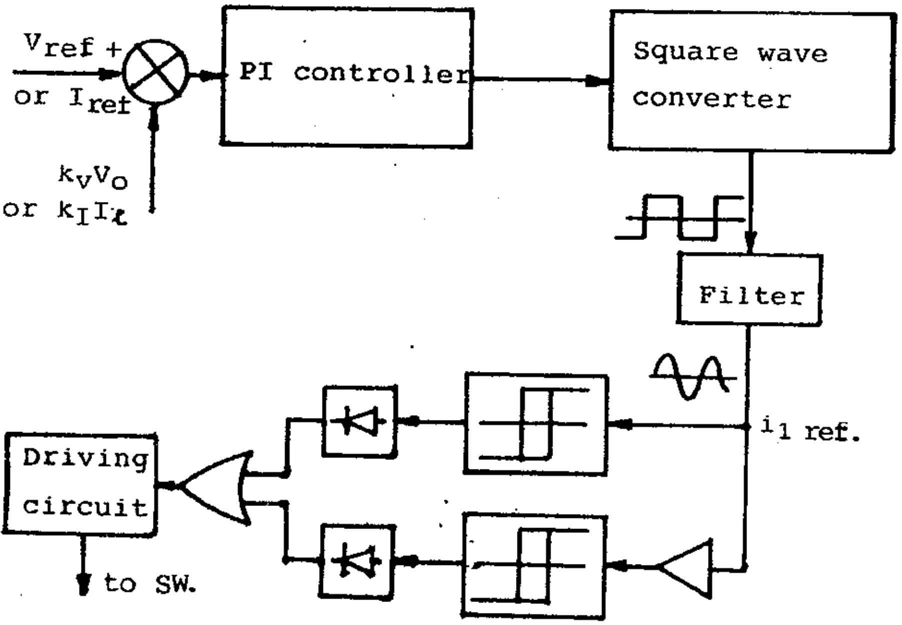


Fig. 3. Control system block diagram.

the supply current i_1 will flow through the loop v-L_1SW. such that,

$$v = i_1 R_1 + L_1 di_1 / dt \qquad (1)$$

subject to the initial values at the switching instant. Meanwhile, the capacitor C discharges via the switch into the load circuit and the capacitor C_o. Thus, from the equivalent circuit of mode 1.

$$\begin{aligned} e &= 1/C \int (-i_2)\, dt \\ &= L_2\, di_2/dt + R_2\, i_2 + 1/C_o \int (i_2 - i_\ell)dt \qquad (2) \end{aligned}$$

and

$$\begin{aligned} V_o &= 1/C_o \int (i_2 - i_L)\, dt \\ &= R_L\, i_\ell + L_\ell\, di_\ell / dt \qquad (3) \end{aligned}$$

Depending on the circuit parameters and operating conditions, voltage of the capacitor C may fall to zero (mode 2). In this mode, the current i_2 continues circulating via the diode D. It follows that equations 1 and 3 above are still applicable but equation 2 becomes,

$$0.0 = L_2\, di_2 / dt + R_2\, i_2 + 1/C_o \int (i_2 - i_\ell)\, dt \qquad (4)$$

If the switch is now turned off, the system changes to mode 3 and the capacitor C will charge such that

$$v = i_1 R_1 + L_1\, di_1 / dt + 1/C \int i_1\, dt \qquad (5)$$

as shown in Fig. 2c. However, at the small values on the supply voltage wave the rectifier operates in mode 4, e.g. , the supply current falls to zero.

Parameters of the power circuit can be determined according to the range of the switching frequency and acceptable percentage of the output ripple. Consider equations 1 and 4. The rate of change of i_1, is determined by the value of L_1. Accordingly, at certain hysteresis width the switching frequancy is determined by the value of L_1. However, the capacitance C can be determined according to the value of L_1. The resonant frequency given by $f_r = 1 / 2\pi\sqrt{L_1 C}$ should be sufficiently lower than the switching frequency to prevent resonant phenomenon in the AC circuit. Nevertheless, the higher the values of L_2 and C_o the better the output current and voltage but on the expense of the system time response. Therefore, L_2 and C_o should be of reasonable values.

4. THE CONTROL CIRCUIT:

The proposed control circuit is shown in Fig.3. The circuit comprises a PI controller, a DC-to-AC converter and two hysteresis comparators. The PI controller is used to reduce the steady-state error in the system response to zero. If output voltage control is required, V_o is detected and compared with V_{ref}. The error signal is fed to the PI controller to regulate the load voltage. However, the error signal between I_{ref} and the detected current I_{ℓ} is similarly used to regulate the load current. A circuit is built to convert the d.c. output from the PI controller to a.c. square wave in synchronism with the supply voltage. Then, the square-wave is filtered via a linear filter to obtain the fundamental component. A multiplier can be used to achieve the same purpose. However, the employed circuit is cheaper but on the expense of introducing a delay time of about 60 msec. The difference between the output of the DC/AC converter ($i_{1\,ref}$) and the detected current (i_1) is applied to the hysteresis comparator (comp 1) to create a sinusoidally waveshaped supply current during the positive half-cycle. However, a cascade combination of an inverter and a similar hysteresis comparator (comp 2) is used to creae a sinusoidally wave shaped supply current at the negative half cycle. The hysteresis comparator uses an operaional amplifier and acts as follows: the output is 1 when the current (i_1) reaches ($|i_{1\,ref}| - H/2$), and O when (i_1) reaches ($|i_{1\,ref}| + H/2$). The required gate signal is accordingly given by the simple logic shown in Fig.3. The gate signal is amplified via the gate drive circuit to drive the fast switching switch (IGBT).

5. SYSTEM MODELING:

For simplicity, the following main assumptions are taken into consideration : losses in the fast recovery diodes and the IGBT switch 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 are neglected.

Consider Fig.2 and equations 1 to 5, the differential equations during various modes of operation can be rewritten as follows:

Mode 1 : [SW is ON, $e > o$ and $i_1 > o$].

$$di_1/dt = v/L_1 - R_1\, i_1/L_1$$

$$de/dt = -i_2/C.$$

$$di_{\ell}/dt = v_o/L_{\ell} - R_{\ell}\, i_{\ell}/L_{\ell}$$

$$dv_o/dt = (i_2 - i_{\ell})/C_o$$

$$di_2/dt = e/L_2 - R_2\, i_2/L_2 - v_o/L_2$$

Mode 2: [SW. is ON , $e = o$ and $i_1 > o$]

$di_1 / dt = v/L_1 - R_1 i_1 / L_1$

$di_\ell / dt = v_o / L_\ell - R_\ell i_\ell / L_\ell$

$dv_o / dt = (i_2 - i_\ell) / C_o$

$di_2 / dt = - R_2 i_2 / L_2 - v_o / L_2$

Mode 3: [SW. is OFF, $e > o$ and $i_1 > o$]

$di_1 / dt = v/L_1 - R_1 / L_1 - e / L_1$

$de / dt = i_1 / C$

$di_\ell / dt = v_o / L_\ell - R_\ell i_\ell / L_\ell$

$dv_o / dt = (i_2 - i_\ell) / C_o$

$di_2 / dt = - R_2 i_2 / L_2 - v_o / L_2$

Mode 4: [SW. is OFF, $e > o$ and $i_1 = o$]

$di_\ell / dt = v_o / L_\ell - R_\ell i_\ell / L_\ell$

$dv_o / dt = (i_2 - i_\ell) / C_o$

$di_2 / dt = - R_2 i_2 / L_2 - v_o / L_2$

When the hysteresis control shown in Fig.3 comes into effect, the switching frequency and duty-factor of the IGBT vary continuously. In order to follow such an operation, the system equations are solved numerically. However, constants and operating conditions of the experimental setup are listed in Appendix A. Nevertheless, input / output characteristics are obtained by application of the formulas given below; The distortion factor DF:

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

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} , V_s .

The ripple factor RF:

$$RF = (V_{o\,max.} - V_{o\,min.}) \times 100 / V_o$$

The supply reference current ($i_{1\ ref.}$) can be related with the output of the cascade combination of the PI controller and the DC/AC converter. The transfer function of the PI controller is of the form,

$$G_1 = K_1 (1 + ST_1) / ST_1$$

where , K_1 : gain of the controller
T_1 : time constant of the controller

However, the maximum value of the supply current reference $I_{1\ ref}$ is determined by :

$$I_{1\ ref.} = (X - 0.5) / 2(1+ST_2)$$

where X : output of the PI controller.
T_2 : delay time of the DC/AC converter.

6. SIMULATION AND EXPERIMENTAL RESULTS:

Fig.4 shows the experimental and calculated supply voltage and current waveforms at different reference levels. It can be seen that the supply current is nearly sinusoidal with a unity displacement power factor. To give more details about the supply current its frequency spectrum is shown in Fig.5 The current was detected via a shunt of 1.1 Ω resistance and analysed using an FFT analyser. From Figs. 4 and 5, it is obvious that nearly sinusoidal supply current has been achieved particularly at higher current levels. However, Figs. 6 and 7 show that ripples in the output voltage and current are very low.

As shown in Fig.8, this converter can control the output voltage from 20% to more than the source voltage . The distortion factor at certain load inductance increases as the DC voltage command decreases. This is because the ratio of the hysteresis width to the supply current increases at low levels of the DC voltage command. However, above 25% of load voltage the input power factor is nearly unity. Since the circuit power rating is relatively low, efficiency is not high. It is about 80% over a wide range of V_L at low load inductance and increases to 85% at higher load inductance due to reduction in the switching losses.

Fig.9 shows the ripple factor versus V_o/V_s. The ripple factor decreases as the DC voltage command decreases. However, it is lower than 2.5% at different load voltage command and at various load inductances. Parameters of the PI controller (K_1 and T_1) are determined via simulation results to achieve accurate response with a minimum of transient overshoot. Fig. 10 shows the response of current control for step-up and step-down change of about 25% in reference current (I_{ref}). However, the response for sudden change in load resistance of about 25% is shown in Fig.11. It shows that the output current can be maintained constant if the load resistance is changed. However, the transient period lasts about 100 m-sec . Figs.12 and 13 show the transient response of voltage control for

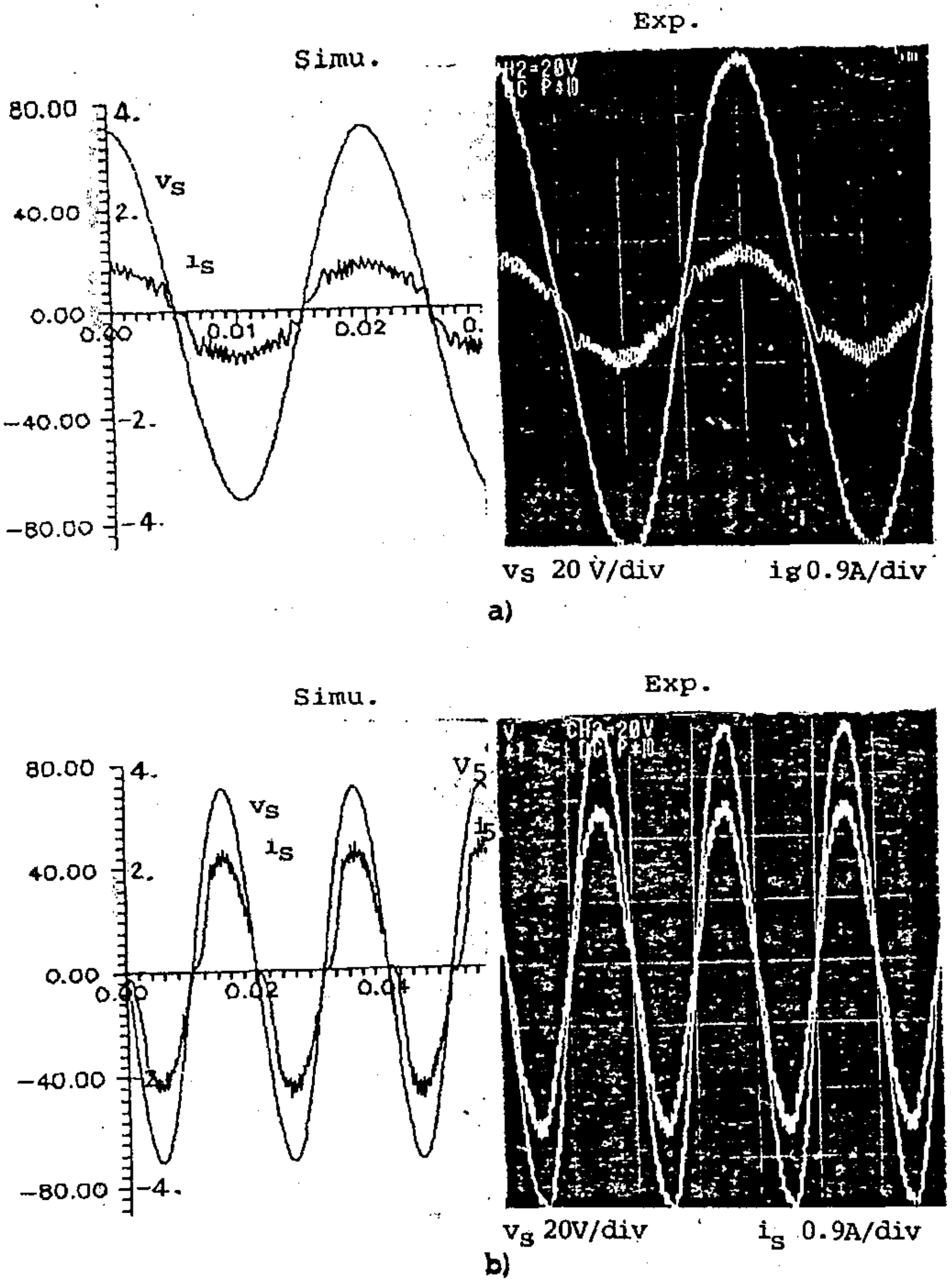


Fig. 4. Supply voltage and current waveforms.
a) At low reference level.
b) At high reference level.

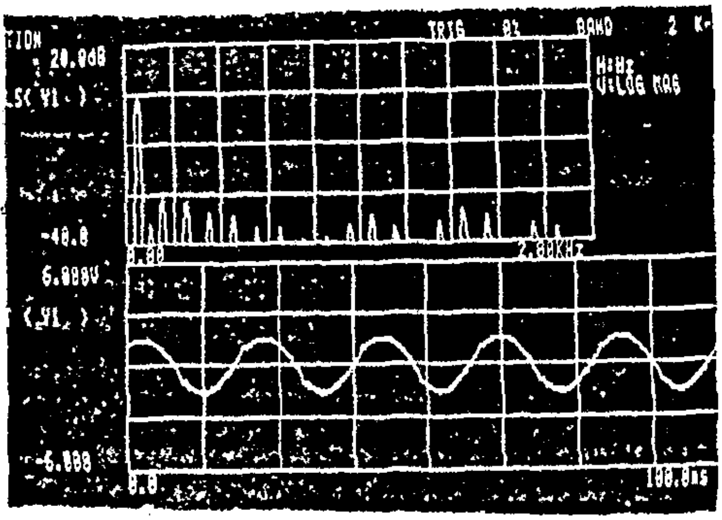


Fig.5. Frequency spectrum of supply current.

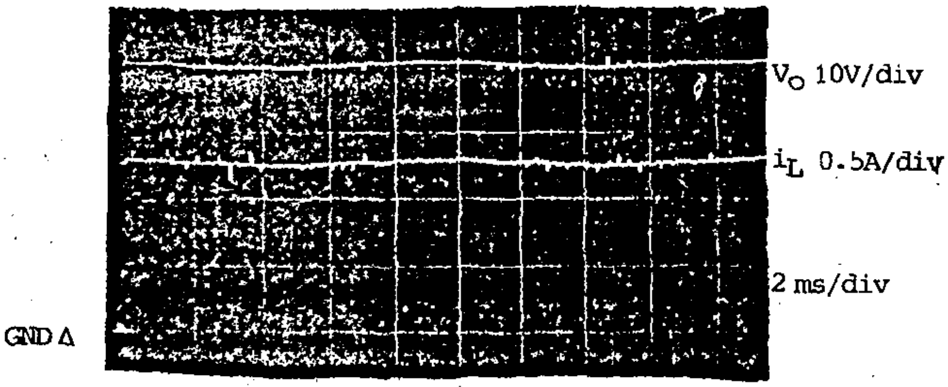


Fig. 6. Load voltage and current wave shape.

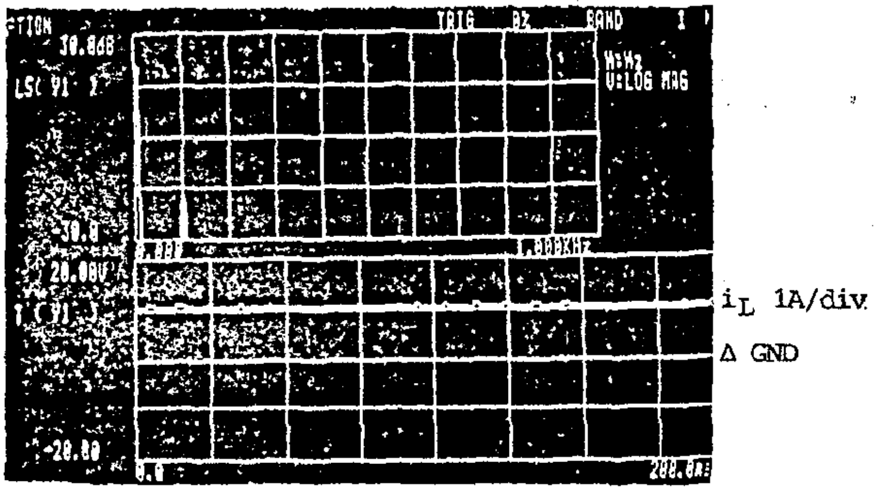


Fig. 7. Frequency spectrum of load current.

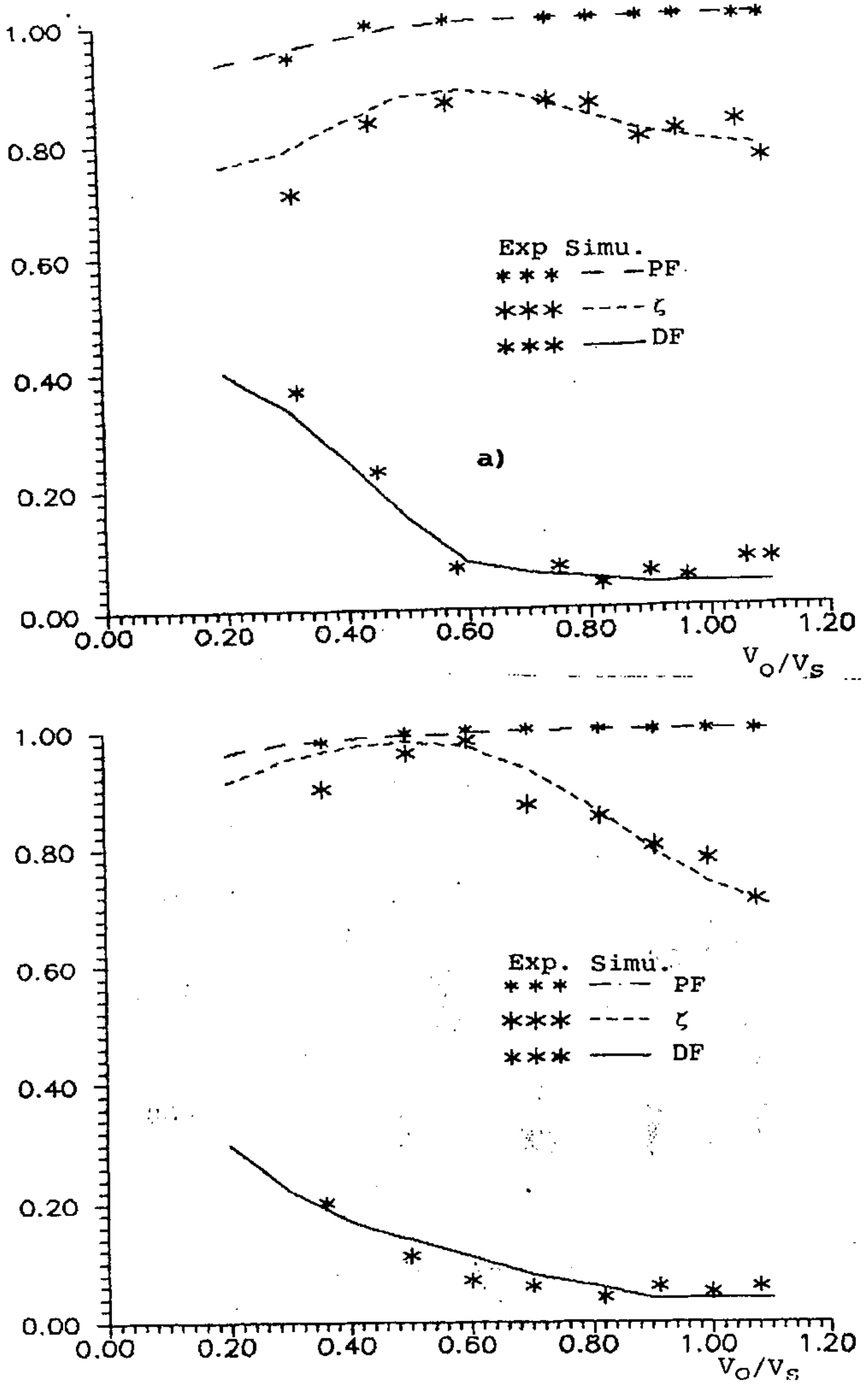


Fig.8. Power factor, Efficiency and Distortion Factor versus V_o/V_s.

a) At $L_\ell = 11$ mH b) At $L_\ell = 41$ mH

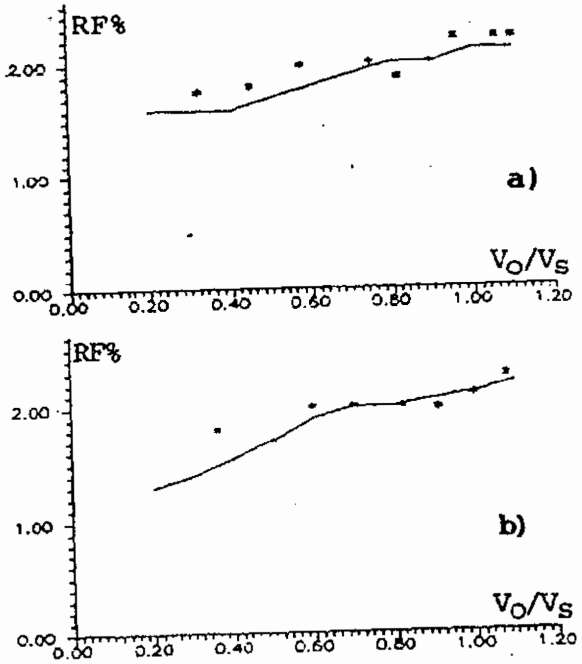


Fig. 9. Ripple factor versus V_O/V_S
a) At $L_\ell = 11$ mH b) At $L_\ell = 41$ mH

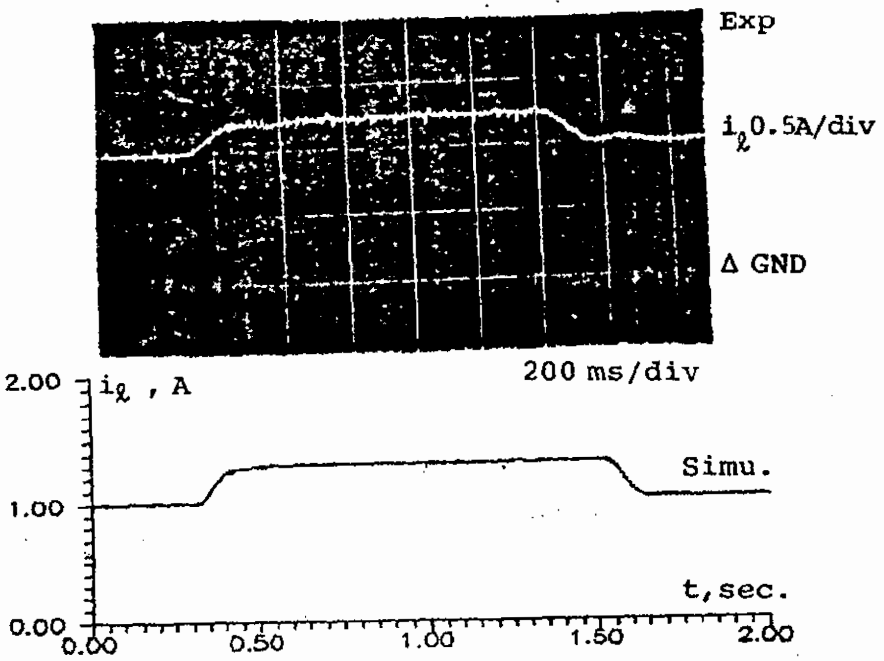


Fig. 10. Transient responses of current control due to step change in the output current reference.

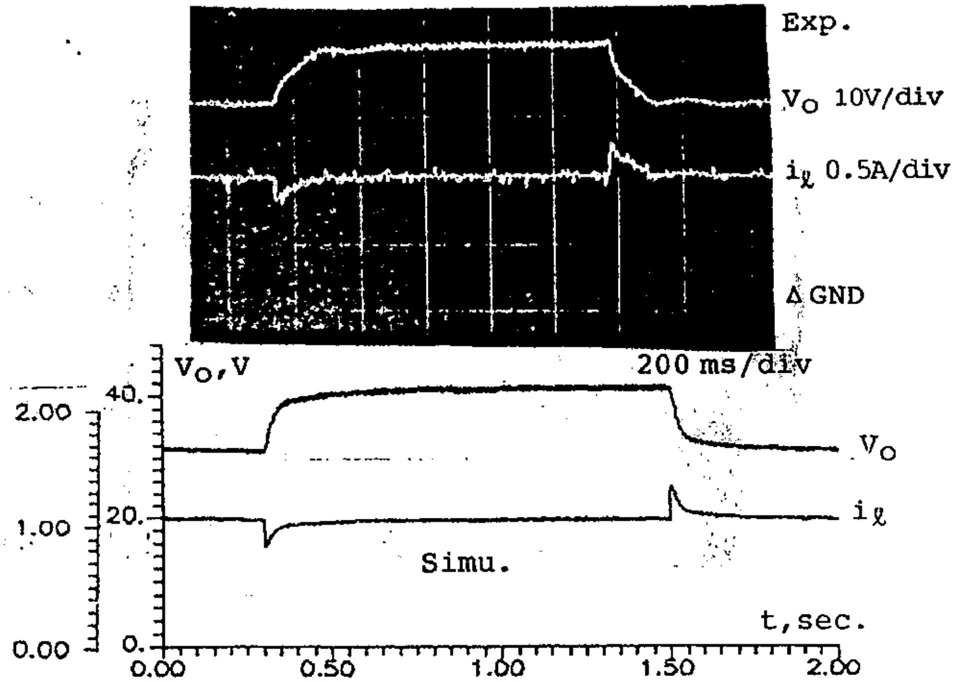


Fig.11. Transient responses of current control due to step change in the load resistance.

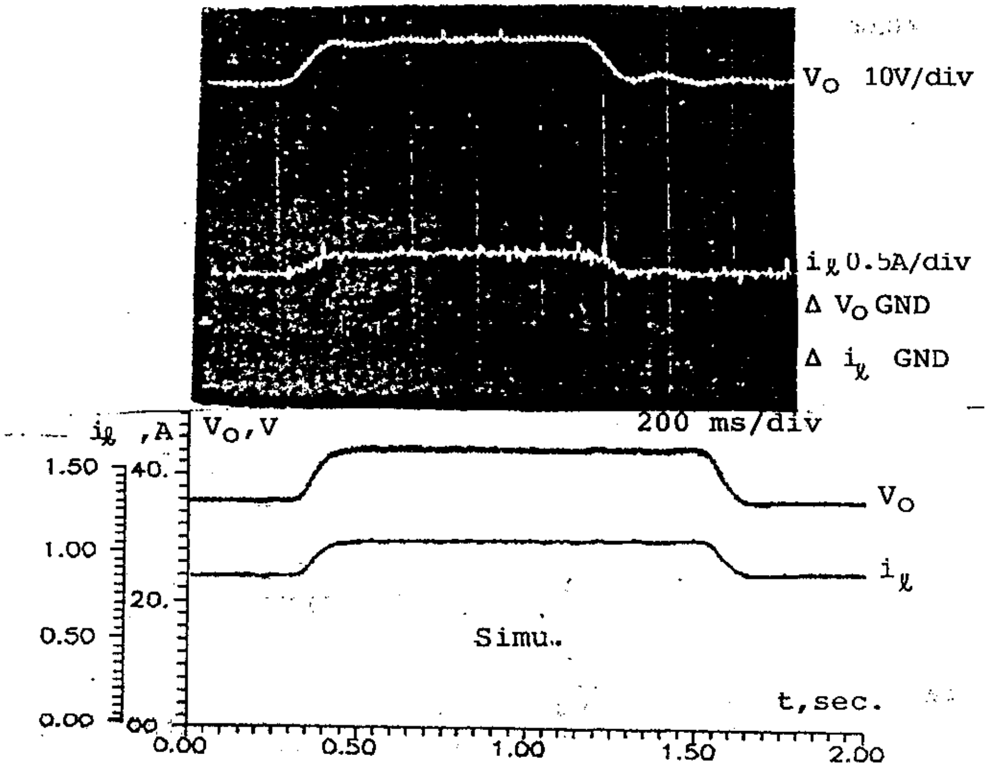
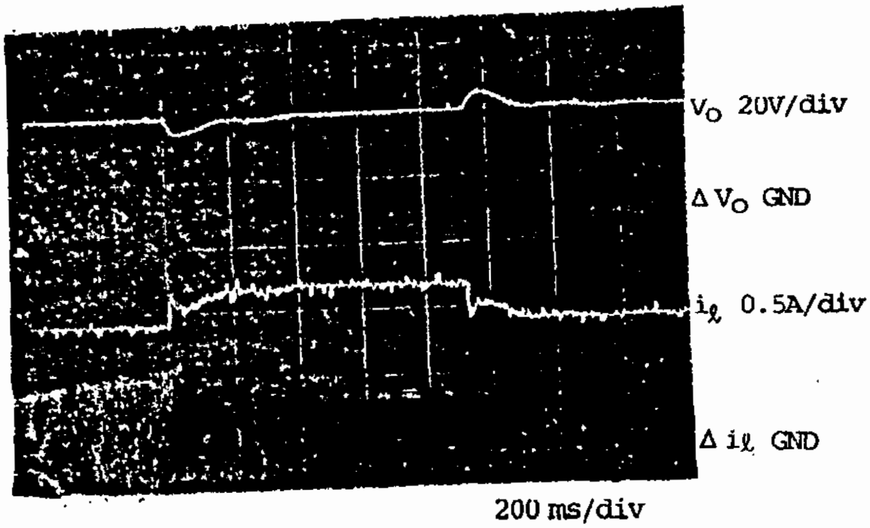


Fig.12. Transient responses of voltage control due to step change in the output voltage reference.



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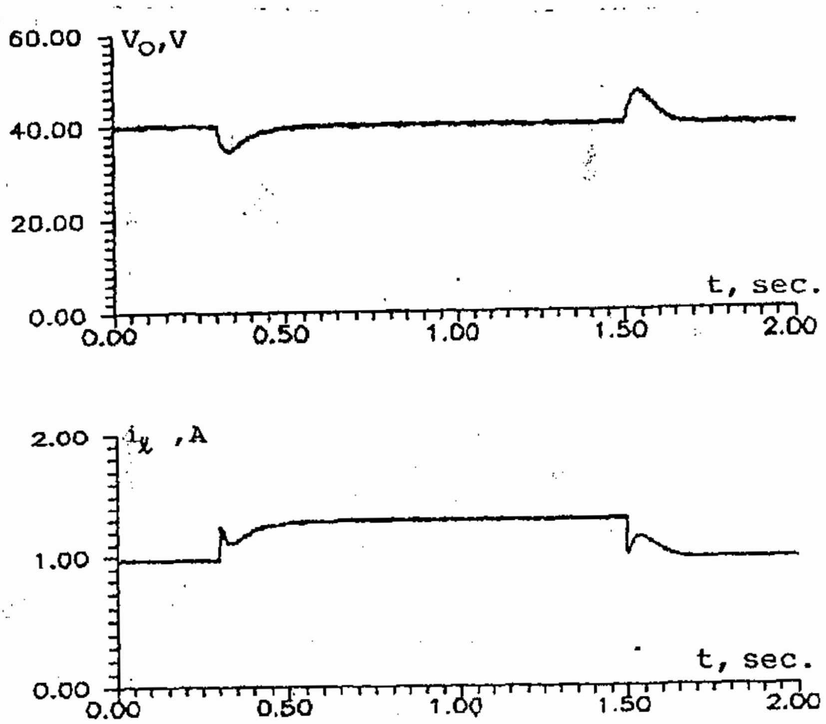

Fig. 13. Transient responses of voltage control due to step change in the load resistance.

a step change of about 25% in reference voltage (V_{ref}) and for a sudden change in load resistance of about 25% , respectively. In Fig.12, the output voltage follows the reference and in Fig.13 V_o is maintained constant when the load resistance is changed.

7. CONCLUSIONS:

A single-phase AC-to-DC buck-boost converter with high-quality input-current and output-voltage is presented. From the results, it has been shown that a nearly sinusoidal supply current and nearly unity power factor can be achieved.

The steady-state and dynamic response of the system are studied. Simulation and experimental results are reported and shown to be in good agreement.

Transient response for load current control and / or output voltage control have been reported. It has been shown that the employed control is effective and accurate. The employed DC/AC converter of the conrol system can provide an economically regulated DC supply but on the expense of some delay in the time responses. However, the system time response may be satisfactory for practical applications if extremely fast response of current or voltage regulation is not required.

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APPENDIX (A)

Data and parameters of the experimental set-up:

$V_s = 50$, $H = 0.4\ \mathrm{A}$, $L_1 = 24\ \mathrm{mH}$, $R_1 = 1.4\ \Omega$,
$C = 5\mu\mathrm{F}$, $L_2 = 290\ \mathrm{mH}$, $R_2 = 1.4\ \Omega$, $C_0 = 1000\ \mu\mathrm{F}$
$R_{\ell} = 41\ \Omega$, $L_{\ell_1} = 11\ \mathrm{mH}$, $L_{\ell_2} = 41\ \mathrm{mH}$.

The conroller parameters of the current control

$K_1 = 0.4$, $T_1 = 0.027$ sec and $K_I = 10$ V/A

The controller parameters of the voltage control

$K_1 = 0.4$, $T_1 = 0.02$ sec. and $K_V = 0.25$ V/V

ملخص البحث

التحكم التمثيلى لمحوال كوك لتحقيق اداء عالى

يقدم البحث طريقة جديدة للتحكم التمثيلى فى منبع جهد (أو تيار) موحد. والدائرة الأساسية تتكون من قنطرة موحدات ذات وجه واحد متبوعة بمحوال كوك الذي يمكن عن طريقه الحصول على جهد خرج موحد أعلى أو أقل من جهد المصدر .

ويشتمل نظام التحكم المقترح على متحكم تمثيلى تناسبى تكاملى لكى يعمل على تثبيت جهد (أو تيار) الخرج عند المستوى المطلوب .

ويتم تحويل خرج المتحكم الى موجة جيبية تتناسب قيمتها مع هذا الخرج ومتزامنة مع جهد المصدر ، ثم مقارنة الموجة الجيبية مع تيار المصدر لكى يمكن الحصول على شكل جيبى تقريبا وفى نفس الوجه مع جهد المصدر وذلك عن طريق تشغيل مفتاح الكترونى سريع بدائرة كوك.

تم بناء الدائرة المقترحة وإختبارها حيث أعطت أداء عاليا بالنسبة لتيار المصدر وكذلك بالنسبة لجهد الخرج ولقد أبرزت النتائج العملية أن تيار المصدر جيبى تقريبا وفى نفس الوجه مع الجهد مما يجعل معامل القدرة عاليا جدا بالنسبة للمصدر (تقريبا واحد).

وقد تم إختيار أداء النظام فى الحالة المستقرة وكذلك فى الحالة الانتقالية للحصول على جهد خرج ثابت (أو تيار خرج ثابت) عند إحداث تغيير مفاجئ في الحمل أو جهد الأساسى . كما تم تحليل أداء النظام نظريا وقورنت النتائج النظرية بالمعملية حيث حققت تطابقا مرضيا.

والطريقة المقترحة اقتصادية من حيث التحكم في جهد أو تيار الخرج ولكن على حساب تأخر فى الاستجابة مقداره حوالى ١٠٠ مللى ثانية وهى مناسبة للأحمال التى لا تحتاج الى استجابة سريعة جدا.