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INTERNAL REPORT

PHASE DETECTORS

BY

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NO. 15

PHASE DETECTORS
THEIR APPLICATION IN RADIOMETERS.

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Introduction.

It has been attempted in the following report to present generally the principles of the more usual types of phase detectors and to discuss the reasons for the choice of a particular kind for use in a hydrogen line radiometer constructed here.

Phase-sensitive detectors of one form or another have been known for a long time, but have assumed a new importance in recent years as a result of their widespread application in radiometers employing switching. This is a method introduced by Dicke /1/ to overcome the problem of instability in gain and local noise in receivers used for measuring weak noise signals. It consists of switching the receiver back and forth between the signal and a comparison source at a frequency at which system fluctuations have a negligible component. As the noise from both the sources has the same nature, switching between them results in obtaining a noise signal modulated to a degree dependent on the difference between the temperature of the signal and comparison sources. The device used, at a later stage in the receiver, to extract the wanted information by separating the weak modulation at the switching frequency from the band of noise frequencies also present, is the phase detector or synchronous detector as it is often called. The latter name is the less misleading of the two when used in connection with radiometers where the amplitude of the modulation frequency is measured and not its phase angle.

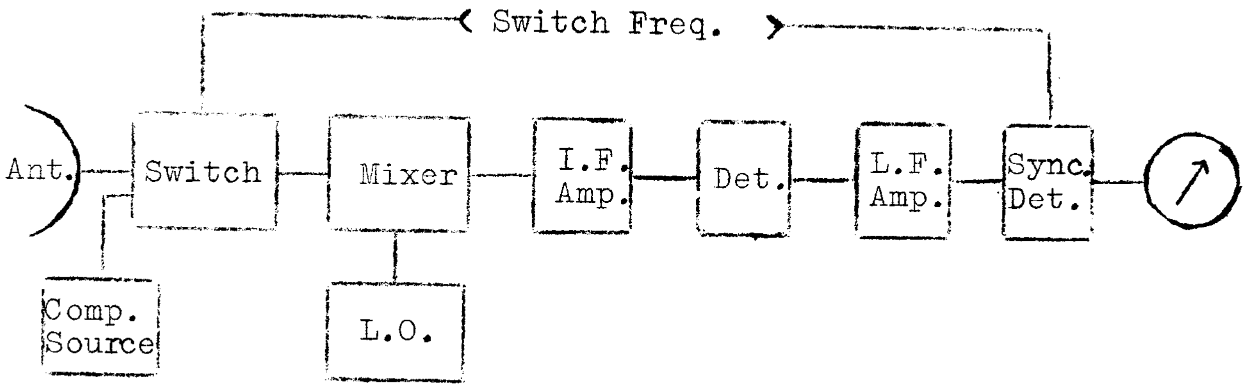


Fig. 1. A switching radiometer.

An examination of the block diagram of a switching-type radiometer Fig. 1, reveals the fact that the switch circuit and the synchronous detector are the two foreign elements, so to speak, which have no counterparts in an ordinary communications receiver; further, that they are, in principle, similar, namely mixers used for combining a chosen low frequency with a noise signal. In the first case, modulation is achieved and in the second, demodulation. It is this relative importance of the synchronous detector that has prompted the writing of a separate report on a single unit in a large and complicated radiometer although neither the discussion nor the circuits presented here are new. This report together with other internal reports about equipment constructed at this institution are meant primarily to facilitate the work of those concerned with their operation and improvement in the future.

Switch-type Phase Detectors.

Of the different types of phase detectors we shall only discuss those employing switching as they are of special interest to us. Considered as a black box, Fig. 2, a phase detector has a signal input, a reference input and an output and functions so that if the signal voltage has the exact frequency of the reference source the output voltage contains a d.c. component which is a function of the amplitude of the signal voltage and of the phase angle between the signal and reference wave forms. A knowledge of this function will enable, for example, the phase angle between two sinusoidal voltages of the same frequency to be determined by feeding them into the two inputs and measuring the output voltage with a d.c. instrument. In switch-type phase detectors the reference input has a rectangular form corresponding to two steady states with minimal transition periods between and a repetition rate which we shall term the reference frequency.

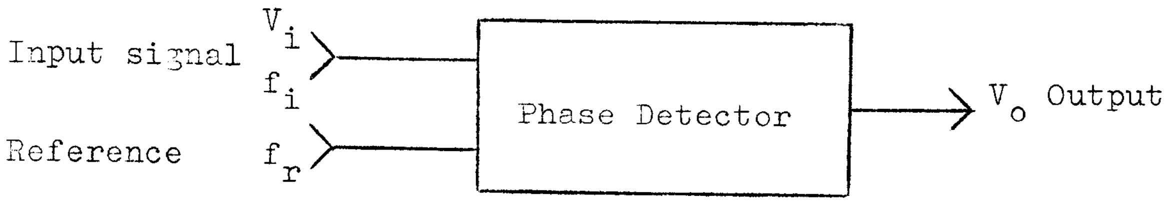


Fig. 2. $\bar{V}_o = F(\emptyset, V_i)$ if $f_i = f_r$.

Mechanical switches.

It is not necessary that the reference input shall consist of a voltage or current waveform; mechanical switching would be equally effective and in fact the simplest kinds of phase detectors are those with mechanical switches. Fig. 3 shows four

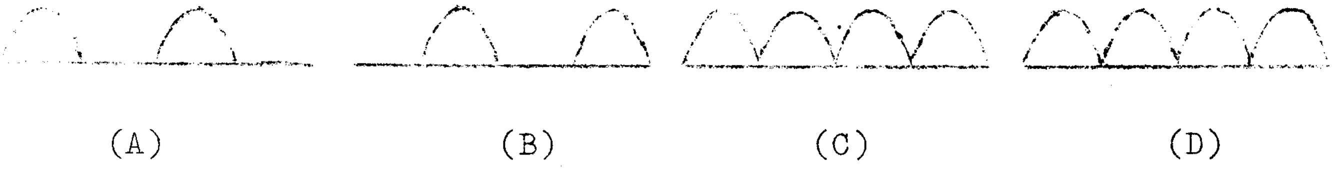

(A) (B) (C) (D)

Fig. 4. Output waveforms of sine-wave input in phase with reference source.

The effect is the same as would have been obtained by passing the signal through rectifiers. Half-wave rectification is got from (A) and (B) and full-wave rectification from (C) and (D). The commutator of a two-pole d.c. generator and the second set of contacts in a synchronous vibrator achieve just this latter result. The polarity of the output voltage can be reversed by interchanging the leads to the switch contacts. The phase-sensitivity of these detectors, however, comes into play only if the phase angle between the input voltage and the switching cycle is varied by amounts differing from nπ. Fig. 5 gives an illustration of the output waveforms obtained for phase differences of 45, 90 and 135 degrees.

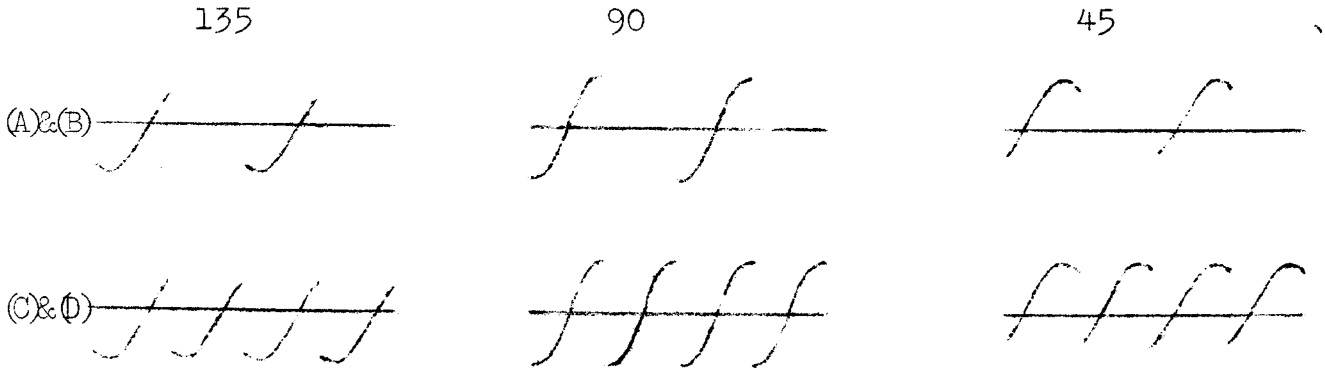


Fig. 5. Waveforms obtained for different phase angles.

It is clearly seen that the average d.c. output voltage is a sinusoidal function of the phase angle between the signal and the reference as shown in Fig. 6.

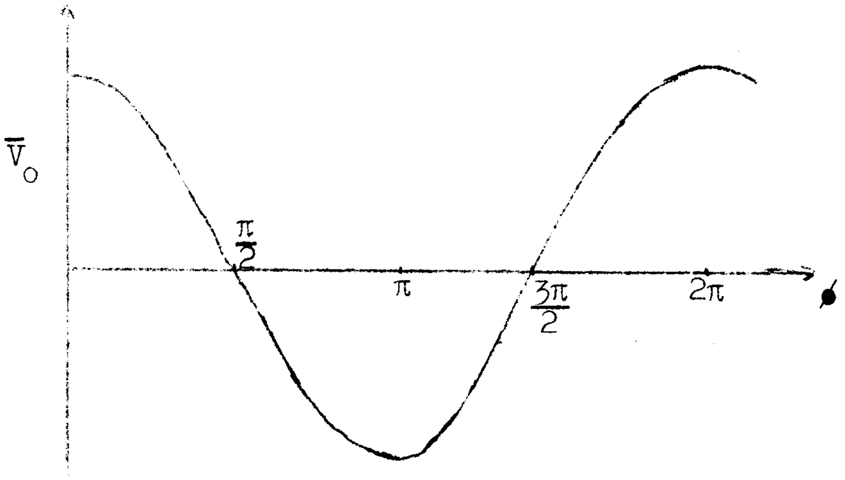


Fig. 6. Average output voltage as a function of ϕ.

The output waveforms produced by (A) and (C) are equivalent to those produced by (B) and (D) respectively. The only difference between shunt and series circuits is that the former are preferable when the output impedance of the signal source is high and the latter when it is low. The advantages of using circuits (C) and (D) when possible instead of (A) and (B) are the same as those of a full-wave rectifier over a half-wave one, namely, absence of dead periods resulting in a more uniform loading of the source and relative ease of filtering off unwanted a.c. components.

Before going on to discuss the behaviour of a phase detector at signal frequencies other than the reference frequency, an understanding of which is essential to appreciate its performance in the presence of noise, it might be interesting to see what the electronic equivalents of the above described mechanical switches look like.

Electronic switches.

Simple as mechanically switched phase detectors are, it is not always convenient nor even desirable to have them in receivers. Surface oxidation and contact noise, among other things, render their use less suitable in radiometry than in power applications. Almost invariably, non-linear devices like vacuum tubes or copper oxide or germanium rectifiers are used as elements in phase detecting circuits in small-signal electronic equipment. These circuits could be roughly classified into those using multi-element vacuum tubes and providing amplification as well as phase detection; those in which switching does not take place but which work, for example, on the sum and difference principle; and those switched only by the reference signal and providing no amplification. It is this last category which corresponds to the class of mechanical switches described in the preceeding section and to which the following discussion will be restricted.

Fig. 7 illustrates the development of the equivalent of a single-pole single-throw switch using diodes. Germanium or similar rectifiers could very well be used in this as in all the following circuits instead of the vacuum diodes shown in the figures. In (B) of Fig. 7 two diodes are connected in series with a battery in such a way that the battery voltage tends to send a current through them. If a signal source (A) of voltage less than the battery source were now connected to the point p between the diodes, the signal would be conducted through the diodes and down to ground through the mid-point of the battery.

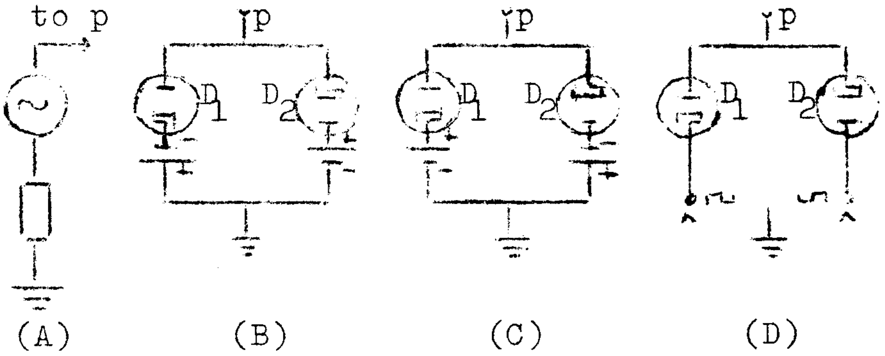
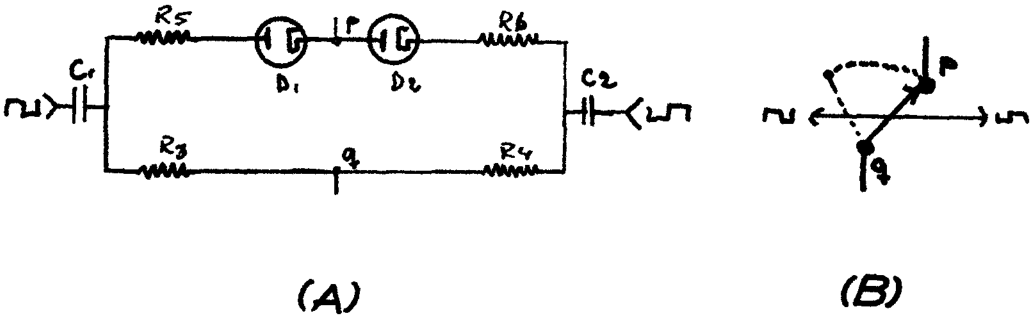


Fig. 7. A simple switch using diodes.

The same experiment repeated with the poles of the battery interchanged as in (C) would result in no signal current through the circuit, as both diodes are biased off by the positive and negative voltages on the cathode of D_1 and anode of D_2 respectively. Replacing the battery by a balanced square-wave generator as in (D) would combine the characteristics of (B) and (C) on a time basis, and provide isolation of the point p every half cycle and connection to ground through each diode and half the square-wave generator impedance every other half cycle. A more usable form of the circuit of (D) is given in Fig. 8 (A).

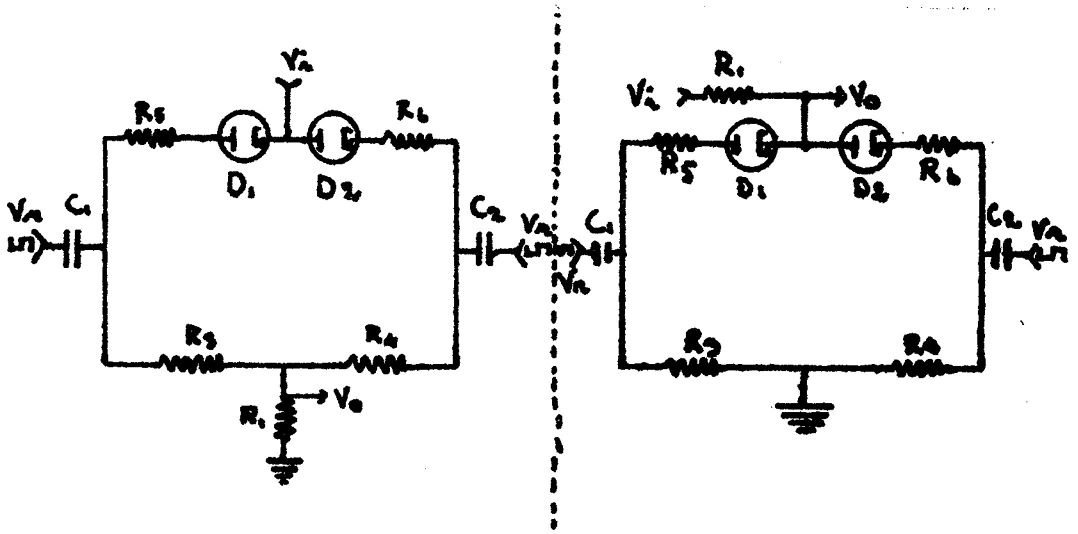


(A) (B)

Fig. 8. An electronic equivalent for a s.p.s.t. switch.

The push-pull square-wave voltages are fed in through two condensers C_1 C_2 large enough to have a low impedance at the switching frequency. The junction q of the two equal resistors R_3 R_4 is used as the signal return instead of the midpoint of the square wave generator as in the previous case, thus achieving together with C_1 and C_2 complete d.c. isolation from the switching source. Resistors R_5 R_6 of equal value are included in series with the diodes to limit the current through them during the conduction half cycle and to keep the point p electrically midway between the condensers in spite of inequalities in the characteristics of D_1 and D_2. In effect, the point p is alternately isolated from and connected to the point q at the switching rate. The circuit of

Fig. 8 (A) taken as a unit can therefore, with certain limitations, be considered as equivalent to a simple single-pole single-throw switch (B) which is operated mechanically at the same rate as the switching frequency. Two such units could be connected together to function as a single-pole double-throw switch and so on.



(A) Series operation. (B) Shunt operation.

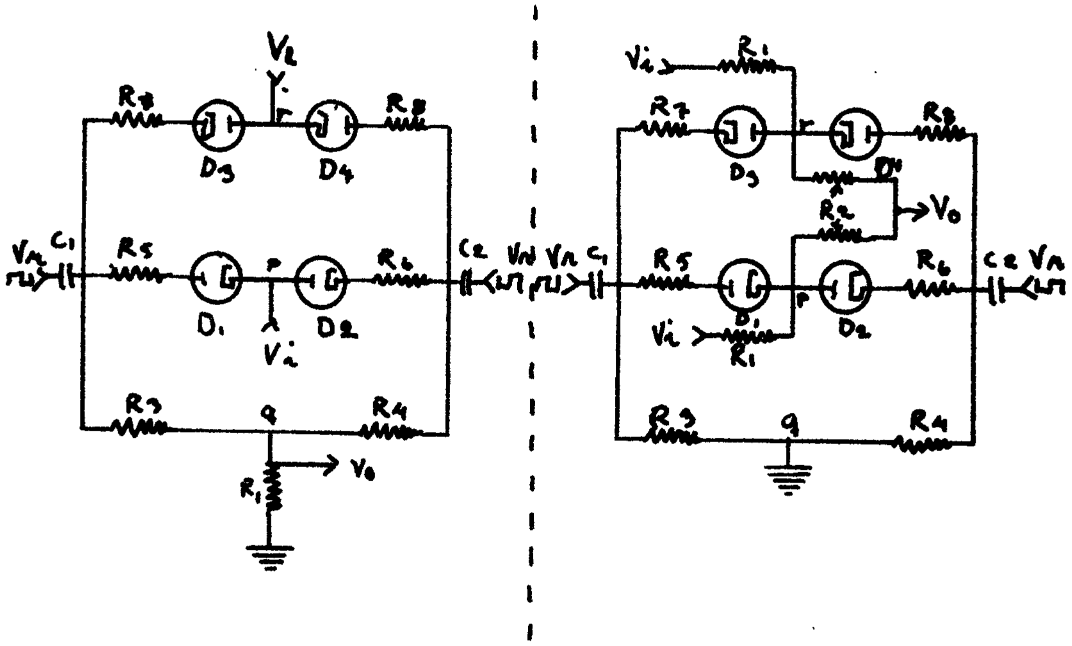
Fig. 9 Half-wave phase detectors using diode switching.

Fig. 9 shows how the circuit of Fig. 8 (A) can be combined with a single extra resistor R_1 in two different ways to provide the equivalents of the half-wave series and shunt connected phase detectors of Fig. 3 (A) and (B). The limitations to be borne in mind to obtain satisfactory operation of these phase detectors are:

a) The magnitude of the switching voltage must be large enough to hold the diodes non-conducting over the excursions of the signal voltage.

b) The signal current through R must not exceed the current through the diodes.

c) The time constants of the circuits C_1 R_3 and C_2 R_4 must be large compared to the period of the switching frequency. Putting together two of these units in a suitable manner gives us the full-wave phase detectors of Fig. 10.



(A) Series operation. (B) Shunt operation.

Fig. 10. Full-wave phase detectors using diode switching.

They correspond to the circuits of Fig. 3 (C) and (D) and can be used in their stead with the same limitations as for the half-wave circuits described in the preceeding paragraph. To connect the inputs in push-pull and the outputs in parallel as was done before, it is necessary only to add an extra diode arm as the same resistance arm can serve both diode arms. In (B) two resistors R_2 have to be introduced, as in the corresponding mechanical case to prevent short-circuiting the switch. This last full-wave shunt-connected circuit has been used in sensitive radiometers /2/ and is usually depicted in bridge form as in Fig. 11 below.

It is not accurate in this last case to say that each arm of the input is short-circuited to ground every other half cycle. In point of fact, the impedance of the switch sections is far higher than that of the condensers feeding in the signal (no series resistances used), and these together act as a time constant of the function of which we shall hear more anon.

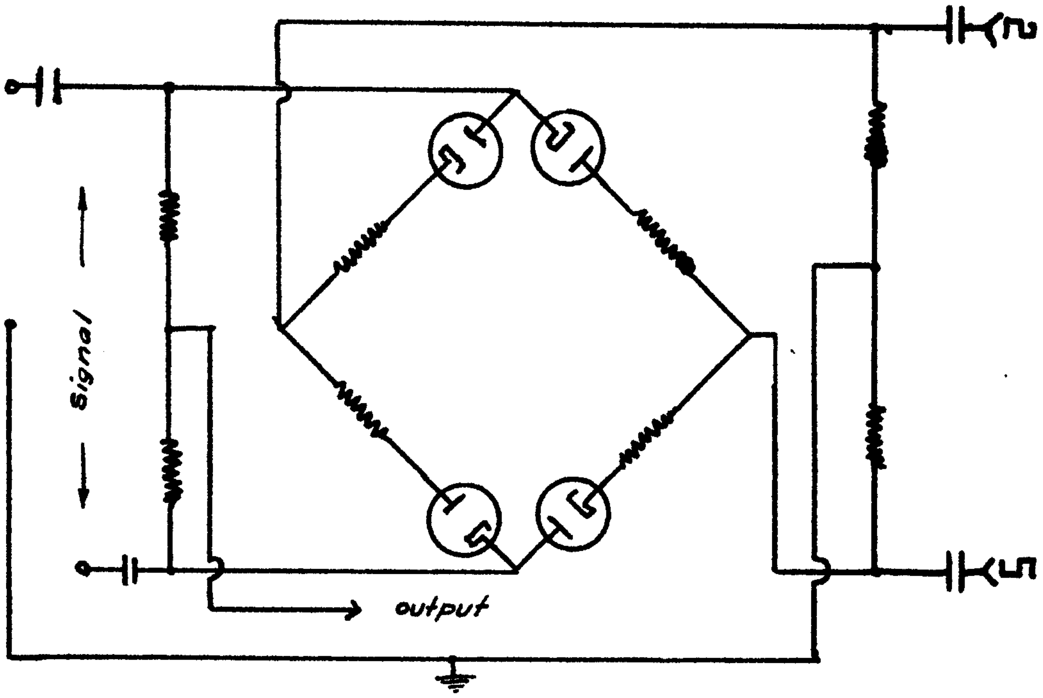


Fig. 11. Shunt connected full-wave phase detector.

Response to other frequencies.

So far we have only discussed the effect of a phase detector on a sinusoidal wave having the same frequency as the reference source. In this section, other frequencies will also be dealt with. To facilitate discussion of the process of switched phase detection a few simplifying assumptions will be made.

1) A full-wave phase detector is used.

2) The transition from one stable state to the other is instantaneous.

3) Each switch section has either infinite or zero impedance depending on its position. In other words, one half-wave section cuts off the signal completely from the output while the

other section conducts the signal unattenuated to it.

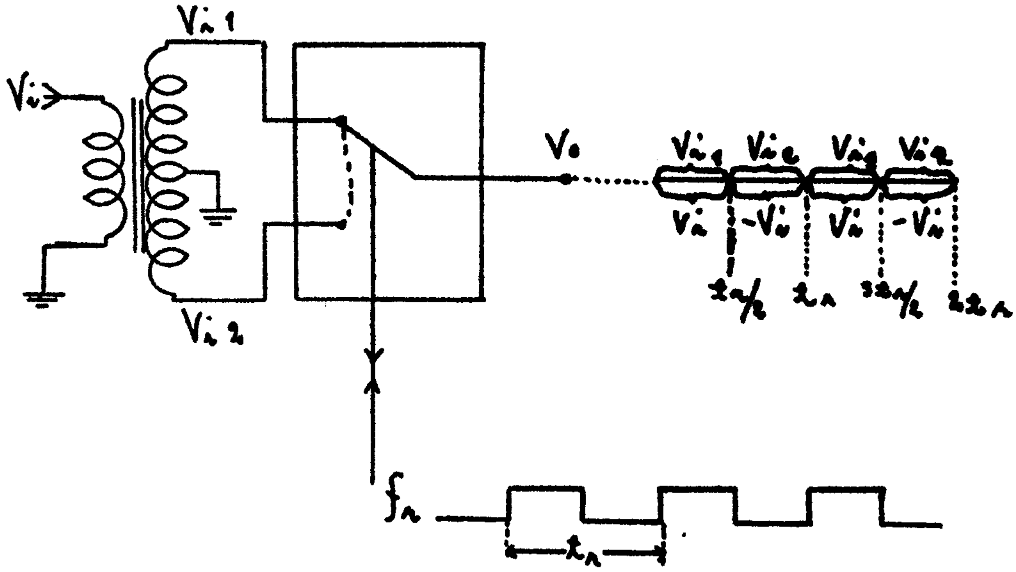


Fig. 12. An ideal full-wave phase detector.

In Fig. 12 an ideal phase detector having the above characteristics is represented. The signal V_i is fed to a phase-splitting device such as a center-tapped transformer and the two equal out-of-phase voltages V_{i1} and V_{i2} are connected to the two inputs. Assuming the transformer to be a lossless one having a 2:1 turns ratio, $V_{i1} = -V_{i2}$ and if $V_1 = V_{i1}$, we have $V_{i2} = -V_i$.

The output V_o is therefore either V_i or $-V_i$ depending on the instantaneous position of the switch. Let t_r be the period of the reference frequency f_r.

V_o is then V_i for a period $t_r/2$ seconds, $-V_i$ for the next $t_r/2$ seconds, V_i again for $t_r/2$ seconds and so on. It should be noted that no mention of the frequency of the input signal has been made. Whatever its frequency or waveform, the result of passing it through the phase detector would be as shown in Fig. 13, where the output waveform is obtained by simply breaking up the input into units $t_r/2$ seconds long, and inverting every other about the X-axis. In all cases where the input signal can be represented as a function of time the above method can be used to obtain a picture of the output, which may then be further analysed. The method is useless, however,

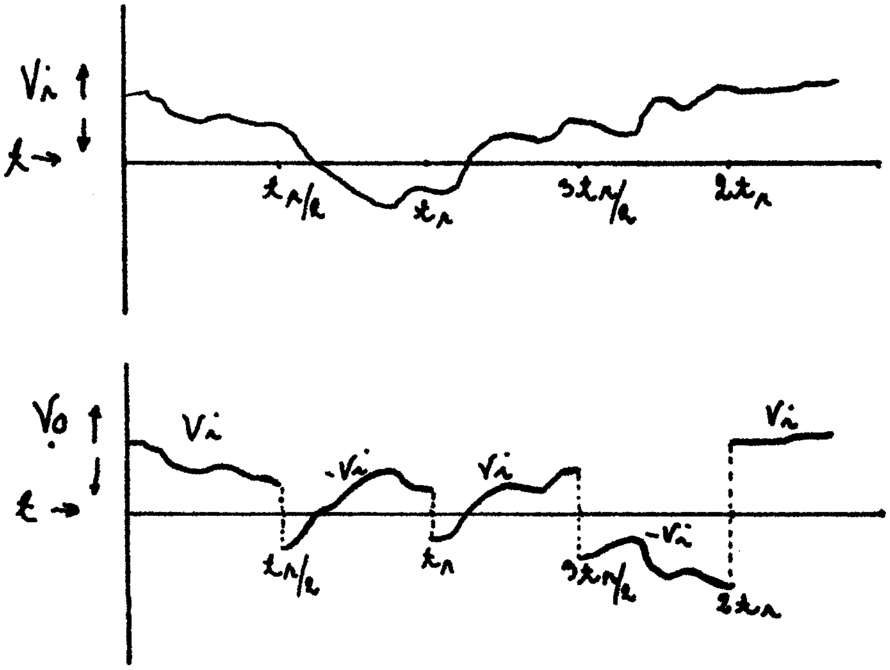


Fig. 13. Phase detection of an arbitrary waveform.

when one is dealing with an input signal which cannot be exactly pictured in time, as for example, a band of noise frequencies where a statistical distribution of power versus frequency, and absence of correlation is all the knowledge one has of the incoming signal. A composite picture may yet be built up with a knowledge of what would happen to a sine-wave at each of the frequencies making up the noise band.

Time constant.

To return for a moment to a sinusoidal wave (A) Fig. 14 having the reference frequency f_r and in phase with it, the output waveform got after phase detection (B) appears identical to that got by ordinary full-wave rectification (C). If resistors R_1 of value very much higher than the output impedance of the signal source were connected to the outputs of the phase detector and rectifier, the currents through them would follow the voltage waveforms and have instantaneous values of $V_o(\text{ins.})/R_1$. The power consumed in the resistors would be the same in both cases and equal to $(V_o\text{rms})^2/R_1$.

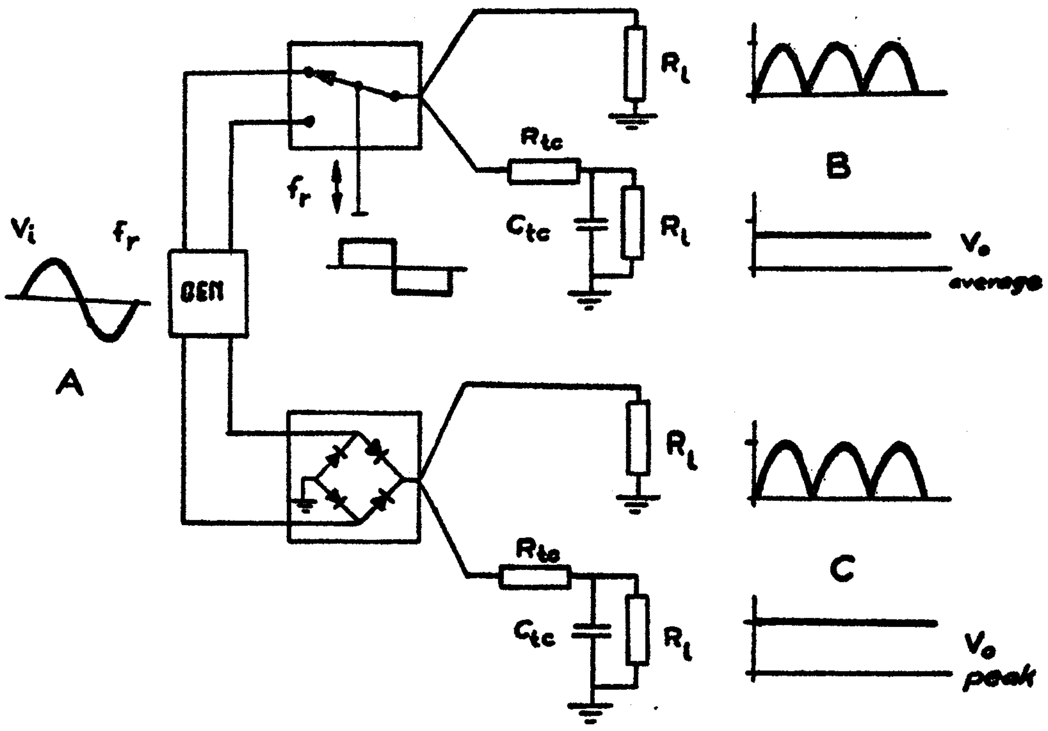


Fig. 14. Function of a time constant in phase detection.

The difference between the two cases appears with the inclusion of an integrating circuit before resistor R_1. R_{tc} and C_{tc} are chosen such that $R_{tc} \ll R_1$ and $R_{tc}C_{tc} \gg t_r$. The voltages over R_1 and the corresponding currents through them are no longer equal but V_o (ave.) in the phase detector case and V_o (peak) in the rectifier case. R_1 in both cases is a light load which discharges the condenser by a negligible amount from one cycle to another.

The explanation for the different voltages obtained is simply that in the rectifier case the condenser C_{tc} cannot be discharged through R_{tc} and the source when the signal voltage sinks below the potential to which it is charged because of the rectifiers in the circuit. The phase detector, on the other hand, is a bilateral device which allows of both charging and discharging with the result that the condenser will

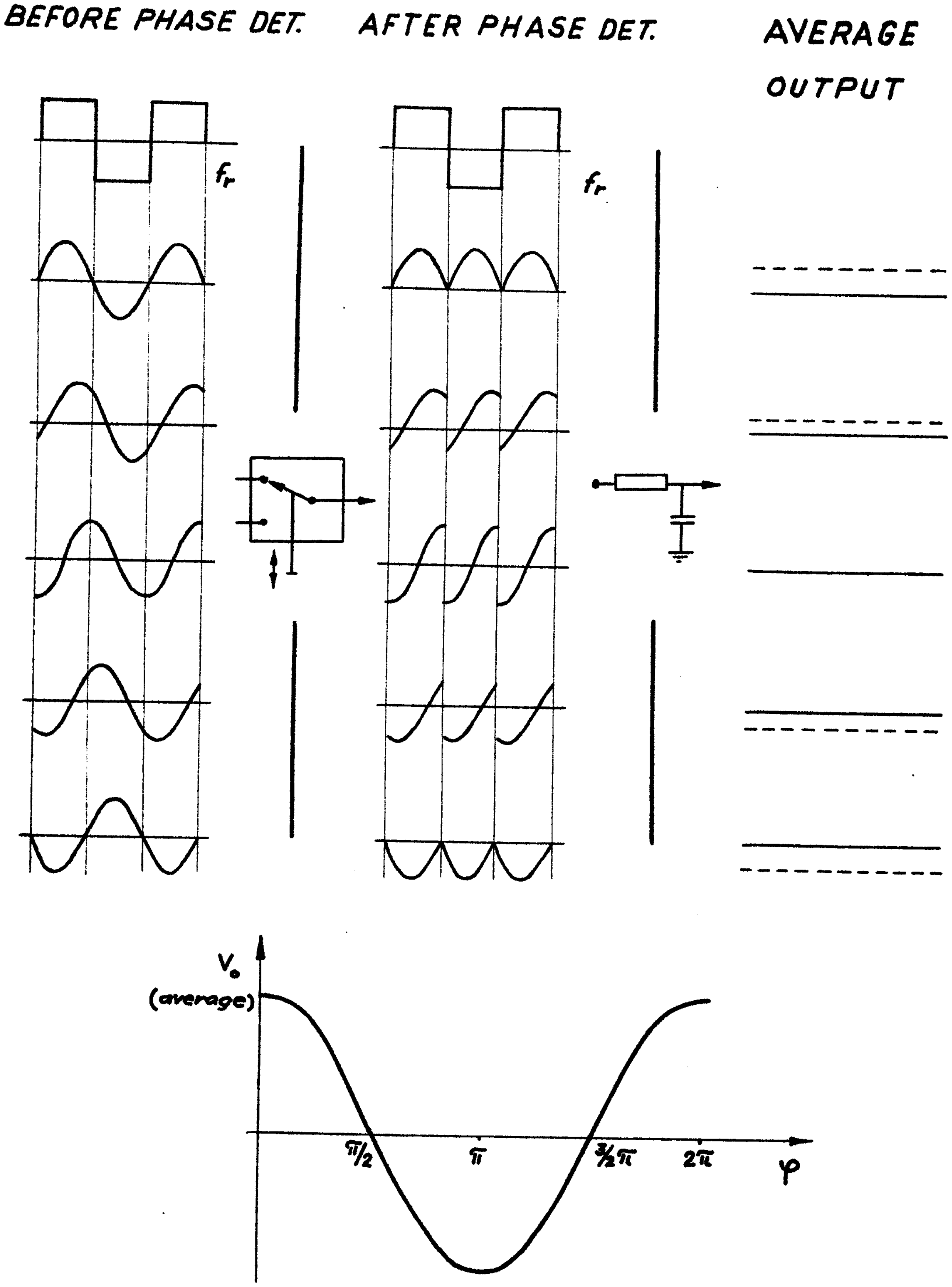


Fig 15.

Average output as a function of phase angle.

be charged to the average value of the output voltage. If the output is considered to consist of a steady d.c. component plus a ripple voltage having a fundamental component of frequency $2f_r$ and a number of harmonics, the condenser will acquire a potential corresponding to the steady d.c. component on which will be superimposed any part of the ripple voltage that is left after attenuation by the filter circuit.

It is seen thus that an integrating circuit of some type is a necessary item after a phase detector if the average voltages spoken of in the first section of this report are to be realised and measured on an instrument. The curve of Fig. 6 reproduced in Fig. 15 can be obtained experimentally by varying the phase angle of the input signal and measuring the voltage across R_1. Sufficient time must be allowed, of course, after each change of phase angle for the integrating circuit to adjust itself to the new level before the d.c. voltage is read off.

An arbitrary frequency f.

Let a sinusoidal voltage $V_i(t)$ having a frequency f be passed through a phase detector of the foregoing kind switched at a frequency f_r. The voltage V_o emerging from the phase detector can be expressed as a product of the input voltage and a function $F_r(t)$, if the function has a value +1 for a period of $t_r/2$ seconds, a value -1 for the next $t_r/2$ seconds etc., where $t_r = 1/f_r$. See Fig. 13.

$$V_o(t) = V_i(t)\, F_r(t) \qquad (1)$$

The Fourier expansion for a rectangular pulse train of the form shown in Fig. 16 (A) when $T = 2t_o$ is

$$Y(t) = 2B_{ave}\left(\frac{1}{2} + \frac{2}{\pi}\cos\frac{2\pi t}{T} - \frac{2}{3\pi}\cos 3\frac{2\pi t}{T} + \ldots\ldots\right) \qquad (2)$$

with all the odd harmonics of $\frac{2\pi}{T}$ and $B_{ave} = B\frac{t_o}{T} = \frac{B}{2}$.

$$V_o = \frac{2A}{\pi}\left\{ \cos[(\omega+\omega_r)t+\varphi]+\cos[(\omega-\omega_r)t+\varphi]-\frac{1}{3}\cos[(\omega+3\omega_r)t+\varphi] - \frac{1}{3}\cos[(\omega-3\omega_r)t+\varphi]+\ \dots\right\} \qquad (8)$$

From this last expression (8) a number of interesting deductions can be made.

a) When the signal frequency is the same as the reference frequency, that is $\omega = \omega_r$ the second term becomes independent of time and is equal to $\frac{2A}{\pi}\cos\varphi$ thus giving the magnitude of the d.c. component which is $\frac{2A}{\pi}$ when $\varphi = 0$, $-\frac{2A}{\pi}$ when $\varphi = \pi$, 0 when $\varphi = \frac{\pi}{2}$ or $\frac{3\pi}{2}$ and has intermediate values for other values of φ . The average value of a rectified sine-wave is $\frac{2}{\pi}$ of the peak value and this is just what was shown graphically in Figures 6 & 15. The other terms correspond to $2f_r$, $4f_r$, $6f_r$, etc., which with their added coefficients represent the ripple components consisting of all the even harmonics of the reference frequency.

b) If the input sine-wave has a frequency corresponding to an odd harmonic of the reference frequency e.g. $(2n-1)f_r$ then the $2n^{th}$ term becomes time independent and results in a d.c. component of value $\frac{2A}{(2n-1)\pi}\cos\varphi$. It is seen that (a) above is just a special case of (b). The remaining terms are ripple components similar to the ones in the above instance but with different coefficients.

c) It the input sine-wave corresponds to an even harmonic of the reference frequency, no time-independent term is yielded thereby signifying the absence of a d.c. component in the output. A.C. components corresponding to all the odd harmonics of the reference frequency are generated.

d) It the input is not a multiple of the reference frequency but is just any frequency at all, the output will contain a spectrum comprising the sum and difference beats of the signal with the reference frequency and all its odd harmonics, the coefficients being inversely proportional to the order of the harmonic. A signal lying very close to the switching frequency could be considered to have the same frequency as the reference source but with a slowly changing phase angle. The output would then include a slowly varying d.c. component having a maximum value equal to the average voltage and a rate of variation equal to the frequency difference. The same argument shows a frequency lying close to one of the odd harmonics would produce a slowly varying d.c. component having a maximum value 1/n of that in the previous case where n is the order of the odd harmonic in question.

e) If the input signal is time-independent and is for example, a steady voltage of value A, the output is given by

$$V_o = 2A \left(\frac{2}{\pi} \cos\omega_r t - \frac{2}{3\pi} \cos 3\omega_r t + \ldots\right) \qquad (9)$$

which is another way of saying that the output is a square wave having a frequency f_r and going both positive and negative to the value A*). The average d.c. component in the output is zero. A slow variation of the d.c. input would appear as a modulation envelope on the square wave carrier.

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*) This method of converting d.c. to a.c. has found an interesting and unusual application at power levels /3/ in the Swedish State Board's high voltage d.c. transmission system to Gotland, an island 60 miles off the coast of Sweden. Six special high voltage mercury arc valves developed by ASEA are grid-switched in an elegant arrangement to convert the cable-transmitted d.c. from the mainland into three phase a.c. for distribution on the island. A similar arrangement on the mainland is also grid-switched and uses the properties illustrated in Fig. 15 to regulate the d.c. output to the cable by changing the phase angle of the switching voltage with respect to the a.c. input.

Fig. 17 illustrates graphically points b), c) and e). It is clearly seen that for even harmonic inputs no d.c. component can result, as in each position of the switch, whatever the initial phase, an equal number of complete positive and negative half cycles go through. Also shown is the special instance of a square wave input of reference frequency.

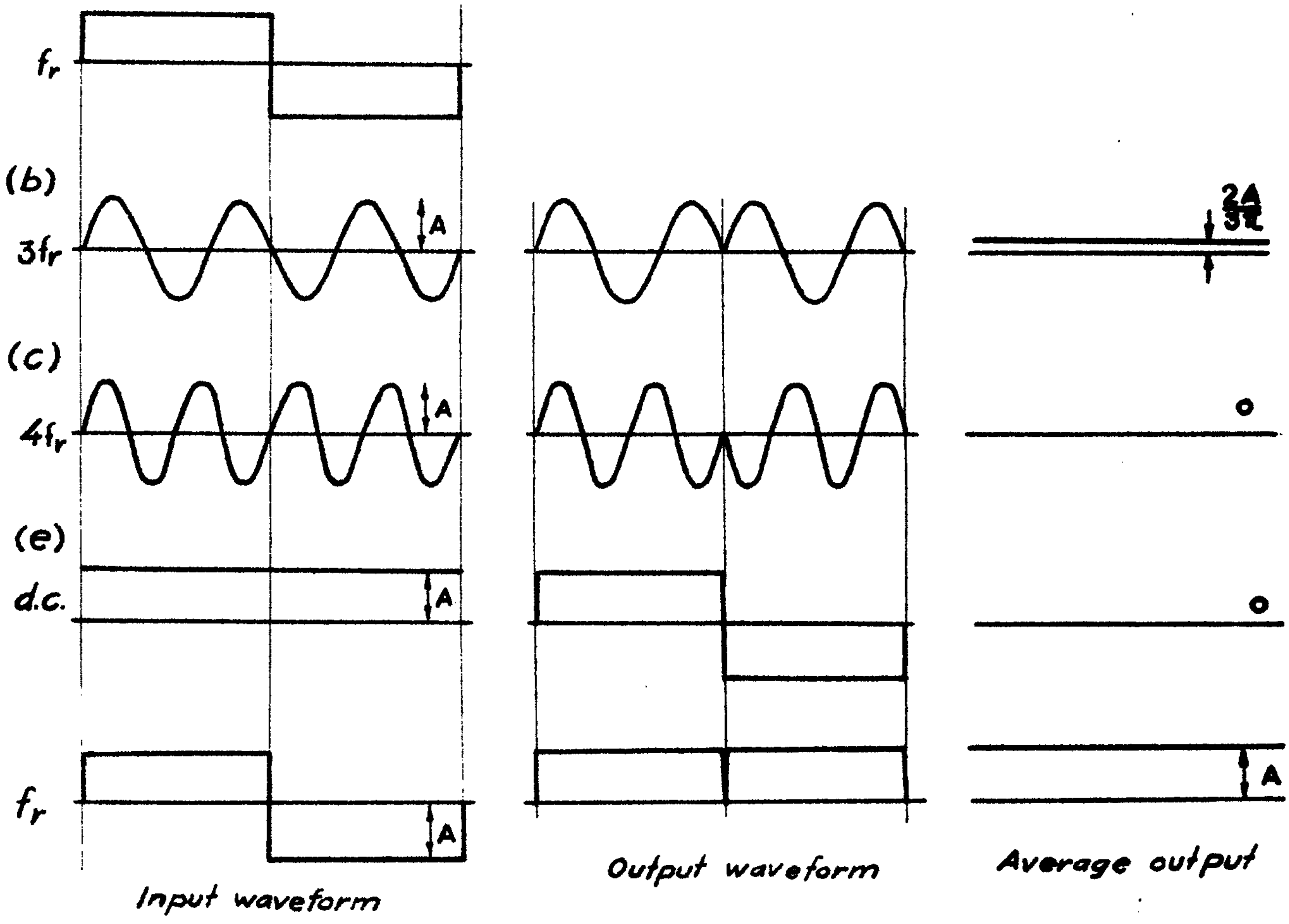

Fig 17

Phase detection of other frequencies than the reference

Phase detector as mixer.

Phase detectors are often called mixers where the reference source acts as local oscillator. The spectrum of beat frequencies obtained is certainly reminiscent of a mixer, but in order to avoid confusion, the following points must be noted.

1) The signal frequency is never present in the output.

2) The local oscillator frequency does not normally appear in the output. The only exception is in the case of the signal having a frequency which is an even harmonic of the L.O. frequency, when a component is produced as a beat note.

3) Beats between the signal and even harmonics of the L.O. are not present in the output.

4) The mixer responds even to a d.c. signal input.

5) An in-phase square-wave input of L.O. frequency gives pure d.c. in the output.

6) Beat frequencies are not produced between different components in the signal input as would happen in an ordinary unbalanced mixer.

When operated in conjunction with an integrating circuit as is normal:

7) Signal inputs corresponding to the L.O. frequency or one of its odd harmonics gives a d.c. output whose amplitude is a function of the phase, amplitude and harmonic order of input.

8) The mixer discriminates against input frequencies which are even harmonics of the L.O.

Response to a noise band.

Equipped now with a knowledge of the changes that any single-frequency signal would undergo in passing through a phase detector, we can proceed to consider the conditions actually obtaining in a switched radiometer. In Fig. 18 (A) is represented the band of noise frequencies present in the last Intermediate frequency amplifier prior to detection, and in (B) after quadratic

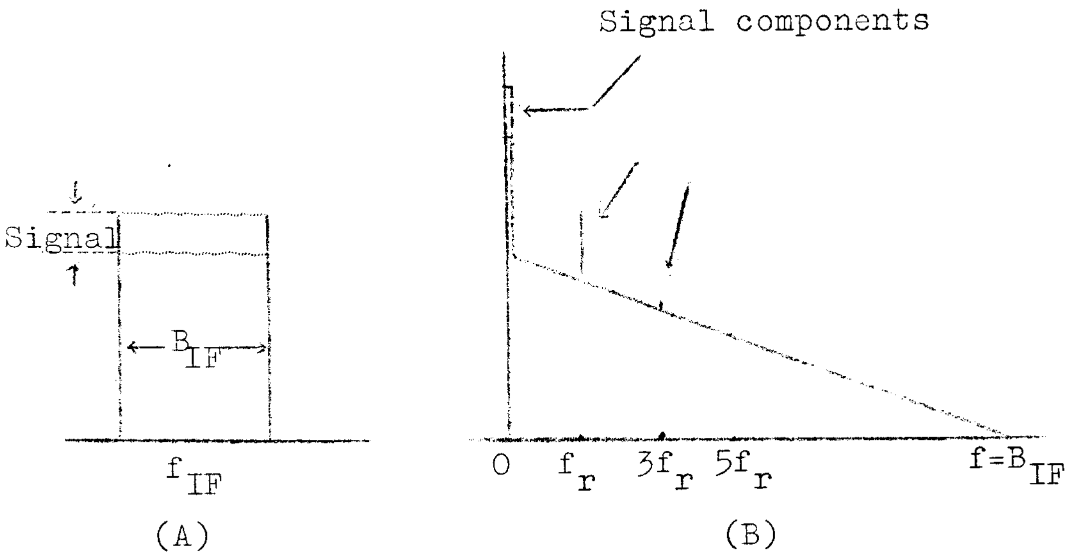

Fig. 18. Noise band before and after quadratic detection.

detection. In the receiver in question the switching is done in frequency, thus tuning the input alternately to a frequency within the spectral line and to a frequency just outside it. The upper level in (A) corresponds to the noise received when on the spectral line and the difference between the two levels represents in exaggereated form the increase of noise due to the contribution from the spectral radiation.

Fig. 18 (B) shows the form the power-frequency distribution takes after detection. The receiver and background noise give rise to a d.c. component and to all frequencies from zero to B_{IF} where B_{IF} is the bandwidth of the narrowest Intermediate frequency amplifier. The contribution from the signal, which in the pre-detection stage existed as a square-wave modulation envelope on the noise carrier, now appears as all the components that result from the rectification of a square wave. They are, namely, a.c. components corresponding to the switching frequency and its odd harmonics, and a d.c. component all of which are shown in the figure. The information required, giving the signal strength, is contained in these frequencies which are superimposed on the noise band and must be separated from it.

The necessity of having an integrating circuit after a phase detector has been dealt with earlier. An integrating circuit is in essence a low pass filter, and although usually referred to by its time constant can be equally well designated by its bandwidth. If the bandwidth of the filter is B_{tc} (usually of the order of 0.002c/s), all that can go through it besides d.c. voltages are a.c. components lying between zero and B_{tc} c/s.

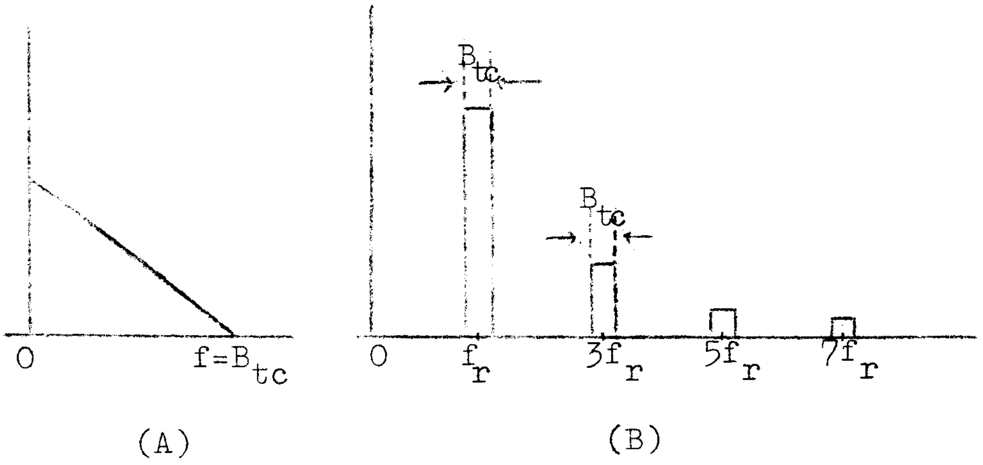

Fig. 19. Low-pass filter by itself and with phase detector.

When this filter, Fig. 19 (A) is used together with the phase detector, only the frequencies lying in the bands shown in (B) can contribute to the output as seen in the analysis of the previous section.

Superimposing this on the output of the detector, Fig. 20, we see that the information required is contained just within these bands and that the phase detector and filter together succeed in eliminating the rest of the unwanted frequencies. The noise components within these narrow bands can go through of course, and appear on the recording. It might be thought that an unlimited increase of the time constant and consequent decrease of bandwidth will reduce the amount of unwanted noise and thus better the sensitivity. Two factors, however, set a limit to this in practice. One of them is the zero stability of the equipment and the other is the time taken to make measurements. The signal reaching the recording instrument is a varying voltage giving a profile of the spectral line, and slow as the variation may be it corresponds to a definite bandwidth which must go through the filter if the profile is not to be distorted.

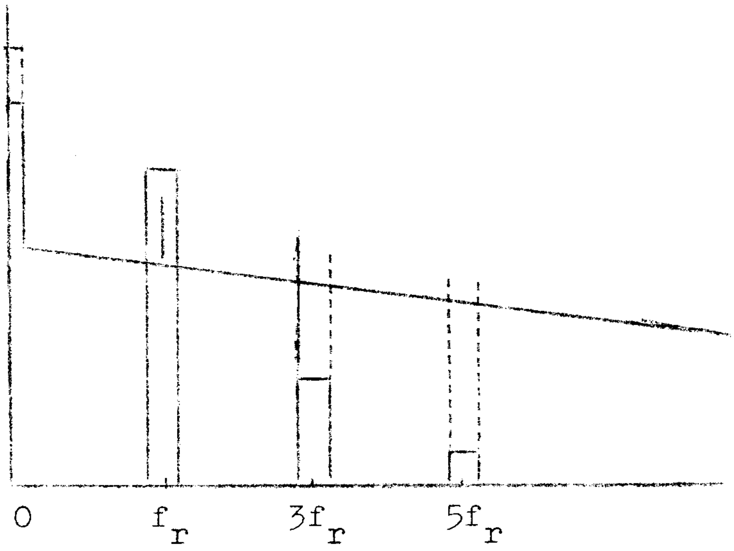

Fig. 20. Parts of the noise band which can come through.

If the sensitivity of the phase detector at the frequency f_r is taken as 1, the sensitivity at $3f_r$ is one-third, it is one-fifth at 5f and so on, as seen in the previous section. The amount of signal component present within these narrow bands also decreases in the same proportion. Taken together, the contribution from the higher order frequencies decreases as the square of the order of the harmonic. Even though diminished by the decreasing sensitivity of the phase detector, the noise contributions from the higher order bands would also come in and be registered on the recording. As almost 90 % of the signal information is contained in the component at the switching frequency and as excess noise would only overload the tubes in the low frequency amplifier after the detector, an audio filter is incorporated in an early stage in the audio amplifier. The band pass of this filter is indicated approximately in Fig. 21. It attenuates the harmonics sufficiently to restrict the response of the phase detector to only those frequencies contained in the small band around f_r.

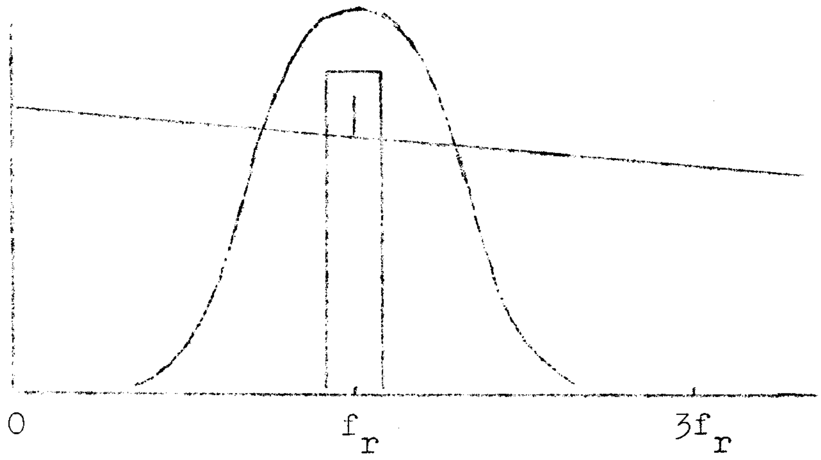

Fig. 21. The audio filter before the phase detector.

An additional reason for the audio filter is that the slow variation of the signal causes sidebands around f_r, $3f_r$ etc., whose separation from these frequencies is proportional to the order of the harmonic. As the frequency of the output of the phase detector is equal to the separation only and independent of the order of the harmonic, the inclusion of the other bands would cause a slight distortion of the profile.

A practical circuit.

The criteria that decide the choice of a particular phase detector circuit for a radiometer are sensitivity and zero stability. From the point of view of sensitivity any of the full-wave circuits described in the section on electronic switches could be used succesfully in a radiometer. The half-wave circuits are not desirable as they cause an apparent deterioration of the noise figure of the receiver. In a full-wave phase detector the average d.c. voltage resulting from the signal component is doubled, whereas the uncorrelated noise voltages are added quadratically thus giving an improvement of $\sqrt{2}$ over the half-wave type.

A phase detector can be said to have good zero stabilty if the potential of its output terminal does not drift in the absence of a signal. Take the case of the half-wave circuit of Fig. 22. The point p will be at ground potential when the diodes are cut off as the back resistance of the diodes is considerably higher than the load resistor R_1. But during the conduction half cycle, point p will be at ground potential only if the ratio of the resistances in the arms E and F is the same as in the arms G and H. As a rule R_5 is made equal to R_6, and R_3 to R_4, but $E = R_5+R_{d1}$ and $F = R_6+R_{d2}$, and an inequality between R_{d1} and R_{d2} will upset the balance. As mentioned earlier R_5 adn R_6 are chosen very much higher than R_d so that R_5+R_{d1} will very nearly be equal to R_6+R_{d2} even if $R_{d1} \neq R_{d2}$. The disadvantage of doing this is that the impedance of the switch is increased providing less and less of a short circuit to ground during the conduction period. In any case, high stability is required of the four resistors as any inequality resulting from temperature changes etc., would make itself felt despite constancy of the diode internal resistances. The potentiometer R_q in the circuit is to enable accurate setting of the zero level.

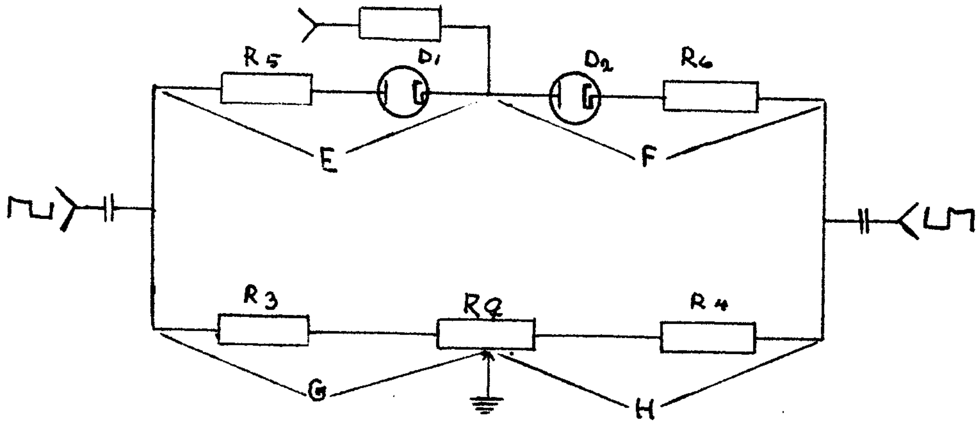

Fig. 22. A half-wave phase detector.

Fig. 23 shows an alternative circuit arrangement. Two extra diodes have been added and their mid-point has been

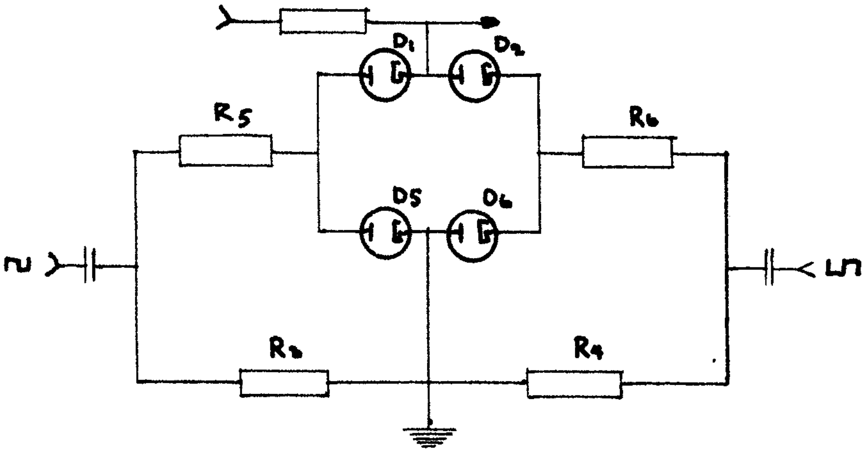

Fig. 23. A half-wave phase detector using four diodes.

grounded. A simple analysis will show that for a given current through the diodes a small variation in the internal resistance of one of them will shift the potential of point p less than in the previous instance. Further, small changes in the external resistances have no longer the same effect as before. The impedance to ground has also decreased as the signal does not have to go round the whole circuit but only through the diodes. The resistors R_5, R_6 must be halved to obtain the same current through the diodes as when there were only two.

A disadvantage of this circuit is that the zero level is dependent on the equality of the ratios of the diode impedances in the bridge formed by the four diodes. If a large number of tubes is available it is possible to match them so that the discrepancy from ground potential is negligible at the signal levels used. Small drifts occur during the initial period after switching on, but once warmed up good stability is obtained. An alternative to matching the diodes is to include a low resistance potentiometer in the bridge formed by the diodes and to balance out any inequality. Two of these units could be combined in push-pull for use as a full-wave phase detector. In this arrangement, Fig. 24, the resistors R_3 and R_4 which played necessary roles in all the other circuits become redundant and can be omitted. This is the cir-

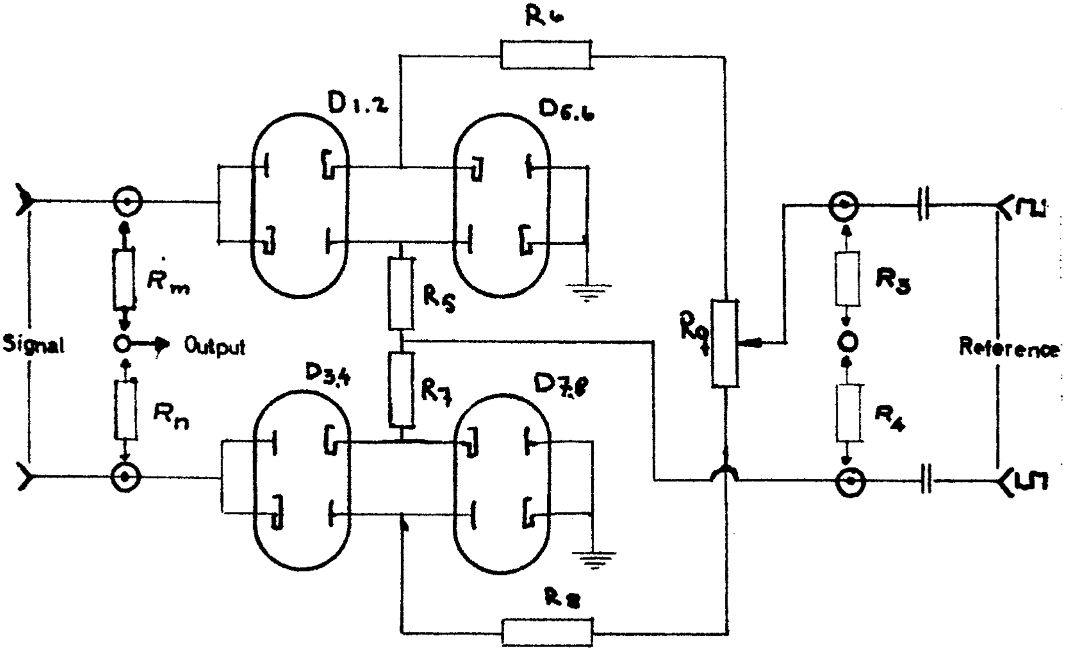

Fig. 24. A full-wave phase detector using eight diodes.

cuit actually used in our radiometer and which has performed satisfactorily.

To facilitate experimentation the resistors R_3, R_4, R_m and R_n were made up as plug-in units. These four resistors together with the four double-diodes constitute movable elements. It is possible by merely plugging in suitable combinations to obtain the circuits of Fig. 22, Fig. 23 and Fig. 11. As normally operated, all elements except R_3 and R_4 are left in.

In a practical circuit, the transition from one state to the other is never instantaneous and the duration of the two states often tends to depart from equality. Both these factors are dependent on the purity of the waveform from the square-wave generator. An unsymmetrical square wave switching a phase detector will make it respond to even harmonics, and decrease its sensitivity to the switching frequency. In our receiver, good symmetry of the square wave is ensured by obtaining it from a bistable multivibrator triggered by a pulse