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Low and very low level DC amplifiers (Part III) Modulators and demodulators

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FOREWORD

In Ref.[61] it is stated that "The ability to process these low level d-c voltages to a range suitable for transmission is one of the major problems of modern telemetry".

This text is an attempt to bring together in a clear and orderly manner the basic information about the theory and the design of low level and very low level d-c amplifiers. Two such d-c amplifiers were built and their performance is discussed.

The text is subdivided into five parts :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
I.A.S, Aeronomica Acta A - N° 32 - 1964.

V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Part I and II deal with the basic theory of d-c amplifiers proper. The types of modulators and demodulators used in modulated d-c amplifiers are discussed in Part III. In Part IV we take up the design of a d-c amplifier with characteristics (performance, weight, size, power requirements,...) suitable for space applications. Finally Part V contains the abstracted references to which we refer in the text.

M. Nicolet.

AVANT-PROPOS

Dans la référence[61], on note que : "La possibilité d'adapter ces basses tensions continues à un domaine adéquat pour la transmission est un des principaux problèmes de la télémesure moderne".

Ce texte est un essai pour rassembler, sous une forme claire et ordonnée, les informations fondamentales concernant la théorie et l'utilisation des amplificateurs de tensions continues de faibles et de très faibles niveaux.

Le texte est divisé en cinq parties :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

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V. Literature and References.
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Les deux premières parties se rapportent à la théorie fondamentale des amplificateurs d-c. Les types de modulateurs et de démodulateurs utilisés dans les amplificateurs d-c modulés sont discutés dans la partie III. L'utilisation d'un amplificateur d-c pour les applications spatiales ainsi que les caractéristiques (performance, poids, forme, puissance, exigences,...) sont discutées dans la partie IV. Finalement, la partie V contient les références citées dans le texte ainsi que leurs résumés.

M. Nicolet.

VOORWOORD

In Ref.[61] wordt gezegd dat "Het beheersen van de technieken die nodig zijn om deze zwakke gelijkspanningen om te zetten in signalen die kunnen overgeseind worden één van de grootste problemen is van de moderne telemeting".

Deze tekst is een poging om op een klare en ordelijke wijze de grondgegevens samen te brengen betreffende de theorie en het ontwerpen van gelijkstroomversterkers voor zwakke en zeer zwakke signalen. Twee zulke gelijkstroomversterkers werden gebouwd en hun eigenschappen worden besproken.

De tekst is onderverdeeld in vijf delen :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

IV. A modulated d-c amplifier for microvolt signals,
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V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Deel I en II behandelen de basistheorie van de eigenlijke gelijkstroomversterker. De types van modulatoren en demodulatoren, die gebruikt worden in gemoduleerde gelijkstroomversterkers, worden besproken in deel III. In deel IV handelen we over het ontwerpen van een gelijkstroomversterker met eigenschappen (gewicht, afmetingen, voedingsvereisten,...) die hem geschikt maken voor ruimtetoepassingen. Deel V eindelijk bevat de referentiën met korte inhoud, naar dewelke we in de tekst verwijzen.

M. Nicolet.

VORWORT

In Referenz[61] steht geschrieben dass : "Die Möglichkeit dieser schwachen d-c Spannungen zu einem Gebiet nützlich für die Übertragung zu verwenden, ist eines der wichtigsten Problemen der moderne Fernmessung".

Dieser Text ist ein Versuch, um die Grundinformationen über die Theorie und die Benützung der d-c Verstärker für schwachen und sehr schwachen Spannungen in einer klaren und geordneten Weise vorzustellen.

Der Text besteht aus fünf Teilen :

I. Theory (I),
I.A.S, Aeronomica Acta A - N° 23 - 1963.

II. Theory (II),
I.A.S, Aeronomica Acta A - N° 24 - 1963.

III. Modulators and demodulators,
I.A.S, Aeronomica Acta A - N° 31 - 1964.

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V. Literature and References.
I.A.S, Aeronomica Acta A - N° 33 - 1964.

Die zwei ersten Teile haben Bezug auf die Grundtheorie der d-c Verstärker. Die verschiedenen Modulatoren und Demodulatoren die in modulierten d-c Verstärker gebraucht werden, sind im dritten Teil diskutiert. Die Verwendung eines d-c Verstärker für Raumforschung sowie die technischen Daten (Leistung, Gewicht, Form, Kraft, Anforderung,...) sind im vierten Teil diskutiert. Der fünfte Teil enthält die im Text angegebenen Referenzen sowie die Zusammenfassungen.

M. Nicolet.

CONTENTS OF PART III.

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LOW AND VERY LOW LEVEL DC AMPLIFIERS (Part III)

MODULATORS AND DEMODULATORS.

by

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As we have already stated in chapter 5, d-c amplification can be obtained by first converting the d-c signal to an a-c signal (modulation), then amplifying this a-c signal in an a-c amplifier, whereafter the amplified a-c signal is converted back to a d-c signal (demodulation) so that the overall function of the system is to yield an output d-c signal which is an amplified replica of the input d-c signal.

The conversion of the d-c signal into an a-c signal is done by a modulator and the conversion of the amplified a-c signal back into a d-c signal is obtained by the use of a demodulator.

MODULATORS

In this chapter we will discuss many of the various types of modulation systems which are in use or which have been proposed for the amplification of d-c signals. The importance of the modulating technique lies in the fact that so far it is the method that yields the most accurate way to amplify low-level and very-low-level d-c signals. Electromechanical modulators (also called " electromechanical choppers ") are nowadays the basic elements of every d-c amplifier which is able to recognize as low as 1 microvolt or even lower[108].

The basic function of the modulator is to accurately multiply two variables: the d-c input signal and another signal that is called the carrier. The carrier is a periodic changing signal so that the product of d-c input and carrier will also be a changing signal (except if the input is zero). The latter signal is then amplified by the a-c amplifier, whereafter it is multiplied by other functions (the demodulating carrier and eventually the filter transfer function) in order to finally yield a d-c signal again but of an amplified level with respect to the input d-c signal.

Although a perfect modulator would modulate the signal without adding any disturbance (= noise), it is in reality not possible to build such an ideal modulator: hence its output will always contain a certain amount of unwanted noise.

Modulators work(63) by modifying the conductance or impedance of some element of the modulator as a function of time. Time, in turn, is controlled either by a voltage or current representative of the carrier, or by the geometry of a mechanically variable element. Depending on the nature of the modification and the mode of controlling time, modulators can be classified as follows(63):

1. Electromechanical modulators:
    a. Magnetically driven choppers.
    b. Crystal driven choppers.
    c. Aircoupled choppers.
    d. Variable-reactance modulators.
    e. Induction or galvanometer modulators.
2. Electronic modulators:
    a. Multi-element vacuum-tube modulators.
    b. Vacuum-diode modulators.
3. Solid-state modulators:
    a. Semiconductor-diode modulators.
    b. Transistor modulators.
    c. Dielectric modulators.
    d. Nonlinear-resistor modulators.
    e. Thermistor modulators.
    f. Photoconductive modulators.

4. Magnetic modulators:
   a. Odd-harmonic modulators.
   b. Even-harmonic modulators.
   c. Magneto-conductive modulators.

1. Electromechanical modulators.

By " electromechanical modulators " we mean such modulating devices in which the action of modulating is performed by the variation of some mechanical characteristic of the device, the variation being controlled by an electrical signal.

a. Magnetically driven choppers.[(58),(63),(68),(74)]

These modulators (also called " contact modulators ") basically consist of mechanical switches which are opened or closed by the action of a current in a coil. In fact such choppers do not differ basically from relays. The frequency with which the contacts of the switches can be opened and closed depends primarily upon the moving part of the chopper. Usually the latter is a vibrating reed and the operating frequency should be in the neighborhood of the resonance frequency of the reed if optimal performance is desired.

Many failures of contact modulators and also part of the noise they produce are traced directly to the contacts[(93)]. Hence the latter should be well designed and materials for them should be chosen[(93)] on the basis of component design, conductivity requirements, tendency for surface contamination, wear, oxidation resistance, contact pressure, currents and voltages. Materials in use are discussed in Ref.[(93)] and include silver and its alloys, noble metals, refractory metals and copper and its alloys.

The noise of contact modulators (i.e. the r.m.s. voltage at the output of the modulator if no input is present) can be as low as one microvolt into a load of 100 kilohms.

A very good and complete discussion of the contact modulator itself as well as of the equipment used in association with it and some applications such as d-c to a-c conversion is given in Ref.[(74)]. The design of the converter (= chopper) is considered and at the same time the causes of errors and noise (suchas induced e.m.f.'s, thermal e.m.f.'s, stray currents, contact bounce, electrical wear, mechanical wear, contact resistance). In the design of associated equipment are discussed: the phase correction to be applied to magnetically driven choppers, the operating frequency, the stability of the waveform at the output of the chopper, the problems involved when the input of the chopper is not at ground potential, the mounting position of the chopper.

Also other references[(58),(68)] provide good information about the contact modulator.

One of the major advantages of a contact modulator is that it is able to switch between a very low resistance of much less than 0.1 ohm to one of over 10.000 megohms and in very short time intervals.

Some contact modulators also have small size and low weight and do not require much driving power (e.g. 10mA; 6 Volt peak-to-peak for Airpax Model 30 Chopper).

The expected life of contact modulators is about 5.000 working hours.

Mechanical choppers (= contact modulators) can be driven by a sinusoidal source as well as by a square wave source.

Furthermore the driving circuit is not electrically connected to the circuit in which the modulation takes place.

The major disadvantage of contact modulators is that they have moving contacts and at some point these contacts begin to wear. The moving contacts may also get disturbed by vibration or by shocks.

Contact modulators can be used in a variety of circuit configurations. Any circuit requiring almost ideal switching can use them (as far as the disadvantages mentioned above are not objectionable). A basic input circuit for d-c amplifiers is given in Fig. 91. The output voltage e_o will be in the form of a square wave (if the transformer is an ideal one) of which the amplitude is proportional to the d-c input voltage.

Another circuit using a transformer is given in Fig. 92. Here also the output voltage e_o will ideally be a square wave the amplitude of which is proportional to the d-c input.

A complete d-c amplifier circuit based on Fig. 91 but using negative d-c feedback from the output of the d-c amplifier to its input is shown in Fig. 93.

Although transformer coupling as in Figs. 91, 92 and 93 has certain advantages(68) (isolation between input circuit and a-c amplifier, matching of impedances,....) it definitely also causes a lot of problems. Transformers suitable for very-low-level operation (microvolt range and lower) have to be rather special(68) : high permeability and extreme shielding against external magnetic fields are necessary. Sometimes therefore some other coupling method than transformer coupling is desired.

Examples of circuits using capacitive coupling(68),(74) are shown in Figs. 94, 95, 96, 97 and 98 for input circuits and in Figs. 96, 97 and 98 for output circuits.

Circuits which compare two d-c inputs are given in Figs. 99, 100 and 101. One of the two input signals may be a feedback one. These circuits will give a measure of the difference of the two inputs.

The configurations given above (Fig. 91 to Fig. 101) are commonly used ones. More detailed information about circuits using contact modulators can be found in Ref.(68).

b. Crystal driven choppers.[24],[36]

These modulators are also contact modulators but they differ from the magnetically driven choppers discussed above by the fact that their moving part is made of a bending piezoelectric crystal. The crystal is made to bend by an applied voltage signal. By bending back and forth the crystal alternatively opens and closes the switching contacts.

These modulators are not much used.

Since only the driving method differs the rest of the circuitry is as discussed in the section above on magnetically driven choppers.

c. Aircoupled choppers.[15]

These modulators again are only a modification of the magnetically driven type. The driving source here is a system looking like a loudspeaker-microphone system: the "speaker" is the driver unit and produces a pressure wave in a plastic tube through which it is coupled to the "microphone". The latter contains a phenolic diaphragm which vibrates under the influence of the pressure wave and by doing so closes and opens the chopper contacts.

The advantage of this device is[15] that the exciting voltage (which produces the pressure wave through the intermediary of the "speaker") is kept entirely out of the field around the contacts, so that no local noise is generated except the thermal noise due to contact friction.

This chopper is not used in practice.

The circuitry associated with this type of chopper is again the same as the one discussed in the section on magnetically driven choppers.

d. Variable-reactance modulators.[6],[63]

There are several techniques for changing the value of an element of resistance, inductance, or capacitance sinusoidally so that cascading it with a d-c input yields an a-c output proportional to the d-c input. Fig. 102 shows the general configuration.

Variable-resistance systems.[6], [63]

Typical variable-resistance units incorporate a carbon microphone, strain gauge, or rheostat. If the variable resistance varies as

$$R_v = R_o\ (1 + m \cos w_c t)$$

then the output voltage across R_L (Fig. 102) will be :

$$E_o = \frac{R_L}{R_L + R_v} \cdot E_i$$

$$= \frac{R_L}{R_L + R_o + m\, R_o \cos w_c t} \cdot E_i$$

$$= \frac{R_L / R_L + R_o}{1 + mR_o / R_L + R_o \ . \cos w_c t} \cdot E_i$$

Assuming $R_L + R_o \gg mR_o$ we find :

$$E_o \cong \frac{R_L}{R_L + R_o} \left[1 - \frac{mR_o}{R_L + R_o} \cos w_c t \right] . Ei$$

and the a-c component appearing at the output will be :

$$E_{o\ AC} \cong - \frac{m\ R_L\ R_o}{(R_L + R_o)^2} \cdot E_i \cdot \cos w_c t$$

If furthermore $R_L \gg R_o$

then $$R_L + R_o \cong R_L$$

and
$$E_{o\ AC} \cong - \frac{mR_o}{R_L + R_o} \cdot E_i \cdot \cos w_c t$$

An example of a variable-resistance modulator is given in Ref.(6): a modulator is described which uses a carbon microphone mechanically connected to a vibrating piezoelectric crystal.

<u>Variable-inductance systems.(63)</u>

Variable-inductance modulators are not commonly used because of high distortion problems.

<u>Variable-capacitance systems.(27),(29),(63)</u>

The variable-capacitance modulator is the most practical one of the three variable-reactance types. Tuning forks or rotary capacitors are driven at a synchronous speed equivalent to the carrier frequency. Let the capacitance in Fig. 103 assume a value

$$C_v = C_o\ (1 + m \sin w_c t)$$

Attempts to solve the problem (consisting of finding E_o as a function of E_i) lead to unmanageable integrals(29). Wente (1917) obtained a result by assuming the form of the solution to be a Fourier series, and evaluating of the constants by substitution. He found:

$$\frac{E_o}{E_i} \cong \frac{m\, R_L}{\sqrt{R^2_L + \left(\frac{1}{C_o\, w_C}\right)^2}} \cdot \sin\,(w_c t + \varphi_1)$$

where $\varphi_1 = \tan^{-1}\,(^1/\,R_L\, C_o\, w_c)$

A rather elaborate theory is given in Ref.[29] and involves Bessel functions within complicated formulae.

These modulators[63] are used when a very high input impedance is required, and impedances as high as 10^{12} ohms are practical. They exhibit good linearity for small element excursion (up to 0.1 percent), but practical considerations involving mechanical tolerances limit the ultimate accuracy to about 1 percent. Efficiency is low. The input is substantially free of harmonic distortion, although mechanical asymmetries may contribute considerable intermodulation distortion. Short life and component requirements restrict the usefulness of the rotary types.

e. Induction or galvanometer modulators.[21],[50],[63]

An induction modulator is essentially a d'Arsonval movement with the moving coil positioned by the d-c input signal impressed on it (Fig. 104). A-c field coils mounted directly on the magnets produce additive flux fields in the axial direction. This in turn induces an a-c voltage in the moving coil proportional to its position as determined by the d-c signal.

Induction modulator life[63] is quite good because there are no vibrating contacts. In addition the unit exhibits a high gain conversion, requires little filtering of the sinusoidal output, and can have a high sensitivity.

These advantages are somewhat counterbalanced, however, by a considerable null offset (up to 10 millivolts), a linearity of about 2.5 percent, and a relatively large time constant (up to 0.37 sec) depending on the type of damping and the gain requirements.

A more detailed discussion and circuits which contain slight modifications with respect to the circuit of Fig. 104 can be found in Ref.[21] and Ref.[50].

2. Electronic Modulators[63].

By "electronic modulators" are meant modulating devices which are based upon the modulating properties of vacuum tubes.

Electronic modulators have wide flexibility, high impedance levels, and high switching speed. They are simple and low in cost. However they exhibit a number of nonlinearities, high null offsets, low dynamic ranges, and problematic drift. There are two basic classes in this group:

(1) multielement vacuum-tube modulators, in which certain tube characteristics are modified by the modulating signal

and (2) vacuum-diode modulators, in which unidirectional conduction is the modulating means.

a. Multi-element vacuum-tube modulators.[63]

All these modulators are based upon the fact that the output of a vacuum tube with two inputs depends upon each of these inputs. One of the inputs is the d-c signal to be modulated, the other is a carrier. The output then is a varying (hence a-c) signal with its frequency equal to the carrier frequency and with its amplitude depending upon the amplitude and the polarity of the d-c input signal.

Instead of only one input there may also be more of them[63]. It is possible, for example, to get an output signal which is a measure of the difference of two input signals.

The d-c signals as well as the carrier signal can be brought in either at the plate, at any of the grids or at the cathode of a vacuum tube.

If desired a balanced configuration may be used for better performance.

The carrier signal can either periodically displace the operating point of the vacuum tube(s) or it can periodically switch the tube(s) on and off.

Signal-to-noise ratio, relatively low in this class of modulators, restricts it to high-signal level applications. Other disadvantages are[63]:

(1) Low efficiency (about 5 percent) except for the cutoff modulators (about 25 percent)
(2) Rather nonlinear performance except for small input signals.
(3) Serious drift problems resulting primarily from cathode instability.
(4) A frequent requirement for bias voltages or balancing potentiometers.
(5) Sensitivity to plate supply variations.
(6) (On balanced types) problematical accuracy in the cancellation of undesired signals.

Advantages are[63] that the modulators

(1) are flexible.
(2) are inexpensive.
(3) exhibit high input impedance.
(4) have a life expectancy of about 10.000 hours.
(5) have a high carrier frequency range.

A few simple typical circuits are given in Fig. 105 to 109. Other possible circuits and more information about multi-element vacuum-tube modulators can be found in Ref.[63]

b. Vacuum-diode modulators.[63]

Prior to the advances in semiconductor diodes, the vacuum diodes yielded the highest ratio of backward to forward impedance.

They have high null offsets and problematical drift since balance is seriously affected by heater voltage variations. Their on-off condition is usually controlled by a sinusoidal carrier, although a square-wave carrier gives greater dynamic range. Average linearity is about plus or minus 1 percent.

Three modulator circuits using vacuum diodes are shown in Fig. 110 to 112. Other circuits are, of course, possible. In particular the circuits that will be given for semiconductor-diode modulators can also use vacuum diodes instead of semiconductor diodes.

3. Solid-state Modulators(63).

This class of modulators is based upon the characteristics of semiconductive elements or of special dielectric elements.

In modulator applications these elements can be classified as follows:

(1) Semiconductor diodes.
(2) Transistor elements.
(3) Dielectrics such as voltage-sensitive capacitors.
(4) Nonlinear resistors such as Varistors and Thyrites.
(5) Thermistors.
(6) Photoconductive elements.

a. Semiconductor-diode modulators.(57),(63)

Semiconductor-diode or rectifying-element modulators use diodes two ways, either as on-off switches based on the ratio of backward-to-forward resistance, or as nonlinear switches operating on the current-voltage characteristic of the diode.

The disadvantage of solid state rectifying[63] elements is the presence of reverse current when the applied voltage is reversed. The most commonly used rectifying elements for modulators are[63]:

(1) Copper-oxide.
(2) Selenium.
(3) Germanium.
(4) Silicon.

A brief but good discussion of each of these elements is given in Ref.[63]. Their temperature range, reverse voltage, and some other characteristics are considered. It turns out that silicon diodes are ideal for high-performance modulators, especially the on-off type requiring high back resistance and good forward conductance. Also for temperature characteristics silicon is the best. Furthermore, silicon diodes are small, they show negligible ageing effects and have good zero stability. Germanium diodes have in general worse characteristics (e.g. for temperature variations, forward and backward resistances, ageing effects,....). Copper-oxide and selenium diodes are not so good as germanium or silicon.

Some of the typical circuits for semiconductor modulators are:

(1) Basic diode chopper (Fig.113).
(2) Bridge (Cowan) modulator (Fig.114).
(3) Ring modulator (Fig.115).
(4) Diamond modulator (Fig.116).
(5) Full-wave bridge comparator modulator (Fig.117).

Depending on the polarity and magnitude of the reference voltage, the diodes are conducting or nonconducting. In practice the carrier amplitude should be enough greater than the signal amplitude so that, in first approximation, the bridge can be assumed to act as a switch. In a bridge modulator for example this switch closes during every other half-cycle of the carrier and opens during the other. In the ring modulator on the contrary the switch reverses the polarity of the output after each half-cycle.

A typical[63] ring modulator with matched germanium diodes gives a signal-to-noise ratio of greater than 5,000 : 1, a linearity of about plus or minus 1 percent, and a drift rate of 1 millivolt per hour at room temperature operation.

For overall performance diamond modulators[63] give very good results. Null offsets of 0.5 millivolt with a signal-to-noise ratio of 8,000 : 1 and 1 percent linearity are claimed.

Full-wave bridge modulators are basically Cowan bridge configurations in push-pull. By using matched resistors in series with the diodes, the unbalanced effects of the diodes are reduced, though at the same time the operating level of the unit increases.

(Note: The signal-to-noise ratio of a modulator is the ratio of the maximum allowable signal and the noise generated within the modulator).

b. <u>Transistor modulators.[63],[54],[64],[69],[84],[85],[94]</u>

As a nonregenerative switch (that is, a switch that can be maintained in an altered condition only by the continued application of a minimum-level control signal) a transistor can exhibit many megohms impedance in the off condition and less than one ohm in the on condition, with a voltage drop of only a few millivolts. These characteristics make possible high-performance transistor modulators. And since the transistors are not used as amplifiers, parameter changes do not affect performance as a switch.

The switching action depends on the[63] relative polarity of the transistor elements. Thus, when in a PNP transistor for example the base is positive with respect to both the emitter and the collector, the transistor is equivalent to an open switch for in this configuration both junctions of the transistor are biased in the reverse direction. When the polarity reverses, the transistor becomes a closed switch.

Transistorized switches nowadays are competing with electromechanical switches, especially in applications where the inertia of the latter and the presence of moving contacts is objectionable. In general transistorized switches (or also called "transistorized choppers") are much smaller and lighter than electromechanical choppers and require less driving power. They perform the same function as the latter but do not have moving contacts and their troubles (mechanical wearing, electrical wearing,.....). The driving frequency of transistor choppers is therefore not critical either, and this frequency may sometimes be as high as 100 kcs. On the other hand the null stability of transistorized choppers (that is, their output for zero input) is much worse than for electromechanical choppers: their null stability is in the millivolt range. There are, however, nowadays transistor choppers with null stability in the 100 µV range for appropriate loads. Transistor choppers do not have as high an impedance in the off condition as their electromechanical counterpart, nor do they have as low an impedance in the on condition. Input and output load impedances are critical where transistors are used as choppers, and should match the transistor parameters. Furthermore transistor choppers also require a square wave driving source for optimum performance. It should be mentioned also that the driving source voltage must be high enough in order that the biasing of the transistor junctions be completely determined by this driving voltage and not at all by the incoming signal.

In designing transistor modulators, the transistor Zener voltage is of prime importance, because it determines input-signal versus reference (= carrier) - voltage limit. If the Zener voltage for any junction is exceeded, the transistor will not operate properly and may even be destroyed.

For best performance (especially where temperature variations are expected) the transistor chopper is switched between the saturation condition and the reverse bias condition. The phenomena occurring when the transistor enters the saturation region and when it again leaves it (i.e. storing of minority carriers in the base and removing them again) cause a peaked disturbing signal to appear at the output. This signal is part of the noise in a transistor chopper.

Another source of noise due to the switching is that the driving signal appears across at least one of the junctions of the modulator. This will, in the output, show up as a signal of carrier frequency. Balancing is possible by using pairs of transistors but complete balance can never be obtained.

Sources of noise other than the ones mentioned above are these that exist in each transistor. Noise due to temperature agitation of the carriers, noise due to carrier distribution variations between base and collector, noise due to leakage current (I_{co}) and noise resulting from the fact that the base resistance of a transistor is not zero are among the most important noise sources in transistors.

Due to all the disturbances mentioned above the performance of transistorized choppers is still much poorer than that of contact modulators. Random noise in transistor modulators is in the range of 100 μV to 1 mV rms. and 3×10^{-8} amp. respectively.[(69)] Peak values occurring at the switching instants are much higher and have an amplitude of about 20mV. Sometimes better performance[(64),(69)] may be obtained by reversing the transistor (that is, by using the emitter as collector and the collector as emitter).

More details about transistorized choppers can be found in Ref.[(54),(64),(69),(84),(85),(94)]. There the noise and its reduction, the switching characteristics and some mathematical calculations about the physics and the working of transistor choppers are considered.

Since the driving source for transistor choppers is not isolated from the signal path we cannot say that the circuits using these choppers are identical to the ones using electromechanical choppers. However, an electromechanical chopper equivalent of a transistor chopper circuit can usually be found. Several such circuits[68],[94] with their electromechanical counterpart are shown in Fig. 118 to 125.

The advantage of the circuit of Fig. 119 over the one of Fig. 118 is that in Fig. 119 the effects of the driving source voltages and currents will tend to cancel as far as the output is concerned. Indeed the transistors T_1 and T_2 in Fig. 119 are in series and the driving source effects upon each of them will be approximately equal in amplitude (especially when the transistors are matched) but in the opposite direction with respect to the output.

In Fig. 121 the offset voltages due to the driving source will again tend to cancel as far as the output a-c signal is concerned.

If in the above examples we use pairs of transistors instead of one transistor per switching function then a better cancellation of driving source effects upon the output is attained. An example is given in Fig. 126. The working of this circuit is in principle identical to the one of Fig. 121. The only difference is that the modulator in Fig. 126 provides a much better[68] cancellation of the offset voltage due to the driving source.

As seen in the examples given, the transistors may be either PNP or NPN.

c. Dielectric Modulators.[63]

Voltage-sensitive capacitors can be used to form modulators. Some of these capacitors derive their voltage-sensitive property from special ceramic dielectric materials (usually barium titanate) which have a dielectric constant dependent on the electric field across them. Diodes with the external voltage applied in the reverse direction will also exhibit properties of voltage-sensitive capacitors: at a p-n junction the density of charge carriers (electrons in the n region and holes in the p region) is reduced virtually to zero when a voltage is applied across the junction in the reverse direction. As the voltage increases the region of zero carrier density, known as the depletion region, gets wider. In effect this moves apart the two conducting areas and decreases the junction capacity of the diode as if there were two metal plates separated by a dielectric whose thickness was variable. A trade name of silicon diodes used in such applications is "varicaps". Fig. 127 shows the characterictic curve of a typical voltage-sensitive capacitor.[63]

The change of capacitance caused by a change in the input d-c voltage can be sensed in an a-c bridge, giving an a-c output corresponding to the d-c input. Usually the carrier frequency used is high because the capacitances and their changes are small.

Modulators[63] designed with voltage-sensitive capacitors are used for high-input-impedance applications, especially when the d-c input signal varies over a wide range.

d. Nonlinear-resistor modulators.[63]

These modulators basically contain a resistor whose resistance varies as a function of applied voltage. They can be used in a-c bridges.

The Thyrites* and Varistors** are well-known materials whose resistance varies as a function of applied voltage. Their volt-ampere characteristic can be approximated by

$$I = KE^n$$

* General Electric Co.

** International Resistance Co.

where I = instantaneous current passed by the element.

E = instantaneous voltage applied to the element.

K = a constant depending on the shape and size of the unit.

n = an exponent depending on the properties of the unit and on the operating voltage level ($n = 1$ for a linear resistance).

Since n increases with increased voltage level (and can vary from 2 to 6), modulators using these elements are [63] especially designed for high-voltage operation, usually greater than 1 volt. Indeed when the d-c operating voltage increases then also n increases : this will make the input-output transfer function more non-linear in such a sense that the variation of the a-c output amplitude per unit variation of the d-c input amplitude will become larger provided the d-c input amplitude is not too large. The device is then more sensitive in the range of relatively small input voltages (small turns out to mean : of the order of 1 Volt and immediately larger [63]).

Fig. 128 shows the internal resistance as a function[63] of applied voltage for a typical material and Fig. 129 shows a typical modulator circuit[63].

The quiescent value about which the voltage across the nonlinear resistor R_n will vary is given by the d-c input voltage. Hence looking at Fig. 128 we see that the swing of the varying voltage across R_n will also be dependent upon this d-c input voltage.

e. Thermistor modulators[63]

A thermistor is a temperature-sensitive resistor with a high negative temperature coefficient. Its internal resistance is approximately :

$$R = R_c \cdot \varepsilon^{\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)}$$

where R_o = resistance at a reference temperature T_o

T = operating temperature in deg. Kelvin.

β = a coefficient depending on the material. β varies with temperature but may be considered constant over a limited temperature range.

Differentiating the above equation gives the temperature coefficient :

$$\alpha = \frac{1}{R} \cdot \frac{dR}{dT} \cong - \frac{\beta}{T^2}$$

which may be considered to be a constant over a given temperature range provided the latter is not too large.

In a thermistor modulator, a temperature differential caused by the input current changes the thermistor's resistance. This unbalances an a-c bridge and results in an a-c output corresponding to the d-c input voltage.(63) Since there are large thermal time constants involved, this type of modulator can be used only with inputs that vary slowly. In addition, heat transfer between the thermistor and the surroundings may change the modulator into a transducer, resulting in poor modulator performance.

f. Photoconductive modulators.(63)

In several sulfide compounds the internal resistance is a function of the amount of light energy that falls on the exposed surface. Fig. 130 shows the internal resistance of a lead sulfide cell as a function of incident light flux. By modulating the light flux from maximum to minimum intensity it is possible to use the cell as an on-off switch for modulating a d-c input voltage.

Fig. 131 shows the configuration of a basic photoconductive modulator.

Since maximum sensitivity occurs around the frequency of green light, use is made of special glow lamps centered around 5,000 to 10,000 angstroms, depending on the type of sulfide.

The input resistance R_1 in Fig. 131 is adjusted according to the maximum obtainable resistance of the cell as indicated in Fig. 130, and according to efficiency, noise and optimum-output-load considerations. Light modulators [63] are used in medium level applications where low drift and long life are important. Vibration or shocks do not affect the modulator. Restricted temperature range is the limiting parameter, with the highest permissible operating temperature about 80 deg. C. Also the photoconductive material used in the cell should be chosen such that the photoelectric effect be as low as possible. Due to the photoelectric effect light energy is transformed into electrical energy which develops a voltage across the cell output terminals. The latter disturbs the input signal and should therefore be avoided.

A d-c amplifier circuit containing a photomodulator and using feedback [43] is shown in Fig. 132.

A photomodulator as used in a Goldberg compensating circuit (the Goldberg circuit was discussed in chapter 6) is investigated in Ref. [37].

4. Magnetic Modulators [63].

This class of modulators uses the nonlinear characteristics of magnetic materials. A typical magnetic modulator consists of a balanced bridge, with a number of reactors connected so that a change in the d-c input will change the reactances of the bridge in a differential manner, and thereby produce an a-c output proportional to the d-c input.

Magnetic modulators are entirely static. The second harmonic type has a very good null stability (less than 5 μV output for zero input is possible [63]). Furthermore the life expectancy of magnetic modulators is high (about 100,000 working hours). They can also be made very sensitive : 10^{-19} watts per cycle of frequency of the carrier are feasible [63]. (Input is expressed in power rather than in voltage or current because of the inherent low impedance of these modulators). On the debit side, magnetic modulators [63] are rather temperature-sensitive, large in size, heavy, expensive, limited in carrier frequency range, and affected by stray fields, thermal e.m.f.'s and memory effects (due to very large input signals). They also have a relatively low input impedance. (This explains why the input of these modulators is expressed in terms of power rather than of voltage or current).

Basically two types of what is usually meant by magnetic modulators are possible for d-c amplifiers :

(1) The odd-harmonic modulators.
(2) The even-harmonic modulators.

It is for these types that the discussion above is valid.

As a third type, however, that can be considered, is the class of modulators which use the dependence of their conductance upon a magnetic field to modulate the applied d-c input signal. These modulators will therefore be discussed under the heading "Magneto-conductive modulators" .

a. Odd-harmonic modulators.

An odd-harmonic modulator is a magnetic modulator whose output contains a fundamental signal (= signal of modulating frequency) as well as all the harmonics (= signals whose frequencies are multiples of the modulating frequency). (The output of the even-harmonic modulator will be seen to consist of nothing but even harmonics).

To gain a basic understanding of how this type of modulator works let us consider Fig. 133. In this figure each of the two cores contains three windings :

(1) One for the input d-c signal or more exactly for the input d-c current.
(2) One for the carrier signal plus the bias current.
(3) One for the output a-c signal.

We assume the number of turns on each core to be the same for corresponding pairs.

For convenience Fig. 133 is reproduced schematically[(63)] in Fig. 134.

The basic characteristics of the cores giving the flux linkages versus the total magnetomotive force producing these flux linkages is shown in Fig. 135. (For the basic explanation following here it is convenient to neglect hysteresis phenomena and just to consider an " average" curve).

The carrier signal E_c is assumed here to be a sinusoidal voltage. As we see (Figs. 133 and 134) this voltage is applied across the series combination of two coils, one on core 1 and the other on core 2. Let us denote the flux linkages of core 1 by λ_1, and the ones of core 2 by λ_2. Then from Fig. 133 it is seen that instantaneously :

$$E_c = \frac{d\lambda_1}{dt} + \frac{d\lambda_2}{dt} \; .$$

Clearly the current through one of the two carrier coils must equal the current through the other. Let us also denote the d-c bias current by I_b (Fig. 133).

Let us now first consider the d-c input signal to be zero : in that case the quiescent operating point for both cores is the same, notably point A in Fig. 135. (Note that we can to a first approximation assume that the carrier signal is small enough so that we may linearize the curve at point A). Since the cores are now in identical situations we see that :

$$d\lambda_1 = d\lambda_2$$

and that from the equation $E_c = \frac{d\lambda_1}{dt} + \frac{d\lambda_2}{dt}$

we get : $$\frac{d\lambda_1}{dt} = \frac{d\lambda_2}{dt} = \frac{E_c}{2}$$

This means that the induced output voltage (= the one appearing across the output terminals of the device) is given by :

$$E_o = \frac{N_3}{N_1} \frac{d\lambda_1}{dt} - \frac{N_3}{N_1} \frac{d\lambda_2}{dt}$$

(because here the coils work in opposition !)

Hence for zero d-c input signal the a-c output is given by :

$$E_o = \frac{N_3}{N_1} \left(\frac{E_c}{2} - \frac{E_c}{2} \right) = 0.$$

If now a voltage E_i is applied at the d-c input so that it results in a current I_i in the d-c input windings then the quiescent points of the cores will be shifted away from point A and in the opposite direction because the d-c input coils work in opposition. In the configuration shown in Figs 133 and 134 the quiescent point of core 1 will now be shifted toward B in Fig. 135 and the one of core 2 toward C. Obviously because of the nonlinearity of the magnetic characteristic the slopes of the curve at points B and C are not equal. This means that in the equation

$$E_c = \frac{d\lambda_1}{dt} + \frac{d\lambda_2}{dt}$$

it is no longer true that the variations of the flux linkages are equal. Since we assume that we may linearize the curve of Fig. 135 about each of the points B and C as far as the carrier signal is concerned, we may say that at point B

$$d\lambda_1 = k_B \cdot d\mathcal{F}_1$$

and at point C, $d\lambda_2 = k_C \cdot d\mathcal{F}_2$

where k_B and k_C obviously are the slopes of the curve at the points B and C. When the carrier signal is applied it is still true that the currents in the two carrier coils are equal so that $\qquad d\mathcal{F}_1 = d\mathcal{F}_2$

for the magnetomotive forces $\mathcal{F}_1$ and $\mathcal{F}_2$ are direct proportional to the currents and the only currents that vary here are the currents in the carrier coils. In that case then

$$E_c = \frac{d\lambda_2}{dt} + \frac{d\lambda_2}{dt} = \frac{d\mathcal{F}_1}{dt} \cdot (k_B + k_C)$$

and

$$\frac{d\lambda_1}{dt} = k_B \frac{d\mathcal{F}_1}{dt} = \frac{k_B}{k_B + k_C} \cdot E_c$$

$$\frac{d\lambda_2}{dt} = k_C \frac{d\mathcal{F}_2}{dt} = \frac{k_C}{k_B + k_C} \cdot E_c$$

The induced output voltage is now :

$$E_o = \frac{N_3}{N_1} \cdot \frac{d\lambda_1}{dt} - \frac{N_3}{N_1} \cdot \frac{d\lambda_2}{dt}$$

$$= \frac{N_3}{N_1} \left(\frac{k_B}{k_B + k_C} - \frac{k_C}{k_B + k_C} \right) E_c$$

$$= \frac{N_3}{N_1} \cdot \frac{k_B - k_C}{k_B + k_C} \cdot E_c$$

with $k_B < k_C$.

Obviously the output signal depends upon the slopes k_B and k_C, hence upon the d-c input signal.

When the polarity of the d-c input signal changes then also the points B and C (Fig. 135) interchange and thus k_B and k_C so that the output voltage is

$$E_o = \frac{N_3}{N_1} \cdot \frac{k_C - k_B}{k_C + k_B} \cdot E_c \quad \text{with } k_B < k_C$$

for this case. Hence the polarity of the d-c input determines the phase of the a-c output.

Now we can see why an initial bias current I_b was necessary. Indeed if I_b were zero then the d-c input current would shift the quiescent points to two locations B and C symmetrical with respect to the origin of the coordinate system. Since also the curve is symmetrical about the origin we would have that $k_B = k_C$ no matter what the d-c input signal is.

The above discussion gives a basic explanation of how an odd-harmonic magnetic modulator works. Of course, in practice the situation is not so ideal as depicted above : linearizations may not be allowed about the quiescent points, the output current has importance too, there will be some interaction from the carrier coils to the input coils, leakage inductances of the coils may have to be considered, etc.

The initial bias I_b imposes a severe limitation[63] on this type of magnetic modulator, since any bias drift shows up directly as output drift. Indeed in Fig. 135 the points B and C are not only determined by the d-c input but also by the bias and it is the location of these points that really determines the output.

Zero stability is also a problem because of the difficulty of permanently matching the magnetic cores at all points on their magnetization characteristic.

These modulators are not used for accurate low-level d-c amplification because the even-harmonic magnetic modulators turn out to be much better for such application.

b. Even-harmonic modulators[4], [38], [63]

Materials used for even-harmonic modulators are chosen so that there is a rather sharp knee in their magnetic B-H characteristic as shown in Fig.136 which is an idealized picture of what is found in practice.

The basic circuit for an even-harmonic magnetic modulator is the same as the one for an odd-harmonic magnetic modulator except that no initial bias is necessary and that the carrier signal is quite large now. The basic circuit given in Fig. 133 and Fig. 134 is reproduced for convenience in Fig. 137 and Fig. 138.

The carrier signal which is usually a sinusoidal one has an amplitude such that with no d-c signal applied at the input the amplitude of the resulting magnetic field strength H is equal to or greater than the field strength H_k corresponding to the knee of the magnetization curve.

Let us now see what happens. We assume the field strength resulting from the carrier signal to be sinusoidal (this also means that we assume the carrier current to be sinusoidal). We then get waveforms as in Fig. 139 for no d-c input. Obviously the flux and therefore the change in flux is always the same in both cases. Hence the instantaneous output voltage which is in fact proportional to the difference of the flux linkage variations per unit of time of the two cores is

$$E_o = \frac{N_3}{N_1}\left(\frac{d\lambda_1}{dt} - \frac{d\lambda_2}{dt}\right) \text{ and is always zero.}$$

We now assume a d-c input current I_i (Figs. 137 and 138) is applied. Then the corresponding waveforms are given in Fig. 140. Note that the d-c input current shifts the quiescent points of the cores away from the origin but in the opposite directions. The instantaneous output voltage is again proportional to the difference of the flux linkage variations per unit of time of the two cores :

$$E_o = \frac{N_3}{N_1}\left(\frac{d\lambda_1}{dt} - \frac{d\lambda_2}{dt}\right)$$

$$= N_3\left(\frac{d\varphi_1}{dt} - \frac{d\varphi_2}{dt}\right)$$

because $\lambda_1 = N_1\,\varphi_1$

and $\lambda_2 = N_1\,\varphi_2$

Furthermore the flux linkages and the fluxes are also proportional to the flux densities so that

$$E_o = k\left(\frac{dB_1}{dt} - \frac{dB_2}{dt}\right)$$

$$= k\,\frac{d}{dt}\,(B_1 - B_2)$$

where k is a constant.

This explains how in Fig. 140 we found the output signal E_0 graphically starting from the sinusoidal varying field strength and the magnetization curve B-H.

As seen in Fig. 140 we get two periods of the output waveform for every period of the carrier waveform. This is the reason why this modulator is called the even-harmonic modulator : the output harmonics will all be even multiples of the carrier frequency.

The output a-c signal is usually fed into a band-pass filter which then gives at its output a sinusoidal voltage signal that has a frequency which is twice the carrier frequency and that has an amplitude proportional to the d-c input signal. A change in polarity of the input signal reverses the phase of the output voltage.

Although some of the assumptions we have made in our discussion (e.g. the idealized magnetization characteristic, the sinusoidal input current) are not entirely met in practice, it is nevertheless true that the modulator essentially works as explained.

The outstanding feature of the even-harmonic modulator is its extremely low inherent zero drift (less than 5μV is possible[63]). Stability levels of 10^{-18} watts over a bandwidth of 3 cps have been recorded[63]. No bias (as in the odd-harmonic modulator) is necessary. The applications of this type of modulator are almost exclusively in very high gain[63] stable d-c amplifiers. Their performance rivals that of the mechanical choppers. Since we have already discussed the advantages and disadvantages of magnetic modulators in general in the very beginning of this section we will not sum them all up again here.

As in every other type of modulator the magnetic modulator generates noise and zero errors. At least [13] three noise sources exist in the modulator, notably :

(1) Modulated thermal agitation noise which is the noise originated by nearly zero-frequency currents in the signal winding due to thermal agitation effect.

(2) Direct thermal agitation noise which is the noise due to thermal agitation in the resistance (and losses) of the winding near the second harmonic frequency, which is passed on to the amplifier without an intermediate modulation process.

(3) Barkhausen noise which arises from the randomly timed impulses which make up the essentially discontinuous process of magnetization in the core material.

The only absolutely known source of zero error is the magnetic hysteresis[13] and its main effect is to cause a slight memory in the core material which may result from a very heavy d-c overload by an input signal, resulting in the second-harmonic outputs from the modulator before and after the application of the overload being different.

Discussion of noise and zero errors in magnetic modulators is given in ref.[13].

In simple configurations as the one discussed above, leakage flux linkages of the excitation source (= carrier source) may link the output windings. A different approach has been proposed[87]. This approach employs a ferromagnetic medium under the influence of perpendicularly superimposed magnetic fields. The principal advantage of such a scheme is the elimination of inductive coupling between the excitation and the output, which results in a modulator exhibiting extremely low zero offset.

A good mathematical treatment of the even-harmonic modulator is given in ref. [86].

c. Magnetic-conductive modulators.[63], [56], [91]

These modulators are based upon the fact that sometimes electrical properties of materials or junctions can be modified by applying a magnetic field.

Bismuth-alloy modulators [63]

These modulators utilize a class of alloys whose electrical properties are influenced by an applied magnetic field. A modulator operating on the same principle as the photoconductive type of semiconductor can therefore be constructed. For example : the resistance of bismuth-alloy elements is known to be dependent on the magnetic field through the element. By modulating the magnetic field we principally get the same effect as by varying the intensity of a light beam falling on a photoconductive element.

Super-conductive modulators.

Ref. [56] describes a chopping method using a superconductive wire in a very low temperature bath. The superconductivity is however dependent on magnetic fields present. By modulating an applied magnetic field the degree of superconductivity of the wire will be modulated too, and so will be a signal whose amplitude depends on the resistance of the wire.

Ref.[91] discusses a modulating method built up from two superconducting niobium wires which are perpendicular to each other and have a small contact, the latter being superconducting also. Consider Fig. 141. The two wires are 1-4 and 2-3 and the contact is at 5. An a-c current from 1 over 5 to 2 gives rise to a periodically changing circumferential magnetic field. This field is said [91] to quench the contact. In any case the resistance seen when looking into the terminals 3 and 4 is periodically changed by the a-c current existing in the branch 1-5-2. This phenomenon can be used [91] to build a modulating system.

DEMODULATORS

The demodulators used in a modulated d-c amplifier convert the output of the a-c amplifier back to a d-c signal.

Since the output level is usually much higher than the input one the demodulator does not have to be so good as the input modulator. Often therefore use is made of some demodulating configuration which is simple, relatively inexpensive and which also may better meet special requirements (e.g. weight, expected life,...). Synchronism between input modulator and output demodulator is often essential and it is therefore not unusual to see that the demodulator is a unit of the same class, type, etc. as the input modulator.

Demodulator circuits do not differ appreciably from the corresponding modulator circuits with the exception that a d-c signal cannot pass through a transformer or a capacitor whereas an a-c signal can. Thus if a modulator circuit has to be adapted for demodulation purposes, then care should be taken that the output circuitry pass the resulting d-c signal. The input of the device may now contain blocking capacitors or a transformer if desired whereas this was not the case for modulators where the input was a d-c signal.

It is true also that not all modulator circuits can be used for demodulating purposes : some modulators are based upon the fact that their output is an a-c signal and therefore they can only be used for dc-ac conversion and not for ac-dc conversion.

Among the modulators which can readily be used as demodulators are :

(1) Magnetically driven choppers (much used).

(2) Crystal driven choppers.

(3) Aircoupled choppers.

(4) Vacuum-diode modulators.

(5) Semiconductor-diode modulators (much used).

(6) Transistor modulators.

Comparison between modulators.

In ref.[63] a complete table of commonly used modulator types and their performance characteristics is given. The types of modulators included in the table are :

(1) Electromechanical choppers.
(Magnetically driven)

(2) Electronic modulators :
Multielement tubes.
Vacuum diodes.

(3) Semiconductor modulators :
Diodes.
Transistors.
Photoconductive cells.

(4) Magnetic modulators.

The performance characteristics which are given in the table are :

(1) Input characteristics :
Input impedance.
Percent of carrier present at input.
Maximum allowable input.
Input form.

(2) Output characteristics :

Output impedance.
Operating level.
Drift.
Maximum output.
Null offset.
Dynamic range.
Power output.
Distortion.
Linearity.
Symmetry.
Saturation.
Efficiency.
Stability.
Percent of carrier present at output.
Output frequency.

(3) Dynamic response :

Modulation.
Carrier.

(4) Excitation :

Frequency range.
Voltage.
Waveform.
Power.
Source impedance.

(5) Life.

(6) Complexity.

(7) Temperature.

A shorter table with the most important characteristics and in a more practical form is given in ref. [79] and is reproduced in Fig. 142 after up-dating some values.

Chopping waveform generator.

Several modulators use a sinusoidal driving voltage that can be provided by an a-c power line if the desired frequency is 60 cps (U.S.A) or 50 cps (Europe and others). However to reduce hum coming from the power lines it is often better not to use a frequency of exactly 60 cps (or 50 cps). In that case and also if the desired frequency is not 60 cps (or 50 cps) but for example 400 cps, 1000 cps or even higher (10 kc, 100 kc,...) an oscillator providing a sinusoidal output can be used.

If a square wave is desired (for some modulators as for example transistorized ones a square wave is required for optimal performance) then the driving signal can be obtained from an astable multivibrator, Schmitt-trigger or other device yielding such a square wave. A few examples can be found in ref. [(25), (59), (61), (66)].

The use of a triangular driving source waveform for magnetic modulators is discussed in ref. [(13)] and a magnetically keyed pulse forming circuit to drive a sampler demodulator in ref. [(59)].

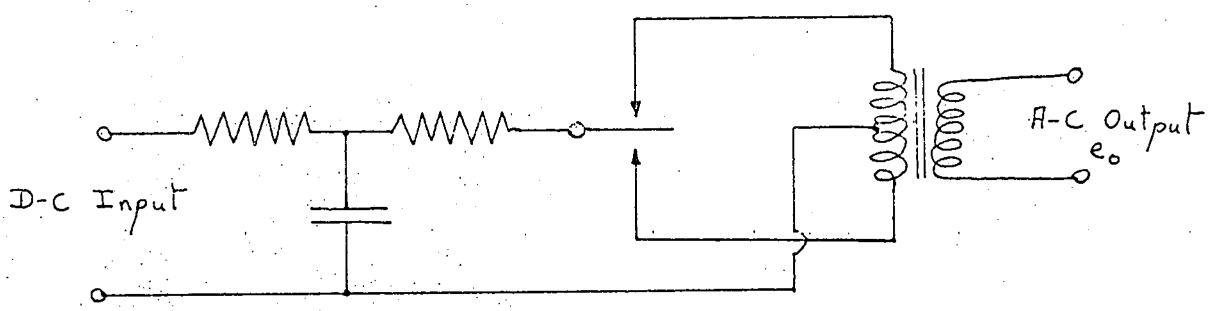


Fig. 91

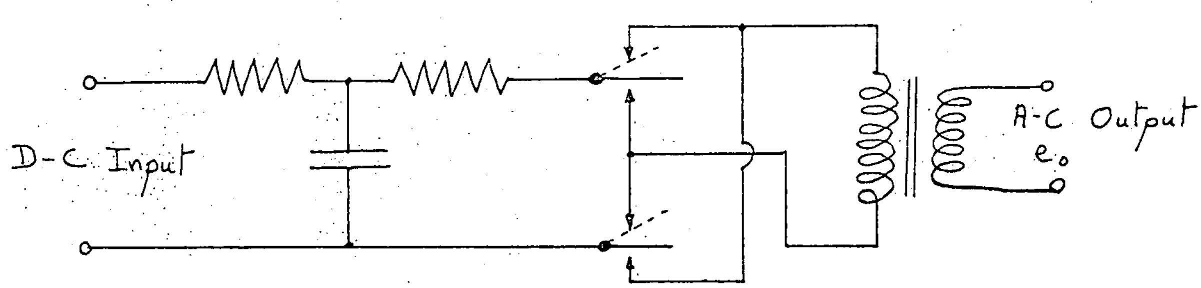


Fig. 92

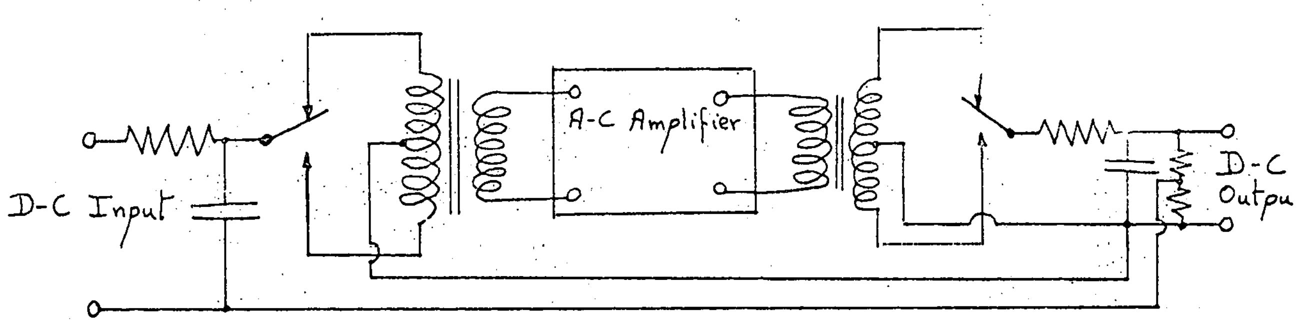


Fig. 93

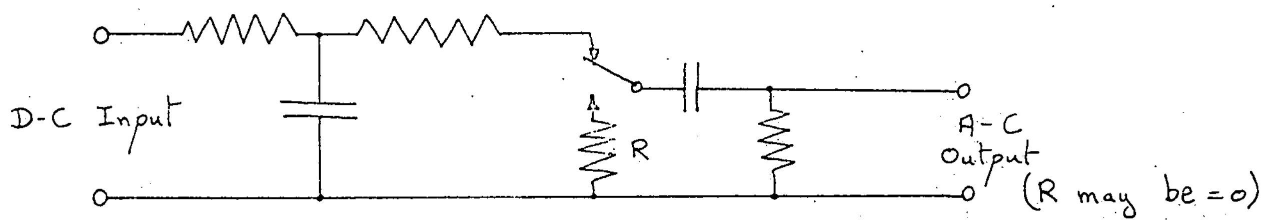


Fig. 94

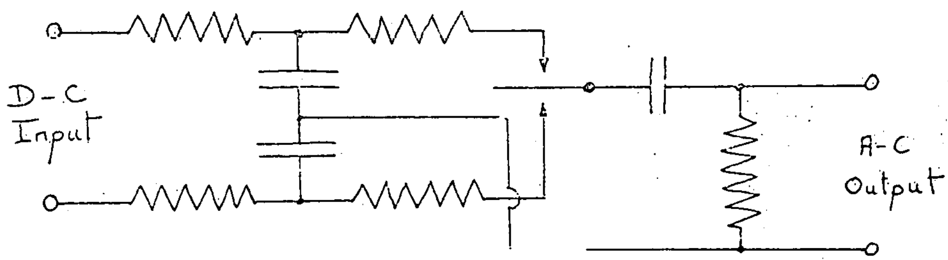


Fig. 95

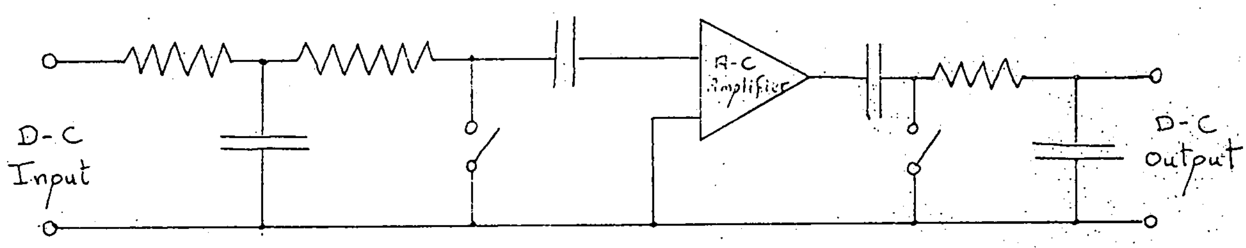


Fig. 96

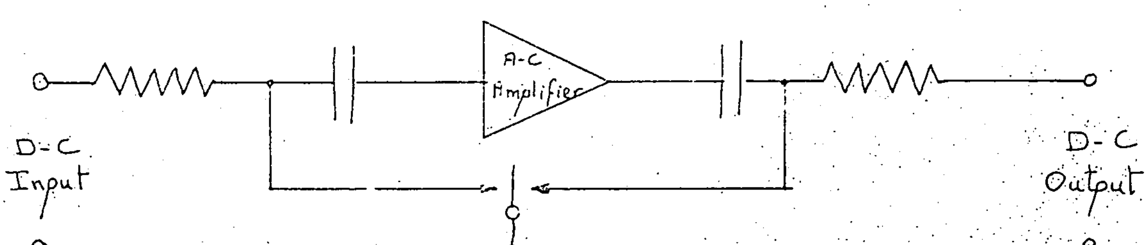


Fig. 97

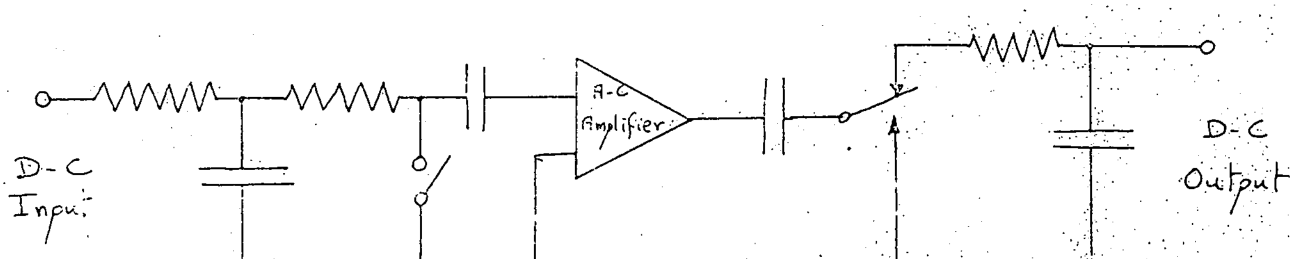


Fig. 98

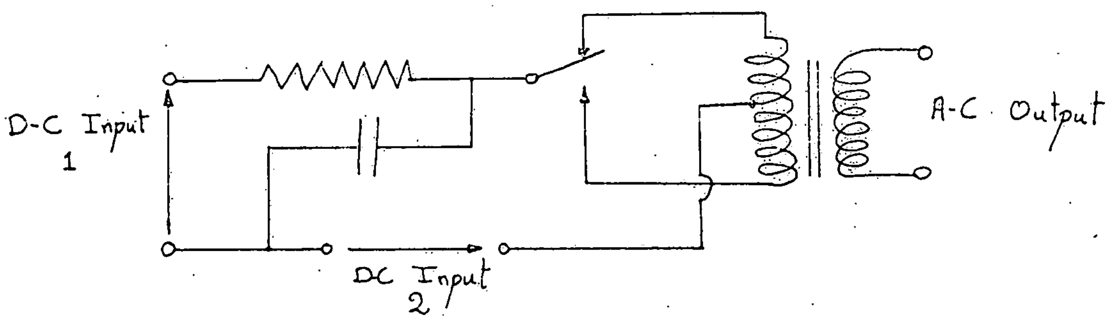


Fig. 99

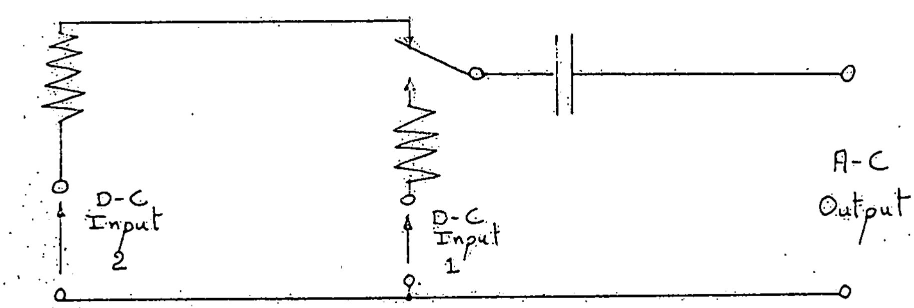


Fig. 100

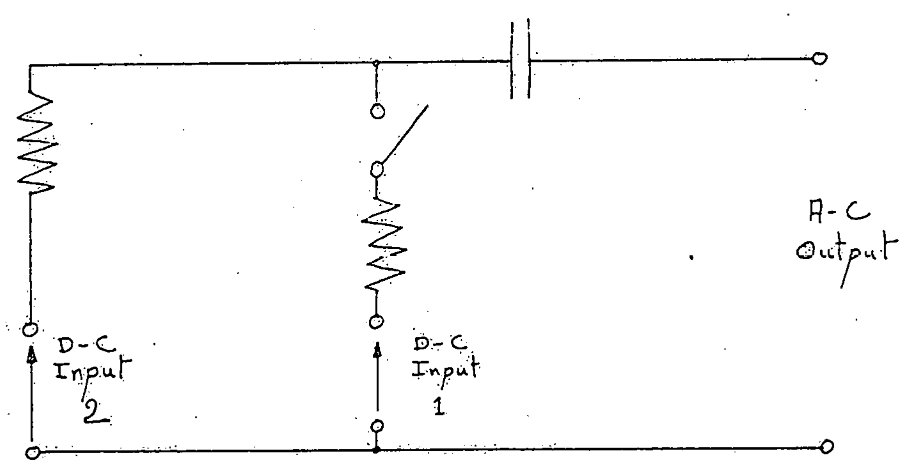


Fig. 101

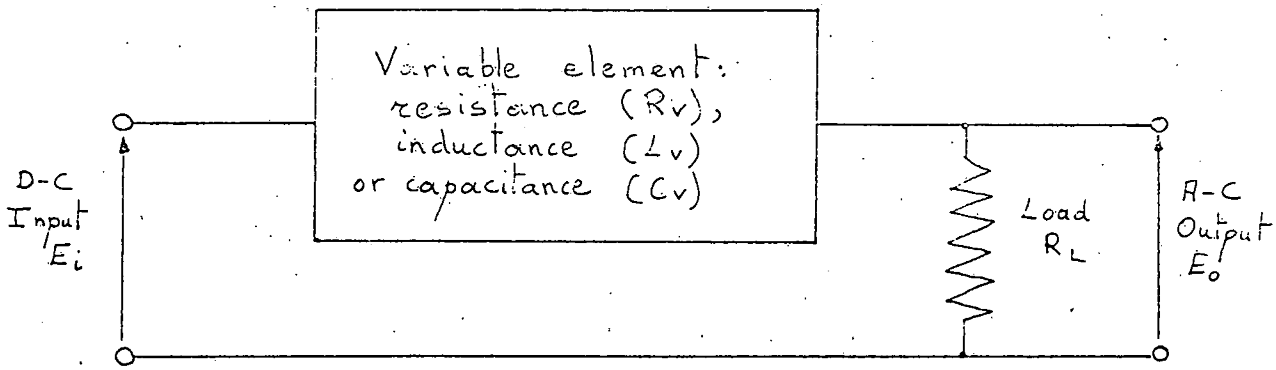
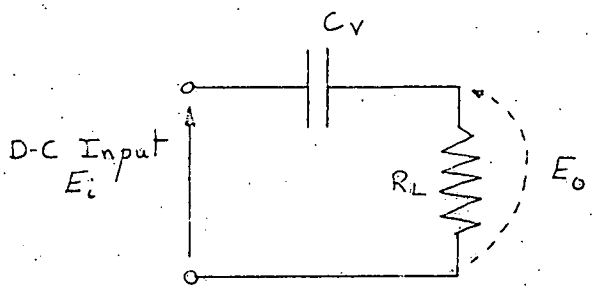
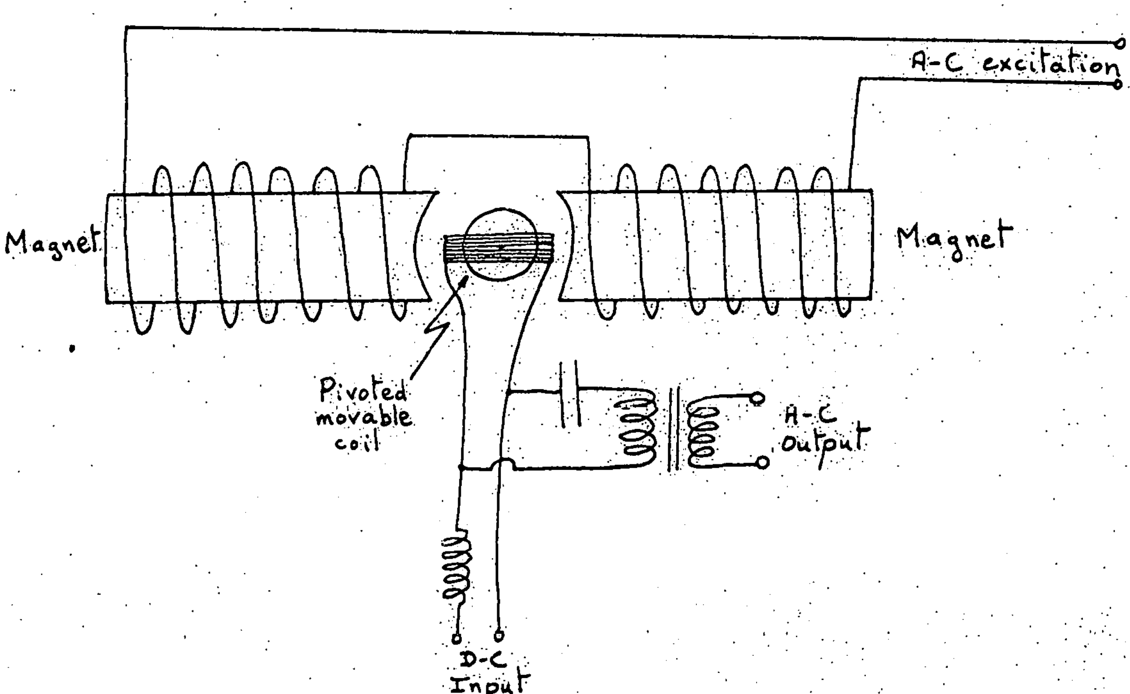


Fig. 102



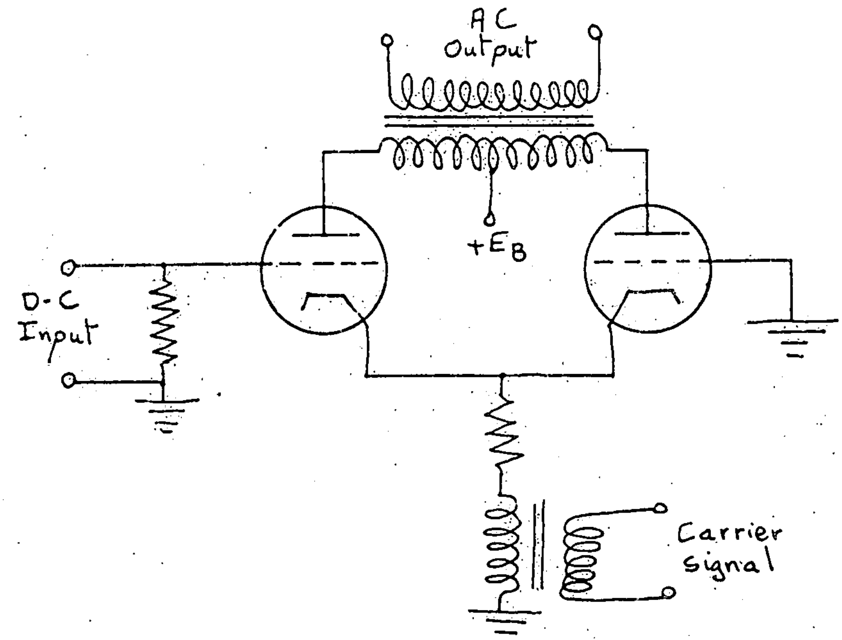
$$C_v = C_o (1 + m \sin \omega_c t)$$

Fig. 103



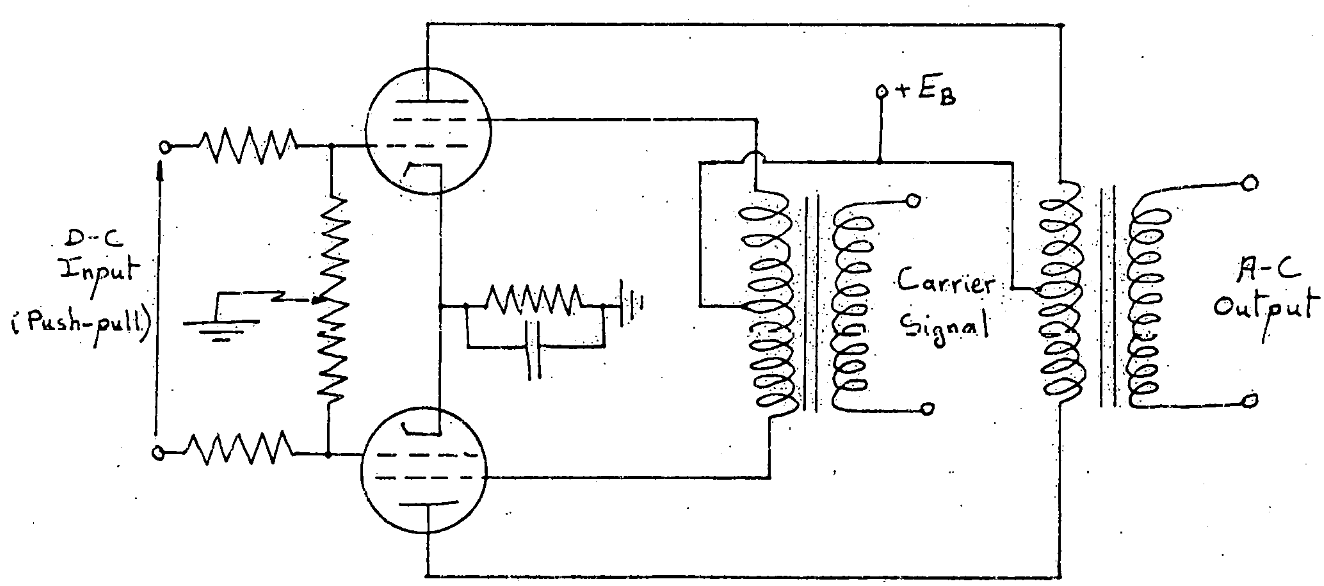
Induction modulator

Fig. 104



Cathode modulation

Fig. 105



Secondary-grid modulation.

Fig. 106

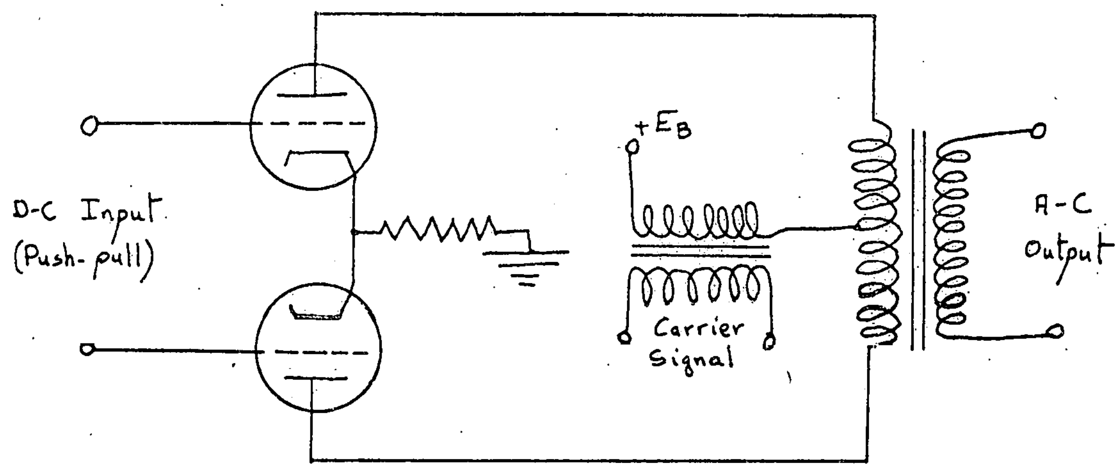
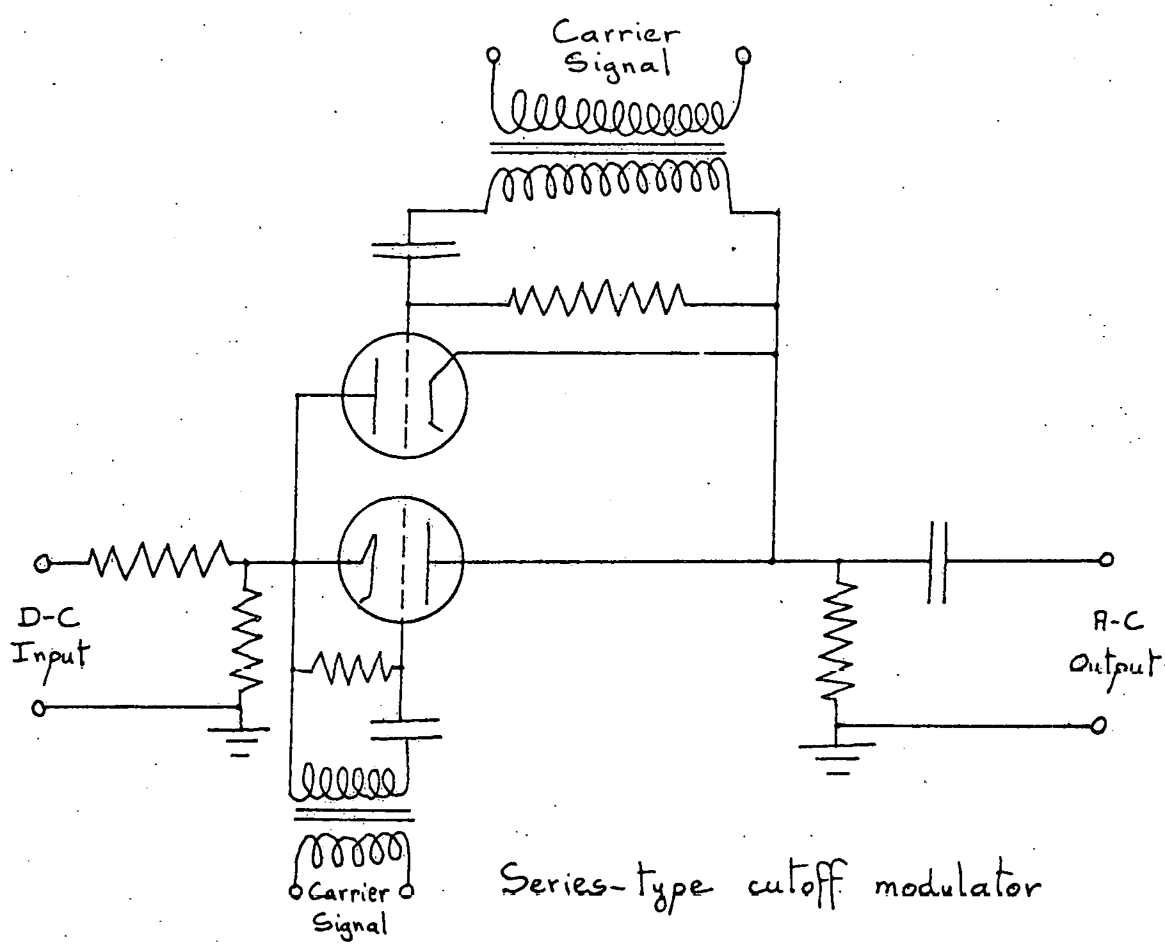


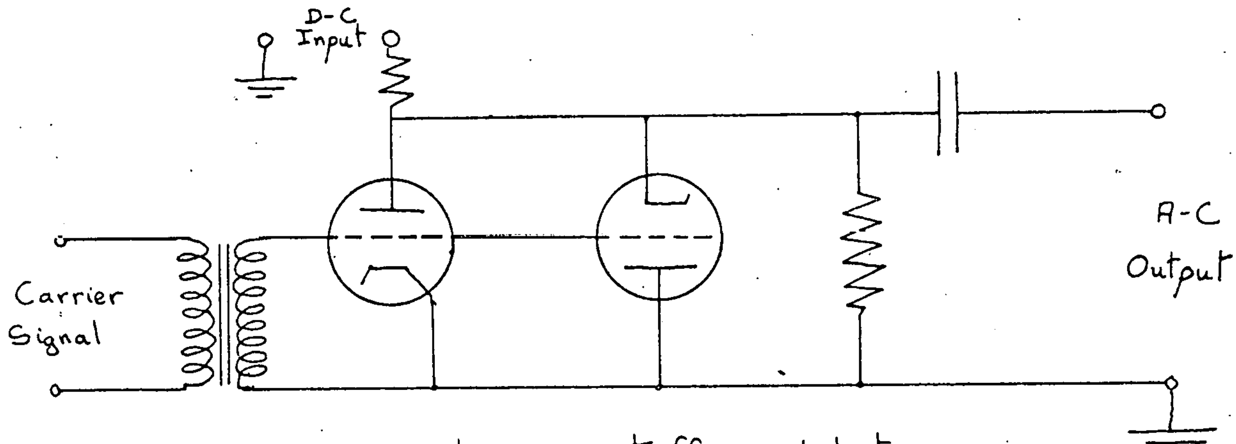
Plate modulation.

Fig. 107



Series-type cutoff modulator

Fig. 108



Parallel-type cutoff modulator

Fig. 109

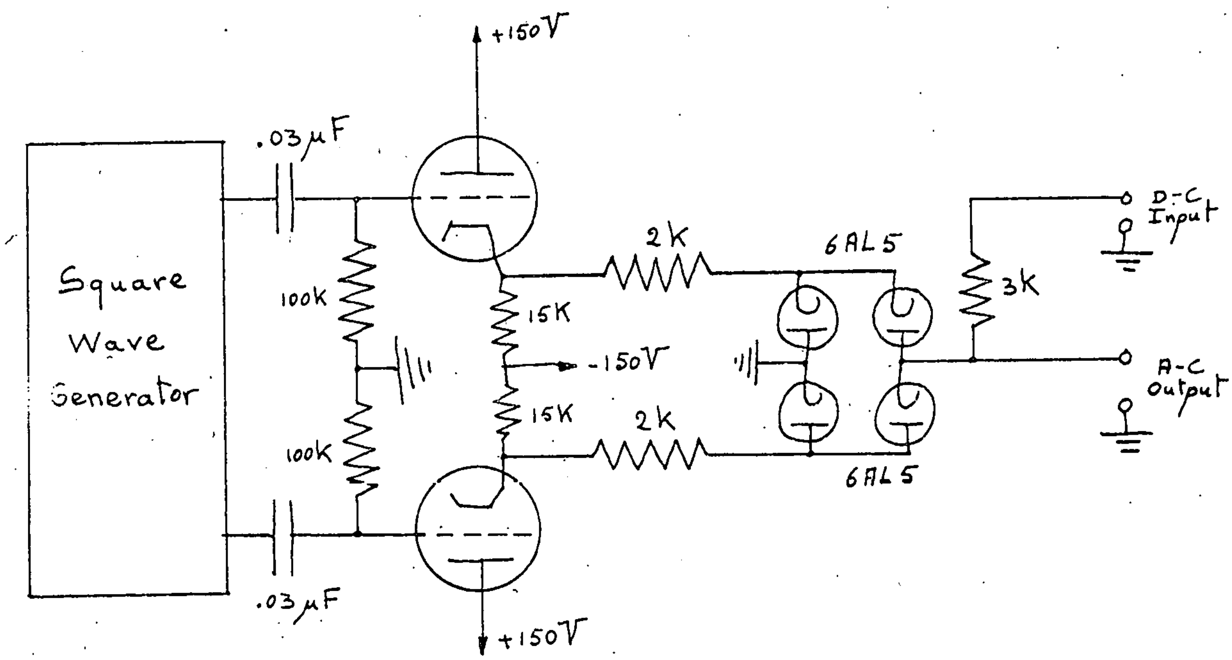


Fig. 110

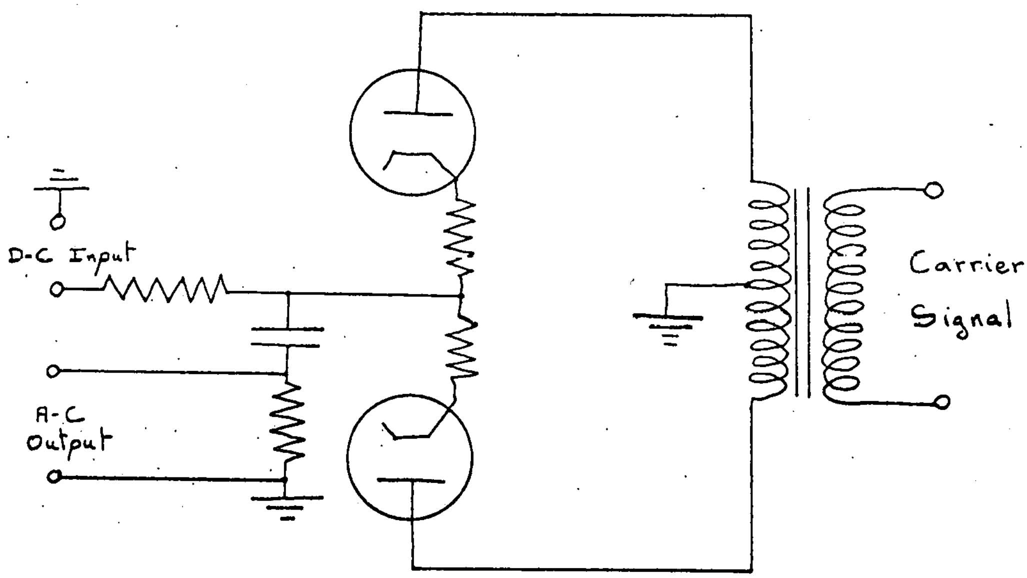
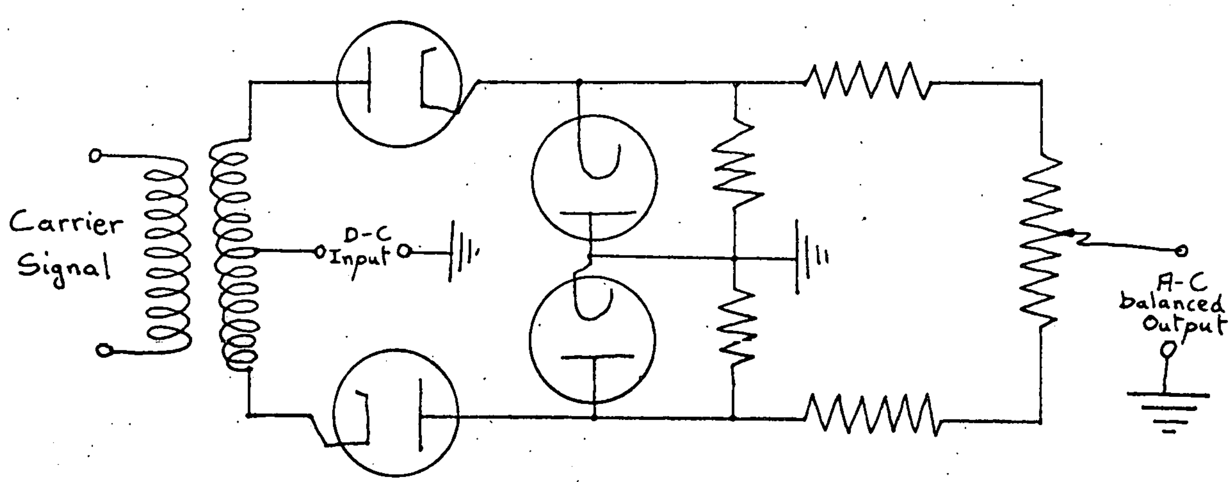
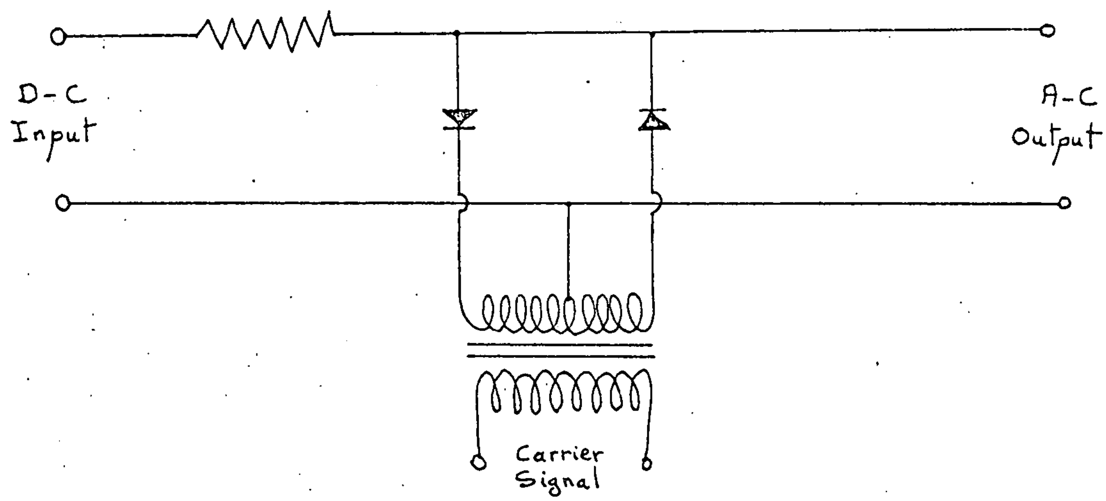


Fig. 111



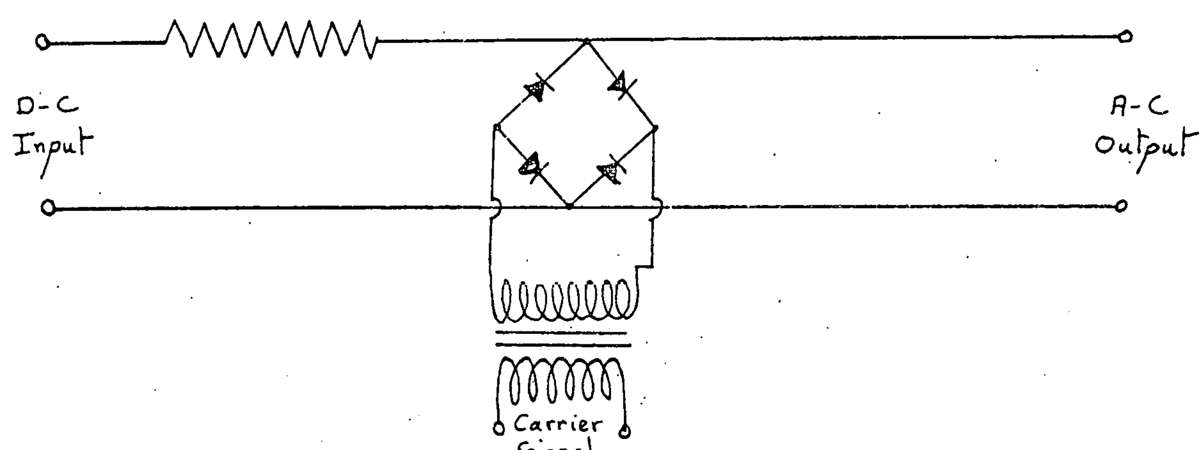
High-performance diamond modulator

Fig. 112



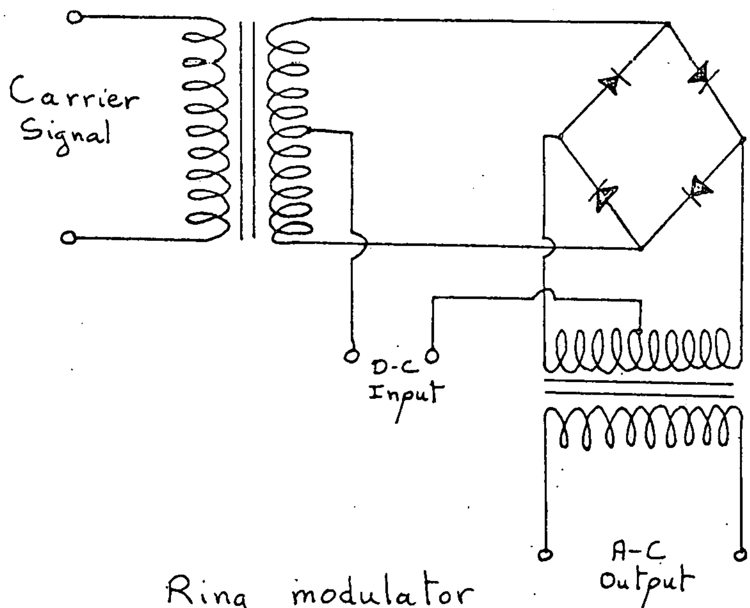
Basic diode chopper

Fig. 113



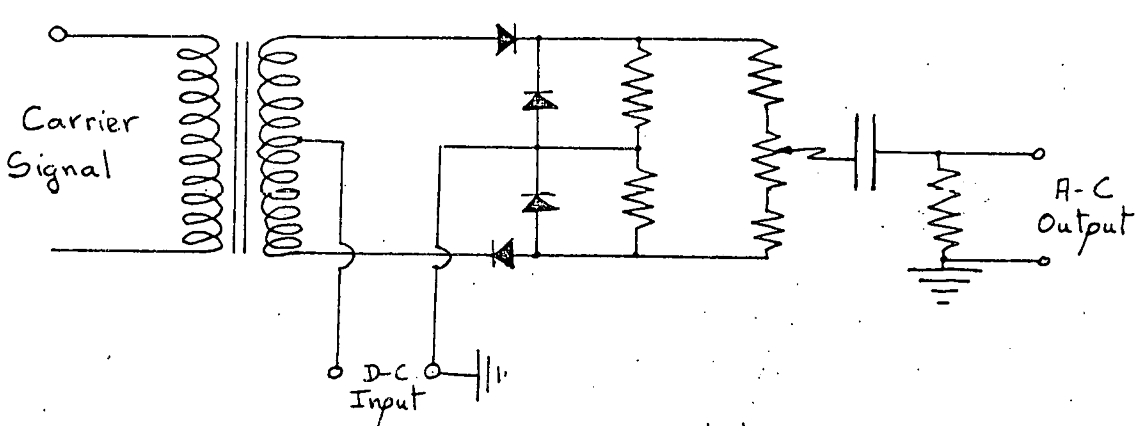
Bridge or Cowan modulator

Fig. 114



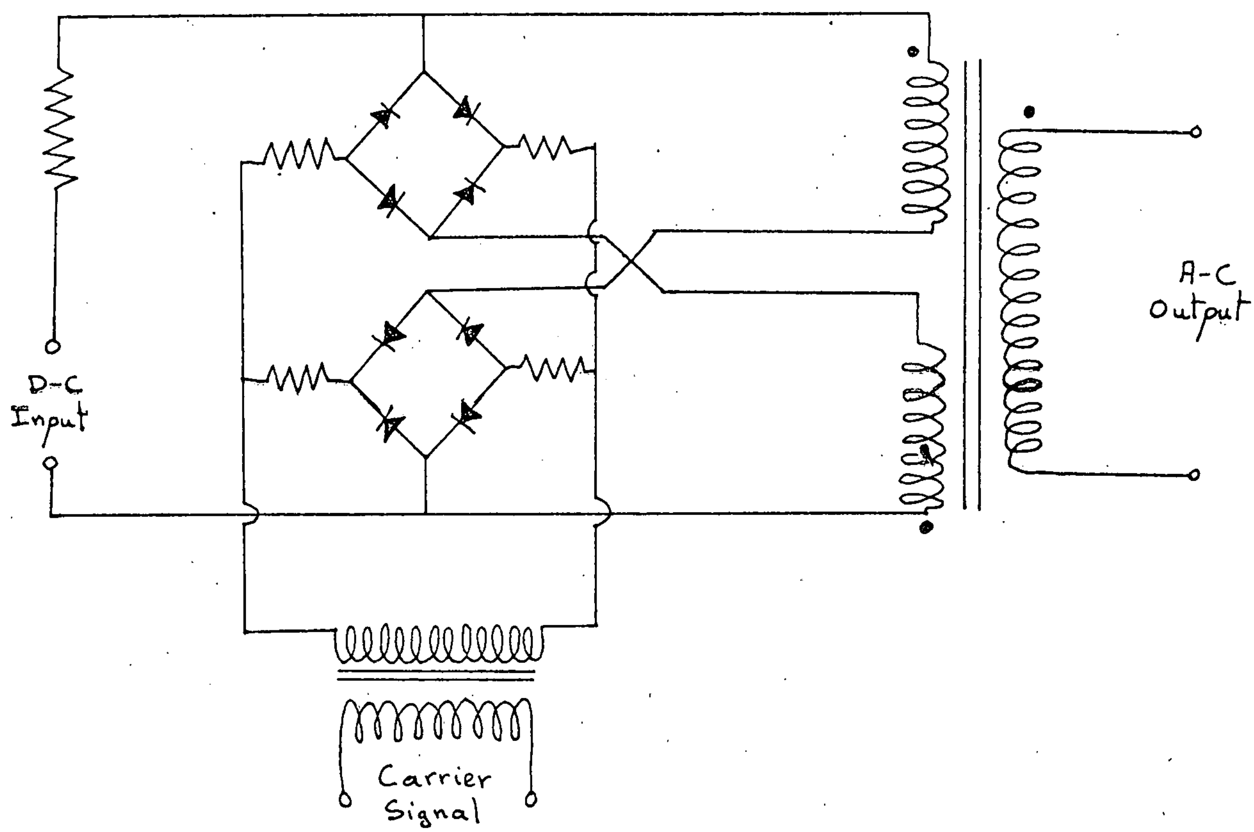
Ring modulator

Fig. 115



Diamond modulator.

Fig. 116



Full-wave bridge modulator.

Fig. 117

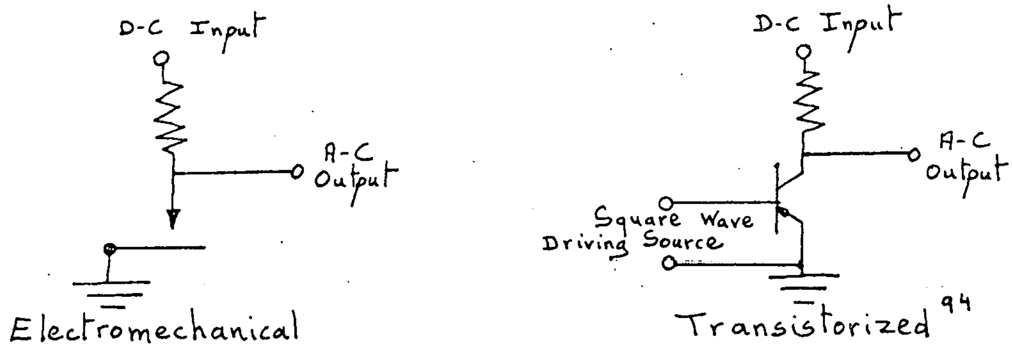


Fig. 118

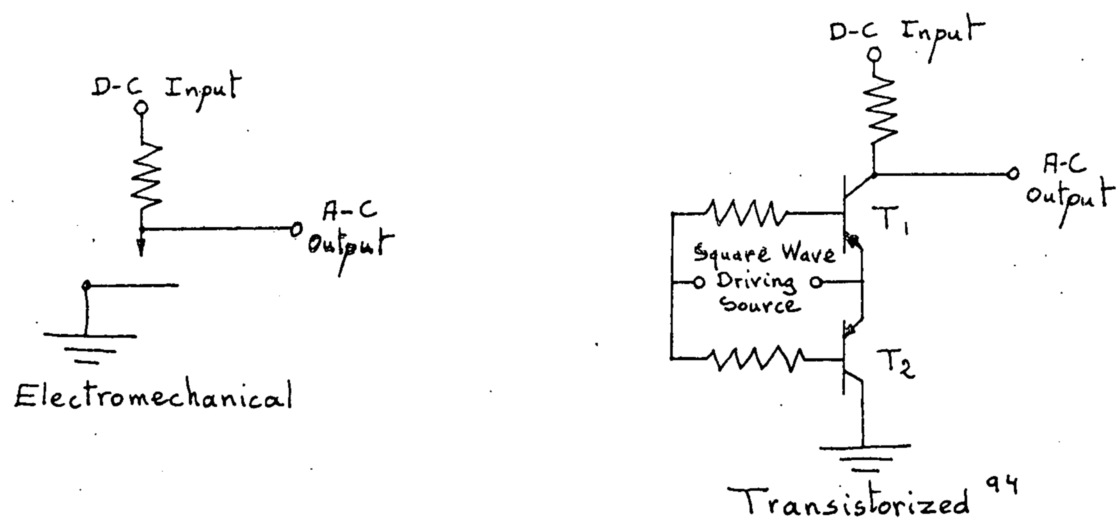


Fig. 119

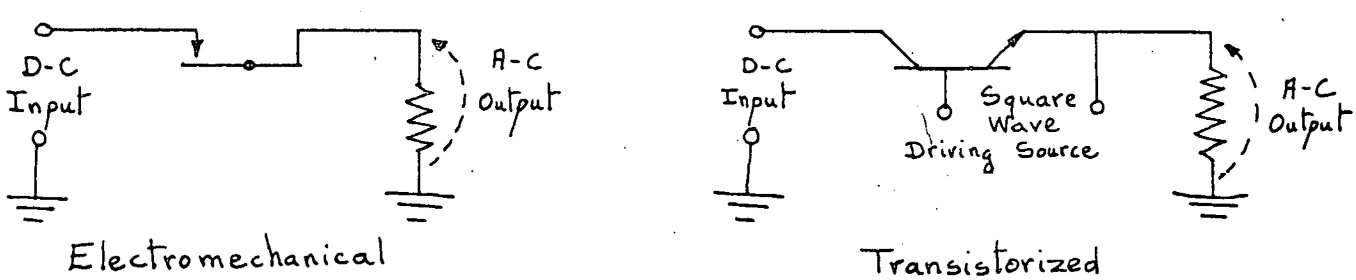


Fig. 120

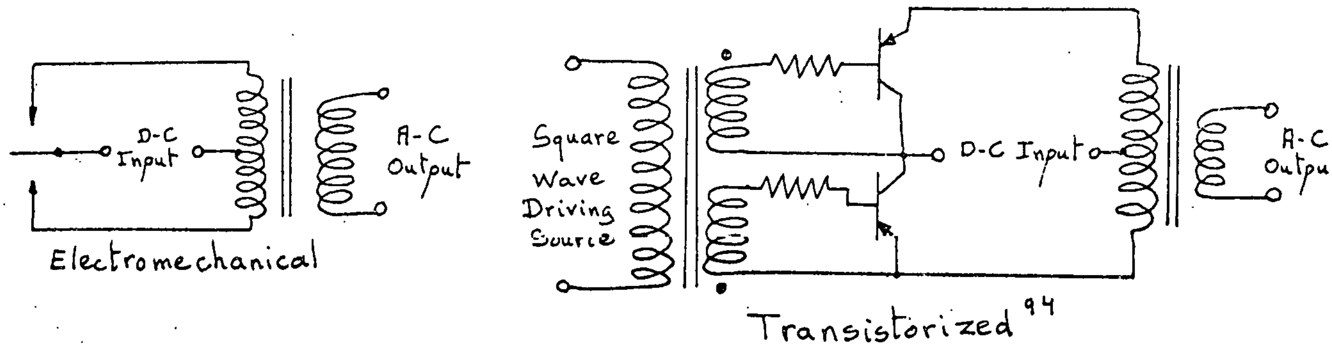


Fig. 121

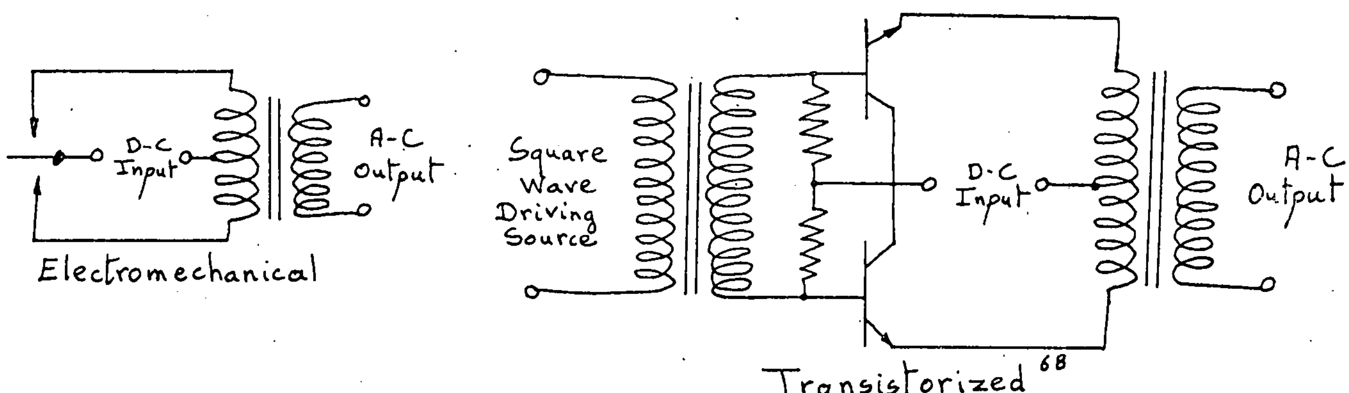


Fig. 122

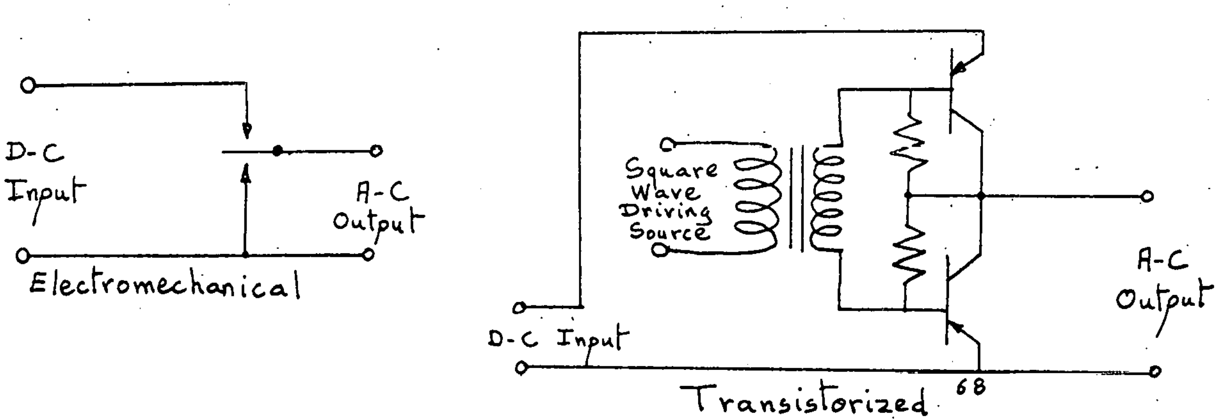


Fig. 123

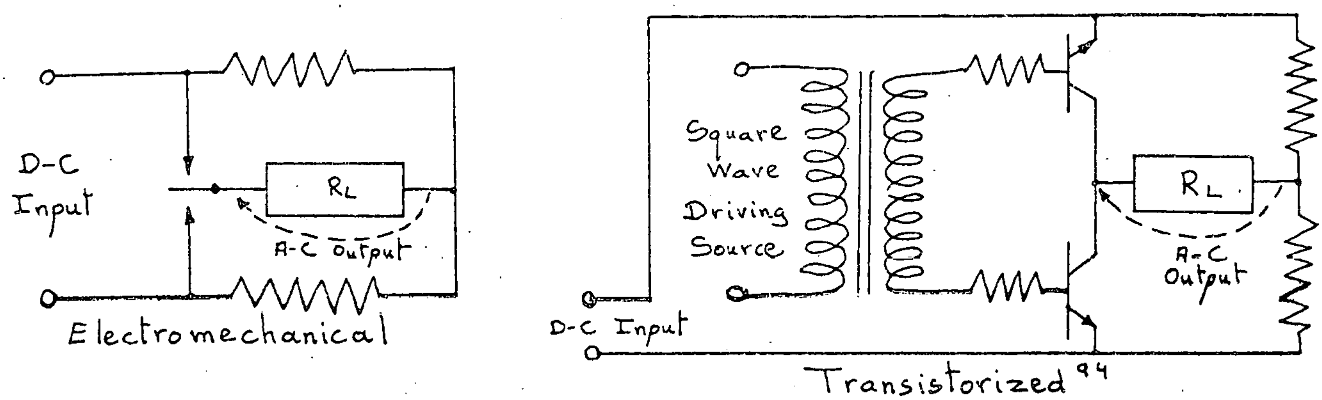


Fig. 124

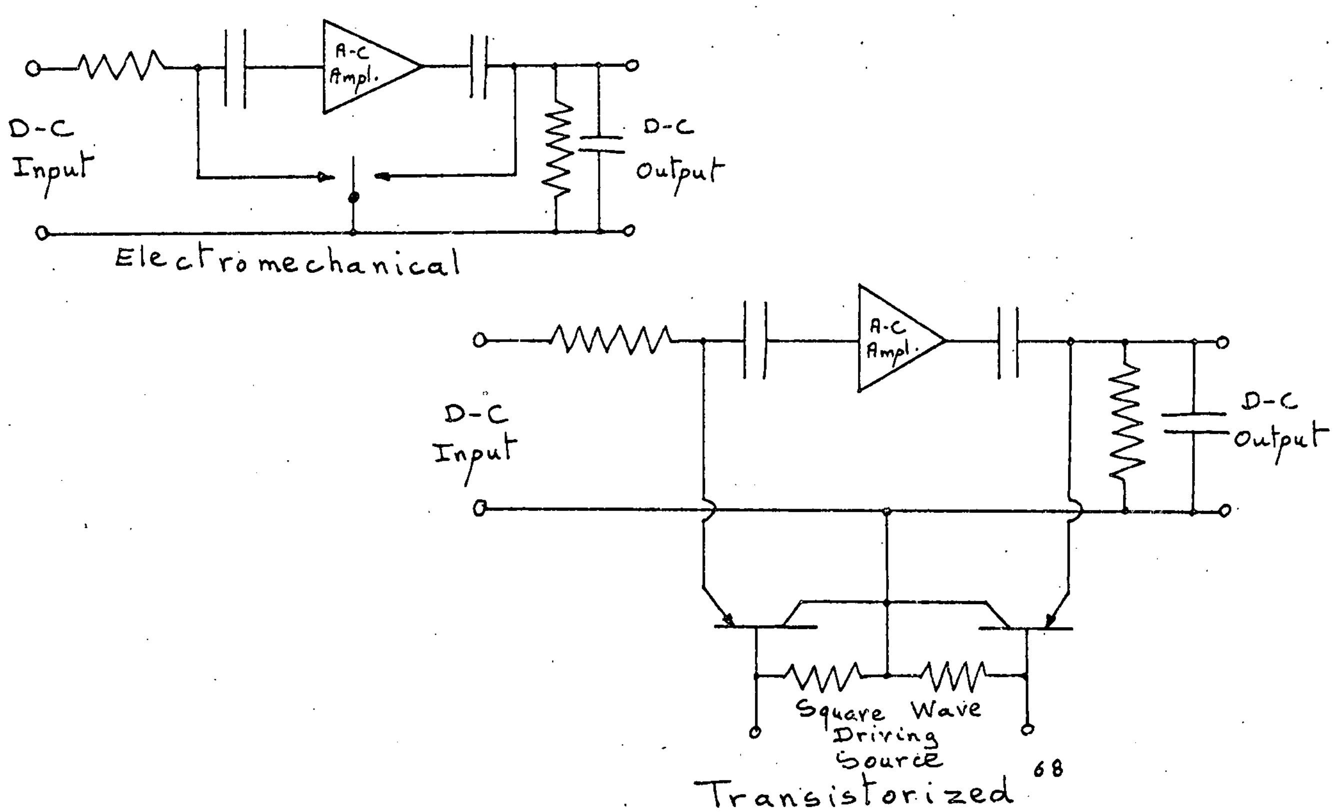
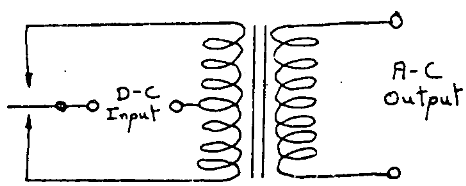
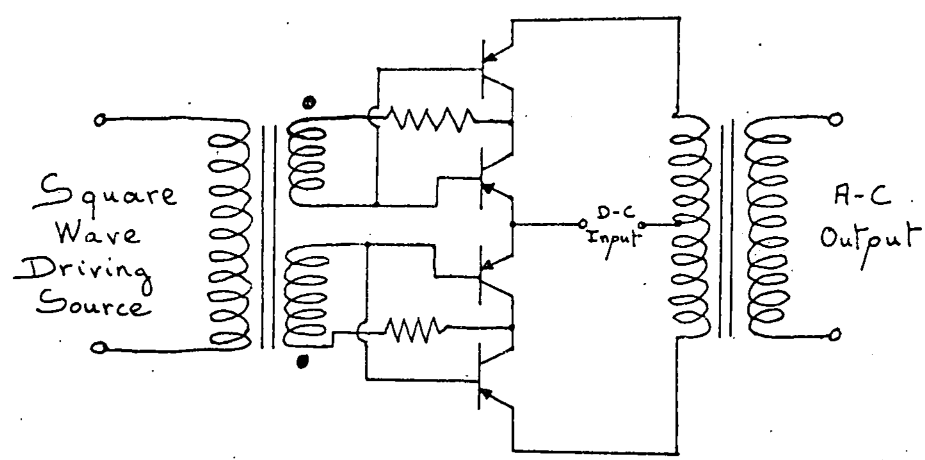


Fig. 125



Electromechanical



Transistorized[63,68]

Fig. 126

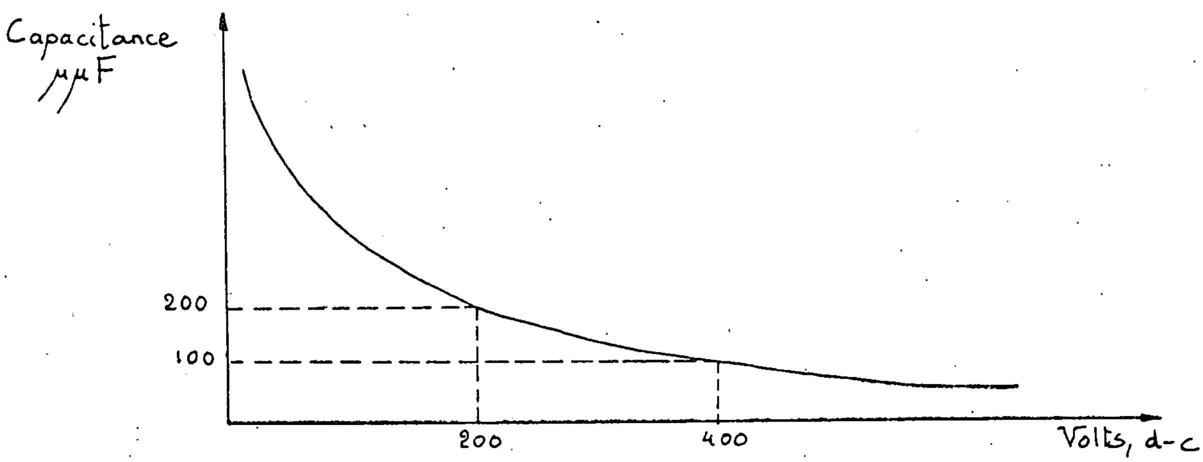


Fig. 127

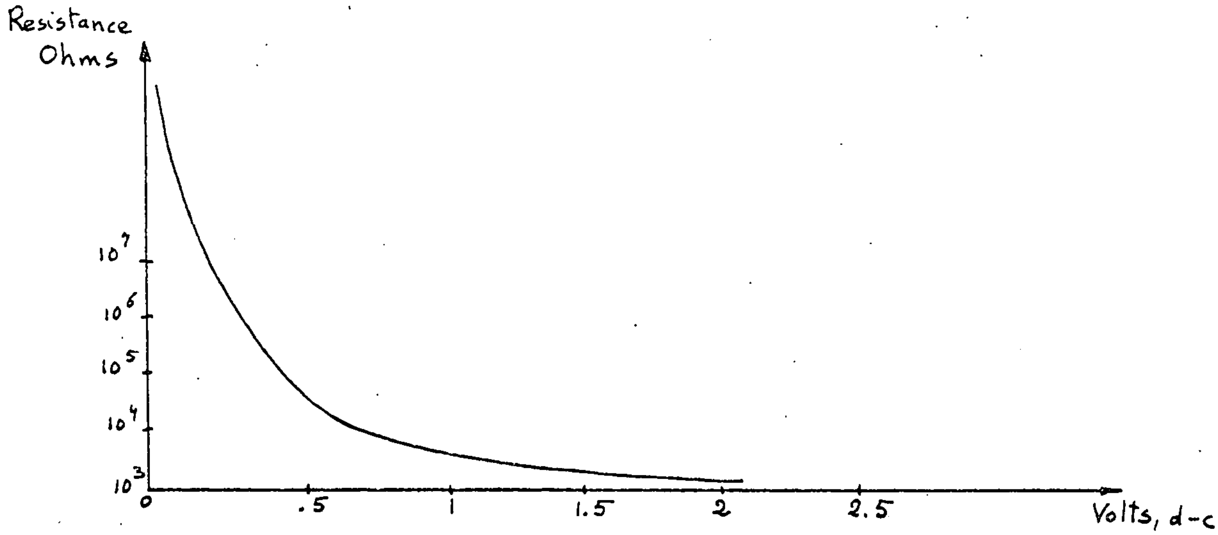


Fig. 128

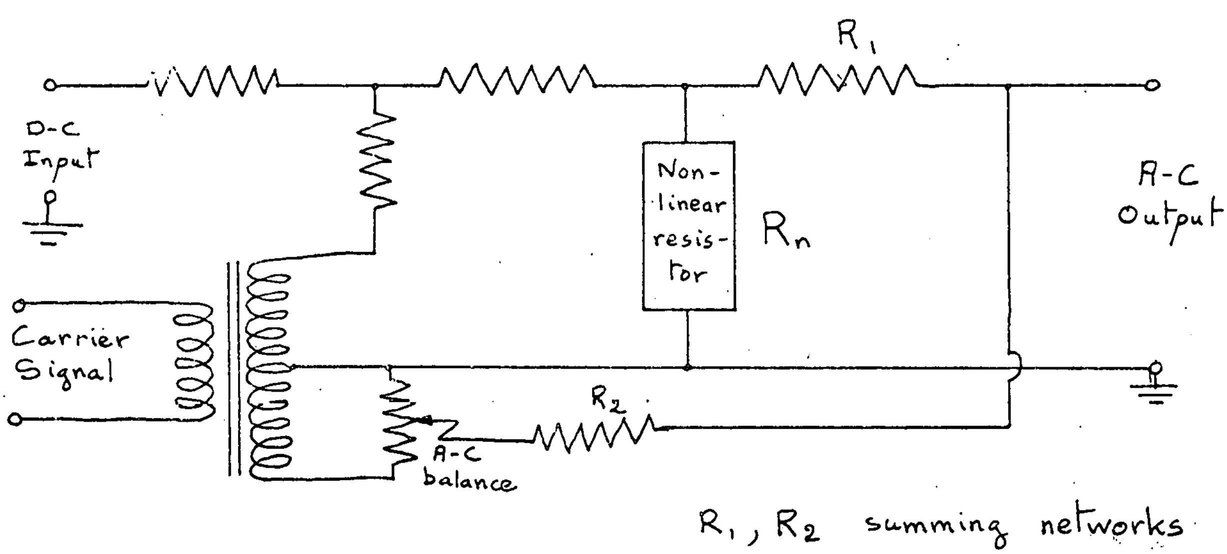


Fig. 129

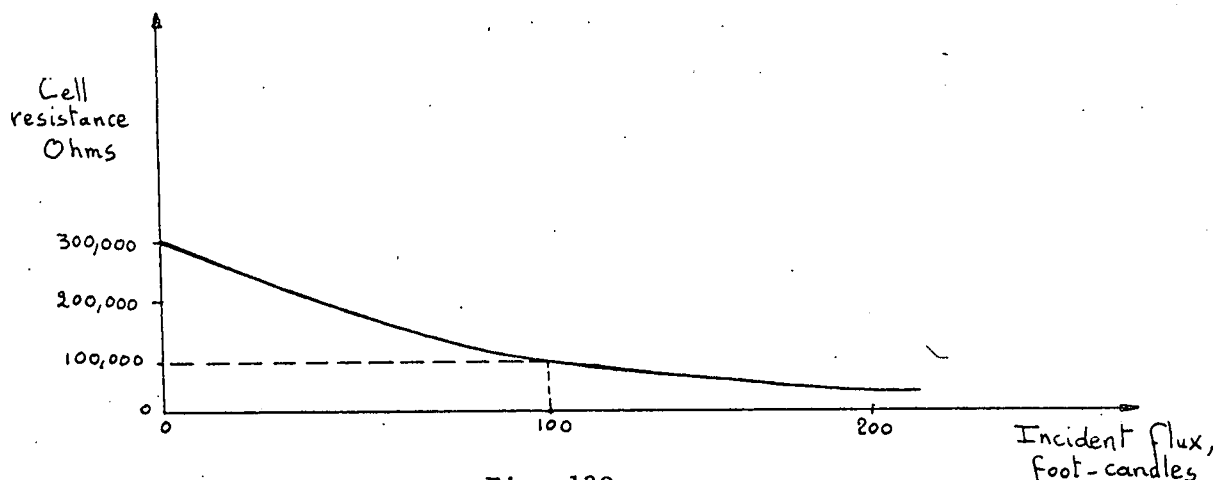


Fig. 130

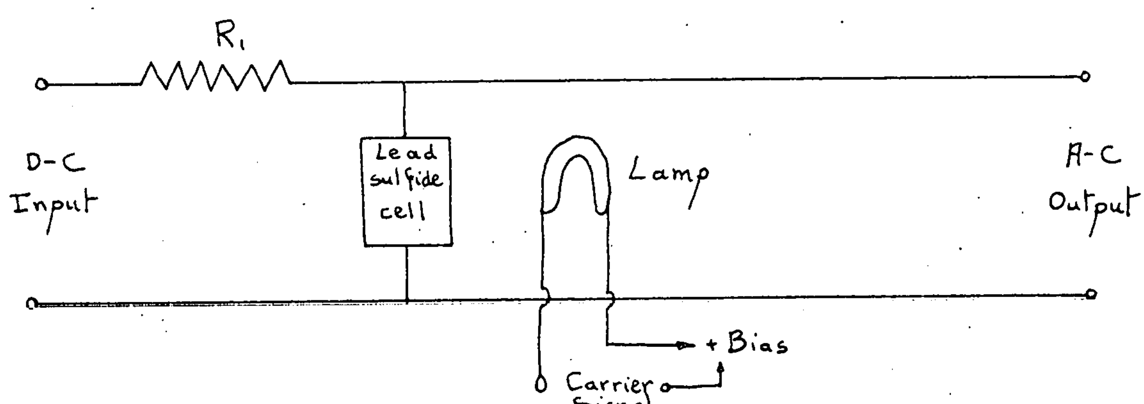


Fig. 131

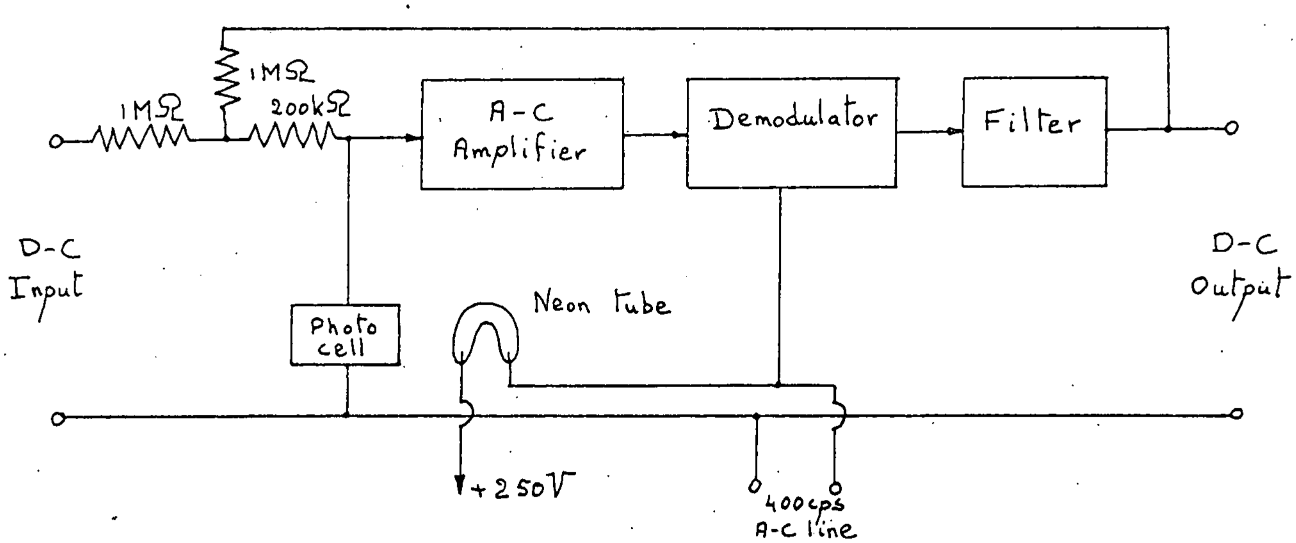
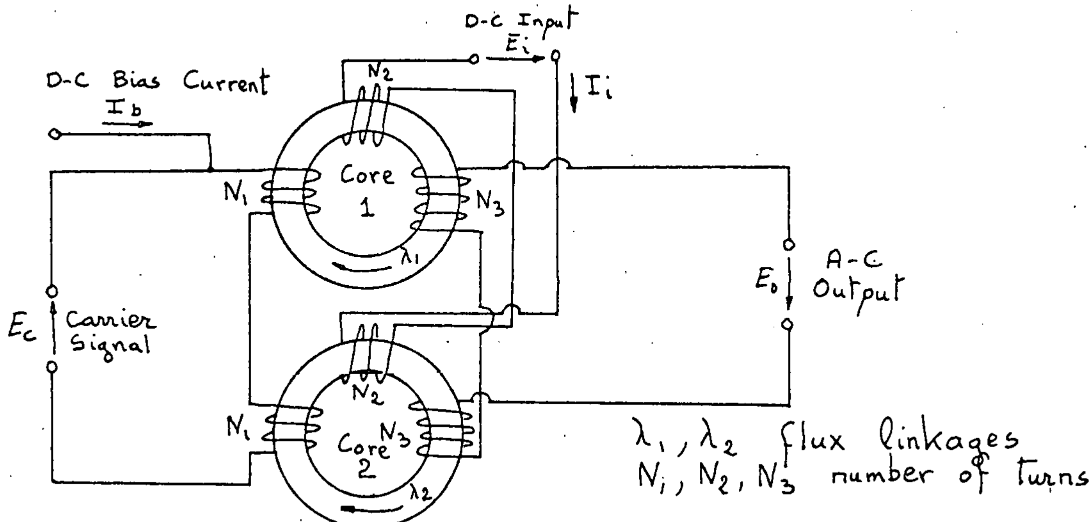

1MΩ
1MΩ
200kΩ
A-C Amplifier
Demodulator
Filter
D-C Input
D-C Output
Photo cell
Neon tube
+250V
400cps A-C line

Fig. 132



Fundamental-frequency or odd-harmonic magnetic modulator.

Fig. 133

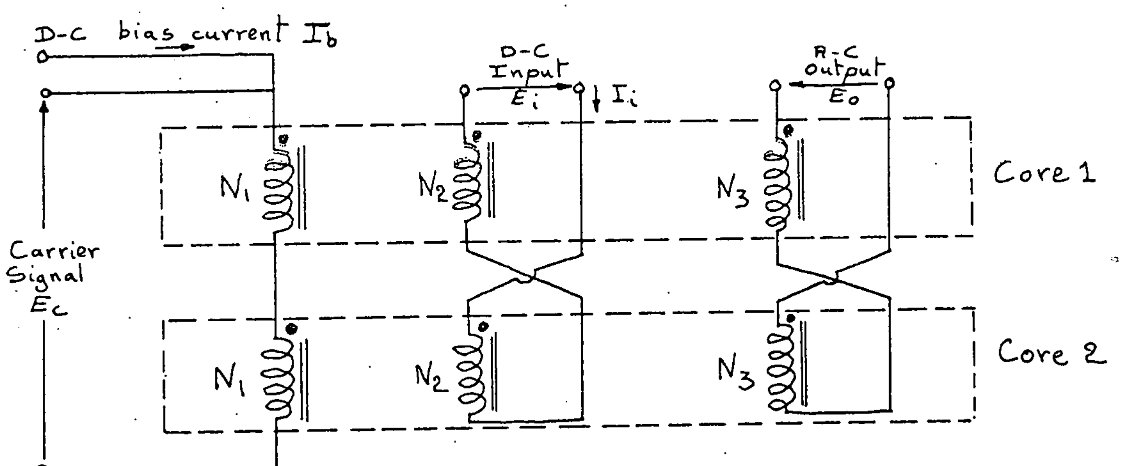


Fig. 134

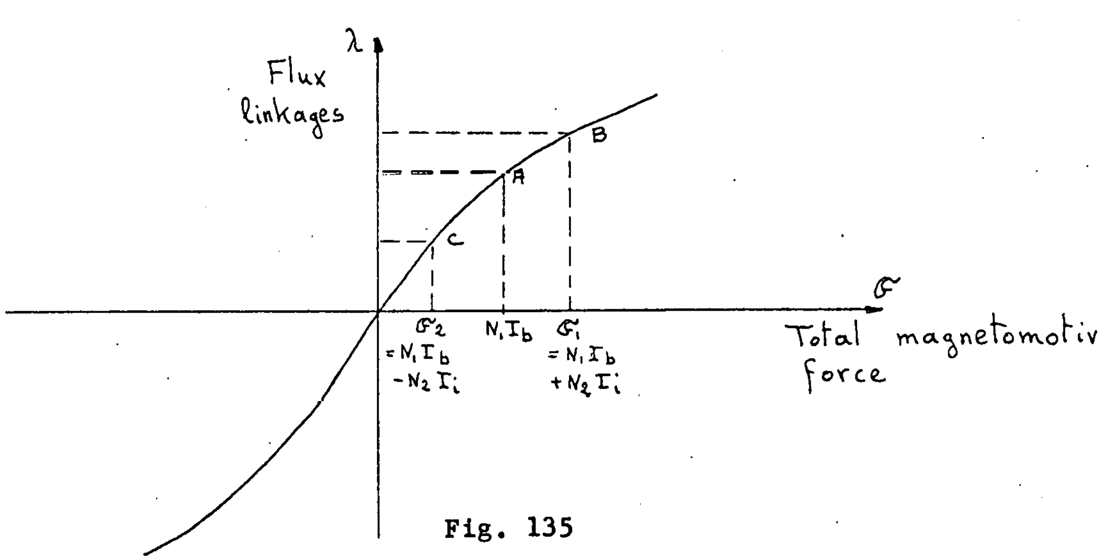


Fig. 135

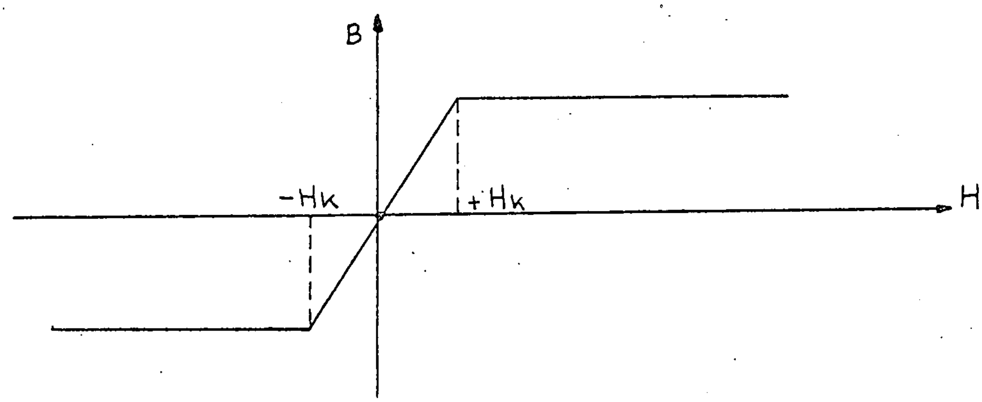
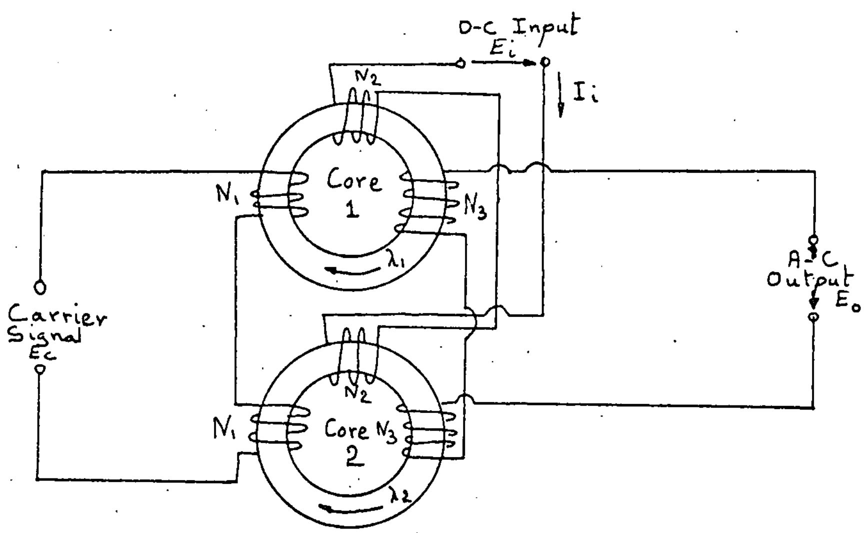


Fig. 136



Even-harmonic magnetic modulator

Fig. 137

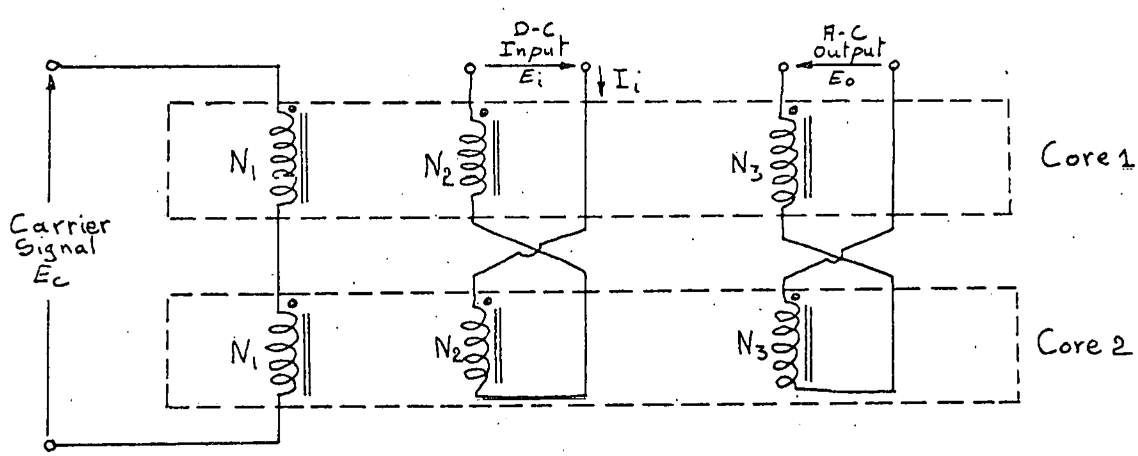


Fig. 138

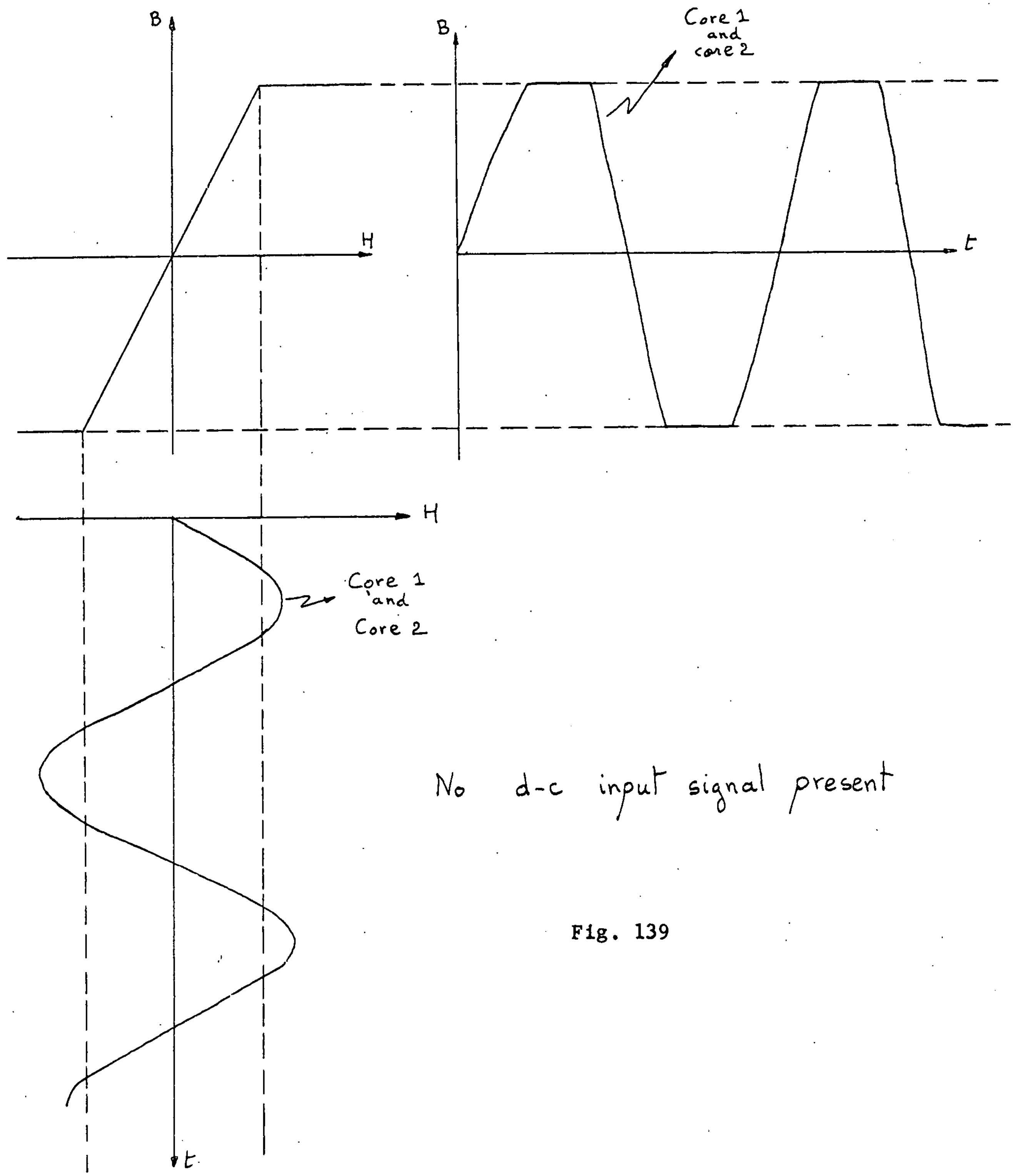
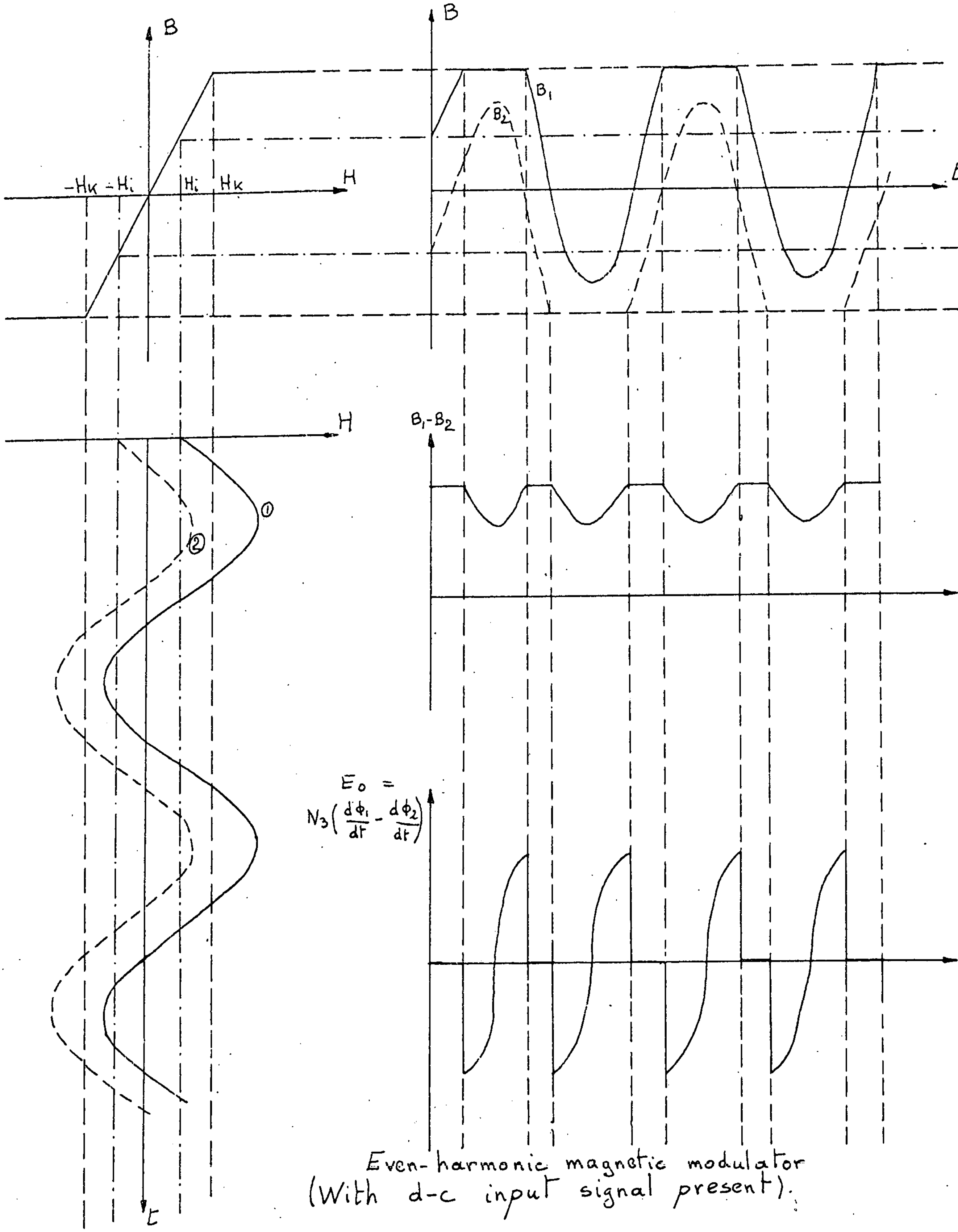

B
H
B
Core 1 and core 2
t
H
Core 1 and Core 2
t
No d-c input signal present

Fig. 139



B
H
$-H_K$ $-H_i$ H_i H_K
t
B_1
B_2
$B_1 - B_2$
$E_0 = N_3\left(\frac{d\phi_1}{dt} - \frac{d\phi_2}{dt}\right)$
Even-harmonic magnetic modulator
(With d-c input signal present).

Fig. 140

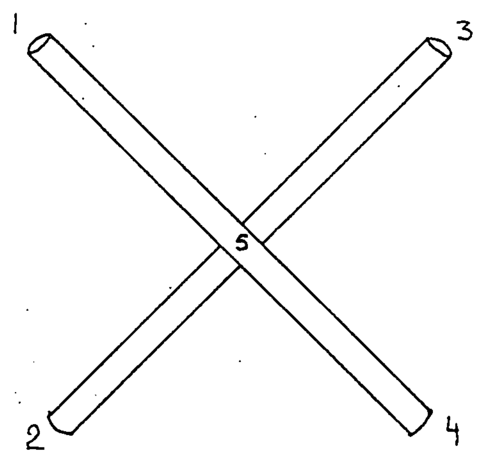


Fig. 141

Characteristics of Modulators for d-c amplification by d-c to a-c conversion

Modulator	Life (Hours)	Max. Exciting Frequency*	Temp. Range (°C)	Input Impedance (Ohms)	Null Offset (Volts)	Drift (Volts)	Signal-to-noise ratio	Freq. response at 400 cps**	Remarks on Application
Electromechanical Chopper	5,000	600 cps	- 65 to + 200	10^{10}	1 μv-1 mv	1 - 10μv	10^7	20 °/o	Inexpensive, rugged, high linearity
Crystal diode	>10,000	2.5 mc.	- 55 to + 150	$<10^4$	100 μv-1 mv	10 mv	8,000	10-20 °/o	Good linearity, low power requirements
Transistor	>10,000	100 kc	- 50 to + 90	$<10^4$	100 μv-1 mv	1 mv	2,000	10-20 °/o	More sensitive than diode, low power
Multigrid Tube	varies	>10 kc	- 65 to + 100	$>10^6$	1 - 10 mv	25 μv/min	500	-	Fair linearity, temperature sensitive
Vacuum diode	varies	10 kc	- 65 to + 100	$<10^4$	>1 mv	1 μv/min	2,000	10-20 °/o	Drift a problem, will take high voltage
Magnetic Amplifier	100,000	10 kc	- 75 to + 200	3,000	>10 mv	5 μv	500	to 5 °/o	Noise problem at low signal levels and low frequencies
Induction Galvanometer	-	200 kc	- 65 to + 100	-	10 mv	5 μv	-	-	Sensitive to vibration and shock
Variable Capacitance Modulator	-	-	- 65 to + 100	10^{12}	10 μv-1 mv	100 μv	-	-	Measures small currents; expensive
Photoconductive Modulator	>10,000	1 kc	- 80 to + 100	$>10^6$	>200 μv	<1 mv	3,000	-	Temperature-limited by type of photocell

* Values are generally used limits; exciting frequency of choppers, for example, goes as high as 1,800 cps; 60 cps and 400 cps are dominant.

** " Frequency response at 400 cps " = percent of carrier frequency (the latter assumed to be 400 cps) that can be passed by the modulator[68].

FIG. 142