A HARMONIC-FREE CURRENT-LINK AC TO AC POWER SUPPLY: DYNAMIC ANALYSIS AND DESIGN

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ABSTRACT – In this paper, the dynamic analysis and design of an AC to AC power supply with DC current link is presented. Despite many advantages of such a structure, its application in fixed frequency power supplies has received very little attention in the literature. Different issues related to dynamic analysis of the proposed system are considered. These include a simple averaging technique for modeling switching function generators, the concept of Internal Model Controllers, and necessary condition to avoid multiple crossing in ramp comparison methods. Theoretical and experimental results obtained from a DSP-based laboratory type setup are presented.

1. INTRODUCTION

Fixed frequency AC to AC power supplies are mainly used in situations where the frequency of existing AC source does not match the frequency required by the load. Major applications of these systems are in remote power supplies with high-speed high-frequency turbine generators, marine power supplies and windmill generators.

A conventional AC to AC power supply normally consists of a diode (or phase-controlled) rectifier, an intermediate DC voltage link, and a Voltage Source Inverter (VSI). Such a system suffers mainly from the following drawbacks:

1. Highly distorted input current which does not comply with today's requirements imposed by utility companies,
2. Sluggish transient response of the inverter stage due to low-pass filter in the feedback path.

To eliminate the above drawbacks, different configurations have been proposed by researchers. One of these structures, which has received very little attention in the literature, is current-link AC to AC converter with front-end PWM rectifier and voltage-controlled current source inverter at the output stage. It has been shown that using this structure not only eliminates the above drawbacks, but also has other advantages such as smaller size (due to lower magnetic components), inherent regeneration capability and more rugged operation. Therefore, a research was conducted for systematic analysis and design of an AC to AC fixed frequency power supply with intermediate DC current link [1,2]. This paper presents the dynamic analysis of the proposed system including modeling, selection of control system structure and control strategy, and control system design criteria.

Figure 1.a shows the block diagram of the proposed system with two main sub-sections: A Current Type PWM Rectifier (CTR) and a voltage-controlled Current-Type Inverter (CTI). Also shown in Fig. 1.b is the power circuit structure of the proposed system. Note that the switches have to have reverse voltage blocking capability.

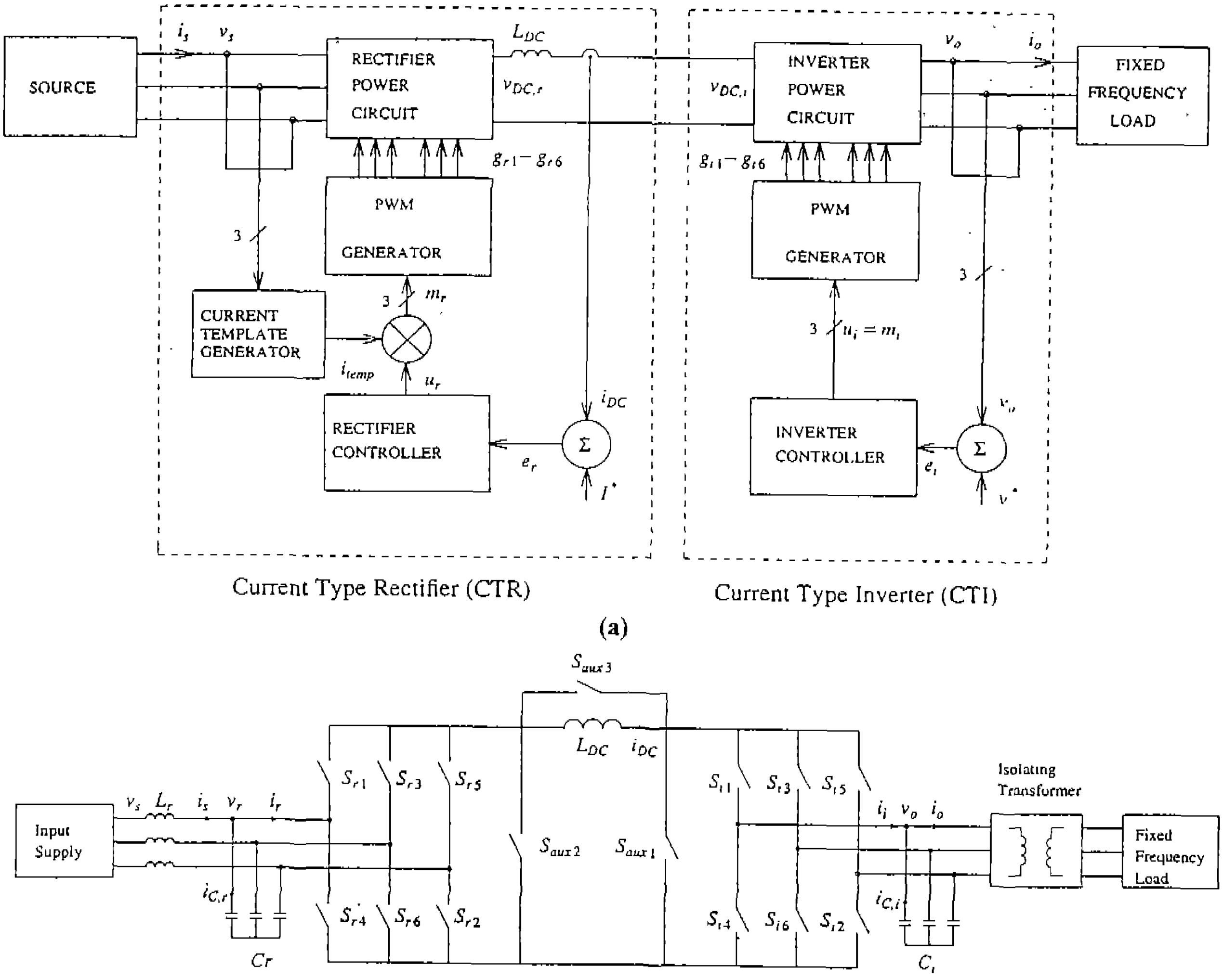
The proposed system operates in fixed DC current mode. The AC/DC/AC conversion is performed using Pulse-Width Modulation (PWM) techniques, and the amplitude of AC quantities is controlled by means of modulation index control. The basic system operation and steady-state analysis of the system have been presented in other papers [1,3].

From the standpoint of dynamic analysis, the system is divided into two decoupled control systems. This makes the analysis and design considerably simpler.

A switching converter is a highly non-linear system. To construct a linear model from such a system, an averaging technique is used based on the local average value of signals, which is explained in Sec. 2.

Using the above mentioned approach, linearized models are obtained for the rectifier and inverter. The inverter modeling, however, needs more attention. As a matter of fact, since the PWM generation technique in the proposed system produces a dependency in PWM pattern of phases [2], thus a simple single-phase equivalent circuit does not lead to accurate results. Therefore, it is necessary to develop a more elaborate model based on all three phases.

The PWM generation core in the proposed system is based on so-called ramp comparison method. When using this method, the closed-loop gain has to be limited in order to avoid unpredictable high switching frequencies due to a phenomenon called multiple crossing. This issue is discussed in this paper and the necessary condition to avoid multiple crossing is derived.



(a)

(b)

Fig. 1 (a) Block diagram and (b) power circuit structure of the proposed AC to AC power supply with DC current link.

To achieve a fast transient response, the strategy of tracking control systems is employed for the inverter section. Further, it is shown that how by using the concept of internal model controllers [4,5] in the inverter controller design, any steady-state tracking error can be eliminated.

To confirm the effectiveness of the proposed strategies and the validity of the analysis, an experimental system was built using a high performance DSP-based digital controller [6]. The dynamic design of the experimental system was carried out using emulation method [7], i.e., the results of s-plane design were discretized using corresponding techniques. In so doing, time delays are introduced in the original control system, which were properly taken into consideration.

2. MODELING OF SWITCHING CONVERTERS

A switching converter is an example of a non-linear system. Many techniques have been proposed to model such systems by well-behaved linear systems [8]. A majority of these techniques rely on the averaging of variables in the system. In this paper, the concept of **local average** is used to model and analyze the dynamic behavior of the system. The local average of a signal is defined by

$$\bar{x} = \frac{1}{T_c}\int_{t}^{t-T_c} x(t)dt \qquad (1)$$

where by definition $\bar{x}$ is called the local average of x, and $T_c = \frac{1}{f_c}$ is the period over which the local average is calculated. The local average is actually a moving average of a signal taken over the preceding interval of length T_c.

3. RECTIFIER DYNAMIC ANALYSIS

Rectifier Modeling

Consider the rectifier section in the block diagram of Fig. 1.a. This block has two major functions. First, it forces the input currents to be in phase with input voltages, i.e., maintains unity power factor operation. Secondly, it regulates the link current for constant DC current operation. The operation of this section is as follows. Line voltages are sensed to generate current templates for unity power factor operation. Also, the output current is fed back to the controller. The PWM pattern generator block then produces the appropriate gating signals with respect to these inputs. Based on the employed PWM technique described in [2], the rectifier can be modeled as shown in Fig. 2. In this figure, comparators are the basic switching function generators used in conventional ramp comparison methods. The output of these blocks, S_r, denotes the rectifier switching functions.

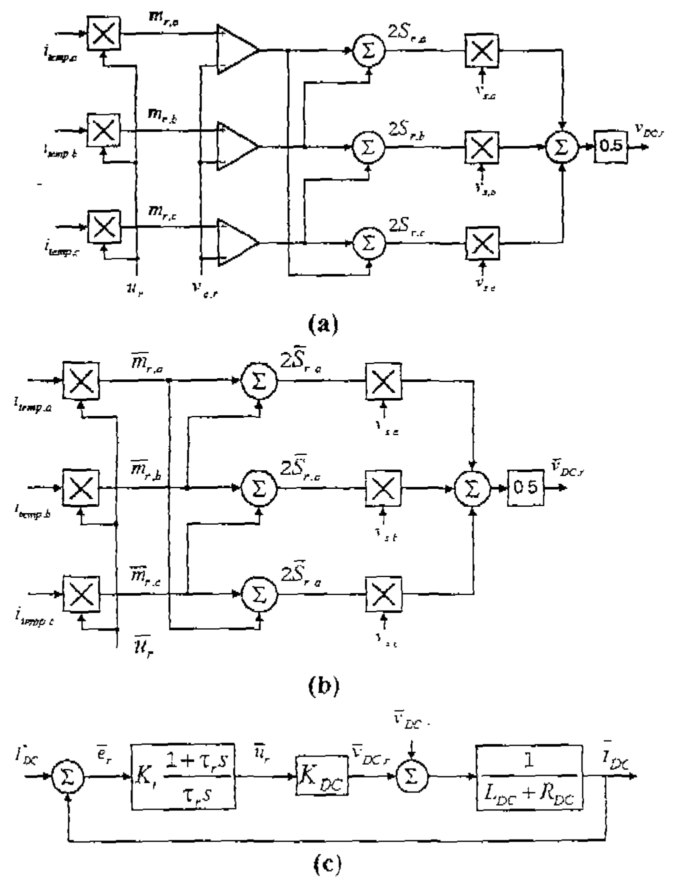


Fig. 2 Rectifier model representing (a) instantaneous quantities, (b) average quantities, and (c) complete block diagram of the rectifier section

Using the concept of local average of signals, the rectifier average model can be obtained from the instantaneous model, as shown in Fig. 2.b. As can be seen, the basic switching function generators have disappeared. In this model, average variables are shown by bar notation Since all signals in this model closely approximate sinusoidal quantities during steady-state, thus using trigonometric relationships [3] the average model is simply reduced to a simple gain from the average control signal $\bar{u}_r$ to the average output voltage $\bar{v}_{DC,r}$. This gain can be calculated from Fig. 2.b as [3]

$$K_{DC} = \frac{\sqrt{6}}{2} V_{l,s} \tag{2}$$

where $V_{l,s}$ is the rms value of the input line voltage.

Rectifier Control System Strategy

The rectifier supplies a constant current in the DC link by controlling its average output voltage. In other words, the variation in the average value of the inverter input voltage $\bar{v}_{DC,i}$ (due to load variation) is compensated in such a way that the net DC voltage across the DC link filter remains constant. Such a control action can be easily accomplished using a *PI* controller. Based on this, the complete block diagram of the rectifier control system is shown in Fig. 2.c, where the link filter is modeled by a low-pass *RL* filter and the load disturbance is modeled by $\bar{v}_{DC,i}$.

Closed-Loop Gain Consideration

The controller gain, K_r, in the average linear model of Fig. 2.c has some limitation in actual switching system because of a phenomenon called **multiple crossing**. This phenomenon happens in ramp comparison methods when the maximum rate of variation (or slope) of the modulating signal exceeds the slope of the segments of the carrier signal. This situation leads to undesirable high switching frequency.

The above statement can be mathematically written as

$$\max \frac{\Delta m_r}{\Delta t} < \frac{\Delta v_{c,r}}{\Delta t} \tag{3}$$

where m_r and $v_{c,r}$ are the rectifier modulating and carrier signals respectively. Generally speaking, the maximum rate of variation of signals in a linear system is a function of its bandwidth. On the other hand, for a linear system with fixed location of closed-loop zeros and poles, the closed-loop bandwidth increases by gain [7]. Therefore, to avoid multiple crossing, the closed-loop gain should be limited. It is shown in [2] that the following relationship has to be hold to avoid multiple crossing in the rectifier control system:

$$K_r < \frac{\sqrt{2} f_{c,r} L_{DC}}{V_{l,r} + V_{l,o}} \tag{4}$$

where K_r is the controller gain, $f_{c,r}$ is the frequency of the carrier signal (assuming triangular carrier), L_{DC} is the DC link inductance and $V_{l,r}$ and $V_{l,o}$ are the rms value of the input and output line voltages respectively.

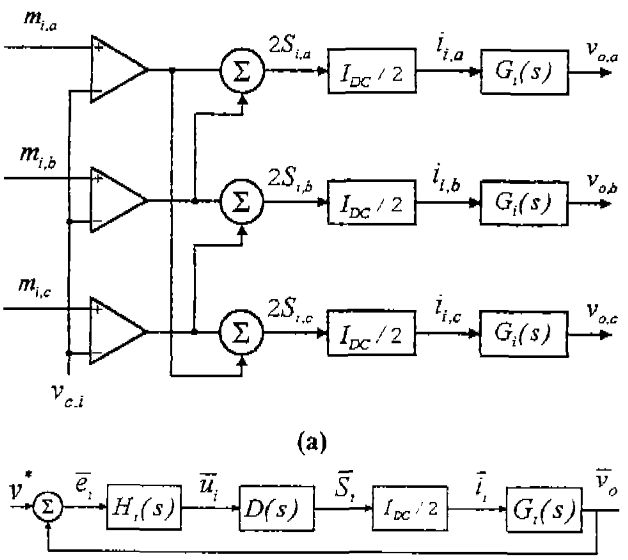
4. INVERTER DYNAMIC ANALYSIS

Using similar approach described in the previous section, the average model of the inverter can be obtained as shown in Fig. 3.a In this model, the transfer function from the inverter output current, i_i , to the output voltage, v_o, including the output filter and the load is shown by $G_i(s)$.

Examination of the inverter three-phase model showed that the equivalent single-phase model cannot readily obtained. This was expected due to the existing interconnection between three phases caused by the employed PWM method. This coupling effect is taken care of by a proper transfer as will be shown shortly.

Inverter Control System Structure Strategy

To achieve fast dynamic response cause by various disturbances, the inverter control strategy is selected based on tracking control systems. In this scheme, the instantaneous value of the output voltage is forced to track the sinusoidal reference signal. This scheme does not need a low-pass filter in the feedback loop, resulting in considerably higher closed-loop bandwidth and thus faster dynamic response. Figure 3.b shows the single-phase block diagram of the inverter control system. In this figure, the coupling effect of other phases is represented by $D_i(s)$, and $H_i(s)$ is the inverter controller transfer function.



(b)

Fig. 3 (a) Average model of the inverter, (b) complete single phase block diagram including the effect of other phases.

A controller transfer function is usually selected based on the dynamic performance of the system. The steady-state performance of the system, however, is also affected by this transfer function [7]. Specifically, conventional controllers (such as *PI* or *PID*) cannot result in zero steady-state tracking error for a sinusoidal reference signal in the proposed control system. Note that accuracy, i.e., zero tracking error, is one of the most important steady-state requirements in the proposed system.

Considering Fig. 3.b, if the controller can produce a sinusoidal signal even with zero excitation, then the system could achieve zero steady-state tracking error. From the system point of view, a transfer function with two complex conjugate poles can do such. This is in agreement with a theory known as Internal Model Theory [4,5] in control systems which states:

For perfect asymptotic tracking, the loop transfer function must contain an internal model of the unstable poles of the reference signal.

Based on the above argument, the general expression for the inverter controller transfer function may be written as

$$H_i(s) = K_i \frac{s^2 + a_1 s + a_2}{s^2 + \omega_i^2} \qquad (5)$$

where ω_i is the inverter fundamental frequency and K_i, a_1 and a_2 are the controller parameters.

Gain Consideration

with the same reasoning explained in the previous section, the inverter gain also has to be limited to avoid multiple crossing. It is shown that the necessary condition for so doing is [2]

$$K_i(\omega_i \sqrt{2}\, V_p + \frac{I_{DC}}{C}) < 4 f_{c,i} \qquad (6)$$

where K_i is the inverter controller gain, ω_i is the inverter fundamental frequency, V_p is the rms value of the output phase voltage, C is the output capacitor and $f_{c,i}$ is the inverter carrier frequency.

5. THEORETICL VERIFICATION

In this section, an illustrative example is given to demonstrate system performance.

System Description

The results shown in this example corresponds to computer simulation of a 400 KVA, 460 V 60 Hz to 480 V 50 Hz system. The calculation of size of components is given in [2], and here only dynamic performance of this system is illustrated.

Results

Figure 4 shows the transient response of the system to ± 100% step load change. As can be seen, voltage

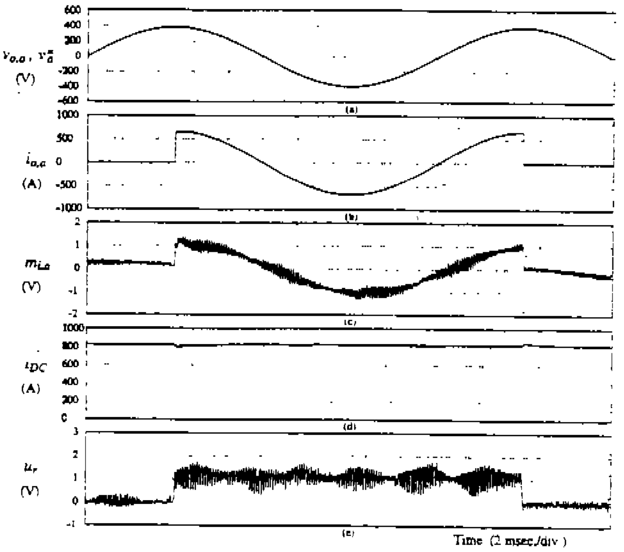


Fig. 4 System transient response to ± 100% step load change.

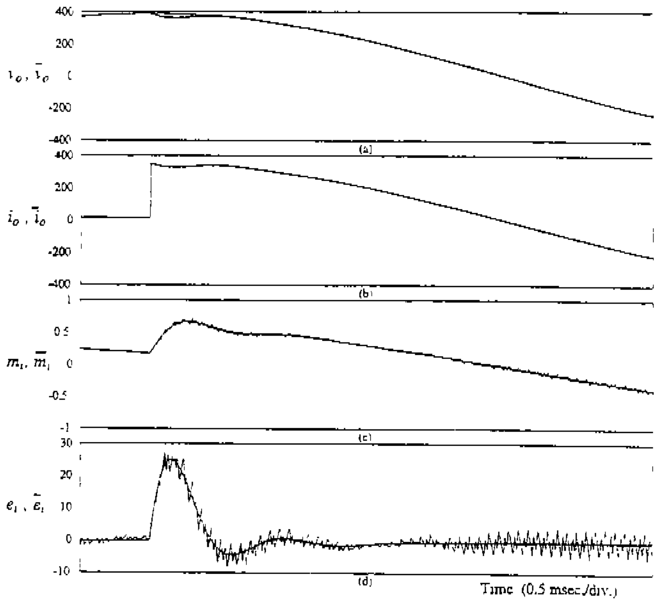
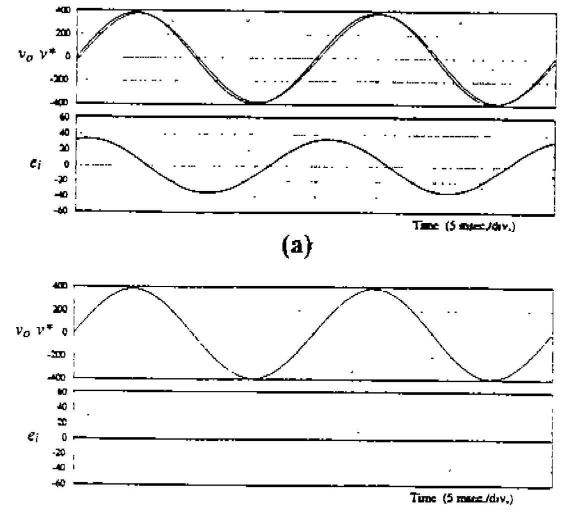


Fig. 5 Transient response of the inverter obtained from linear average model superimposed on the waveforms resulting from simulation of the actual switching system

distortion is very low during transients due to high system bandwidth.

Figure 5 illustrates the transient response of the inverter obtained from linear average model superimposed on the waveforms resulting from simulation of the actual switching system. The close agreement shows the validity of modeling.

Figure 6 shows the output voltage superimposed on the reference signal and also error signal for two cases: (a) With *PI* controller and (b) with proposed internal model controller. Zero steady-state tracking error is quite clear in the latter case.



(b)

Fig. 6 Output voltage and error signal for the inverter section for two cases: (a) with *PI* controller and (b) with internal model controller.

6. EXPERIMENTAL VERIFICATION

A laboratory-type experimental system was built to verify theoretical analysis. The core of this setup was a high performance DSP-based digital controller [6]. Therefore, all controllers were realized using digital techniques.

To realize digital controllers in the experimental setup, emulation method was used [7]. In this method, the controllers are designed in the continuos time (i.e., s-plane), and then discretized using available techniques. Experiments showed that in so doing, different time delays caused by zero-order-hold behavior of the system (as much as $T_S/2$, where T_S is the sampling frequency) and data transfer mechanism (as much as T_S) have to be properly taken into consideration, otherwise the actual results could be significantly different from the predicted results.

The experimental system is a 2 KVA, 110 V 60 Hz to 110 V 50 Hz system. Again, steady-state design of this system is considered in [2]. The switching frequency for this system was set to about 5 KHz. All the following waveforms are obtained both from the experimental system and computer simulation.

Figure 7 illustrates the transient response of the rectifier to 70% load change at the system output. Note that the gain has been intentionally reduced to slow down the transients and make comparison more clear.

Figure 8 demonstrates the inverter transient response to 70% load change. Again the gain has been reduced for better observation of agreement between experimental and theoretical results.

7. CONCLUSION

In this paper, the different aspects of dynamic analysis of a current-link AC to AC power supply were investigated. A simple, yet accurate, modeling approach was presented based on the local average value of signals. The application of tracking control systems in the inverter control system was described. It was shown that how by using the concept of internal model controllers, zero steady-state tracking error is achievable. All analytical results were verified by computer simulation and also by the help of a DSP-based experimental setup.

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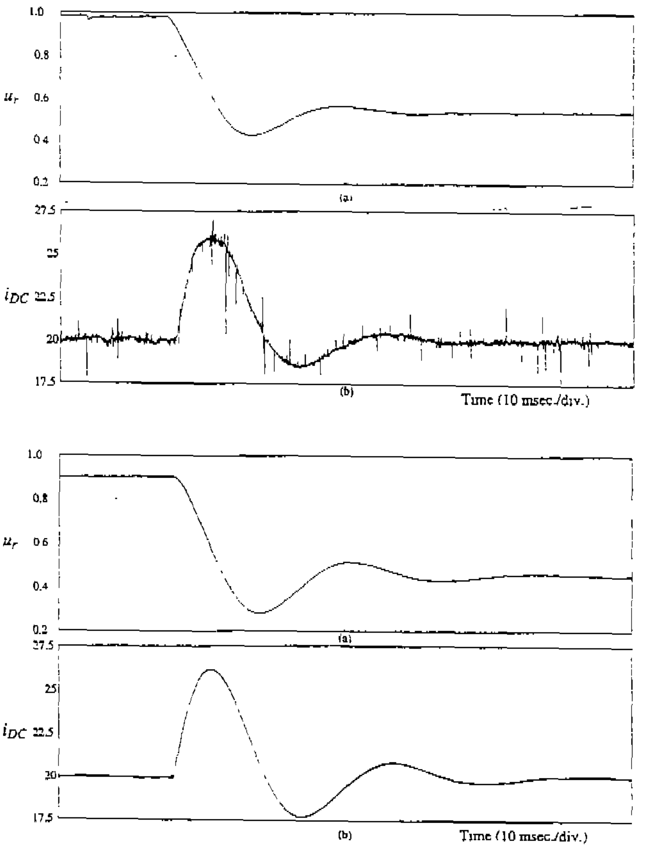

Fig. 7 Experimental results corresponding to the rectifier

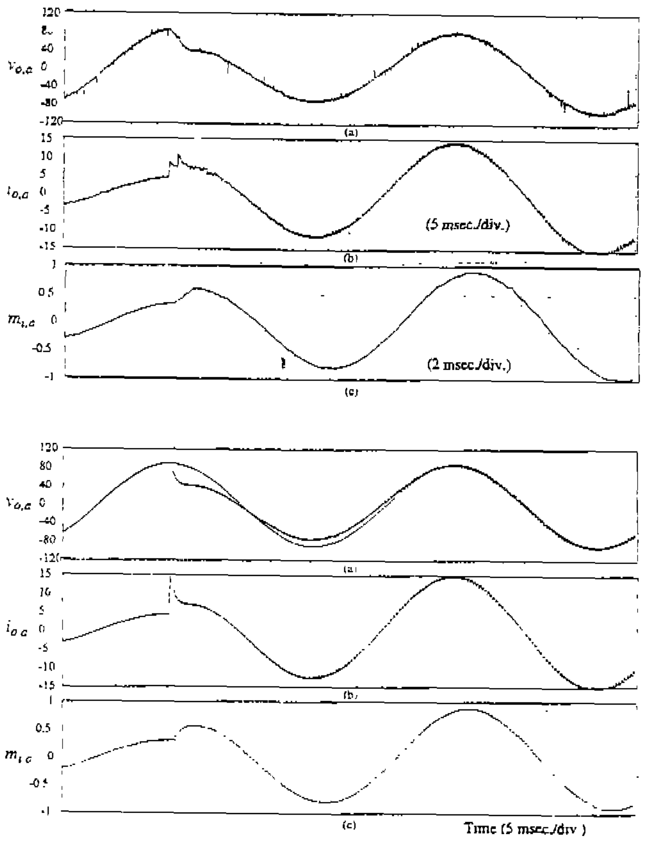

Fig. 8 Experimental results corresponding to the inverter