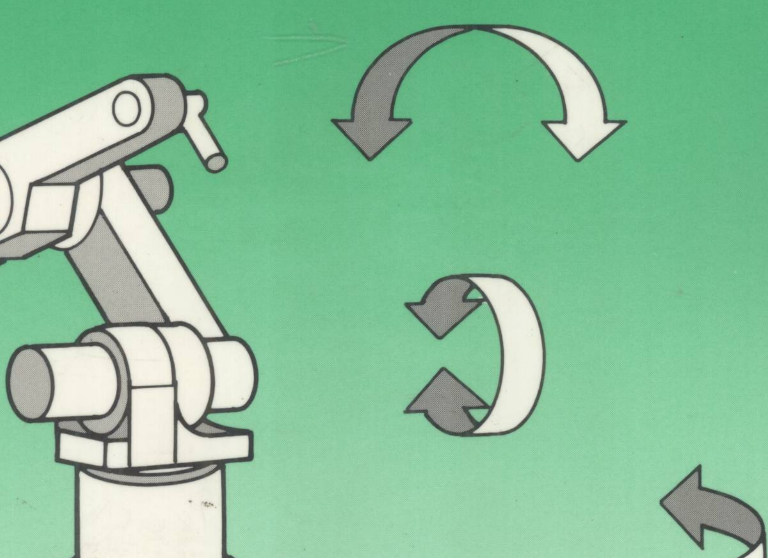
ADVANCED CONTROL SYSTEM TECHNOLOGY

C J CHESMOND
P A WILSON & M R LEPLA



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Edward Arnold
A division of Hodder & Stoughton
LONDON MELBOURNE AUCKLAND

First published in Great Britain 1991

British Library Cataloguing in Publication Data

Chesmond, C. J.
Advanced control system technology.
I. Title II. Wilson, P. A. III. Pla, M. R. Le
629.8

ISBN 0-340-54550-X

Typeset in 11/12 Times by MS Filmsetting Limited, Frome, Somerset
Printed in Great Britain for Edward Arnold,
a division of Hodder and Stoughton Limited,
Mill Road, Dunton Green, Sevenoaks, Kent TN13 2YA,
by St Edmundsbury Press Limited, Bury St Edmunds, Suffolk
and bound by Hartnolls Limited, Bodmin, Cornwall

Preface

In the preface to the companion volume – *Basic Control System Technology* – which was first published in 1990, the release of the present volume was foreshadowed. It was also pointed out that the two monographs were to be treated as complementary; this approach has indeed been followed.

For the reader who is entering the Automatic Control field for the first time, it is advisable to have read the *Basic* volume before embarking on the present one. In fact, it has been expedient in a few places to cross-refer the reader of the *Advanced* volume to information presented in the other.

Technology is moving fast, with computers now dominating the role of Controller in feedback loops. Of necessity, much of this book concentrates on those aspects of computer hardware and software which are relevant to automatic control systems.

Moreover, the rapid overlapping of such fields as Data Communications, Feedback Control, Computer Engineering and Software Engineering has been reflected intentionally in this *Advanced* volume. This represents the situation as it now stands, with the technology. Thus, the competent Control Engineer now needs to have a good working knowledge of all of these fields, particularly in the way in which they inter-relate when controlling plant automatically. The Control Engineer, now more than ever before, needs to embrace the *holistic* systems approach to which reference was made in the preface of the *Basic* volume.

The present work has been produced by three authors, so as to draw on as wide a range of expertise as possible. In addition, we should particularly like to thank our good friend Ian Brown for the help given in preparing the chapter on realtime operating systems.

Acknowledgements would not be complete without including the steadfast support of our wives during the long hours needed to compile this material.

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1

Signal and Data Conversion

1.1 Introduction

It is commonplace for the output signal of one element in a control loop to be incompatible with the input signal requirements of the element which it is intended to drive. It therefore becomes necessary to interpose special hardware, in order to convert the characteristics of the driving signal to the appropriate form. Examples of configurations in which this would be necessary are the following:

- a transducer with a pneumatic output signal required to drive into an electronic controller
- a digital transducer required to drive into an analog electronic controller
- a synchro control transformer required to drive a DC servoamplifier.

Many other examples are easily conceived. Hardware which is capable of providing signal conversion of this nature will obviously be very varied in nature, depending largely upon the forms of the input and output signals of concern, and, for this reason, a survey of the alternative elements available must necessarily be limited in extent in this particular volume. (Note, for example, that complete volumes have been devoted just to analog-digital and digital-analog conversion techniques.)

The range of hardware available for signal conversion is summarised in Table 1.1., which should be interpreted by making reference to the Key. It should be noted that, if necessary, signal converters may be cascaded: thus, for example, an AC voltage signal may be converted into a set of signals representing parallel digital data by cascading together a demodulator and an analog-digital converter having parallel digital outputs. The type of hardware to which reference is made in the key of Table 1.1 will now be described in detail, with the exception of those previously described in *Basic Control System Technology*.

1.2 Voltage–to–current converters

Section 8.5.3 in *Basic Control System Technology* described how negative feedback may be used in order to create a voltage-controlled current source. A specific application of this technique is shown in Fig. 1.1.

It is readily shown for this configuration that, provided the amplifier output voltage V_o is not saturating and the amplifier can be regarded as 'ideal',

$$\frac{V_i}{R_1} + \frac{I_L R_D}{R_2} = 0$$

Solving for I_L yields $I_L = -\frac{R_2}{R_1 R_D} V_i$

Table 1.1 Signal conversion hardware

TO \ FROM	DC voltage	DC current	AC voltage (single)	AC synchro voltage pattern	AC resolver voltage pattern	Serial digital data	Parallel digital data	Pneumatic pressure (3 to 15 psi control air)
DC voltage	–	E	G			O	P	X
DC current	A	–						Y
AC voltage (single)	B		–	H	L	Q	R	
AC synchro voltage pattern				–	I	S	T	
AC resolver voltage pattern				I	–	U	V	
Serial digital data	C			J	M	–	W	
Parallel digital data	D			K	N	W	–	
Pneumatic pressure (3 to 15 psi control air)		F						–

Note (1) A blank entry signifies that no component exists to effect a conversion directly: conversion may be achieved by cascading two or more of the listed devices

(2) H, L and X, the section references given in the Key are to be found in the companion volume *Basic Control System Technology*.

Key:

A	current feedback around a high gain amplifier	: refer to Section 1.2
B	modulator; phase-sensitive, where necessary	: refer to Section 1.4
C	analog-digital converter (ADC) with serial output	: refer to Section 1.6
D	analog-digital converter (ADC) with parallel output	: refer to Section 1.6
E	resistor; with bufferred load, where necessary	: refer to Section 1.3
F	current—to—air converter (transducer)	: refer to Section 1.19
G	demodulator (rectifier); phase-sensitive, where necessary	: refer to Section 1.5
	or RMS-to-DC converter	: refer to Section 1.13
H	synchro control transformer with locked rotor, or use one line-to-line voltage	: refer to Section 3.2.5
I	Scott-T connected transformer pair	: refer to Section 1.10
J	synchro-digital converter with serial output	: refer to Section 1.11
K	synchro-digital converter with parallel output	: refer to Section 1.11
L	resolver control transformer with locked rotor, or use one line-to-line voltage	: refer to Section 3.2.6
M	resolver-digital converter with serial output	: refer to Section 1.8
N	resolver-digital converter with parallel output	: refer to Section 1.8
O	digital-analog converter (DAC) with serial input	: refer to Section 1.7
P	digital-analog converter (DAC) with parallel input	: refer to Section 1.7
Q	multiplying digital-analog converter (MDAC), with sinewave reference and serial input	: refer to Section 1.7
R	multiplying digital-analog converter (MDAC), with sinewave reference and parallel input	: refer to Section 1.7
S	digital-synchro converter with serial input	: refer to Section 1.12
T	digital-synchro converter with parallel input	: refer to Section 1.12
U	digital-resolver converter with serial input	: refer to Section 1.9
V	digital-resolver converter with parallel input	: refer to Section 1.9
W	shift register or counter	: refer to Section 1.14
X	gauge pressure transducer with voltage output	: refer to Section 5.4
Y	air-to-current converter (transducer)	: refer to Section 1.18

References to Sections 3.2.5, 3.2.6 and 5.4 above are to be found in the companion volume, *Basic Control System Technology*.

Sections 1.15, 1.16 and 1.17 contain descriptions of code converters, frequency-voltage converters and voltage-frequency converters, respectively, which cannot logically be entered into Table 1.1 but which sometimes feature in data conversion.

The limiting value for I_L is related to the saturation value $V_{o_{sat}}$ of the amplifier output voltage by $I_{L_{max}} = \dfrac{V_{o_{sat}}}{R_D + R_L}$ and $V_{o_{sat}}$ will usually be 1.5 to 2 volts (V) in magnitude less than the voltage of the amplifier supply rails (which is typically 12 V, 15 V, or 18 V).

The principal disadvantage with the network of Fig. 1.1 lies in the fact that the load must 'float', because the network requires the dropping resistor to be tied to signal common. This problem can be eliminated by interchanging R_D and R_L and feeding back the voltage drop $I_L R_D$ through a differential amplifier stage, as shown in Fig. 1.2.

The operation of the differential amplifier stage is described in Section 12.2.3 of *Basic Control System Technology* and the version shown here has a voltage gain of unity. The formulae quoted above for I_L therefore still apply.

Where the range of I_L is required to be offset (by, for example, 4 milliamperes (mA)), this can be effected by injecting an appropriate bias current into the negative input terminal of the inverting amplifier.

Figure 1.3 shows a simpler version (which only uses one operational amplifier) of the network of Figure 1.2. Analysis shows that, provided the relationship $R_2 R_3 = R_1 R_D$ is satisfied and the amplifier is not saturated, the output current I_L is related to the input voltage V_i by the expression

$$I_L = \frac{-V_i R_2}{R_1 R_D}; \text{ moreover, } I_L = -V_i/R_D \text{ if } R_1 = R_2.$$

The limiting value of I_L is given by

$$I_{L_{max}} = \frac{V_{o_{sat}}}{R_D\left(1 + \frac{R_L}{R_3}\right) + R_L}; \text{ if } R_L \ll R_3,$$

then their approximates to $I_{L_{max}} \cong \dfrac{V_{o_{sat}}}{(R_D + R_L)}$.

Figure 1.4 shows a non-inverting alternative to the network of Figure 1.1. For this arrangement, $I_L R_D = V_i$, so that $I_L = V_i/R_D$. Again, R_L and R_D may be interchanged if a differential amplifier stage is inserted into the feedback path. If required, I_L may be offset by adding a suitable bias to the input of the non-inverting amplifier, using the type of input resistor network described in Section 12.2.2. of *Basic Control System Technology*.

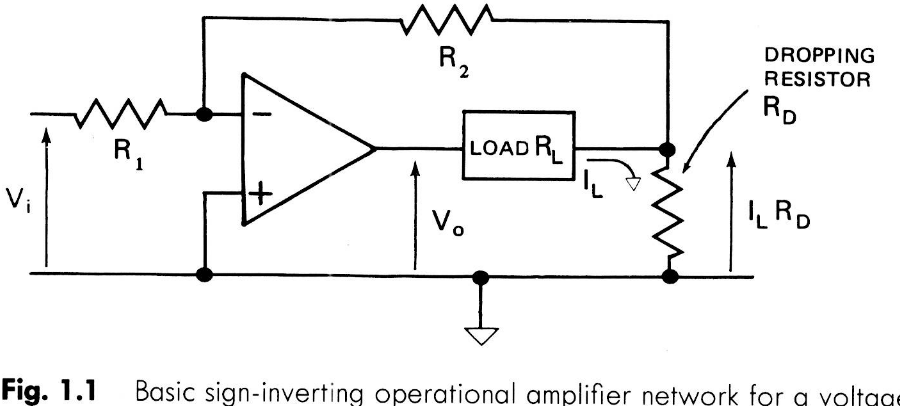

Fig. 1.1 Basic sign-inverting operational amplifier network for a voltage-controlled current source with a floating load

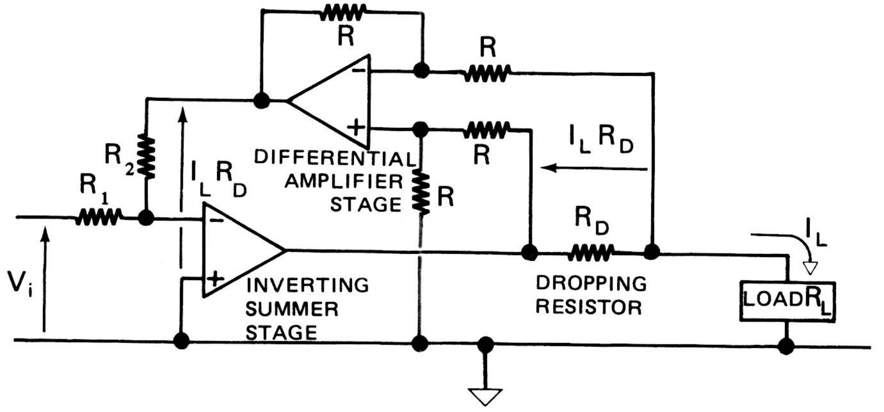

Fig. 1.2 Sign-inverting operational amplifier network for a voltage-controlled current source, with a grounded load

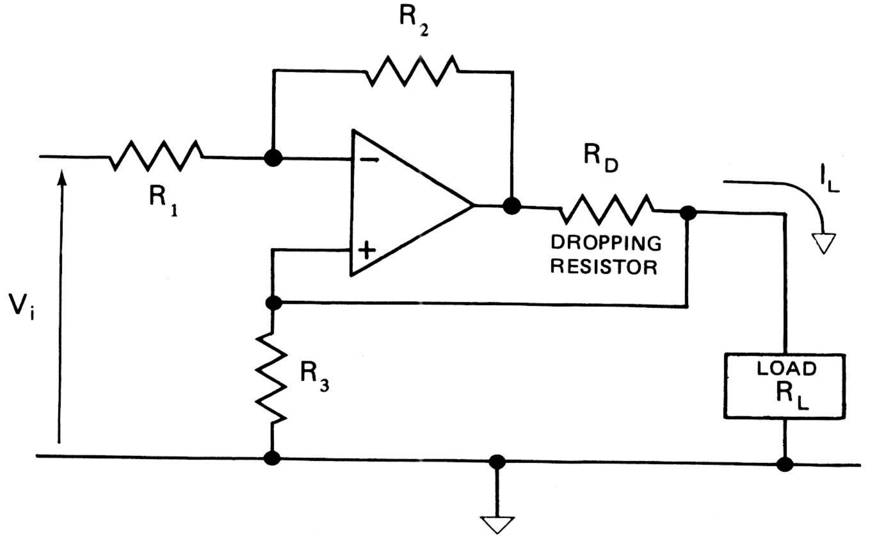

Fig. 1.3 Alternative and simpler sign-inverting operational amplifier network for a voltage-controlled current source, with a grounded load

The configurations shown here will be suitable for converting either DC or AC signals; power to the operational amplifier must be supplied for bipolar operation in the latter case.

Where the source of V_i has a low internal resistance and sufficient current drive, it may be possible to drive the load R_L directly from the source (yielding $I_L = V_i/R_L$), rendering the amplifier stages unnecessary.

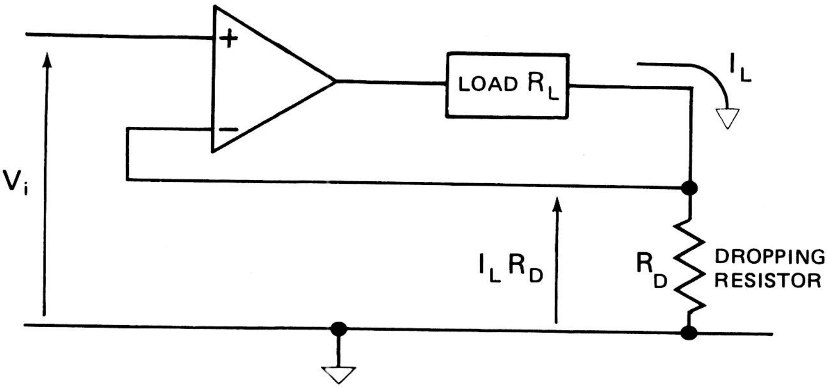

Fig. 1.4 Simple non-inverting operational amplifier network for a voltage-controlled current source, with a grounded load

1.3 Current–to–voltage converters

The usual method for converting a current signal into a voltage signal is by use of an appropriate dropping resistor. Figure 1.5 shows one possible configuration, which assumes that it is appropriate to connect one side of the resistor R_D to signal common.

The buffer amplifier must be included where the load resistance R_L is likely to vary and is sufficiently low as to create a significant shunting effect on R_D. The amplifier may be inverting or non-inverting, as required, typically using the configurations discussed in Section 12.2 of *Basic Control System Technology*: referring to these networks, $R_D I_i$ becomes the voltage source V_1 and the other source V_2 is redundant unless required as a bias source to offset V_o.

Where the dropping resistor cannot be tied to signal common, for whatever reason, it may be floated and allowance made for this by use of a

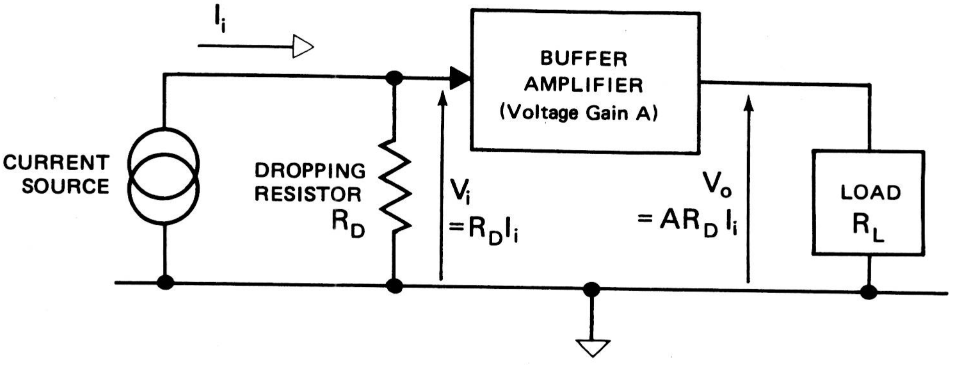

Fig. 1.5 Simple configuration producing a current-controlled voltage source

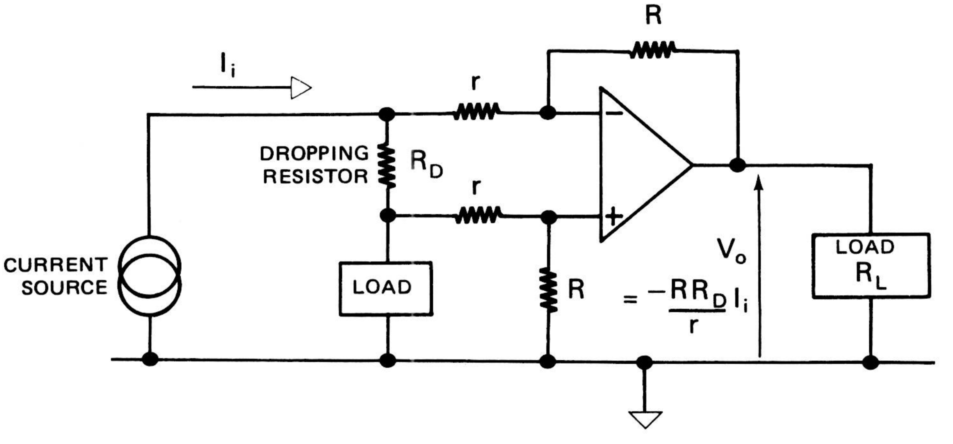

Fig. 1.6 Use of a differential amplifier in a current-controlled voltage source configuration

differential amplifier network of the type described in Section 12.2.3 of *Basic Control System Technology*: this is shown in Fig. 1.6.

The configurations shown here will be suitable for converting either DC or AC signals: in the latter case, the operational amplifier must be supplied for bipolar operation.

The process industries are currently tending to standardise on 1 to 5 V DC for the voltage signal range, in contrast to 4 to 20 mA DC for the most common current signal range: in this particular case, the dropping resistor would require to have a value of 250 ohm, assuming the amplifier stage to have a voltage gain of unity.

1.4 Modulators

The function of a modulator, in the control system context, is usually to convert a DC voltage into an AC voltage of fixed (carrier) frequency, such that the magnitude (defined in terms of either peak on RMS value) of the AC is proportional to the magnitude of the DC. This process, in a Telecommunications context, is referred to as 'suppressed – carrier amplitude modulation'.

Wherever the DC voltage is going to reverse in polarity, corresponding to a reversal in the sense of the data being represented by the DC signal, it is usual to cause the AC voltage to reverse its phase relative to the phase relationship pertaining before the occurrence of the DC sign reversal. The type of modulator which can achieve this phase reversal is said to be 'phase-sensitive'. Figure 1.7 shows typical waveforms for various input signal conditions and assumes that the output waveform is required to be sinusoidal.

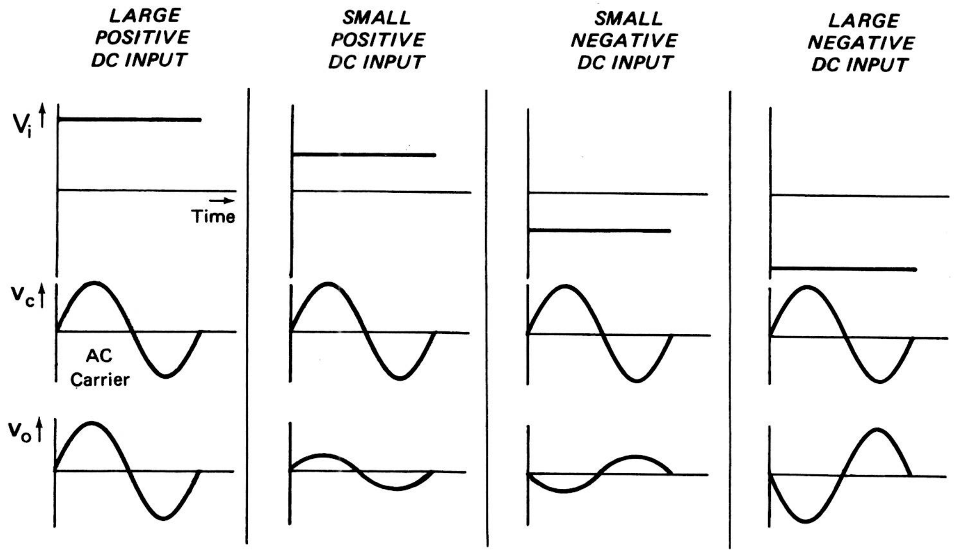

Fig. 1.7 Representative waveforms for a phase-sensitive modulator

Figure 1.8 represents the static characteristic required for the Phase-Sensitive Modulator (PSM).

The negative RMS output voltage values are to be interpreted as a reversal in the relative phase of the output voltage waveform.

The most common type of PSM network currently uses a monolithic analog multiplier: such a device is capable of multiplying together two analog voltages, as indicated in Fig. 1.9. Not shown in this diagram are

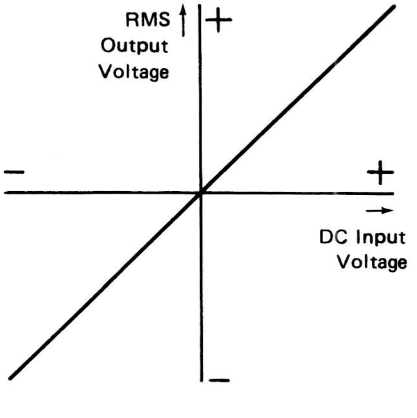

Fig. 1.8 Representative static characteristic of a phase-sensitive modulator

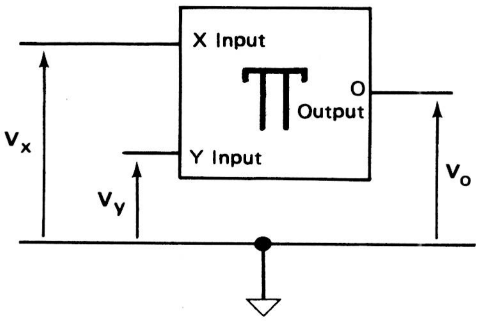

Fig. 1.9 Symbolic representation of an analog multiplier

external components usually necessary for setting output nulls, sensitivity, and for providing output power boosting: refer to Section 2.4.2 for further details.

The law for such a device is typically of the form $v_o = \frac{v_x v_y}{10}$, where v_x, v_y and v_o are in volts (V). Thus, $v_o = 10\,V$ when $v_x = v_y = 10\,V$. It is commonplace for the excursions of v_x, v_y and v_o to be limited to the vicinity of 10 V, so that external attenuation or amplification of signals may be necessary, depending on the particular application. In PSM applications, the multiplier is required to handle all four possible alternative combinations of input signal polarity (i.e. + + , + − , − + , and − −), so that it needs to be configured for 'four-quadrant' operation. Figure 1.10 shows such a multiplier being used as a PSM: it behaves according to the formula $v_o = kV_i V_{ref_m} \sin \omega_c t$, where k is a constant.

The phase-sensitive relationship may be expressed more clearly by rewriting the equation in the form:

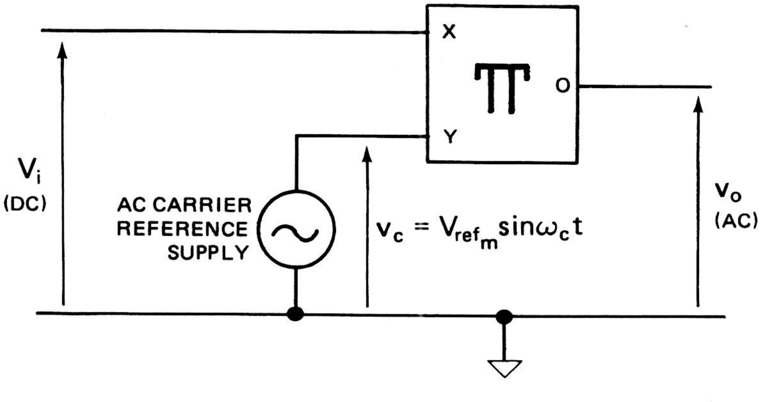

Fig. 1.10 Use of an analog multiplier as a phase-sensitive modulator