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HIGH SPEED VOICE FREQUENCY TELEGRAPH OPERATION BETWEEN SYDNEY AND PERTH

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Introduction: The landline telegraph facilities of the Overseas Telecommunication Commission between Sydney and Perth consisted until early 1953 of one voice frequency telegraph circuit of the orthodox type, established by tandem connecting a Sydney-Adelaide channel and an Adelaide-Perth channel. This circuit was leased from the Department on a full time basis, and when required an additional channel of the same type was made available. In order to augment these facilities, it was decided to replace these channels with channels capable of operating at about twice the speed. The first of these channels was placed in operation on a part time trial basis in April 1953. After some months trial operation it was evident that reliable high speed operation was practical, and the channel was handed over in September to the O.T.C. on a full time basis, although some improvements still had to be made. At the same time work on the second channel was commenced, and this was put into service immediately prior to the Royal Visit.

The problems encountered in establishing high speed channels of such great length, that is 2680 miles, were many and varied, and the successful completion was due to the effective co-operation of the engineering staff in N.S.W., W.A., S.A., Victoria, Research Laboratories, Postal Workshops, Melbourne and Central Office. The more important technical details of the high speed channels are described herein, together with measures taken to improve the reliability. Most of these measures were concerned with basic principles of transmission, and since they apply also to the operation of orthodox VFT systems, they should be of interest to readers concerned with such systems.

Speed Requirement: The design requirements in regard to speed were that the channels should operate reliably at speeds up to 162 W.P.M. Wheatstone, equivalent to 162/1.2 = 135 bauds, and preferably up to 180 W.P.M. or 150 bauds.

The maximum permissible speed of a VFT channel is, all other conditions being equal, directly proportional to the bandwidth. The relation between speed and bandwidth can however not be generally stated since distortion and operating margins are also involved. Thus an orthodox VFT channel is known to be capable of satisfactory operation at the teleprinter speed of 50 bauds, and it apears fairly generally accepted that satisfactory operation can be achieved at 66 bauds. Jolley (1) quotes the maximum speed as 80 bauds under favourable conditions. It was further known that the Overseas Telecommunication Commission had operated the leased Sydney-Perth VFT channel at speeds up to 80 W.P.M., equal to 67 bauds, with reasonably satisfactory results considering the length of the circuit, and the fact that the circuit consisted of two VFT channels in tandem.

The nominal bandwidth of orthodox VFT channels is 120 c/s, and, based on the foregoing considerations, it was decided to make the bandwidth of the high speed channels twice as great, that is 240 c/s.

Frequency Allocation of High Speed Channels: The only purely technical condition regarding the carrier frequency of the high speed channels is that it should, for distortion reasons, be much greater than the signalling speed, say not less than 1000 c/s. There were however a considerable number of practical considerations. First of all, at the time the first high speed channel was put into service, the only landline telecommunication facilities between Adelaide and Perth consisted of two 3-channel carrier telephone systems, plus two programme channels and one multi-office physical trunk. One of the six telephone channels was used as a bearer circuit for an 18-channel VFT system. In order not to degrade the five telephone channels, as would be the case if speech plus duplex (S + DX) operation were adopted, and for convenience, it was desired to associate the high speed channel with the 18-channel VFT system. This system was however used to capacity, and in order not to reduce the total number of channels, the high speed channel was arranged to occupy the frequency of the non-existent channel 19 (2580 c/s) whilst the existing channel 18 was dropped. The choice of the frequency 2580 c/s involved a foreseen risk of excessive amplitude and phase distortion due to the close proximity of the upper cut-off frequency of the VFT bearer (2800 c/s), and it was found necessary, as described later, to improve the performance of the bearer circuits in order to obtain satisfactory performance.

The frequency 2580 c/s was adopted also for the Sydney-Adelaide section in the case of the first high speed channel. The second channel is carried for the entire distance on wide-band channels (300-3400 c/s), but it might be necessary under emergency conditions to patch it on to a channel of a 3-channel system, and the frequency 2580 c/s was therefore also adopted for this channel, despite the fact that three channels, 18, 19 and 20, have to be dropped where the high speed channels are associated with a 24-channel VFT system.

As far as possible the second high speed channel has been associated with equipment and routes not associated with the first channel, but due to lack of alternative routes, for instance between Port Augusta and Kalgoorlie, a complete separation has not been possible.

First High Speed VFT Channel—Early Development: The first channel was to be associated with an S.T.C. 18-channel VFT system between Perth and Adelaide, and between Adelaide and Sydney with a VFT system consisting of a 24 channel G.E.C. terminal in Adelaide and an 18-channel S.T.C. terminal in Sydney. This 18-channel Sydney terminal will be replaced shortly by a 24-channel G.E.C. terminal. The methods of filter design differ between the G.E.C. and S.T.C. terminals, but both methods were known, and appropriate high speed filters of twice the nominal bandwidth were made (nominal bandwidth 240 c/s and midfrequency 2580 c/s). In the case of the 24-channel G.E.C. terminal, the normal filters for channel 19 were simply replaced by the high speed filters, whilst the filters of channels 18 and 20 were disconnected at the "common" side. In case of the 18 channel S.T.C. terminals the filters associated with channel 18 were replaced by high speed filters. The compensating network in these terminals consists normally of an inductor in parallel with a series—resonant circuit; the former compensates for the lack of a channel below channel 1, and the latter for the lack of a channel above channel 18, but since the high speed channel replaced channel 18, and operated on the frequency of channel 19, the series resonant circuit was disconnected, and no compensation for the lack of channels above the high speed channel was made in the early stages. The two individual sections (Sydney-Adelaide and Adelaide-Perth) were tandem connected in Adelaide "via DC," that is the double current signals from the receive relay of the amplifier detector were used to control the static modulator of the following channel.

Trials by O.T.C. between Sydney and Perth revealed that the required speeds were obtainable, but for short periods only, and that the reliability of the circuit was unsatisfactory at 150 W.P.M. The amplifier detectors were to some extent responsible for the lack of reliability, and to improve the reliability it was decided to eliminate the amplifier detectors and the static modulators from the through-connection in Adelaide. This was done simply by connecting the output terminals of the receive filter (via an amplifier with suitable gain) to the input terminals of the corresponding send filter. The receive filter is a two-section filter, and an investigation revealed that one section only was necessary, when this through connection arrangement was adopted, and the overall bandwidth of the channel was in consequence widened somewhat by removing the superfluous filter section from the circuit. At the same time work was proceeding to improve the amplifier detectors at the terminal stations, and some improvements in the reliability was noticed, but the grade of service remained unsatisfactory.

Swinging Bias: An examination of the fault returns for the channel revealed a large number of complaints regarding "swinging bias". The word "bias" is in this sense a term for the indication of a centre-zero mA-meter in the double current receive leg, when "reversals" or equally long "marks" and "spaces" are transmitted in rapid succession from the transmitting terminal. If a constant mark is received the meter gives an indication of say + 25mA, whilst an indication of —25mA is obtained during a constant space. During reversals the deflection should of course be OmA, but if a constant deflection of + 5mA is obtained, the circuit is said to exhibit a marking bias of 5 mA. The word "swinging" indicates that the bias reading is not constant, but varies in a swinging fashion. In such cases the needle moves in a similar manner to the needle of a db-meter, used to measure the receive level on a non-synchronised carrier telephone channel. This is perhaps the reason for the rather general assumption that non-synchronism of modulator and demodulator oscillators is the primary cause of swinging telegraph bias.

TABLE 1—OVERALL TELEGRAPH DISTORTION IN %

Speed	Input Level to Amplifier Detector Relative to Nominal (db)	Type of Signal (Teletype)					
		1:1	2:2	6:1	1:6	Q9S	Q9S Rev.
125 Bauds or 150 W.P.M. Wheatstone	10	7	18	10	4	16	16
	8	3	15	10	9	9	9
	5	1	6	3	10	8	7
	0	0	7	5	8	8	8
	—5	2	10	7	3	10	10
	—8	4	11	9	4	12	12
	—10	17	17	18	17	23	22
	—15	F	F	F	F	F	F
66 Bauds or 80 W.P.M. Wheatstone	10	9	4	6	2	8	8
	8	4	1	4	6	8	6
	5	2	1	2	6	8	6
	0	2	2	4	3	4	3
	—5	4	3	4	2	4	3
	—8	4	4	5	1	4	4
	—10	8	10	11	7	9	9
	—15	F	F	F	F	F	F
150 Bauds or 180 W.P.M. Wheatstone	10	3	21	12	16	24	24
	8	5	14	7	20	16	17
	5	6	8	5	20	16	16
	0	5	10	7	18	11	13
	—5	4	11	10	15	15	15
	—8	3	12	11	7	18	17
	—10	13	24	20	16	35	35
	—15	F	F	F	F	F	F

Note 1. "F" indicates "Failure," that is either complete failure or erratic operation.

Note 2. The bias control on the amplifier detector was adjusted for zero distortion, on reversals at a speed of 125 bauds at normal level.

A thorough investigation of conditions leading to swinging bias, revealed however that the primary cause is intermodulation in the VFT bearer circuit between the VFT channels. The relatively simple problem of intermodulation between two tones has been discussed in a previous Journal (2), where it was shown that a number of frequencies, differing from the original two frequencies, are produced whenever two tones are transmitted simultaneously through an equipment unit. The number of different frequencies transmitted simultaneously over an 18-channel VFT bearer may be as high as 18, and the number of intermodulation products of significant amplitude may be many thousands, and the frequency of many hundreds of these may coincide with the frequency of any arbitrarily chosen VFT channel. Consider, for instance, a relatively quiet period, when most channels will be in the rest-condition. In this condition a number of tones will be transmitted over the VFT bearer; intermodulation will occur, and the frequency of a number of intermodulation products will coincide for instance with the frequency of the high speed channel. If the VFT frequencies originate from a mechanical multitone generator, and if the bearer circuit is a synchronised carrier telephone circuit, these intermodulation frequencies will be exactly equal to the frequency of the high speed channel, and the addition of these unwanted signals to the wanted signal may cause a marking or a spacing bias. If however the VFT frequencies are obtained from individual oscillators or if the bearer circuit is not synchronised, then the intermodulation frequencies will differ slightly from each other and from the frequency of the high speed channel, resulting in a beat effect between the wanted and unwanted frequencies, which in turn may cause swinging bias.

Telegraph Distortion and Bias: The daily line-up of a telegraph channel includes a "bias"-adjustment, that is an adjustment of a potentiometer in the receiving amplifier detector to obtain zero reading of a DC milliammeter in the receive leg, when reversals are being transmitted over the channel. It is generally assumed that this method ensures zero telegraph distortion on reversals, but this assumption may often be incorrect. Thus, for instance, if the voltages of the negative and positive telegraph batteries differ, say one is 130 — 5 V and the other 130 + 5V, then the zero bias adjustment would in effect result in an adjustment to 5/130 = 0.04 or 4% telegraph distortion. (With equal positive and negative telegraph voltages and a standard loop current of 25 mA a telegraph distortion of 4% on reversals would cause a bias reading of (4/100) × 25 = 1 mA.)

Further, in case of interference into the telegraph channel, a "swinging" bias may be obtained. Not infrequently the swing may be so rapid that the bias meter is unable to follow and stays at zero deflection. During the work on the high speed channels, distortions up to 25% on reversals were for this reason measured even though the bias appeared to be zero and perfectly steady. Where possible, it would thus be desirable to abandon the adjustment to zero bias, and replace it with an adjustment to zero telegraph distortion as measured on a telegraph distortion measuring set.

Permissible Signal/Interference Ratio on VFT Channels: The intermodulation interference between VFT channels discussed in the previous section is characterised by its synchronous or near synchronous nature. There is of course also interference of a non-synchronous nature, such as, for instance, crosstalk from telephone channels, intermodulation interference from telephone channels if the bearer circuit is a channel of multichannel carrier telephone system, "static" if transmission over open-wires is concerned, etc.

The signal/interference ratio is the ratio, measured at the output of the receive filter, between the level of a permanent (marking) tone and interference peaks in the absence of the tone, both measured under terminated conditions. The minimum permissible ratio, is difficult to determine for reasons similar to those applicable to the relationship between maximum speed and bandwidth as discussed earlier. It would appear from a study of C.C.I.T. documents and from Departmental tests performed in this respect, that a ratio of not less than 30 db should be achieved whenever the circuit has been attended to, and that the circuit will require attention if the ratio during operation falls as low as 20-25 db.

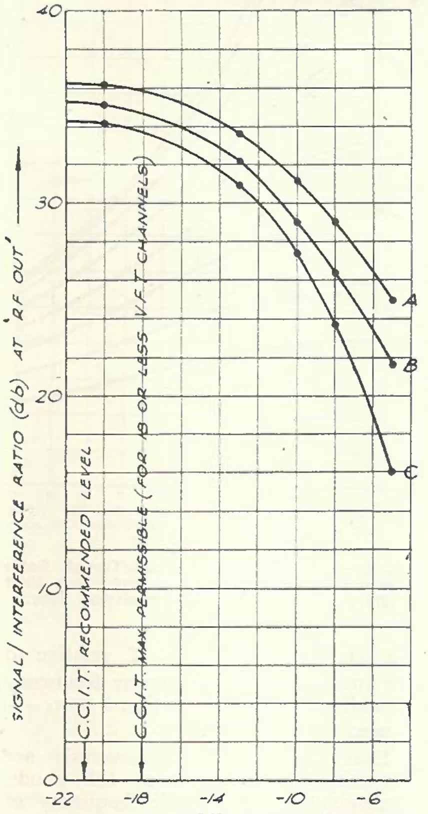


Fig. 1.—Intermodulation Interference, 9-Ch. VFT System Operating over Channel of:

(A) 3-channel carrier telephone system without repeaters.

(B) 3-channel carrier telephone system with 9 repeaters.

(C) Three 3-channel carrier telephone systems in tandem, no repeaters.

It will be apparent now that very low VFT levels on the bearer circuit will result in a low signal/interference ratio, due to "basic" noise on the bearer circuit. Very high VFT levels will also result in a low signal/interference ratio, due to the increase in intermodulation interference. It is consequently clear that there is, in each case, an optimum operating level per VFT channel.

Optimum Operating Level: Laboratory experiments on 3-channel carrier telephone equipment from two different manufacturers revealed that the degree of intermodulation in the receive path of a terminal under normal conditions is much higher than in the transmit path, due mainly to the demodulator amplifier. Another series of laboratory tests was made with a 9-channel VFT system to determine the amount of intermodulation interference under various conditions. The results are graphed in Fig. 1. The abscissa gives the input level per VFT channel relative to test level (-13dbm) at "Mod. In" of the carrier telephone channel used as the bearer, and the ordinate gives the ratio in db of signal/interference at "R.F. Out" of the VFT receive filter of channel 9, when continuous tones (marks) are transmitted over the eight VFT channels. The VFT frequencies were obtained from individual oscillators, and the carrier telephone channels were not synchronised, and consequently the interference level varied to a marked extent. The curves given correspond to the interference peaks as obtained over a period of approximately one minute. It is of interest to note that the addition of 9 repeaters does not increase the interference essentially, whereas the interference is considerably higher when the bearer circuit consist of three carrier telephone channels in tandem, than when it consists of one carrier telephone channel only. As would be expected, the graphs indicate that the interference increases rapidly with increasing VFT levels, and since the interference, as stated above, is produced mainly in the receive terminal, it is realised that abnormally high incoming VFT levels, whether caused by incorrect line-up of VFT or carrier system, or by a reduction in line attenuation, for instance, as a result of weather changes, will cause excess intermodulation interference and swinging bias.

The C.C.I.T. (3) and C.C.I.F. have, in co-operation, investigated the question of optimum levels on VFT bearer circuits. They recommend that a level per VFT channel of $10.\log 5/24^2 = -21$db relative to carrier telephone test level be used for all VFT systems, irrespective of the number of channels (not exceeding 24). When a bearer circuit has a relatively high noise level, it may not be possible to obtain satisfactory operation at this level, and a level of $10.\log 5/18^2 = -18$db relative to carrier telephone test level may be used, provided the number of VFT channels does not exceed 18. This level is the highest level permitted under any circumstances if the bearer circuit is a channel of a carrier telephone system. In other cases the level may be increased to $10.\log 5/n^2$ relative to voice-frequency test level, where n is the number of VFT channels, but under no circumstances whatsoever should a VFT channel be operated at a higher relative level than $10.\log 5/12^2 = -15$db.

These recommendations are based on such considerations as interference from VFT bearer circuits into telephone circuits and vice versa, on inter VFT channel intermodulation interference, noise on bearer circuits, etc. An investigation of a considerable amount of available results of such measurements together with results of special supplementary tests supported this choice of level. In this regard it is of interest to note that the 18-channel Perth-Adelaide VFT system was operated at a relative level of about –13db, and that the complaints regarding swinging bias were greatly reduced when the relative level was altered to –18db in accordance with C.C.I.T. and C.C.I.F. recommendations.

Attenuation and Phase Distortion: For economic reasons it is necessary to limit the frequency band occupied by each VFT channel, and consequently the VFT signals suffer attenuation distortion in the transmission path. In addition to attenuation distortion, the signals may also suffer phase distortion. In the case of orthodox VFT systems very few precautions need be taken to ensure that the phase distortion is insignificant relative to the attenuation distortion, whereas phase distortion may be significant on high speed channels.

Consider, for instance, transmission of reversals at a speed corresponding to a cyclic frequency of f_s c/s (the corresponding speeds in bauds being $2.f_s$), and assume that the VFT carrier frequency is f_0 c/s. It is then well known that the square-wave modulated VFT signal, corresponding to the transmission of reversals, may be considered as consisting of a number of frequencies f_0, $f_0 \pm f_s$, $f_0 \pm 3f_s$, $f_0 \pm 5f_s$, -----. If there is no attenuation or phase distortion in the transmission path, these frequencies will appear at the input to the receiving amplifier detector with the same relative amplitudes and phases as at the transmitting end, and they will consequently add up to a square-wave modulated signal. If there is attenuation and/or phase distortion, the relative amplitudes and/or phases at the receiving end will differ from the transmitted, and they will no

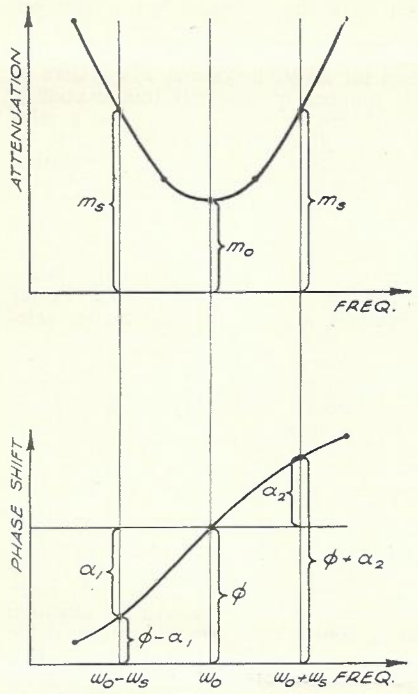


Fig. 2.—Parameters of Transmission Path of VFT Channel.

longer add up to a square-wave modulated signal.

The amount of attenuation distortion may be indirectly determined by measuring the loss/frequency characteristic of the channel. Similarly the phase distortion could be indirectly determined by measuring the phase shift/frequency characteristic, but such measurements on carrier telephone circuits with non-synchronised modulator and demodulator oscillators require special instruments (4, 5) not available in Australia. An alternative method not requiring any special instruments was, therefore, developed. This method is based on a study of the envelope of the received signals, when reversals are being transmitted at such high speeds that the $f_o \pm 3f_s$, $f_o \pm 5f_s$, etc. frequencies are suppressed due to the restricted band width of the channel. The only frequencies left to be considered are consequently the frequencies f_o, $f_o - f_s$ and $f_o + f_s$, and the signal corresponding to these may be written:

$$e = e_o . \left\{ \sin \omega_o t + \tfrac{1}{2} \sin (\omega_o - \omega_s) t + \tfrac{1}{2} \sin (\omega_o + \omega_s) t \right\} .$$

where : e = instantaneous value of signal
e_o = amplitude of carrier frequency
$\omega_o = 2\pi f_o$
$\omega_s = 2\pi f_s$
t = time.

Assuming that the loss/frequency characteristic is symmetrical about the carrier frequency as shown in Fig 2a, and that the phase shift/frequency characteristic is as shown in Fig. 2b, then the received signal e_r may be written:

$$e_r = e_o . \left\{ \frac{1}{m_o} . \sin (\omega_o t - \phi) + \frac{1}{2.m_s} \sin [(\omega_o - \omega_s) t - (\phi - \alpha_1)] + \frac{1}{2.m_s} . \sin [(\omega_o + \omega_s) t - (\phi + \alpha_2)] \right\}$$

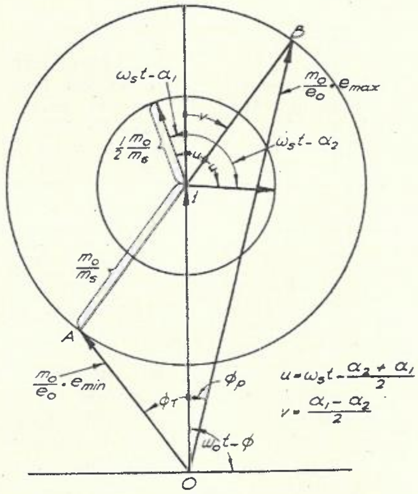
or:

$$\frac{m_o}{e_o} . e_r = \sin (\omega_o t - \phi)$$

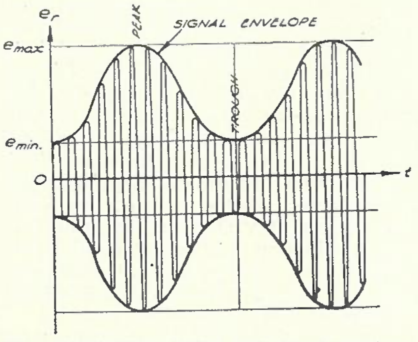
$$+ \tfrac{1}{2} . \frac{m_o}{m_s} . \sin [(\omega_o - \omega_s)t - (\phi - \alpha_1)] +$$

$$+ \tfrac{1}{2} . \frac{m_o}{m_s} . \sin [(\omega_o - \omega_s)t - (\phi + \alpha_2)]$$

The received signal, or rather $\frac{m_o}{e_o} . e_r$, may be illustrated vectorially as shown in Fig. 3a, where the point of the corresponding vector moves up and down the line A-B. The vectors from the origin, O, to the points A and B are representative of the minimum and maximum values respectively, of the amplitude of the received signal, which is illustrated in the usual form in Fig 3b. It is seen that e_{max} corresponds to the "peak" of the signal envelope and e_{min} to the "trough" of the envelope. The ratio in db between the amplitude at the peak and that at the trough, 20 log $\frac{e_{max}}{e_{min}}$, is defined as the "peak/trough ratio," and may be calculated, as shown in Appendix 1, in terms of 20. log m = $\frac{20.\log m_s}{20.\log m_o}$ and $\alpha = \alpha_1 - \alpha_2$. The results of this calculation are graphed in Fig. 4, where the ordinate is the peak/trough ratio, the abscissa is the attenuation at the side frequencies $f_o \pm f_s$ relative to the attenuation at the carrier frequency f_o, whilst the phase distortion $\alpha = \alpha_1 - \alpha_2$ is used as parameter.



(a) Vector diagram.



(b) Instantaneous value and signal envelope.

Fig. 3.—Illustration of Received Signal: e_r

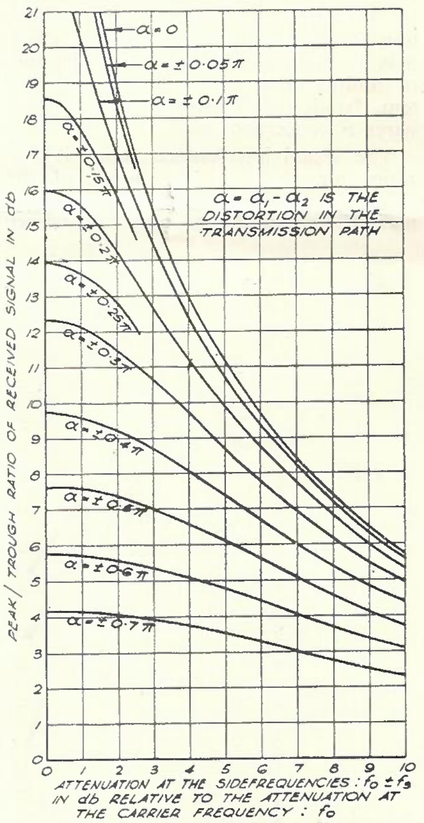
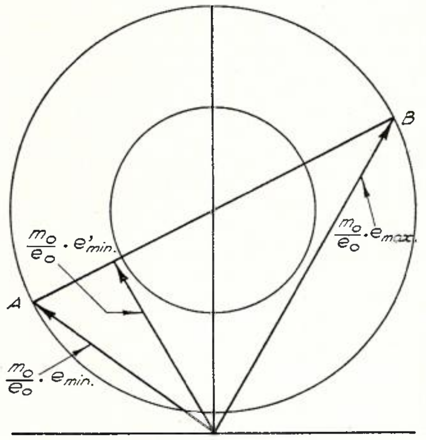


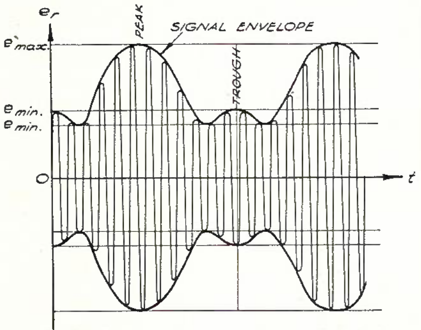
Fig. 4.—Determination of Peak/Trough Ratio from a Knowledge of the Loss and Phase Shift Characteristics of the Transmission Path.

Thus as an example: Reversals are transmitted at a speed of 150 bauds, corresponding to a cyclic frequency of 75 c/s. Reference to the loss/frequency characteristic of the channel concerned reveals, that the loss at the two frequencies situated 75 c/s on either side of the carrier are individually suppressed 4 db more than the carrier. The peak/trough ratio determined by a calculation from the peak and trough values of the received signal as viewed on an oscilloscope is 9.5 db. How great is the phase distortion α? The answer is read directly off the graph in Fig. 4 and is $\alpha = \pm\ 0.3\ \pi = \pm\ 54^0$.

In certain cases Fig. 3a may assume the appearance of Fig. 5a, and in this case e_{min} is no longer the absolute minimum value, this now being e'_{min}.



(a) Vector diagram.



(b) Instantaneous value and signal envelope.

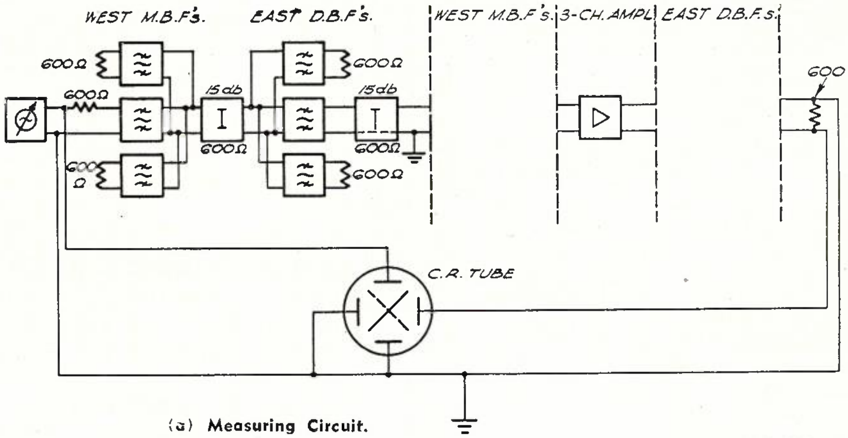
Fig. 5.—Alternative Appearance of Fig. 3 under Certain Conditions of Large Phase Distortion and Small Attenuation of Side Frequencies.

The received signal is illustrated in Fig. 5b, where the trough possesses a little peak. Whenever such a signal is viewed on the oscilloscope at the receiving end, it may be suspected either that excessive phase distortion exists, or that the frequencies $f_0 \pm 3f_s$, $f_0 \pm 5f_s$ are not sufficiently suppressed between the sending and the receiving end.

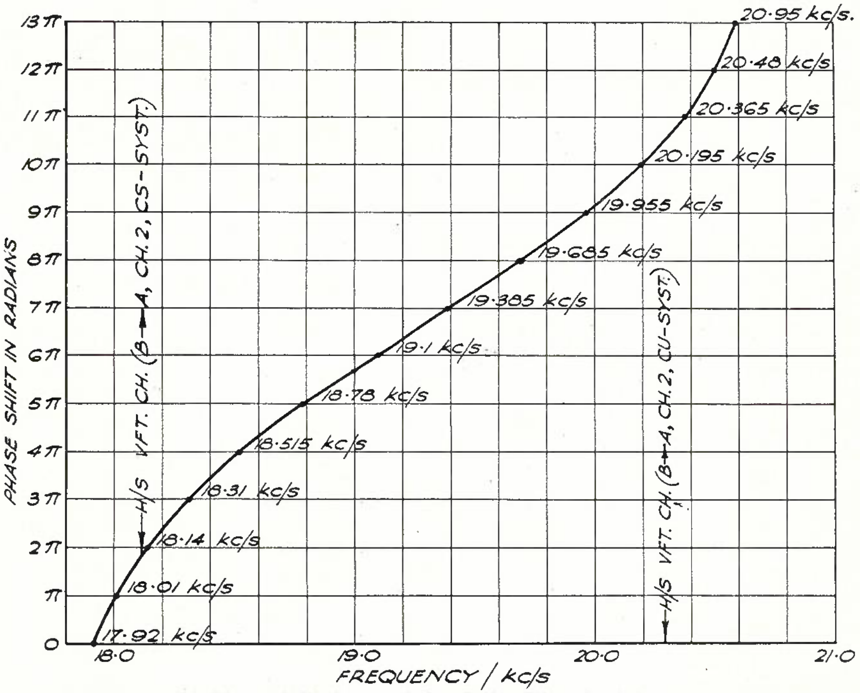
Attenuation and Phase Distortion in the Transmission Path of the First High Speed VFT Channel: The graph presented in Fig. 4 readily enables a determination to be made of the relative importance of attenuation and phase distortion at high rates of reversals, whereupon a well founded decision may be taken as to which of the two might be reduced to improve the transmission efficiency of the transmission path.

In case of the first high speed channel, a series of tests made in analogy with the example in the previous section revealed that phase distortions up to $\pm\ 0.7\ \pi$ were in existence at high speeds. From basic considerations it would be expected that the excessive phase distortion would originate from filters and loaded cables, particularly if the frequency of the high speed channel were situated close to the cut-off frequency. An examination revealed that the lengths of loaded cable employed as parts of the VFT bearer are small, and that this source of phase-distortion could be ignored. Phase distortion would however be likely in the modulator and demodulator bandpass-filter of the Perth-Adelaide 3-channel carrier telephone system which provides the VFT bearer channel over this section. Channel 2 of the CS system was employed as the "regular" VFT bearer, so that the line frequency of the high speed channel was 18.12 kc/s. This frequency is close to the cross-over frequency of the directional filters, of which there are 20 between Perth and Adelaide (1 at each terminal and 2 at each of the 9 repeaters), and some phase distortion could be expected for this reason.

In order to determine the magnitude of phase distortion, measurements of phase shift/frequency characteristics were undertaken using a cathode ray oscillography to determine phase shifts in multiples of π (6). In order to obtain enough points on the characteristics to determine the distortion, it was necessary to measure the phase shift of a number of units in tandem. The circuit used for measurements on the modulator and demodulator bandpass filters is shown in Fig. 6a and the result of the measurement in Fig. 6b. It is seen that a reasonably accurate graphical determination of phase distortion is not possible over the narrow band of the high speed channel, but by means of a relatively simple mathematical approach as shown in Appendix 2, an accurate determination may be made.



(a) Measuring Circuit.



(b) Phase shift characteristic of the filters in (a).

Fig. 6.—Phase Shift in MBF's and DBF's of 3-Channel Carrier Telephone System.

In this manner the phase distortion curves shown in Fig. 7 were obtained. The total amount of phase distortion, as determined from these curves, was found to be considerably less than the values predicted from measurements of peak/trough ratios. A calculation of phase distortion caused by the long open wire carrier telephone bearer circuit gave a figure of less than 1° at a cyclic telegraph speed of 100 c/s, and it appeared then reasonable to assume that the major amount of the phase distortion not accounted for was caused by the lack of proper compensating networks in the VFT terminals.

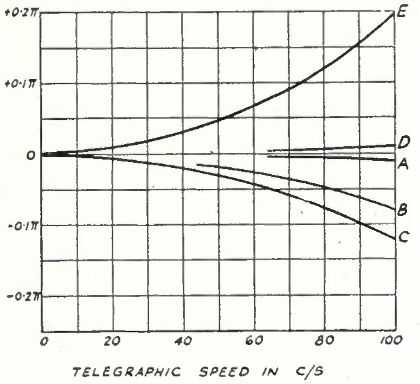


Fig. 7.—Phase Distortion of Various Types of Equipment in the Transmission Path of the First High Speed VFT Channel.

(A) MBF's and DBF's of two broadband carrier telephone channels in tandem (Sydney-Melbourne and Melbourne-Adelaide).
(B) MBF's and DBF's of a channel of a 3-channel carrier telephone system (Adelaide-Perth).
(C) Directional filters of Adelaide-Perth 3-channel carrier telephone system, when channel 2 of CS system is used as VFT bearer (direction of transmission: Adelaide to Perth).
(D) As (C), but using channel 2 of CU system as VFT bearer.
(E) Bypass filter, Adelaide.

Some immediate improvement was achieved by using channel 2 of the Adelaide-Perth 3-channel CU system as VFT bearer instead of channel 2 of the CS system (see curves C and D of Fig. 7). The design and manufacture of suitable compensating networks to be associated with the VFT filters was also undertaken. It was doubtful however whether this action was sufficient to ensure a satisfactory operating margin, and it would therefore also be desirable to improve the bandwidth of the channel.

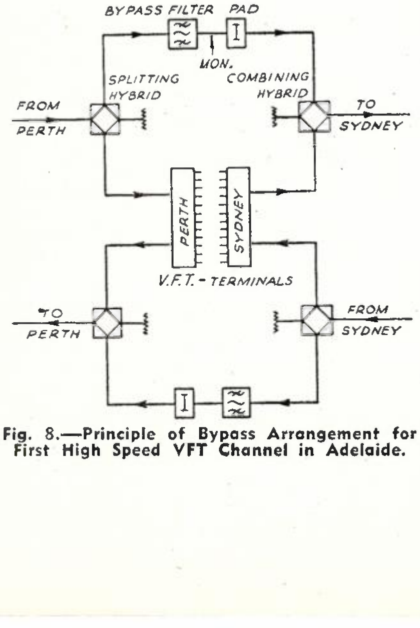
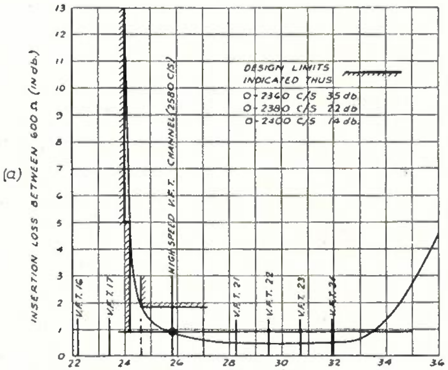
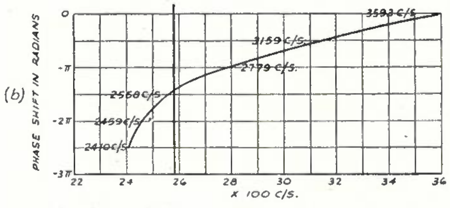


Fig. 8.—Principle of Bypass Arrangement for First High Speed VFT Channel in Adelaide.

For this reason the design and manufacture of a special arrangement to bypass the VFT terminals in Adelaide was undertaken. The principle adopted is illustrated in Fig. 8. Considering for instance the Perth to Sydney direction of transmission, it will be seen that the signals associated with the Perth-Adelaide VFT bearer are split into two paths by the splitting hybrid. One path is taken to the receive side of the Perth VFT terminal, which will function normally. The other path is taken to a bypass filter. The characteristics of this filter are shown in Fig. 9, and it is seen that it will pass the signals associated with the high speed channel and channels 21 to 24. These signals are thereupon combined with the signals from the Sydney VFT terminal and transmitted to Sydney.



(a) Insertion loss.



(b) Phase shift.

Fig. 9.—Characteristics of the Bypass Filter for the First High Speed VFT Channel in Adelaide.

It is seen that the high speed channel together with channels 21 to 24 bypass the VFT terminals in Adelaide altogether, and these channels may consequently be used for direct Sydney-Perth traffic. The arrangement has proved reliable, and due to the strict design requirements imposed upon the bypass filter, its presence does not impede the performance of the high speed channel and channels 21-24 to any significant extent.

The phase distortion in the bypass filter is shown in Fig. 7 (curve E), and it is seen that it overcompensates slightly for the phase distortion in the modulator and demodulator bandpass-filters of the 3-channel carrier telephone system. The installation of the compensating networks at Sydney and Perth and the bypass arrangement in Adelaide has removed practically any signs of phase distortion in the transmission path of the high speed channel, and the small residual phase distortion is negative if channel 2 of the CS system is used as VFT bearer, and positive if channel 2 of the CU system is used.

The work just described was completed in August 1953, and resulted in a noticeable improvement in lost time. Although several other improvements were programmed, the circuit was now capable of giving reasonable service and it was handed over to O.T.C. for full time operation.

High Speed Amplifier Detector (7,8): No suitable Telegraph Distortion Measuring Set for measurement of telegraph distortion at speeds in excess of 120 bauds had been available up to this time, but as such a set was considered to be an indispensable tool for the development of a high speed amplifier detector, the possible sources for such a set were investigated. It was found that the S.T.C. Telegraph Distortion Measuring Set, type 74001 could be modified to operate at speeds up to the maximum attempted, namely 150 bauds (180 W.P.M.) (7).

The high speed amplifier detector developed is similar in general principles (9) to the A.P.O. type amplifier detector. A simplified schematic, illustrating a few interesting design details, is shown in Fig. 10. In order to achieve low telegraph distortion R6 must necessarily be large. A value of 10 Mohms is used in the A.P.O. amplifier detector and in some commercial units, but experiments revealed that a value of 5 Mohms could be used without serious increase in distortion. Too high a value of R6 is likely to decrease the reliability of the unit, due to the fact that unwanted leakage currents or grid currents as low as one microampere passing through this resistor would affect the grid-bias on the two valves and seriously impair the performance. In order to keep the grid currents at a minimum the tubes used must be tested for the presence of small amounts of gas in the envelopes. The most likely serious leakage current would flow from the primary winding to the secondary of transformer T2, the primary being at a DC potential of + 130V and the secondary at about — 24V. A small calculation reveals that a leakage resistance of 150 Mohms would be responsible for a leakage current of one microampere. Without the use of special transformers it would not be possible to maintain a leakage resistance of sufficient magnitude, say greater than 300 Mohms under hot and humid conditions, and arrangements were therefore made to lead all leakage currents to that end of R6 which is remote from the two grids. This was done by applying, through a 10 kohm protective resistor R30, a potential of —24 volts to the screens, cores and cans of the transformers T1 and T2, which of course

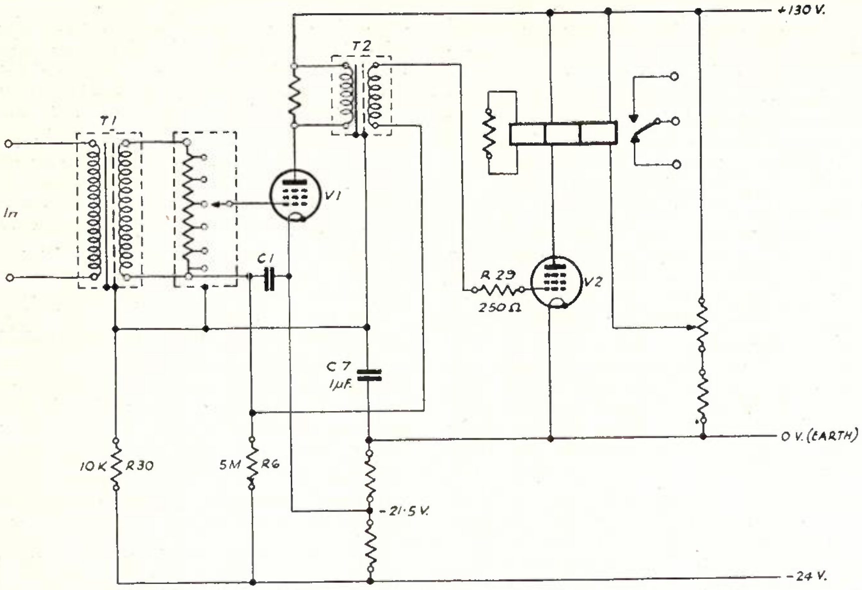


Fig. 10.—Simplified Schematic of High Speed VFT Amplifier Detector.

had to be mounted insulated from the panel. The same precaution was taken with the framework of the input potentiometer. The necessary AC-earth for these units is provided via capacitor C7. Even with these precautions taken the performance was significantly affected by hot and humid weather, due to leakage in the terminal plate of T2. The primary and secondary windings are each taken to four terminals on the terminal plate, and in order to overcome the leakage problem, the arrangement illustrated in Fig. 11 was adopted.

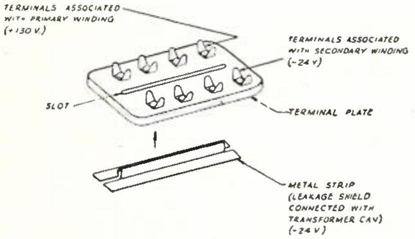


Fig. 11.—Method of Eliminating Leakage Between the Primary and Secondary Terminals.

The effect of the leakage shield is to "absorb" all leakage currents from the terminals associated with the primary winding, and thus prevent these currents from passing through the resistor R6. With these precautions taken, tests revealed no perceptible deterioration in performance of the unit under hot and humid conditions (100° F and 80-90% relative humidity).

In order to ensure stability under all operating conditions, it was necessary to incorporate the resistor R29 to prevent any tendency to parasitic oscillations of valve V2.

A considerable number of tests and investigations in respect of performance and stability was carried out in order to determine the best type of receive relay and the best method of adjustment for it. The choice fell on the Carpenter Relay, type 3H10, which was already being used in certain orthodox types of VFT equipment.

It may be mentioned that the poling of the interstage transformer is of major importance, since the AVC range is greatly reduced if the poling is incorrect. It had been suggested that it might be desirable to use two tubes in parallel to drive the receive relay, but experiments revealed that the driving current obtainable from one tube is quite ample, and furthermore the two tubes would have to be matched to obtain satisfactory performance. Although it is possible to select matched tubes, it is quite likely that their characteristics would differ as they aged, so that the performance would gradually deteriorate, and the idea was not adopted.

The high speed amplifier detectors were designed primarily for maximum reliability, of course with due regard to low distortion, and they have given satisfactory service since they were installed in January, 1954. Their performance is illustrated by the distortion measurements on the channel in Table 1, whilst the reliability has been indicated by the small amount of maintenance which has been required.

Frequency Response of VFT Bearer Circuits: An examination of the frequency responses of the Perth-Adelaide VFT bearer circuits (channels of the 3-channel carrier telephone systems), revealed poor responses to such an extent that the frequency response of the high speed channel was seriously affected. It was further found that the frequency responses of the regular and emergency bearer differed to such an extent that the level incoming to Perth on the high speed channel changed nearly 5 db when the Perth-Adelaide VFT system was patched. The C.C.I.T. has not yet recommended the maximum level change permitted under these conditions, but a figure of 1.75 decibel appears to be under consideration (10).

In view of the poor responses and certain other undesirable conditions experienced, a complete overhaul of the Adelaide-Perth 3-channel carrier telephone systems was undertaken. The description of this work, which was commenced in August, 1953, and completed in January, 1954, is outside the scope of this article, but reference will be made to the conditions affecting the performance and reliability of the high speed channel.

The poor frequency responses were found to be due mainly to incorrectly wired transformers. In general a number of incorrectly wired transformers was experienced in most States during the development, installation and testing of the high speed channel. In a considerable number of cases, the internal wiring of otherwise identical transformers was found to differ, and in other cases the external wiring had been incorrectly connected both by the manufacturer and by the Department.

Interference into VFT Bearer Circuits: Measurements of noise and interference on the VFT bearer circuits gave highly varying and generally excessive results. This was found to be mostly due to definite equipment faults, such as dry joints, overloading of amplifiers, ageing of electrolytic capacitors, etc., but a substantial part was found to originate from excess 2VF signalling levels on the other channels of the carrier telephone systems. If signalling occurs simultaneously on two or more telephone channels, the signalling tones will intermodulate and some of the intermodulation products will appear as interference on the VFT bearer circuit (2).

Since the number and magnitude of these intermodulation products increase very rapidly with increasing signalling levels, it is of major importance that signalling levels on carrier systems do not exceed a certain maximum limit. The C.C.I.F. recommended (Florence 1951) that the following levels relative to the channel test level should not be exceeded:

800 c/s : — 1db
1200 c/s : — 3db
1600 c/s : — 4db
2000 c/s : — 5db
2400 c/s : — 6db
2800 c/s : — 8db
3200 c/s : — 8db

These levels are the levels which would be measured with continuous non-interrupted signalling tones applied to the channel. The frequencies of the 2VF signalling equipment employed by the Department are 600 c/s and 750 c/s, and the maximum level permitted by the Department for these frequencies is 0 db.

Some States were using levels of 3-4 db above this limit resulting in interference levels on the VFT bearer circuits of the same order as the level per telegraph channel. It has in most cases been possible to adopt the specified limit of 0 db, but some exceptions have been necessitated by the existence of high-loss junction circuits and other technical difficulties. Measures have been taken to counter these difficulties, and it is expected that the consequent general reduction of 2VF signalling levels to 0 db, will significantly reduce the interference problems on telephone, programme and VFT circuits.

Some sources of interference eliminated during the overhaul were crosstalk due to common power supply impedances, noise due to noisy power supplies, noise due to a faulty main earth busbar, crosstalk from carrier systems on adjacent bearer circuits, intermodulation due to abnormal channel and group responses, intermodulation due to a fault in a group amplifier and due to incorrectly functioning AGR equipment, noise due to dry joints and bad contacts, noise due to unbalanced equipment units being wired "upside down", intermodulation due to non-effective limiters, and interchannel crosstalk due to an incorrectly wired balance/unbalance transformer.

The psophometric noise on any of the telephone channels now very rarely exceeds —58 psophometric dbm, resulting in more reliable operation of the high speed channel and improved quality of telephone channels.

Stability of Bearer Circuit Equivalents: It was realised in the early stages of the project, that excessive variations of overall equivalents of the bearer circuits were responsible for a substantial portion of "lost time" on the high speed channel. In order to obtain a clear picture of the variations, the incoming levels of continuous marks transmitted between Perth and Adelaide and between Adelaide and Sydney were recorded by means of recording levelmeters over a period of some weeks. The greatest variations were observed on the Perth-Adelaide section. Variations of up to ± 5 db occurred relatively frequently, and at some occasions variations up to ± 8 db were observed.

Simultaneous recordings of incoming pilot levels were also made and compared with the recordings of the incoming marks, and this revealed that pilot level and mark level did not always vary in unison. This phenomenon indicated dry joints and/or bad contacts in the VFT equipment and/or carrier telephone channelling equipment, and this equipment was consequently inspected and examined very meticulously, with the result that a few suspicious joints and contacts were attended to. An attempt was also made to apply vibration testing methods (11, 12) to locate defective connections, but due to lack of suitable vibration testing equipment, the success was rather limited. Further efforts were made employing a technique of continuous monitoring (11, 12) mainly of pilot levels at repeaters, as described in an article by Mr. E. R. Banks in this issue of the Journal, and overall a significant improvement in stability has been achieved.

Second High Speed VFT Channel: It was desired to separate the first and second high speed VFT channels to the greatest possible extent in order that equipment and bearer failures should not cause simultaneous failure of both channels. Unfortunately they cannot be completely separated due to lack of alternative routes, such as for instance between Adelaide and Perth, but a complete separation as far as VFT equipment and carrier telephone equipment is concerned, has been achieved. The second channel is associated with three VFT systems, that is a Sydney-Melbourne, a Melbourne-Adelaide and an Adelaide-Perth (second) system. The installation of 12-channel open wire carrier telephone systems of the broadband type between Adelaide and Perth was completed early in February, 1954, at the same time as the second high speed channel was completed, and this made it possible to use 300-3400 c/s carrier telephone circuits as VFT bearers on all sections of the route, thus practically eliminating the risk of attenuation and phase distortion at the frequency of 2580 c/s chosen for the high speed channel.

The second channel is in most respects similar to the first channel. The VFT terminals in Melbourne and in Adelaide have been completely bypassed by means of arrangements identical to that used for the first channel in Adelaide (see Fig. 8), except that the characteristics of the bypass filters for the second channel permit the high speed channel only to bypass (see Fig. 12). In Sydney the second channel is associated with a 12-channel VFT system of APO type, and since it was not practical to associate the high speed filters with the existing filters, a hybrid arrangement somewhat similar to that shown in Fig. 8 was used. The characteristics of the bypass filters and the use of the hybrids permit monitoring of the high speed channel in Melbourne and Adelaide at the junction of the bypass filter and the pad, as indicated in Fig. 8, and monitoring amplifier detectors have been installed for this purpose.

Improvements in Terms of "Lost Time": Accurate records of "lost time" have been kept for both the orthodox VFT channels and the high speed VFT channels. At the time the first high speed channel was put into operation on a part time trial basis, the lost time was on an average about 90 minutes a day (April, 1953), and at the time it was handed over to OTC for full time use, about 50 minutes a day. The improvements carried out since have

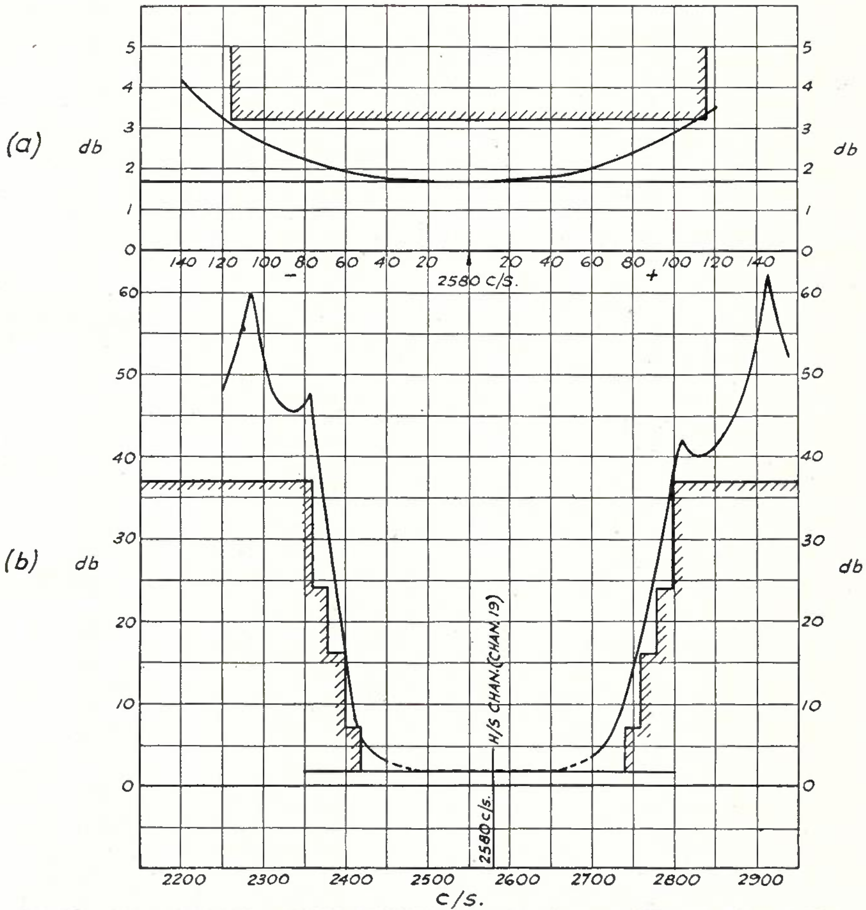


Fig. 12.—Design Limits and Typical Frequency Response of Bypass Filters for Second High Speed VFT Channel in Melbourne and Adelaide.

(a) Insertion loss between 600 ohms in passband.
(b) As (a), but is stopband.

gradually decreased the lost time, so that the lost time per day averaged over one month is generally less than 30 minutes.

The lost time is of course related to the speed at which the channel operates. The maximum speed used by O.T.C. on these channels is 150 W.P.M. (125 bauds), and during "slack" periods a speed of 80 W.P.M. (67 bauds) is used.

Conclusion: Two high speed channels for VFT operation between Sydney and Perth, a distance of 2700 miles, have been installed. The channels are associated with normal VFT systems, and channels of carrier telephone systems are used as bearers over the entire distance. The channels have been designed for a maximum speed of 162 W.P.M. Wheatstone. They have been operated at speeds up to 200 W.P.M. on trial runs of short duration, but the maximum attempted for practical operation is 150 W.P.M. In the initial stages an average of about 90 minutes a day was lost due to fault conditions. A reduction in lost time has been achieved by improvements to the VFT equipment and by an overhaul of the Perth-Adelaide 3-channel carrier telephone system providing the VFT bearer over this section of the route. At present the average lost time is generally less than 30 minutes a day.

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Appendix 1

Derivation of Peak/Trough Ratio.

The trigonometrical law-of-cosines may be applied to the two shaded triangles in Fig. 3a, leading to:

$$\left[\frac{m_o}{e_o}.e_{max}\right]^2 = 1 + \left\{\frac{m_o}{m_s}\right\}^2 - 2.\frac{m_o}{m_s}.\cos(\pi - v) = 1 + \left\{\frac{m_o}{m_s}\right\}^2 + 2.\frac{m_o}{m_s}.\cos\left[\frac{\alpha_1 - \alpha_2}{2}\right]$$

$$\left[\frac{m_o}{e_o}.e_{min}\right]^2 = 1 + \left\{\frac{m_o}{m_s}\right\}^2 + 2.\frac{m_o}{m_s}.\cos v = 1 + \left\{\frac{m_o}{m_s}\right\}^2 - 2.\frac{m_o}{m_s}.\cos\left[\frac{\alpha_1 - \alpha_2}{2}\right]$$

where: e_{max} = maximum amplitude of received signal.

e_{min} = minimum amplitude of received signal

The peak/trough ratio in decibels is $20.\log\frac{e_{max}}{e_{min}}$, or:

$$10.\log\left\{\frac{\left[\frac{m_o}{e_o}.e_{max}\right]^2}{\left[\frac{m_o}{e_o}.e_{min}\right]^2}\right\} = 10.\log\frac{1 + \left\{\frac{m_o}{m_s}\right\}^2 + 2.\frac{m_o}{m_s}.\cos\left\{\frac{\alpha_1 - \alpha_2}{2}\right\}}{1 + \left\{\frac{m_o}{m_s}\right\}^2 - 2.\frac{m_o}{m_s}.\cos\left\{\frac{\alpha_1 - \alpha_2}{2}\right\}}$$

$$= 10.\log\frac{1 + \left\{\frac{1}{m}\right\}^2 + 2.\frac{1}{m}.\cos\frac{\alpha}{2}}{1 + \left\{\frac{1}{m}\right\}^2 + 2.\frac{1}{m}.\cos\frac{\alpha}{2}}$$

where: $m = m_s/m_o$ is the ratio between the attenuation factor at the side-frequencies, $f_o \pm f_s$, and that at the carrier frequency f_o. Expressed in decibels m is the difference between the loss at the side-frequencies, $f_o \pm f_s$, and that at the carrier frequency f_o.

$\alpha = (\alpha_1 - \alpha_2)$ is a measure of non-symmetrical phase distortion. It is measured in radians and defined in Fig 2.

Appendix 2.

Determination of Phase Distortion from the Phase Shift/Frequency Characteristic

Consider a phase shift/frequency characteristic as shown in Fig. 6b. It is desired to find the phase distortion associated with the high speed telegraph channel, when Ch. 2, B—A of the CS system is used as bearer. Bearing in mind that the carrier frequency of this channel is 20.7 kc/s, and that Fig. 6b applies to two sets of MBF's and DBF's in tandem, a new phase shift curve applicable to one set only and with frequencies referred to audio may be drawn as shown in Fig. 13.

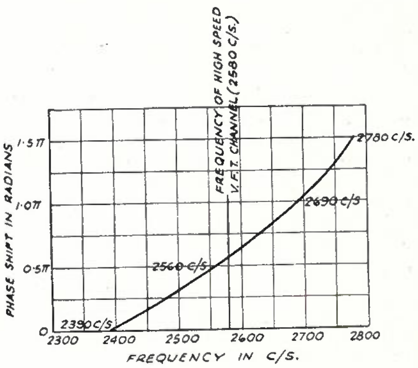

Fig. 13.—Phase Shift Characteristic for One Set of MBF's and DBF's (3-Channel Carrier Telephone System).

This curve may be represented mathematically by a Taylor series. Thus, using the symbols ϕ and f for phase-shift and frequency respectively:

$$\phi = a.\pi.(f - 2390) + b.\pi.(f-2390)^2 + c.\pi.(f-2390)^3 + \ldots\ldots$$

Using the three terms shown, it is possible to determine the coefficients a, b and c in such a manner that the curve represented by this three-term series contains the four points

$$(\phi, f) = \begin{cases} (O\pi, 2390\ c/s) \\ (\frac{\pi}{2}, 2560\ c/s) \\ (\pi, 2690\ c/s) \\ (\frac{3\pi}{2}, 2780\ c/s) \end{cases}$$

This may be done simply by inserting the co-ordinates of these points into the series, whereby three independent linear equations are obtained, and these may be solved for a, b and c.

In order to determine the phase distortion the following symbols are introduced—

ϕ_o : phase shift at 2580 c/s

$\phi_o - \alpha_1$: phase shift at $(2580 - f_s)$ c/s

$\phi_o + \alpha_2$: phase shift at $(2580 + f_s)$ c/s

The phase distortion at the cyclic telegraph frequency, f_s, is defined in Fig. 2 as:

$$\alpha = \alpha_1 - \alpha_2$$

which may be written:

$$\alpha = 2\phi_o - (\phi_o - \alpha_1) - (\phi_o + \alpha_2)$$

and since:

$$2\phi_0 = 2(a.\pi.(2580 - 2390) + b.\pi.(2580 - 2390)^2 + c.\pi.(2580 - 2390)^3)$$
$$= 2(a.\pi.190 + b.\pi.190^2 + c.\pi.190^3)$$
$$\phi_0 - \alpha_1 = a.\pi.(2580 - f_s - 2390) + b.\pi.(2580 - f_s - 2390)^2 + c.\pi.(2580 - f_s - 2390)^3$$
$$= a\pi(190 - f_s) + b\pi(190 - f_s)^2 + c\pi(190 - f_s)^3$$
$$\phi_0 + \alpha_2 = a\pi(190 + f_s) + b\pi(190 + f_s)^2 + c\pi(190 + f_s)^3$$

it is seen that α may be written:

$$\alpha = a.\pi.O - 2.b.\pi.f_s^2 - 6.c.\pi.190.f_s^2$$
$$= -(2.b + 6.190.c)f_s^2.\pi$$

Without knowing the values of b and c, it is thus seen that the phase distortion α is proportional to the square of f_s. Thus, for instance, if $f_s = 190$ c/s, the phase distortion read from Fig. 13 is: $-(1.43 - 2 \times 0.565)\pi = -0.3\pi$, and is for all other reasonably small values of f_s given by:

$$= -0.3.\pi.\left[\frac{f_s}{190}\right]^2$$

AN APPLICATION OF SWITCHING ALGEBRA

E. G. WORMALD.

Introduction

The design of relay contact networks and similar circuits of the switching class, that is, using two-state devices, usually proceeds as a series of logical steps involving repeated redrawing of the circuit as it develops. Even when advantage is taken of the "short-cuts" known to an experienced circuit designer, this method can be very time-consuming and cumbersome when dealing with large contact networks, and hence subject to a considerable risk of working error.

A valuable tool, which may be used either as an alternative or adjunct to the method of repeated drawing, is the algebraic treatment of relay contact networks in the manner expounded by Shannon and others as a specialised extension of the algebra of logic enunciated by Boole (see References). Within operative limitations, its use will generally facilitate the formation of the more involved relay contact networks, allowing a final design to be reached more speedily than would be possible by the usual method.

Switching algebra is based on the representation of any relay contact (or two-state circuit element) as an algebraic quantity, in the form of a letter indicative of the relay or element. Although alternative notations have been used, in these notes all switching quantities will be denoted by upper case letters, unprimed if normally open circuit, primed if normally closed. For example, any make contact on relay D will be designated as D, and any break contact on relay E as E′. D and E′ are then regarded as algebraic quantities which may assume either of two values, 1 or 0, according to whether the corresponding relay is operated or not, or vice versa. Switching algebra in its present state of development takes no account of relay timing or, except as demonstrated later, of the physical association of make and break contacts to form more complicated springsets. It follows that it does not distinguish between ordinary and make-before-break changeover springset arrangements.

Its value as a design tool springs from the fact that if parallel connections of different contacts or contact networks are represented by algebraic products, and series connections as sums, or vice versa, it may be shown that the resultant algebraic expressions obey the commutative, associative and distributive laws of arithmetical algebra. A number of operative theorems, closely resembling their counterparts in arithmetical algebra, may be readily proved for each form of switching algebra. The result is that the steps of rearrangement and simplification involved in the design of complex contact networks can be performed algebraically, eliminating the work otherwise involved in redrawing and checking many interim stages in the design of a circuit.

Forms of Switching Algebra

Four possible forms of switching algebra are known, occurring in two pairs of dual, inverse forms. The members of each pair are related to each other in the same way as any other pair of dual, inverse concepts, for example impedance and admittance operators, in that both are capable of solving any suitable problem, but that for certain classes of problem the computation processes are less involved for one method than its inverse.

The four possible forms of switching algebra are:—

(a) The "hindrance" form propounded by Shannon (4), in which series connections are treated as algebraic sums and shunt connections as products, with open circuits assigned the numerical value 1 and closed circuits the value 0 (zero "hindrance").

(b) The "acceptance" form described in detail by Buffery (7), in which series connections are treated as algebraic products and shunt connections as sums, assigning the numerical values 1 = closed circuit, 0 = open circuit (zero "acceptance"). This is the dual inverse of the "hindrance" form.

(c) The form treated by Montgomerie (6), which is based on Shannon's convention of series-sum/shunt-product and Buffery's convention of 1 = closed and 0 = open circuit.

(d) The dual inverse of form (c), not known to have been described elsewhere. Its conventions are series-product/shunt-sum and 1 = open and 0 = closed circuit.

Compared to forms (a) and (b), the manipulation of forms (c) and (d) requires the use of a comparatively large number of rules which do not conform to the mechanics of ordinary algebra, for example 1. 0 = 1. They will not be further considered, since they are not known to possess any compensating advantage.

Forms (a) and (b) both obey rules which differ from those of arithmetical algebra in only a few respects. Since the sum of switching quantities, which can be of value 0 or 1, is itself a switching quantity of value 0 or 1, the normal rule of addition must be modified in any form of switching algebra. As a result, some theorems involving addition processes also differ from the corresponding rules of normal algebra, although the majority of theorems are identical with their counterparts.

As with impedance and admittance operational methods, the choice between hindrance and acceptance forms should be dictated by the type of problem to be handled. However, it has been stated (8) that the hindrance form has the advantage that "use of the + symbol of addition to indicate a series 'and' connection provides a more natural representation of the physical reality of contact networks than the use of the multiplication symbol", and also (7) that "sums are more easily manipulated than products, that certain transformations possible with hindrances cannot be applied to acceptances, and that admittances are less commonly used than impedances". A counter-claim for the acceptance form can be made, based on the following points:—

(a) The process of opening an established series connection by opening any one of the contacts has a close similarity to the process of reducing a product to zero by reducing any one of the terms of the product to zero.

(b) It requires an open circuit to be assigned the value 0 and a continuous circuit the value 1, which is in line with the conventions used in the algebra of logic (1 = true, 0 = false) and probability theory (1 = certainty, 0 = impossibility). This appears more natural than the converse assignation necessary for the hindrance form.

(c) It is simpler when dealing with the type of problem in which the setting of a group of relays is controlled by a counter or storage circuit of the binary type. The signal stored in each binary element is naturally represented as 0 = normal or unfired, 1 = operated or fired, and before applying the hindrance form of switching algebra, an artificial, and possibly confusing, inversion of signal must be applied between the store output and the contact network.

(d) An example of a type of problem in which this form of switching algebra has definite advantages over its inverse is given at the conclusion of these notes.

Definitions

Before proceeding with a demonstration of the application of switching algebra, the postulates and theorems are set out in the acceptance form, with some explanatory remarks as to their derivation and meaning. For comparison with the postulates and theorems of the hindrance form, from which they may be obtained by inversion, they are set out in the same order as that used in reference (8). Suffixes "a" and "b" to a common postulate or theorem identification number are used to indicate relationships which are duals. The following definitions apply:

Addition: (+) = OR = Parallel.
Multiplication: (·) = AND = Series.
Circuit States: O = Open Circuit.
1 = Closed Circuit.

Postulates

(1) $X = O$ or $X = 1$, where X is a contact or a network.
(2a) $1 + 1 = 1$ (Two closed circuits in parallel constitute a closed circuit).
(2b) $O \cdot O = O$ (Two open circuits in series constitute an open circuit).
(3a) $O + O = O$ (Two open circuits in parallel constitute an open circuit).
(3b) $1 \cdot 1 = 1$ (Two closed circuits in series constitute a closed circuit).
(4a) $1 + O = O + 1 = 1$ (An open circuit and closed circuit in parallel constitute a closed circuit).
(4b) $O \cdot 1 = 1 \cdot O = O$ (An open circuit and closed circuit in series constitute an open circuit).

It will be noted that (2a) is the only postulate not in accordance with the rules of arithmetical algebra.

Theorems

Certain theorems can be of great help in rearranging and simplifying contact networks. These are 3(a), 3(b), 5(a), 5(b), and 11(a) to 14(b) inclusive and their circuit equivalents are shown in Fig. 1.

Addition and Multiplication.

(1a) $X \cdot Y = Y \cdot X$
(1b) $X + Y = Y + X$
(2a) $(X \cdot Y)Z = X(Y \cdot Z)$
(2b) $(X + Y) + Z = X + (Y + Z)$

The series or parallel combination of two or more contacts or networks is independent of their relative order of connection.

(3a) $(X + Y)(X + Z) = X + YZ$
(3b) $XY + XZ = X(Y + Z)$
(4a) $XX = X$
(4b) $X + X = X$

One of a pair of identical contacts or networks in series or parallel may be deleted without affecting the circuit operation.

Negatives, and O and 1

(6a) $(X)' = X'$ The negative of a contact or network X is another contact or network X′ which is a closed circuit for conditions under which X is open, and open when X is closed.
(6b) $(X')' = X$ The negative of the negative of a contact or network is equivalent to the original contact or network.
(7a) $(X \cdot Y \cdot Z \cdot \ldots)' = X' + Y' + Z' + \ldots$
(7b) $(X + Y + Z + \ldots)' = X' \cdot Y' \cdot Z' \ldots$

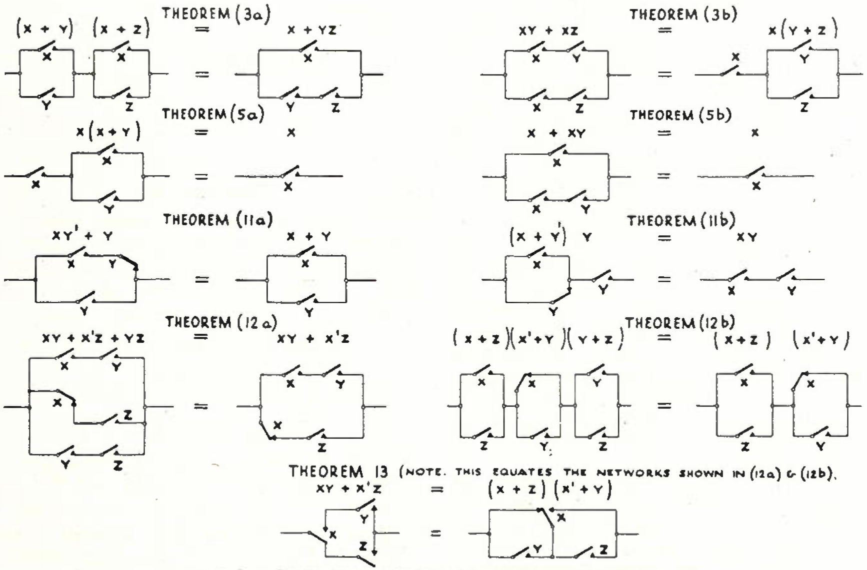

Fig. 1.—Equivalent networks illustrating some theorems.

To obtain the negative of a network, substitute a shunt path for each series path and vice versa, replacing each contact by its negative. To obtain the negative of an algebraic expression, substitute a sum for each product and vice versa, and replace each variable by its negative.

(8a) $X'X = O$ The series combination of a network and its negative constitutes an open circuit.
(8b) $X' + X = 1$ The shunt combination of a network and its negative constitutes a closed circuit.
(9a) $1 \cdot X = X$
(9b) $O + X = X$
(10a) $O \cdot X = O$
(10b) $1 + X = 1$
(11a) $XY' + Y = X + Y$
(11b) $(X + Y')Y = XY$

Supplementary Theorems.

(12a) $XY + X'Z + YZ = XY + X'Z$
(12b) $(X + Z)(X' + Y)(Y + Z) = (X + Z)(X' + Y)$
(13) $XY + X'Z = (X + Z)(X'Y)$
(14a) $f(X) = [A + f(X)_{A=O}] . [A' + f(X)_{A=1}]$
(14b) $f(X) = A . f(X)_{A=1} + A' . f(X)_{A=O}$

, where A is a relay or minor network forming part of a network f(X).

Binary-to-Decimal Conversion Circuit

Until recently, the writer regarded switching algebra as being of little more than academic interest. However, part of the work involved in a recent project included the design of a circuit for converting binary numbers of up to nine digits to their decimal equivalents, and it became obvious that the application of switching algebra would be of very great assistance in designing the complex contact networks required for this purpose. The finished product is an example of the application of switching algebra which is thought to provide such an interesting illustration of its efficacy as to justify its publication in some detail.

The problem was:— A, B, C, ... H, J, are nine relays (or groups of relays if the necessary contact load is found to exceed the capacity of one relay) assigned numerical values of unoperated = 0 and operated = 1, 2, 4, 8 . . . . etc. in a binary counting system requiring a maximum total count of around 500. Contact trees of 5, 10 and 10 outlets respectively are required, to indicate the first, second and third digits of the decimal equivalent of any binary number stored in the counting system. The indication is to be 0 if no other figure is appropriate.

At the outset, it was decided to take advantage of the very great simplification of the problem which would result from a small departure from the usual full binary counting scheme. By restricting the total count on relays A - E to 29 instead of the usual full 31, the units figure of the decimal output was made dependent on the setting of the 5 relays

A - E only, instead of all 9 relays A - J, and the tens and hundreds figures were made dependent on a comparatively simple 3-valued function of relays B - E.

In effect, relays F - H were to indicate the multiple of 30 contained in the number, with relays A - E indicating the remainder 0 - 29. The result was to assign the numerical values operated = 1, 2, 4, 8, 16, 30, 60, 120, 240 respectively to the 9 relays A - J, and to restrict the maximum possible count to 479 instead of 511, which was of little importance.

It was found that the required modification of the counting circuit offered no difficulty. As shown in Fig. 2, the problem could then be broken up into four distinct parts:—

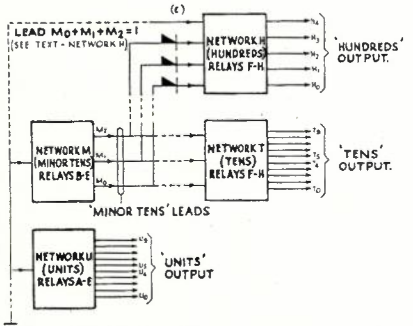

Fig. 2.—Relationship between networks.

(a) A "Units" contact tree to connect one input to one of 10 outputs (U_0 - U_9), depending on the setting of relays A - E, i.e. on that part of the number in excess of an integral multiple of 30.

(b) A "Minor Tens" contact tree to connect one input to one of 3 outputs (M_0 – M_2) depending on the setting of relays B - E.

(c) A "Tens" contact network to connect each of three inputs to a different one of 10 outputs (T_0 – T_9) depending on the setting of relays F - J.

(d) A "Hundreds" contact network to connect each of three inputs to one of five outputs (H_0 – H_4) depending on the setting of relays F - J. The three inputs may all be connected to one of the outputs, or two may be connected to one output and the other to a different output.

It should be noted that the connection of two or three inputs to one output lead results in the connection of two or three inputs to each other. If the same input leads were not also utilised by network T, this would not be important, but to network T such cross-connections of input leads constitute intolerable "sneak paths". To avoid this, network M could be duplicated, but as this would have increased the spring load on relays C and B to the point of requiring the provision of additional relief relays, it was found better to prevent network H returning false earths to the input leads by inserting the series rectifiers shown in Fig. 2.

The method adopted started by writing down all possible combinations of relays B - E in the form shown in Table 1. Odd "Units" and relay A were omitted from the table, because the appearance of A′ in any term denotes an even number, the higher adjacent odd number being obtained by replacing A′ by A, and because the "Minor Tens" output is not dependent on A, that is, whether the number is even or odd.

Table 1.

Units				
0	E′D′C′B′	DB	EC	
2	B	DC	ECB	Spare:
4	C	DCB	ED	EDCB
6	CB	E	EDB	
8	D	EB	EDC	
Minor Tens:	0	1	2	

The position of each entry in the table is appropriate to its numerical value. For example, DB (= 8 + 2 = 10) appears in the column and row appropriate to (Minor) Tens = 1, Units = 0.

Each entry represents a 4-term product in E, D, C and B, primed terms having been omitted for brevity—for example, DB represents the algebraic expression E′DC′B.

Network U

From Table 1, the conditions for any particular Units output were readily determined. For example, the output U_0 (and no other) should be connected to the input if the stored number is 0, 10 or 20—i.e. if the relays are set in the combination E′D′C′B′ or E′DC′B or ED′CB′. Algebraically, the condition for output U_0 may be written as
$U_0 = E'D'C'B' + E'DC'B + ED'CB'$.
Similar expressions for the other four outputs U_2, U_4, U_6 and U_8 could be obtained, but it is more convenient to combine all expressions in one equation. If the connection of an external circuit to output U_0 were represented algebraically as U_0, and similarly for other outputs, the condition for a complete connection to the input through the network and an external circuit could be expressed in switching algebra as:—

$$
\begin{aligned}
I = {} & (E'D'C'B' + E'DC'B \\
& \quad + ED'CB')\,U_0 \\
& + (E'D'C'B + E'DCB' \\
& \quad + ED'CB)\,U_2 \\
& + (E'D'CB' + E'DCB \\
& \quad + EDC'B')\,U_4 \\
& + (E'D'CB + ED'C'B' \\
& \quad + EDC'B)\,U_6 \\
& + (E'DC'B' + ED'C'B \\
& \quad + EDCB')\,U_8
\end{aligned}
$$

In practice the above expression, relating the input to the five outputs, was not written down; for by inspection of Table 1, it was possible to proceed directly to the next stage. It was seen that EC or E′C′ do not appear except in pairs of terms which differ only in that they contain EC or E′C′ as alternatives, suggesting the following regrouping:—

$$
\begin{aligned}
I = {} & [(EC + E'C')D'B' + E'C'DB]\,U_0 \\
& + [(EC + E'C')D'B + E'CDB']\,U_2 \\
& + [E'C(DB + D'B') + EC'DB']\,U_4 \\
& + [EC'(DB + D'B') + E'CD'B]\,U_6 \\
& + [(EC + E'C')DB' + EC'D'B]\,U_8
\end{aligned}
$$

The otherwise spare combination ECDB is utilised by adding it into the coefficient of U_0 in the above expression, changing the top line to (EC + E′C′) (DB + D′B′), the resultant expression being easier to synthesise.

The expression was then in a form allowing the desired contact network to be drawn by inference. The procedure is not obvious however, and some explanatory remarks are in order:—

(a) It will be noted that the only functions of E and C which occur in the above expression are E′C, EC′ and (EC + E′C′). These correspond to the contact assembly shown in section (a) of Fig. 3.

(b) the term (DB + D′B′) occurs in three lines of the expression, indicating the presence in the final network of three contact assemblies of the type shown in section (b) of Fig. 3.

(c) The coefficient of $B'U_0$, i.e. D′(EC + E′C′) is identical with the coefficient of BU_2, and similar relationships exist between U_2 and U_4, U_4 and U_6, U_6 and U_8, U_8 and U_0. This indicated the use of the contact arrangement shown in section (c) of Fig. 3. Combining these partial networks, and using A contacts to provide the odd-even changeover, the complete network shown in Fig. 3 was obtained.

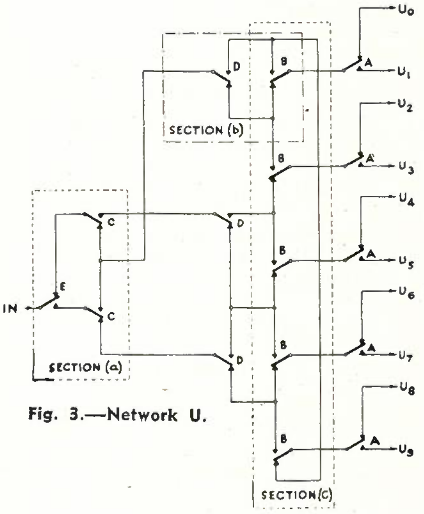

Fig. 3.—Network U.

Network M

This was also derived from Table 1. In this case the input was expressed algebraically in terms of the three outputs M_0, M_1, and M_2 as:—

$$
\begin{aligned}
I = {} & (E'D' + E'DC'B')\,M_0 \\
& + (E'DC'B + E'DC + ED'C')\,M_1 \\
& + (ED'C + ED)\,M_2
\end{aligned}
$$

by remembering that $B' + B = 1$, that
$B'C' + BC' + B'C + BC$
$= (B' + B)(C' + C) = 1$,
and by introducing the otherwise spare combination ECDB into the coefficient of M_2.

The desired contact network, as shown in Fig. 4, was drawn from inspection of the above expression, but the following rearrangement of terms may clarify the process:—

$$I = (E'D' + \underline{E'D}C'B')\,M_0 + (\underline{ED}'C' + \underline{E'D}\,[C'B + C]\,M_1 + (\underline{ED}'C + ED)\,M_2$$

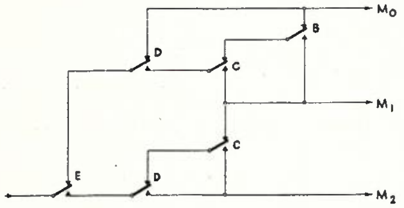

Fig. 4.—Network M.

The two pairs of underlined coefficients indicate the use of two changeover springsets on relay C.

The next stage in the design was to write down all possible combinations of relays F - J and the "Minor Tens" leads in the form shown in Table 2.

In the case of networks T and H, a somewhat different procedure was adopted in manipulating the algebra, because of the multiple inputs M_0, M_1, M_2.

Network T

From Table 2, a set of algebraic expressions can be written down to indicate the conditions appropriate to each of the ten possible outputs. In so doing, terms were grouped for each of the three possible inputs, and any common factors extracted from the coefficients:—

$$T_0 = M_0H'F'\,(JG + J'G') + M_1\,F(J'H'G + JHG') + M_2J'HGF'$$

$$T_1 = M_0J'HGF + M_1H'F'\,(JG + J'G') + M_2F(J'H'G + JHG')$$

$$T_2 = M_0HF'\,(JG + J'G') + M_1\,J'HGF + M_2H'F'\,(JG + J'G')$$

$$T_3 = M_0H'F\,(JG + J'G') + M_1\,HF'\,(JG + J'G') + M_2J'HGF$$

$$T_4 = M_0JH'G'F' + M_1\,H'F\,(JG + J'G') + M_2\,HF'\,(JG + J'G')$$

$$T_5 = M_0HF\,(JG + J'G') + M_1JH'G'F' + M_2H'F\,(JG + J'G')$$

$$T_6 = M_0F'\,(J'H'G + JHG') + M_1HF\,(JG + J'G') + M_2JH'G'F'$$

$$T_7 = M_0JH'G'F + M_1F'\,(J'H'G + JHG') + M_2HF\,(JG + J'G')$$

$$T_8 = M_0J'HGF' + M_1JH'G'F + M_2\,F'\,(J'H'G + JHG')$$

$$T_9 = M_0F\,(J'H'G + JHG') + M_1J'HGF' + M_2\,JH'G'\,F$$

Inspection of the above equations showed that the appearances of J and G are limited to J'G, JG' and (JG + J'G'), indicating the use of J and G relay springsets connected in a similar manner to the E and C springsets shown in section (a) of Fig. 3. The use of one such contact grouping for each of the three inputs M_0, M_1 and M_2 is indicated by the presence, among the terms of the above ten equations, of all possible products of J'G, JG' or (JG + J'G') with M_0, M_1 or M_2. A common connection between pairs of G relay contacts is indicated by the fact that neither of the expressions M_2JG' and $M_0J'G$ appear separately from the other in any of the ten expressions for $T_0 - T_9$.

It will also be noted that the coefficient of F' in the expression for T_0 is identical with that of F in the expression for T_3, and that similar relationships exist for T_3 and T_6, T_6 and T_9, T_9 and T_2, T_2 and T_5, T_5 and T_8, T_8 and T_1, T_1 and T_4, T_4 and T_7, T_7 and T_0. This indicates the use of a chain of F relay contacts in a similar manner to the inter-connected chain of B relay contacts shown in section (c) of Fig. 3.

Bearing these considerations in mind, it was possible to draw the extremities of network T, i.e. that portion of Fig. 5 lying outside the dotted rectangle. The network was completed by adding the H relay springsets, whose arrangement was also guided by relationships seen by inspection of the basic 10 equations. That each of the eight leads into the group of H contacts from the left (such as M_1JG' at the top) appears in series combination with both H and H' among the terms of the various equations indicates the connection of each of these leads to the centre spring of a changeover springset on relay H.

The required inter-connection of the resultant 16 "outside" contacts on relay H to 10 springsets on relay F obviously required some commoning. The necessary connections were also derived by inspection of the basic equations. For example, the appearance of M_1 (J'H'G + JHG') as the coefficient of F' in the expression for T_7, as the coefficient of F in the expression of T_0, and nowhere else among the basic equations indicated and an F contact denoted by -θ-. In this way, the drawing of network T was completed.

Table 2

Tens.					
0	M_0	GFM_1	HGM_2	JGM_0	$JHFM_1$
1	M_1	GFM_2	$HGFM_0$	JGM_1	$JHFM_2$
2	M_2	HM_0	$HGFM_1$	JGM_2	$JHGM_0$
3	FM_0	HM_1	$HGFM_2$	$JGFM_0$	$JHGM_1$
4	FM_1	HM_2	JM_0	$JGFM_1$	$JHGM_2$
5	FM_2	HFM_0	JM_1	$JGFM_2$	$JHGFM_0$
6	GM_0	HFM_1	JM_2	JHM_0	$JHGFM_1$
7	GM_1	HFM_2	JFM_0	JHM_1	$JHGFM_2$
8	GM_2	HGM_0	JFM_1	JHM_2	—
9	GFM_0	HGM_1	JFM_2	$JHFM_0$	—
Hundreds:	0	1	2	3	4

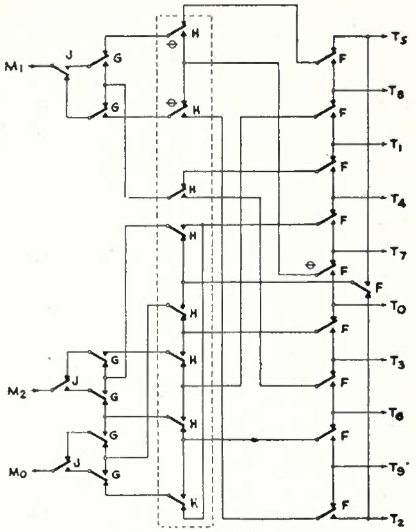

Fig. 5.—Network T.

Network H

From Table 2, a set of algebraic expressions could be written down to indicate the conditions appropriate to the five possible outlets H_0 to H_4. A preliminary survey of the problem showed that terms of the form $X(M_0 + M_1 + M_2)$ would have a frequent occurrence. Since either M_0, M_1 or M_2 must be pre-selected by network (b), $(M_0 + M_1 + M_2) = 1$, and may be realised physically by a continuous circuit (i.e. an earth lead if the output of the network is to be an earth signal). It was apparent that the provision of a fourth input lead of this type would considerably simplify network H. The conditions for each output were then written down:—

$$H_0 = J'H'\,[G' + GF' + GFM_0]$$

$$H_1 = J'\,[HG' + HGF'M_0 + M_1\,(H'GF + HGF') + H'GFM_2]$$

$$H_2 = J'HG\,[F + F'M_2] + J\,H'G'$$

$$H_3 = J\,[HG'\,(F' + FM_0) + H'G]$$

$$H_4 = JG\,[H + H'\,F\,M_1 + H'FM_2]$$

In a similar manner to that outlined for networks U, M and T, the above-expressions were manipulated and interpreted as the network shown in fig. 6.

Conclusion

The saving in time and effort resulting from the use of switching algebra is well illustrated by the above example. The method is in effect, a "shorthand" way of writing down a switching circuit, with certain limitations. It facilitates the comparison of alternative contact networks designed for the same purpose, but is not capable of any process which cannot also be performed equally well, if more slowly, by the conventional method of repeated circuit rearrangements. For example, it gives no indication as to whether an optimum design (generally that involving the least total number of relay contacts) has been found.

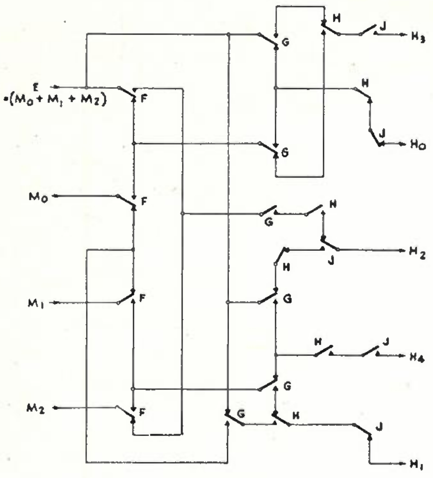

Fig. 6.—Network H.

In the design of contact networks of the "tree" type, either single or multi-input, such as those used as examples in this article, the acceptance form of switching algebra has definite advantages over the hindrance form. The difference between the manipulative processes involved by the use of either form, when applied in this field, is well illustrated by comparison of Appendix 1 with its inverse counterpart, as set out above in the derivation of network U.

It is believed that the major manipulative process (factorisation) involved in the use of the acceptance form comes more naturally, and is consequently speedier and less prone to error, than that of the hindrance form (isolation of common sum terms, often involving the use of theorem (3b) which differs from the corresponding rule of arithmetic algebra). It will also be seen that the acceptance form saves writing time and space because of the reduced number of brackets and addition signs.

Appendix 1: Typical Manipulation Using the Hindrance Form of Switching Algebra

For comparison with the "acceptance" form of switching algebra, network U is here derived by the use of the "hindrance" form. As before, the process starts by writing down:—

To derive the "units" network, the input may be expressed algebraically in terms of the 5 outputs $U_0 - U_4$ as:—

$$\begin{aligned}
I = \ & [U_0 + (E' + D' + C' + B') \\
& (E' + D + C' + B) \\
& (E + D' + C + B)] \\
& .[U_2 + (E' + D' + C' + B) \\
& (E' + D + C + B') \\
& (E + D' + C + B)] \\
& .[U_4 + (E' + D' + C + B') \\
& (E' + D + C + B) \\
& (E + D + C' + B')] \\
& .U_6 + (E' + D' + C + B) \\
& (E + D' + C' + B') \\
& (E + D + C' + B)] \\
& .U_8 + (E' + D + C' + B') \\
& (E + D' + C' + B) \\
& (E + D + C + B')]
\end{aligned}$$

Again, the above expression would not be written down by a circuit designer well versed in the use of the hindrance form of switching algebra. Making use of theorem (3b): $(X + Y)(X + Z) = X + YZ$, the coincidence of added terms wherever $E' + C'$ and $E + C$ occur, suggests the following regrouping:—

$$\begin{aligned}
I = \ & [U_0 + (E' + C' + D + B) \\
& (D' + B' + \{E + C\}\{E' + C'\})] \\
& .[U_2 + (E' + C + D + B') \\
& (D' + B + \{E + C\}\{E' + C'\})] \\
& .[U_4 + (E + C' + D + B') \\
& (\{D + B\}\{D' + B'\} \\
& + E' + C)] \\
& .[U_6 + (E' + C + D' + B) \\
& (\{D + B\}\{D' + B'\} \\
& + E + C')] \\
& .[U_8 + (E + C' + D' + B) \\
& (D + B' + \{E + C\} \\
& \{E' + C'\})]
\end{aligned}$$

Introducing the otherwise spare combination $E + D + C + B$ into the first line, the addend of U_0 in the first factor becomes: $(E + C)(E' + C') + (D + B)(D' + B')$.

The desired contact network may then be drawn as in fig. 3, after noting the effect of certain relationships corresponding to those described for the inverse derivation:—

(a) The appearance of E and C in the above expression is restricted to the functions $(E' + C)$, $(E + C')$ and $(E + C)(E' + C')$, indicating the contact assembly shown in section (a) of fig. 3.

(b) $(D + B)(D' + B')$, occurs three times, indicating the presence of three contact groupings of the type shown in section (b) of fig. 3.

(c) Each of the factors $[U_0 + (E + C)(E' + C') + (D + B)(D' + B')]$ et seq. may also be written as two factors, one containing B and the other B′, for example:—

$$[U_0 + (E + C)(E' + C') + D + B]$$
$$[U_0 + (E+C)(E' + C') + D' + B']$$

It will then be seen that the addend of $B' + U_0$ in one factor, i.e., $(E + C)(E' + C') + D'$, is identical with the addend of $B + U_2$ elsewhere, and that similar relationships exist between U_2 and U_4, U_4 and U_6, U_6 and U_8, U_8 and U_0. This again indicates the use of the contact arrangement shown in section (c) of Fig. 3.

It will be seen that, in applications like this, the indications of specialised contact groupings are harder to recognise in the "hindrance" form of the algebra than in the "acceptance" form.

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9. "Some Observations on Boolean Algebra," T. L. Craven, A.T.E. Journal, Vol. 10, No. 1, January, 1954.

Table 1(A)

Units		Spare:	$E + D + C + B.$
0	$A' + B' + C' + D' + E'$	$D + B$	$E + C$
2	B	$D + C$	$E + C + B$
4	C	$D + C + B$	$E + D$
6	$C + B$	E	$E + D + B$
8	D	$E + B$	$E + D + C$
Minor Tens:	0	1	2

CALCULATION OF BUSBAR DIMENSIONS

M. W. GUNN, B.Sc.

Introduction: Power distribution by means of busbars is used extensively by the Australian Post Office in equipment, power and battery room installations. Power cable is sometimes used for power and battery room wiring but, except for the smallest installations, distribution to the equipment room is always made by busbar. Provision of power leads is made on the basis of (i) a maximum of 1 volt drop from the battery terminals to the most remote equipment rack of the ultimate installation, when the maximum load current of the ultimate installation is passing; (ii) a maximum current density of 500A per square inch for discharge circuits and 1000A per square inch for charge circuits.

For long runs condition (i) determines the size of busbar required, while for short runs condition (ii) is the controlling factor. The use of either copper or aluminium bar has always been envisaged, although until recently, the use of copper has been practically universal. However, substantial cost differences now exist between copper and aluminium, and purchases of aluminium bar of similar dimensions to the standardised copper bars are now being made.

The purpose of this paper is to present graphs which are useful in the design of an installation, and which allow the properties of copper and aluminium bar of most interest in our installations to be compared.

Voltage Drop Calculations

Probably the most useful data for busbar installation design is that which relates the length of run with the size of the busbar required to give a certain voltage drop. The voltage drop on a busbar is given by the formula—

$V = p\ l\ I'$

where V = volts
p = resistivity in ohms/ft./sq.in. cross section
l = total length of busbar in feet
I' = amps/sq. in. cross section,

which gives the following expressions for copper (i) and aluminium (ii) busbar, at 20° C (68° F.).

$V = 8.15.10^{-6}.l.I'$ ....(i)
$V = 13.5.10^{-6}.l.I'$ ....(ii)

Expressions (i) and (ii) show that for a copper busbar $lI' = V.10^{-6}/8.15$, and for an aluminium busbar $lI' = V.10^{-6}/13.5$. For different values of V these expressions give a family of rectangular hyperbolas, and form the basis for Figs. 1 and 2. In these figures the length scaled on the abscissa is that of the busbar run, which equals half the total length of the busbar required.

The resistance temperature coefficients per °C are ·0039 for copper and ·0042 for aluminium at a temperature of 20°C. The resistance of a bar and hence the voltage drop will increase as its working temperature rises above the ambient temperature. For example if a copper busbar is worked at a temperature of 50°C. above an ambient temperature of 20°C, the resistivity used in the above expressions for voltage drop should be increased to $p(1 + \cdot 0039.50)$, that is by approximately 20%. Generally the temperature rise of a busbar working at 500A per sq.in. will approximate 10°C. which involves an increase in the resistivity figures quoted above of approximately 4%. This rise is not significant in most installations. If necessary, allowance for temperatures above 20°C (68°F) can be made in Figs. 1 and 2 by decreasing the current density required at 20°C by the appropriate percentage.

Current Carrying Capacity

The maximum current a bar can carry is governed by its working temperature. The maximum working temperatures are defined by British Standard Specification 159, and for most applications a maximum rise of 40°C above an ambient temperature of 30°C is specified. This temperature rise depends on many factors, for example, the shape of the bar, its emissivity, the proximity of other heat producing conductors, whether it is mounted on its edge, etc. Fig. 3 shows the direct currents which give the above temperature rise for the standard bars purchased by the Department to Serial 186.

Painting a busbar will increase its heat dissipation and thereby improve its current rating. For example busbar coated with dull black paint will carry 20% more current than that indicated in Fig. 3, for the same temperature rise. The covering of a bar with moderate thicknesses of insulation will also increase

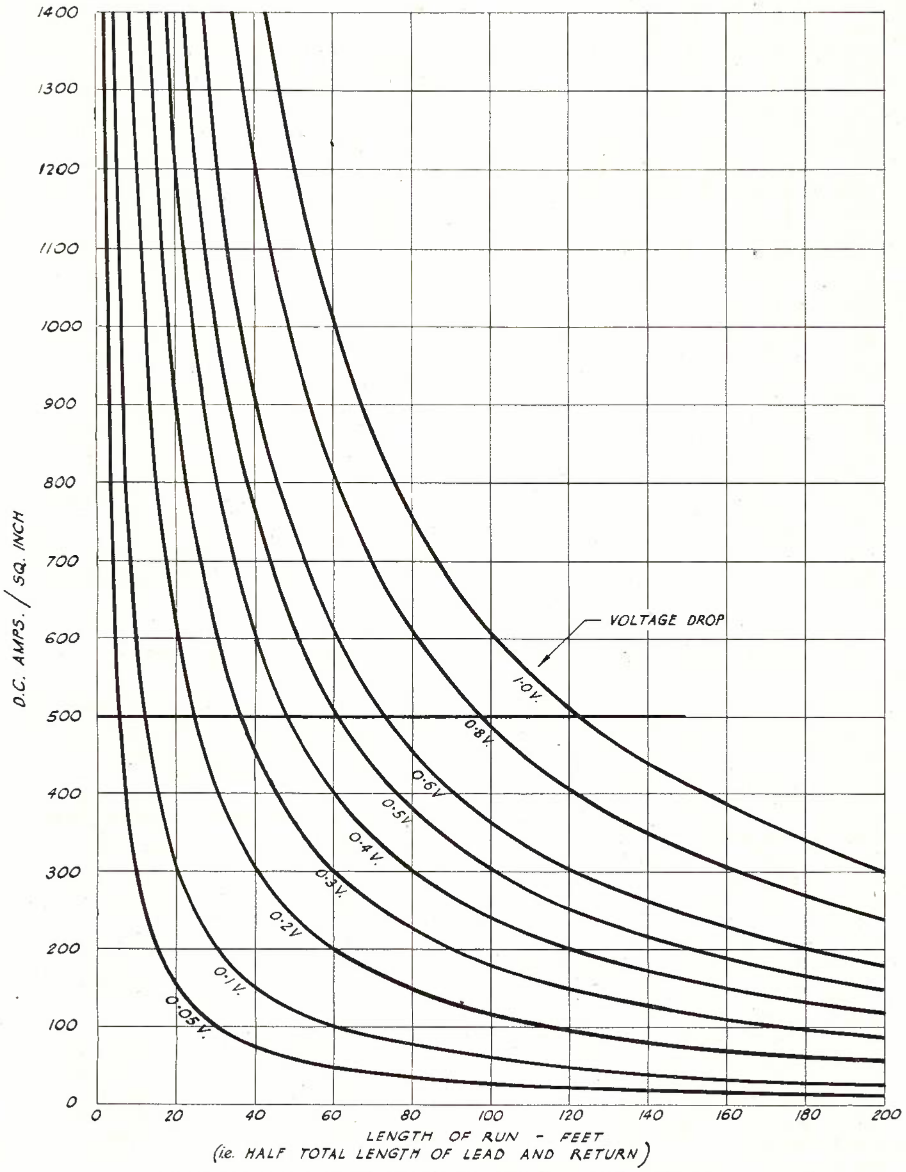

Fig. 1.—Voltage drops in copper conductors at 20° C. (68° F.).

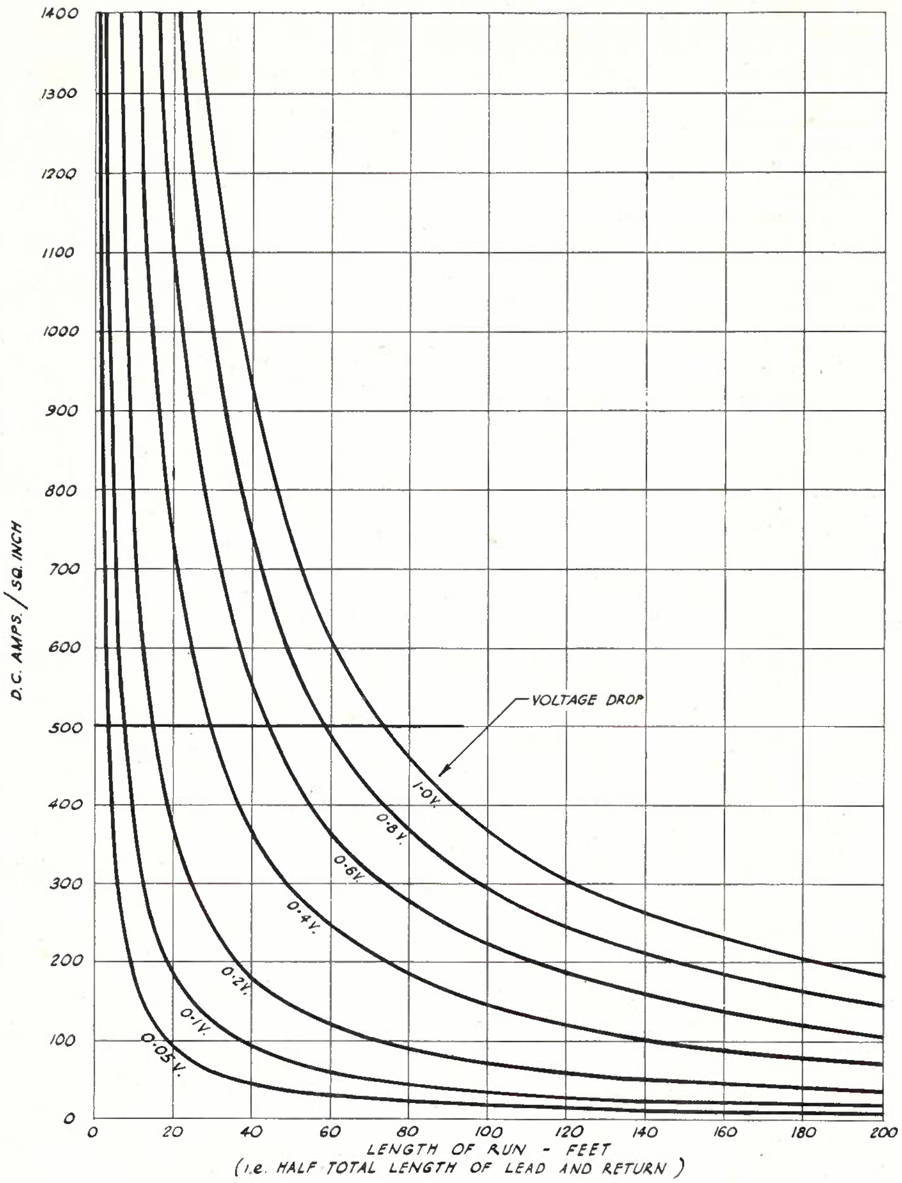

Fig. 2.—Voltage drops in aluminium busbar conductors at 20° C. (68° F.).

the current carrying capacity, as the poor thermal conductivity of the insulation is more than offset by the greater surface area and emissivity. When two or more busbars are run in parallel they can have a lower current carrying capacity than the same number of busbars considered singly. For example two busbars in parallel and spaced apart by a distance equal to the thickness of the bars have a maximum load capacity of 1.85 that of a single bar. This effect is due to the reduced rate of cooling.

Fig. 3 (in conjunction with Figs. 1 and 2) shows that currents greater than the present standard of 500A per sq.in. for discharge circuits could be used in many cases, particularly for short runs and small sizes of bar. A value of 1000A per sq. in. is used in many overseas installations. This figure also shows the decrease in maximum current density as a bar increases in size. For example a 2 x ¼ inch copper busbar can carry approximately 1500A per sq. in. compared with the 1000A per sq. in. limit of a 4 x ½ inch bar.

Design of Non-tapered Busbar Runs

Non-tapered runs are used extensively for smaller installations. The size of busbar required depends on the length of run, the currents carried by the lateral take-offs, the locations of the lateral take-offs, the voltage drop limit and the allowable current density. Fig, 4 is a diagrammatic representation of a busbar run.

In this figure the lateral take-offs are indicated together with the current carried by the main busbar to the take-off, and the end voltages chosen allow for the voltage drops over the last lateral run and fuse (v_1), and the battery fuse and discharge switch (v_5). For this installation, if r is the resistance in ohms /foot of the busbar required, then $2\,r\,(l_1I_1 + l_2I_2 + l_3I_3 + l_4I_4) = v_5 - v_1$ which gives r. The size of bar required is then given by the expression $\frac{8{\cdot}15}{r.10^6}$ sq. in. for copper, or by $\frac{13{\cdot}5}{r.10^6}$ sq. in. for aluminium, and the nearest standard bar to satisfy the cross-section obtained can be chosen. This gives the minimum sized bar required to satisfy the overall voltage drop condition. It must be checked for the current density imposed on the length l_4 and if necessary increased so that the allowable current density will not be exceeded. If the load is effectively concentrated at the end of the run the size of conductor required can be directly read from Figs. 1 or 2. For example the conductor cross-section required for a ·6V drop over a run of 60 feet with a current of 100A, with a maximum current density of 500A/sq. in. is as follows:—

From Fig. 1 the copper cross-section required $= \frac{100}{500} =$ ·20 sq. in. (in this case the current density is the controlling factor)

From Fig. 2 the aluminium cross-section required $= \frac{100}{360} =$ ·28 sq. in.

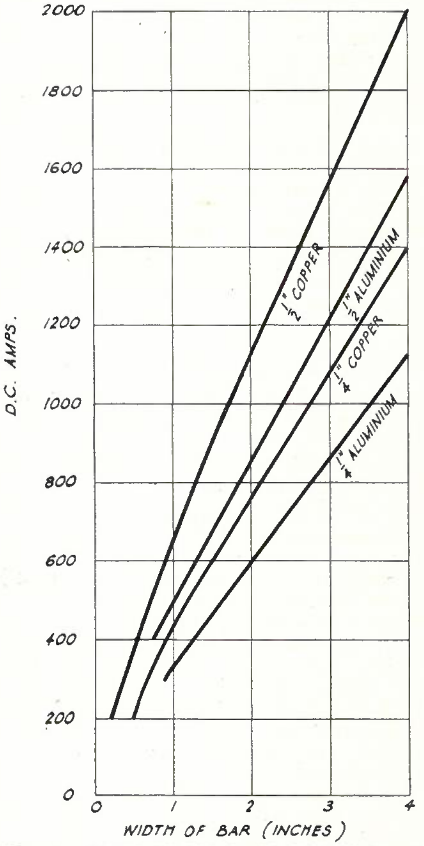

Fig. 3.—Direct current rating of flat copper and aluminium bar mounted horizontally on edge (i.e. thickness dimension) and freely exposed in still air for a temperature rise of 40° C. (72° F.) above an ambient temperature of 30° C. (86° F.).

Design of Tapered Busbar Runs

These installations are designed by setting down the equations governing the cost of the bar required and finding the condition for which this cost is a minimum. A complete design on this basis will give the different cross-sectional areas of bar required for the lateral runs, and the different sections of sub-main and main busbars between the individual take offs.

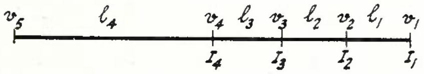

Fig. 4.—Busbar run.

In the case of Fig. 4, some simplification of this procedure is possible as the lateral take-offs are standardised (for example, long line equipment installations use ½ x ¼ inch bars), and a single main run only is required. Considering the last two sections of this installation, the potential (v_2) for which the cost of the bar required for these sections is a minimum can be found as shown in the following.

The cost of a busbar is directly proportional to its length and cross sectional area, that is C ∝ 1.A.

The voltage drop v ∝ $\frac{1.I.}{A}$ where I = current carried.

$$\therefore C \propto \frac{1^2\ I}{v}.$$

The total cost of the last two sections of Fig. 4 is therefore given by:

$$C \propto \frac{1_1^2\ I_1}{(v_2 - v_1)} + \frac{1_2^2\ I_2}{(v_3 - v_2)}$$

and

$$\frac{dC}{d(v_2 - v_1)} \propto - \frac{1_1^2\ I_1}{(v_2 - v_1)^2} + \frac{1_2^2\ I_2}{(v_3 - v_2)^2}$$

for v_3 & v_1 constant.

For a minimum cost $\frac{dC}{d(v_2 - v_1)} = O$

$$\therefore \frac{(v_2 - v_1)^2}{(v_3 - v_2)^2} = \frac{1_1^2\ I_1}{1_2^2\ I_2}$$

$$\therefore \frac{v_2 - v_1}{v_3 - v_2} = \sqrt{k} \text{ where } k = \frac{1_1^2\ I_1}{1_2^2\ I_2}$$

$$\therefore \frac{v_2 - v_1}{v_3 - v_1} = \frac{\sqrt{k}}{1 + \sqrt{k}}.$$

For a busbar run of two sections with fixed end potentials, Fig. 5 gives a ready means of finding the intermediate potential which gives a minimum busbar cost.

The above process can be extended to obtain expressions for

$$\frac{v_3 - v_2}{v_4 - v_2} \quad \text{and} \quad \frac{v_4 - v_3}{v_5 - v_3}$$

Substitution for v_5 and v_1, which are known, in these expressions allows the values of v_4, v_3 and v_2 to be determined. These values then allow the busbar cross-section required for each section of the run to be calculated, or read from Figs. 1 or 2.

Comparison of Copper and Aluminium Busbars

Figs. 1, 2 and 3 allow a ready comparison to be made of the voltage drop characteristics and the current carrying capacities of both types of busbar. In particular, Figs. 1 and 2 show the interchangeability of copper and aluminium bar of similar dimensions. For example in the case of a run designed on a maximum current density of 500A/sq. in. and a maximum voltage drop of ·6V, they show that copper and aluminium bar of similar dimensions can be interchanged for runs up to 45 feet.

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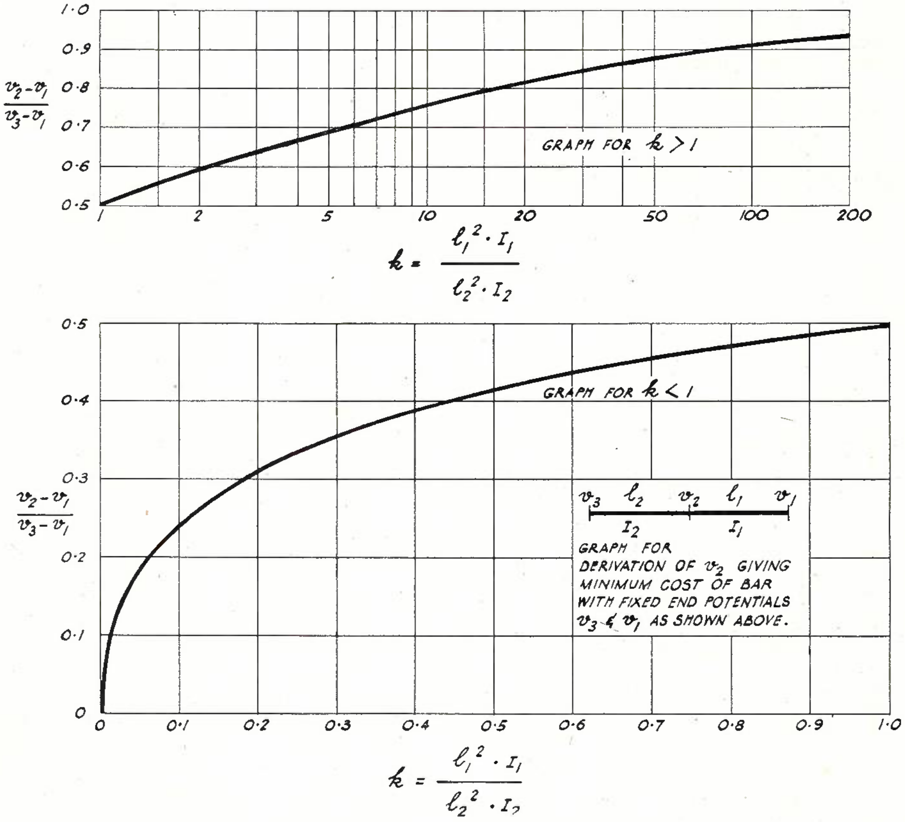


Fig. 5.—Graph for tapered busbar design.

INVESTIGATION OF FAULTS ON THE ADELAIDE-PERTH CU5 THREE CHANNEL SYSTEM

E. R. BANKS, B.E.E., Stud.I.E.Aust.

Introduction

This investigation was undertaken as part of the work aimed at reducing the high average fault incidence on the first Sydney-Perth high speed telegraph channel, the development of which has been dealt with in the paper by S. Dossing, "High Speed Voice Frequency Telegraph Operation between Sydney and Perth". Preliminary measurements and level recordings, taken on the three channel carrier telephone system providing the bearer circuit by the engineers who installed the telegraph channel, showed that many of the interruptions to the channel were due to faults on this system. The measurements of channel responses on the type CU 5 three channel system, Figs. 1 and 2, curves (i), showed that improvements were necessary for several reasons. The high levels on channel 3 in either direction would aggravate any tendency of amplifiers to overload and intermodulation to occur. Further the frequency of the high speed channel, 2580 c/s, was located at a point of negative slope in the B-A (Adelaide-Perth) direction, and the frequency response of the high speed channel was found to be affected by this slope, see Fig. 3.

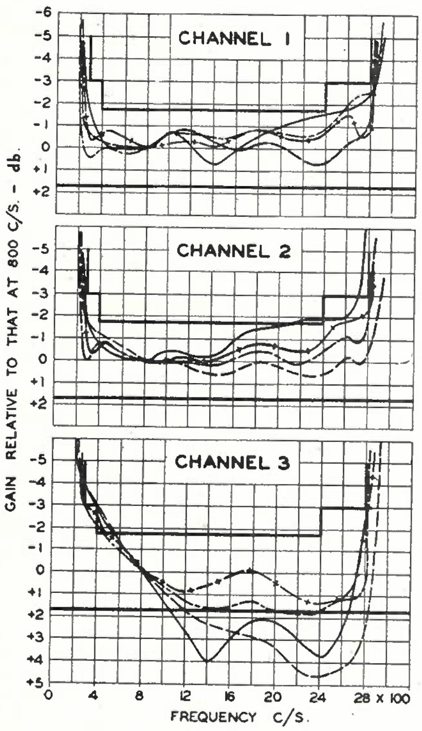


Fig. 1.—CU5 Three Channel System Channel Frequency Responses, Perth-Adelaide.

(i) ———————— measured during installation of first high speed channel.
(ii) —— —— —— measured on arrival at Perth.
(iii) —— – —— measured after initial adjustments.
(iv) —— + —— Final response.

Level recordings of incoming pilot on the CU5 system together with recordings of a mark signal on a spare telegraph channel showed that most of the interruptions occurring to the telegraph channel corresponded with interruptions to the system pilot level, see Fig. 4. Based on this information it was decided to investigate thoroughly the performance of the CU5 system from the point of view of its static and dynamic characteristics, in other words its response characteristics when fault free and its behaviour with changes in line loss and the occurrence of fault conditions.

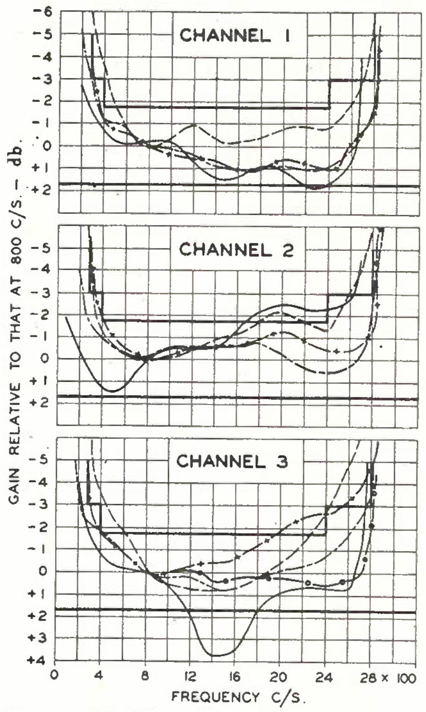


Fig. 2.—CU5 Three Channel System Channel Frequency Responses, Adelaide-Perth.

(i) ———————— measured during installation of first high speed channel.
(ii) —— —— —— measured on arrival at Perth.
(iii) —— – —— measured after initial adjustments.
(iv) —— + —— Final response.
(v) —— O —— extra "J" filter equaliser fitted at Forrest.

Analysis of Static Characteristics of CU5 System

Preliminary Measurements: The first measurements taken were those of the channel responses in both directions of transmission. These are shown in Figs. 1 and 2, curves (ii). It was obvious from these curves that some improvement was necessary to all channels in the B-A direction and at least to channel 3 in the A-B direction. Channel 2 was the one of greatest importance since the high speed telegraph channel was centred on 2580 c/s. in this channel, and at this point the response curve had a distinct negative slope.

Causes of Poor Channel Response: In order to locate and hence rectify these poor channel responses it was decided that the system should be sectionalised, see Fig. 5, and separate measurements taken of:

(i) the high frequency response of the line and repeaters, which could be affected by poor equalisation of certain repeater sections or by faulty filters;

(ii) possible frequency distortion in the voice frequency cable between the Victoria Park carrier terminal and

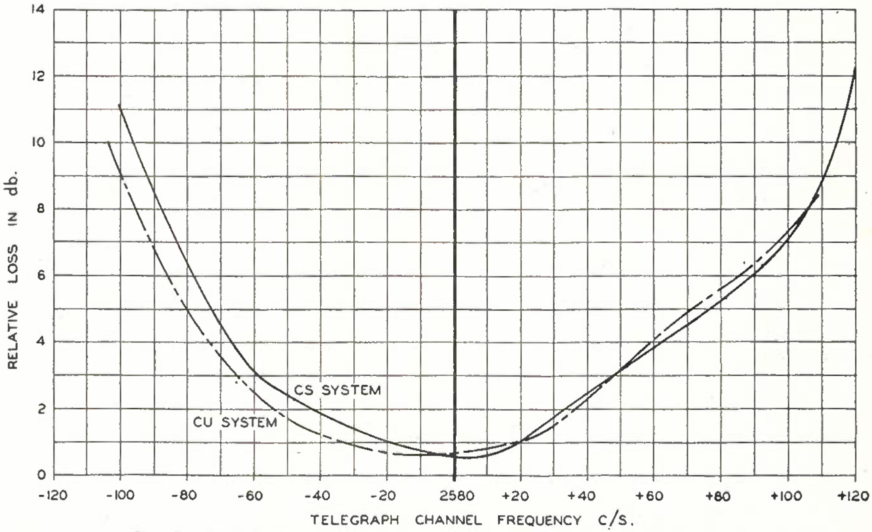


Fig. 3.—V.F.T. Channel Response, Sydney-Perth, Measured 15/8/53.

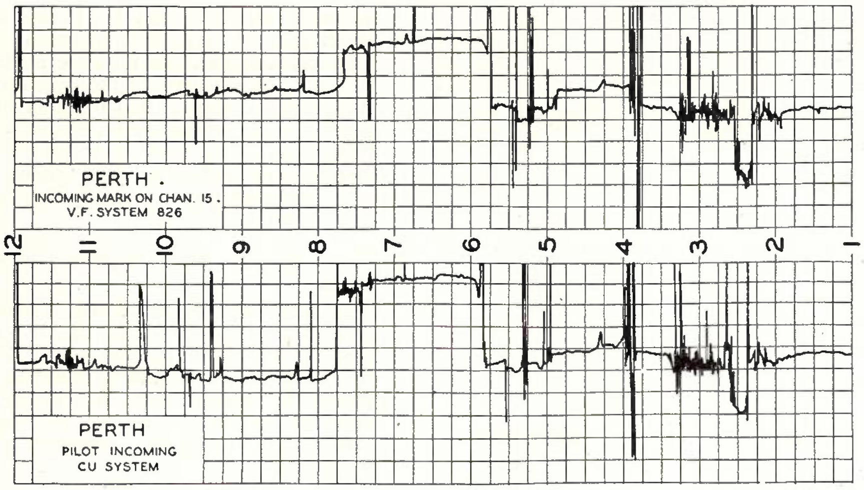


Fig. 4.—Level Recording taken at Perth before the Investigation.

the Perth Trunk Test Room where the carrier telegraph terminal equipment is located.

(iii) Terminal channel equipment responses.

High Frequency Responses: High frequency responses were taken in each direction of transmission and are shown in Figs. 6 and 7. In the A-B direction it can be seen that the poor response on channel 3 has been caused by the early cut off at the low frequency end of the carrier band. This was investigated and it was found that 5.6 kc/s line filter groups had been installed shortly before at Port Pirie and Port Augusta without the necessary "38B" 5 kc/s filter equalizers. These were being forwarded and were to be installed. Also a reduction in the positive slope of the high frequency characteristic would improve this response. This was later done on a trial basis by alterations at two repeaters and the result was an improvement of some 3.5 db at the 2000 c/s. point on the channel. The channel responses of all channels in the A-B direction and the altered high frequency response are shown in Figs. 8 and 1 curve (iii).

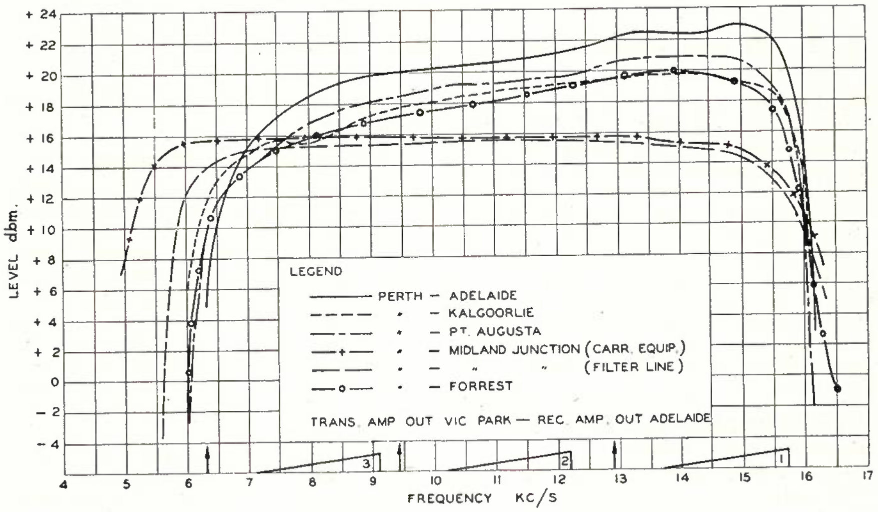


Fig. 6.—CU5 Three Channel System, High Frequency Response, Perth-Adelaide, 14/12/53.

In the B-A direction the high frequency response influenced the channel curves although the effect was not of major importance. The trough around 19 kc/s is reflected in the channel 2 response but the effect of the slight hump at 26-27 kc/s on channel 3 is masked by the cutoff due to the "J" filters installed on the line. The installation of "J" filter equalisers type "D99813" cured this as shown in Fig. 2, curve (iii).

The hump around 25-26 kc/s was located between Port Pirie and Port Augusta. Tests initially showed a hump of about 2.4 db; however further location tests at a later date showed a hump of only 1.2 db. The new Port Pirie repeater was in the process of being cut in during this period and it is thought that the initial tests were carried out when the old cable was connected to the new equipment via jumpers. However, the hump proved not significant in its effect on the channel responses and was therefore disregarded. Comparison of the overall high frequency response before and after the cutover at Port Pirie was completed, tends to support the view that the effect of the hump has been reduced, see Figs. 9, 10 and 11.

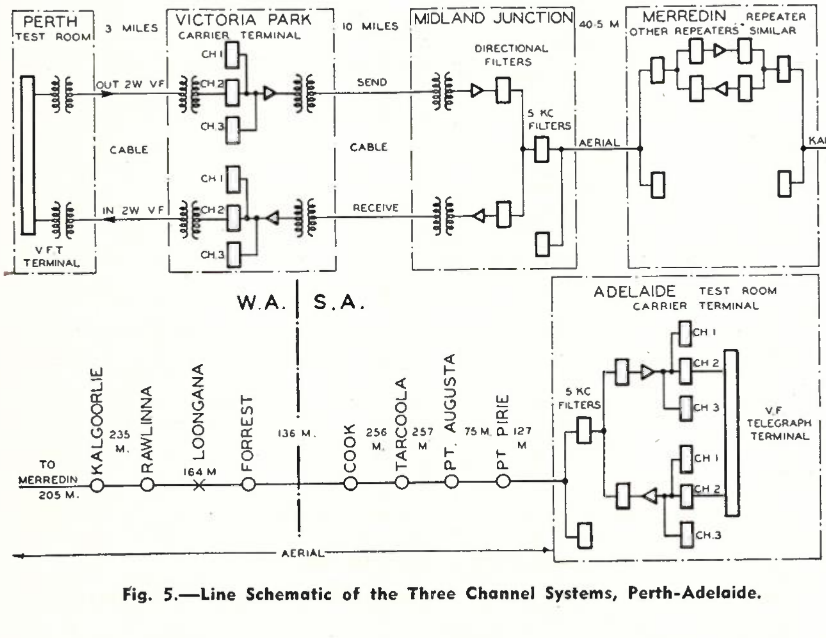


Fig. 5.—Line Schematic of the Three Channel Systems, Perth-Adelaide.

Voice Frequency Cable to Perth: To prove the entrance arrangements from Victoria Park to Perth, channel responses were taken at three points, "demodulator out" at Victoria Park, "return transformer drop" at Perth and "hybrid line" at Perth. It can be seen from Fig. 12 that the responses are not affected by this section of line.

Terminal Responses: The carrier terminal responses were then measured at Adelaide and Victoria Park in the A-B

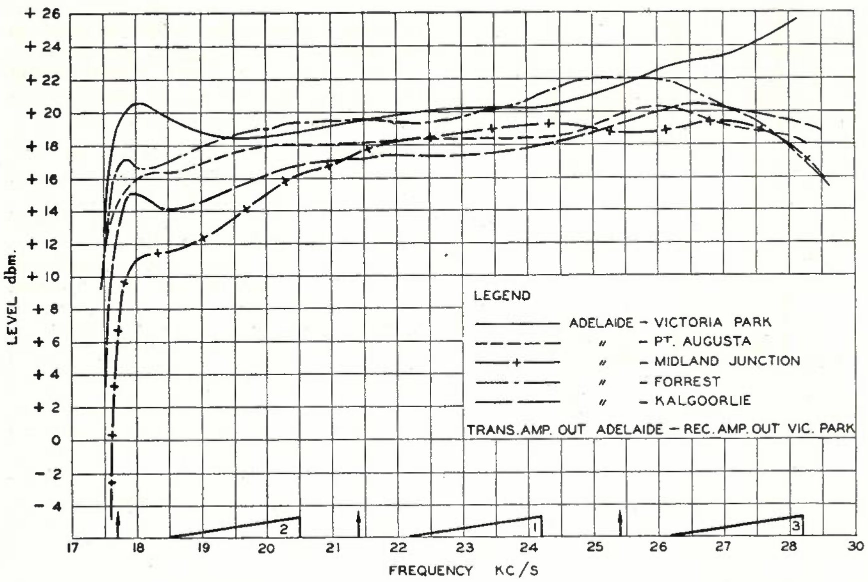


Fig. 7.—CU5 Three Channel System, High Frequency Response, Adelaide-Perth, 14/12/53.

direction, see Figs. 6 and 13, and the Perth receive response, see Fig. 14, looked well outside the limits. A comparative measurement was made on the Albany CU5 terminal, and it was seen that a fault must exist somewhere in the receive side of the Adelaide-Perth CU5 system terminal. After insertion of an impedance matching transformer at the input to the demod. band filters, see Fig. 15, the receive terminal response of the Perth terminal was found to be within the specification as shown dotted on Fig. 14.

Second Response Test: With all these alterations made, namely:

(i) the receive terminal response corrected,
(ii) the "J" filter equalizers installed,
(iii) the 5 kc/s filter equalizers fitted, and
(iv) the line re-equalized on a trial basis at Merredin and Forrest,

the channel responses in both directions were again measured, and are shown in Figs. 1 and 2, curves (iii). At this stage it could be seen that before it was worth while making intermodulation or noise tests on the system, a complete reline under controlled conditions would be advisable. This was evident from the high frequency responses which showed abnormally high levels leaving some repeaters.

Reline of System: The reline of the system was carried out using the method recommended in the handbook, that is the sending of sidebands to line first and after equalization with the manual control, the building out networks and pads, the sending of pilot and the adjustment of sensitivity and tuning.

This lineup took 22 hours in all due to the extreme care taken to try and ensure the best setting for each station. The channel responses measured after lineup are shown in Figs. 1 and 2, curves (iv).

During lineup the following points of interest arose:

(i) **Removal of Basic Equalizers:**

The levels incoming to Port Augusta from Port Pirie were virtually flat. It was thought that by eliminating the basic equaliser the repeater could be used virtually as a flat amplifier. (This course is recommended in the Bell System Practices where necessary.) However, by cutting out the basic equaliser it was found that a hump developed in the high frequency response which could not be eliminated.

This hump was aggravated by slight under-equalization leaving the repeaters, and it was found that closer control could be kept over the system when the equalizer was left in and a small positive slope was maintained. This ensured that the negative slope incoming to the next repeater was not too great and further that the manual control could be set on a reasonably high stop. This gave a margin of reserve gain for bad weather, a necessary consideration especially on a long route such as this.

(ii) **Slope in B-A Amp. response Rawlinna:**

The B-A amp at Rawlinna, which had previously been found to have a slope in it of some 2.2 db, was found to render the regulation at Rawlinna practically useless and it was not until the spare was patched in that equalization could be achieved at Rawlinna.

(iii) **Alternative Settings:**

During the lineup it was found that the same net slope could be achieved with one or two different combinations of the manual control and building out networks, but that there existed an ideal combination which took into consideration the position of the middle channel. Slopes either concave or convex upwards can be achieved, and a slope almost straight but with a tendency to concavity was aimed at.

(iv) **Pilot to Sideband Relativity**

The pilot leaves the transmitting terminal 10 db below the signal. However at certain repeaters it leaves at less than 10 db away from the 800 c/s. level on the adjacent channel. This was found to be an indication that a slope existed on the high frequency response between the pilot and the sideband. The achievement of the best pilot to sideband relativity is a good way of obtaining the best high frequency response.

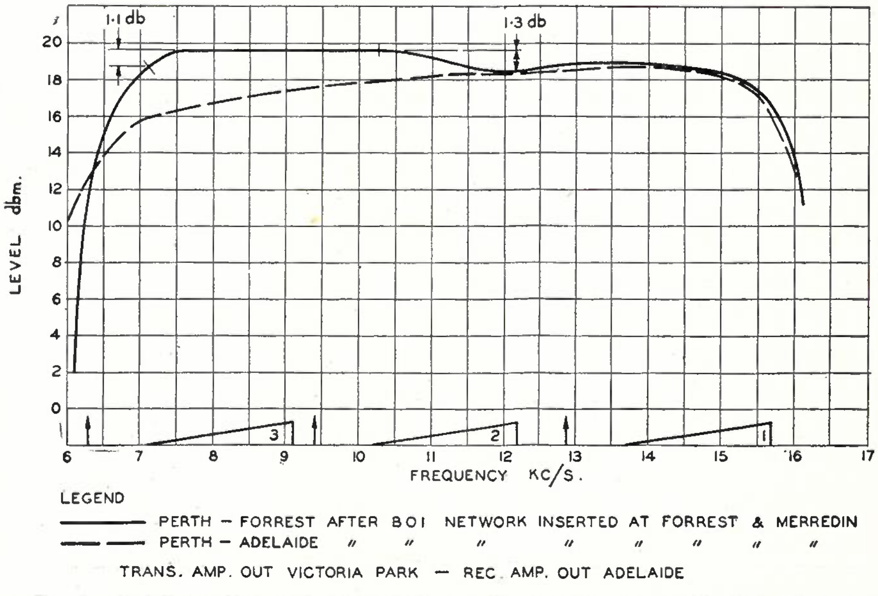


Fig. 8.—CU5 Three Channel System, High Frequency Response, Perth-Adelaide, 15/12/53.

Third Response Tests: The channel responses after lineup, see Figs. 1 and 2, curves (iv), all showed the same general trends as before, but channel 3 in the B-A direction had deteriorated since the previous measurement. This was followed up and it was found that since the last tests the installation of "J" filters had proceeded and that the "J" filter equaliser installed at Midland Junction was no longer sufficient to compensate for the "J" filters on the line. However, the channel was tested for speech and V.F. signalling and found to be satisfactory. After a further "J" filter equalizer was installed on this line the response improved to that shown in Fig. 2. Channel 3 in the A-B direction had improved still further and channel 2 in both directions was more suitable as a bearer for a telegraph system than it was previously. Having regard to the long route and numerous repeaters, it was thought that the channel responses shown were reasonable.

Noise and Intermodulation Tests: Measurements of basic noise were made on the system in both directions and intermodulation tests conducted in the A-B direction using a noise generator. The measurements appear below.

Basic Noise

	Ch. 1	Ch. 2	Ch. 3
A - B	- 53	- 44*	- 49*
B - A	- 55	- 56	- 54

The tests refer to weighted noise measured with 2 B noise set at a point of + 4 dbm reference level. The noise level was found to vary between 44 and 51 during the tests marked *.

Intermodulation Test—A-B Direction

Channels Disturbed	Ch. 1	Ch. 2	Ch. 3
1 and 3	X	- 57	X
2 and 3	- 54	X	X
1 and 2	X	X	- 52

Analysis of Dynamic Characteristics of CU5 System

For some time before this investigation, D.C. recording milliameters had been used to monitor the level of pilot arriving at both Perth and Adelaide on the system. Also a mark signal on channel 15 of the associated telegraph system had been monitored in a similar way. The resulting traces showed clearly that a good deal of the trouble being encountered on the high speed telegraph channel was due to instability on the 3-channel CU system which acted as bearer for the telegraph circuit.

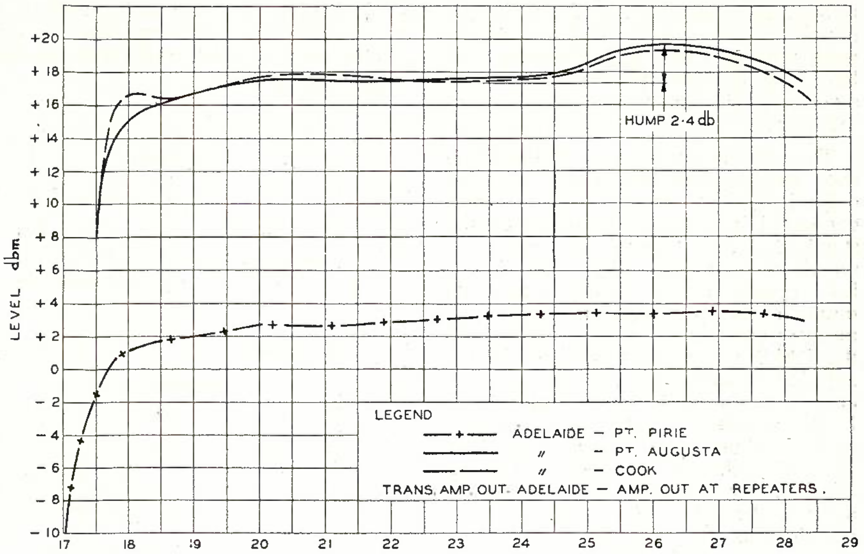


Fig. 9.—CU5 Three Channel System, Location of the Pt. Pirie Hump, 11/12/53.

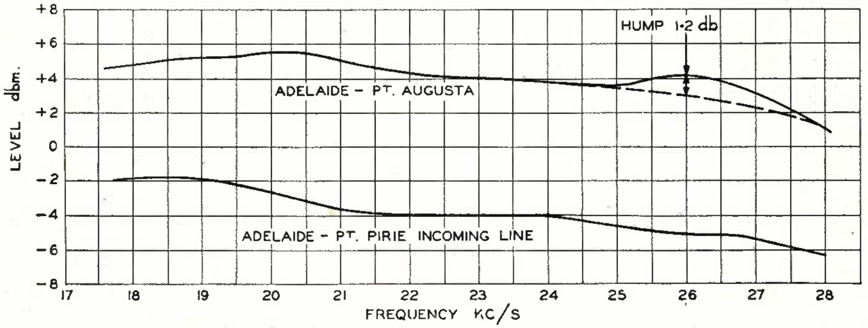


Fig. 10.—Tests on the Pt. Pirie Cable, 12/1/54.

Installation of Recorders: From the recordings already to hand and fault reports available, it was apparent that a majority of the faults were of an intermittent nature and were rarely located, due to the length of the circuit involved. Therefore it was proposed to extend the use of recorders on the pilot of the system and break the route into four main sections. Recorders were placed at Perth, Kalgoorlie, Forrest, Port Augusta and Adelaide to monitor the pilot

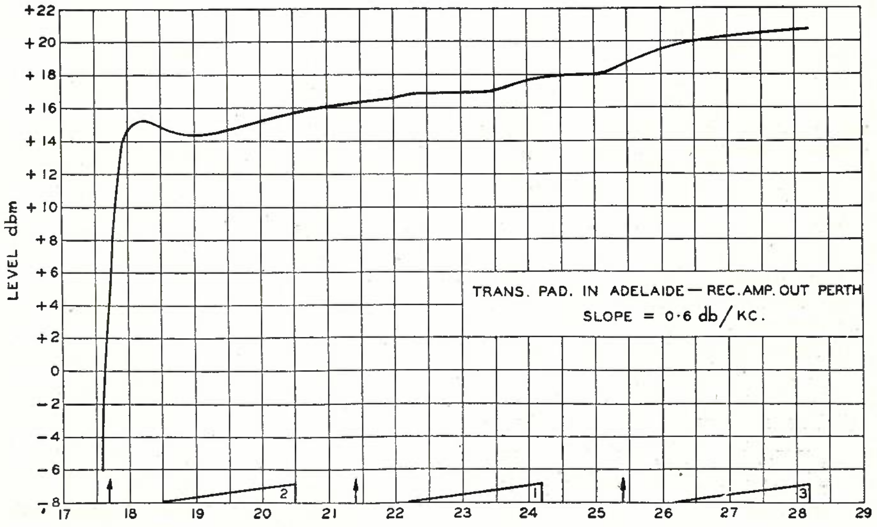


Fig. 11.—CU5 Three Channel System, High Frequency Response, Adelaide-Perth, 17/1/54.

in both directions, see Fig. 5. When the initial results were to hand recorders were sent to Cook and Tarcoola and later one to Rawlinna to help isolate sections of the route under suspicion at the time.

The recorders used were of the Evershed and Vignoles type 1 ma full scale deflection D.C. meters. These were connected in place of the meter on the standard A.P.O. transmission measuring set via a rectifier and the T.M.S. in the level condition was bridged across the output of the pilot pick-off filter at the repeater concerned, see Fig. 16. Using the T.M.S. as an amplifier, the gain was adjusted to enable the recorder to operate at centre scale for normal pilot level. It was arranged that the charts be sent to Perth about twice a week where they were divided into 24 hour periods and all charts for a particular day glued one beneath the other to facilitate their examination.

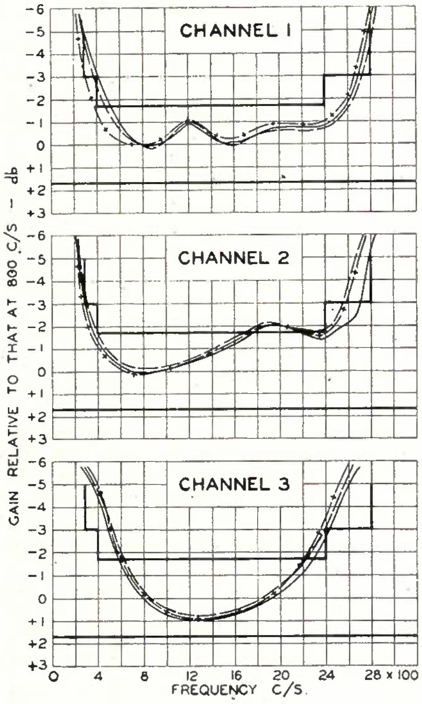


Fig. 12.—CU5 Three Channel System, B-A Response Check on the Perth V.F. Cable Arrangements.

———— 4 wire Victoria Park.
—— —— 4 wire Perth.
—— + —— 2 wire Perth.

First Analysis: Several distinct conclusions could be drawn from the charts in the first week or two.

(i) The outputs of the pilot oscillators at both Perth and Adelaide were steady and of constant level.

(ii) The sections of the route between Perth and Kalgoorlie and Adelaide and Port Augusta, were stable and not giving rise to any intermittent troubles.

(iii) The traces throughout the route on most Sundays were smooth and quiet indicating that the faults appeared either when staff were working on the plant or when traffic was flowing in any quantity.

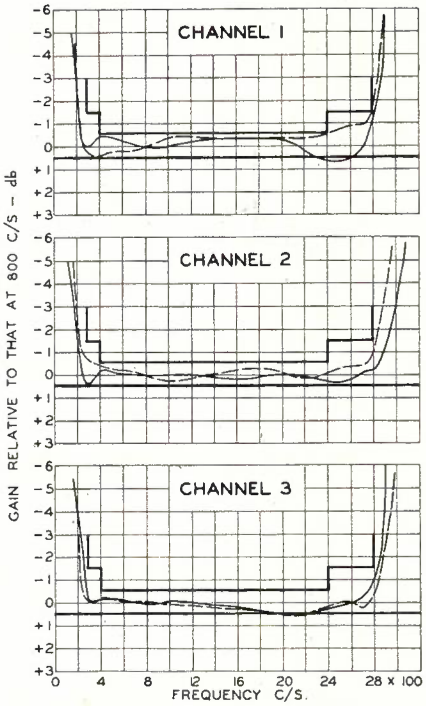


Fig. 13.—CU5 Three Channel System, Terminal Channel Responses A–B.

———— Transmit terminal response, Perth.
—— —— Receive terminal response, Adelaide.

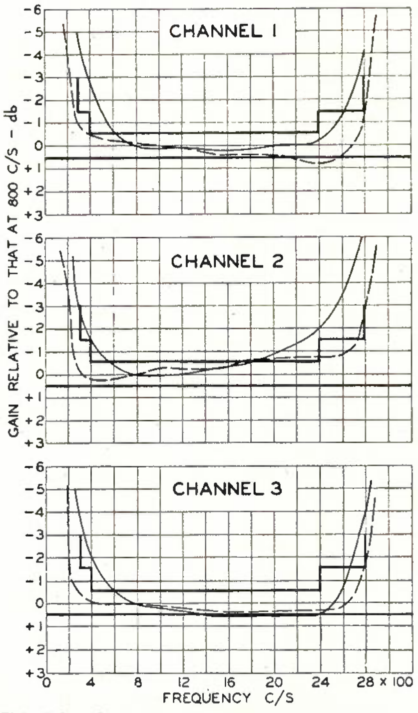


Fig. 14.—CU5 Three Channel System, Perth Terminal Channel Response B – A.

———— Before fault found.
—— —— After fault cleared.

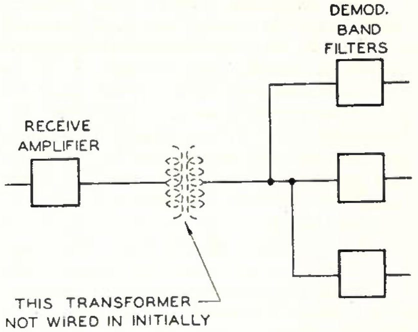


Fig. 15.—Location of missing transformer in Perth Terminal of CU5 System.

(iv) The presence of line parties and engineers on the route cutting in entrance cable and conducting measurements in preparation for the installation of the first 12-channel Type J Telephone system between Adelaide and Perth caused many minor interruptions to the circuit. Throughout the tests this work coupled with the major line break at Loongana on 28/12/53, see Fig. 5, when six miles of route was completely wrecked by a severe storm, and subsequent repair work, tended to add an undue number of line faults to the charts. The significant point was that when the installation staff were not working, the line faults decreased markedly. Examples of the types of line interruptions caused are shown on the chart for 12/12/53, Fig. 17. The chart for 13/12/53, Fig. 18, shows the decrease in line faults when installation staff were not working, such as on Sundays and over Christmas.

(v) The main equipment trouble appeared to be between Forrest and Kalgoorlie in the B-A direction and was of a type which indicated overloading, intermodulation or some type of pilot interference related to nonlinearity, see chart for 8/12/53, Fig. 19. The presence of this kick in the

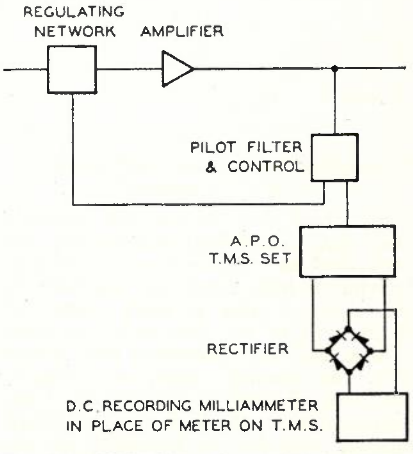


Fig. 16.—Connection of Recording Milliammeter to Monitor Pilot of Three Channel System.

pilot could be seen at Victoria Park, as well as on the traces and an analysis was carried out to see whether the pilot pick-off filter at Victoria Park was faulty. This analysis showed the pilot to be well guarded from normal sideband interference, see Fig. 20.

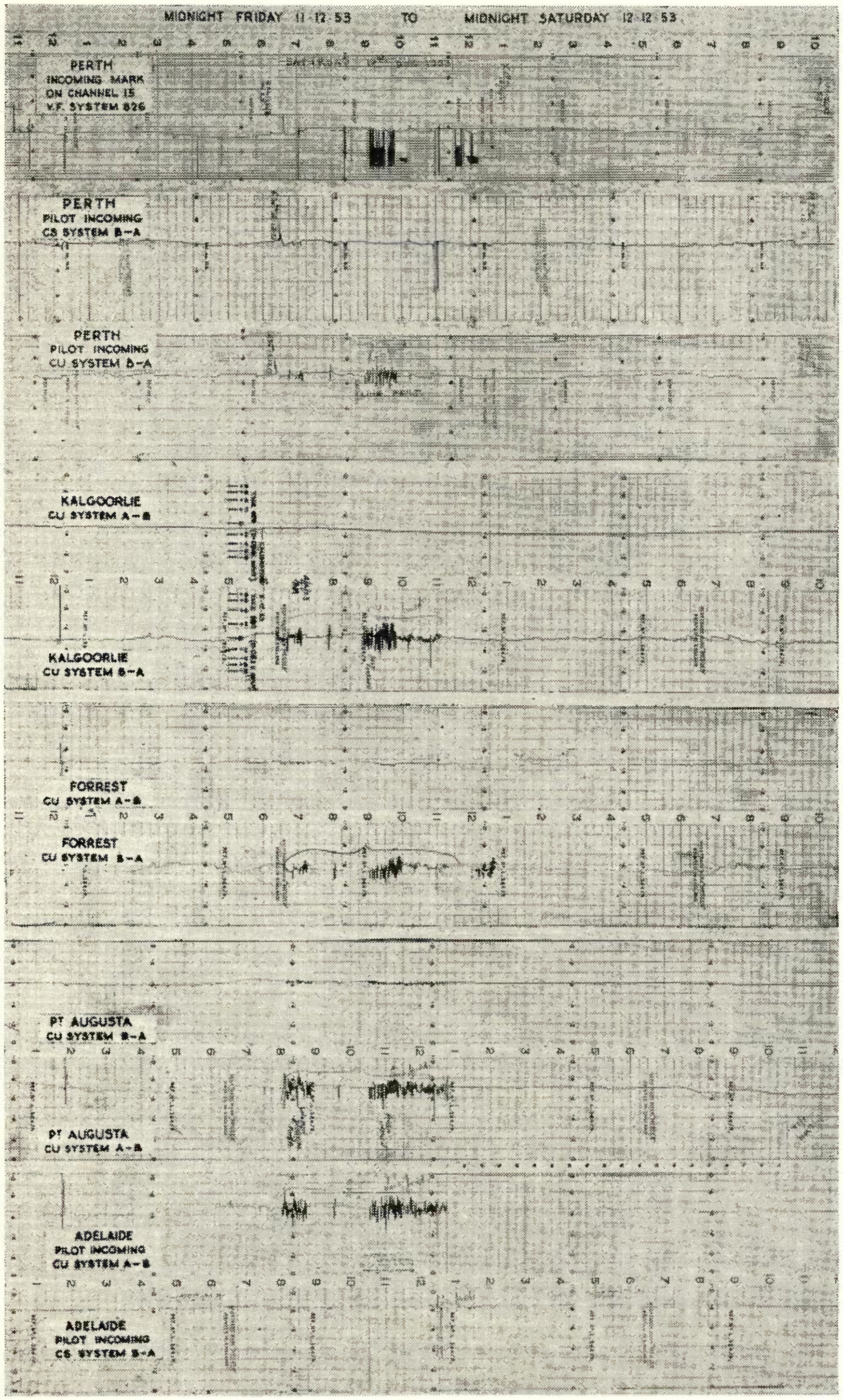


Fig. 17.—Level recordings on Perth (A)-Adelaide (B) 3-channel C.U. system, 12-13/12/53.

NOTES: (1) Sections (a) Adelaide-Pt. Augusta, (b) Pt. Augusta-Forrest, (c) Forrest-Kalgoorlie, (d) Kalgoorlie-Perth.
(2) Times shown on charts are local and are related to Adelaide time, shown on bottom trace.
(3) Level of incoming pilot on C5 system recorded at Perth and Adelaide for comparison.
(4) Calibration varies between instruments, but those shown for Kalgoorlie charts are typical.

(vi) Coupled with this interference was the tendency for the system to lock out high. This will be discussed later.

(vii) The A-B direction was generally stable as the charts indicate.

Rawlinna Overloading: At this stage the technician at each repeater station was asked to conduct an overload test on his amplifiers. The results all proved within the specification except those from Rawlinna where the B-A amplifier was overloading at outputs between +13 and +30 dbm, the specification being +34 dbm. Immediate action to have the spare amplifier patched in was shown by the traces to have cleared the fault. A spare amplifier from Perth was sent and installed. Troubles were found in this amplifier as well but after some effort the repeater was put back and worked successfully for three days. The fault then recurred in a milder form and it was only during a thorough examination of the office later that the amplifier was fixed. The fault this time was a poor tube and since replacing this tube the trouble has not recurred. The final trouble-free chart for 5/2/54, Fig. 21, shows the system after test.

Tendency for System to Lock Out High: It was found during a close study of the system that the overall equivalent tended to go high and lock that way. This fault caused some speculation as to whether the regulating arrangements on the C5 type systems were sufficiently fast to cope with the large changes in temperature and leakage resistance which occur on the transcontinental line at certain times in the day. However, once the major fault was eliminated at Rawlinna the smooth traces showed that such speculation was groundless. The fault was found at Forrest where the low alarm was not locking out the drive. The repeater was driving high to compensate for the fault and when the fault cleared, locking out on the high alarm and hence locking the rest of the route high in the alarm sensitrols. The fault would remain on until the technician at Forrest altered the gain of his repeater by hand. Further a dry joint in the regulating circuit was found to be causing the random level variations of the pilot at Forest in the B-A direction, as shown in Fig. 19.

Repeater Tests: It became clear after the Rawlinna fault was cleared initially, that if possible an inspection of each repeater was necessary in order to ascertain the exact state of the route. This information was not readily available at the terminals, and further the personnel on the spot were not equipped to carry out the necessary tests. Therefore, each repeater was visited and submitted to a standard set of tests and an inspection which covered the points set out below:

i Office batteries
  (a) 24 volt
  (b) 130 volt
  (c) Filtering.
ii Grid bias
iii Repeater earth
iv Original settings
v Pilot tuning and sensitivity
vi Amplifier characteristics
vii Repeater gain
viii Regulator characteristics
ix Regulator flat gain range
x Directional filters response and singing test
xi Pilot alarms
xii Power noise
xiii Office wiring.

Summary of Results: The following is a summary of the faults found at the repeaters.

(i) Faulty cam adjustment on drive circuit of the regulating amplifier in the B-A direction, resulting in no high alarm being given.

(ii) Bias batteries flat or low.

(iii) Tubes responsible for low amplifier gain.

(iv) Pulse Adlake relays sticking, and associated relays with dirty contacts. This tended to hold the sensitrol relay arms in the centre of the meter locked between the restoring fingers.

(v) Regulating amplifier with low gain. Due to this amplifier being of the non-feedback type any tendency of the tube to age caused considerable change in the regulator gain.

(vi) Dry joints in screw connections on the front panel. These connectors had tarnished at certain stations and the result was a tendency to high resistance joints, especially if the screws were not kept firm.

(vii) Intermittent trouble on the 55 V. A.C. drive circuit due to maladjustments on associated relays and the generator contactor circuit.

(viii) The noise output of the amplifiers at most repeaters included crosstalk from other circuits in the office including the programme channel and train control equipment. This was due to the lack of decoupling of the 130 V. supplies to the various systems in the office.

(ix) Pulse cutoff plugs, by means of which the pilot can be pegged, are left half-way in the jacks. This is an incipient fault since slight pressure on the plug will cut the pulse circuit and leave the repeater in a locked condition not able to correct for changes in line attenuation. Further, the condition can occur with plug in a certain position when any vibration tends to open and close the pulse circuit at random. It was recommended that these

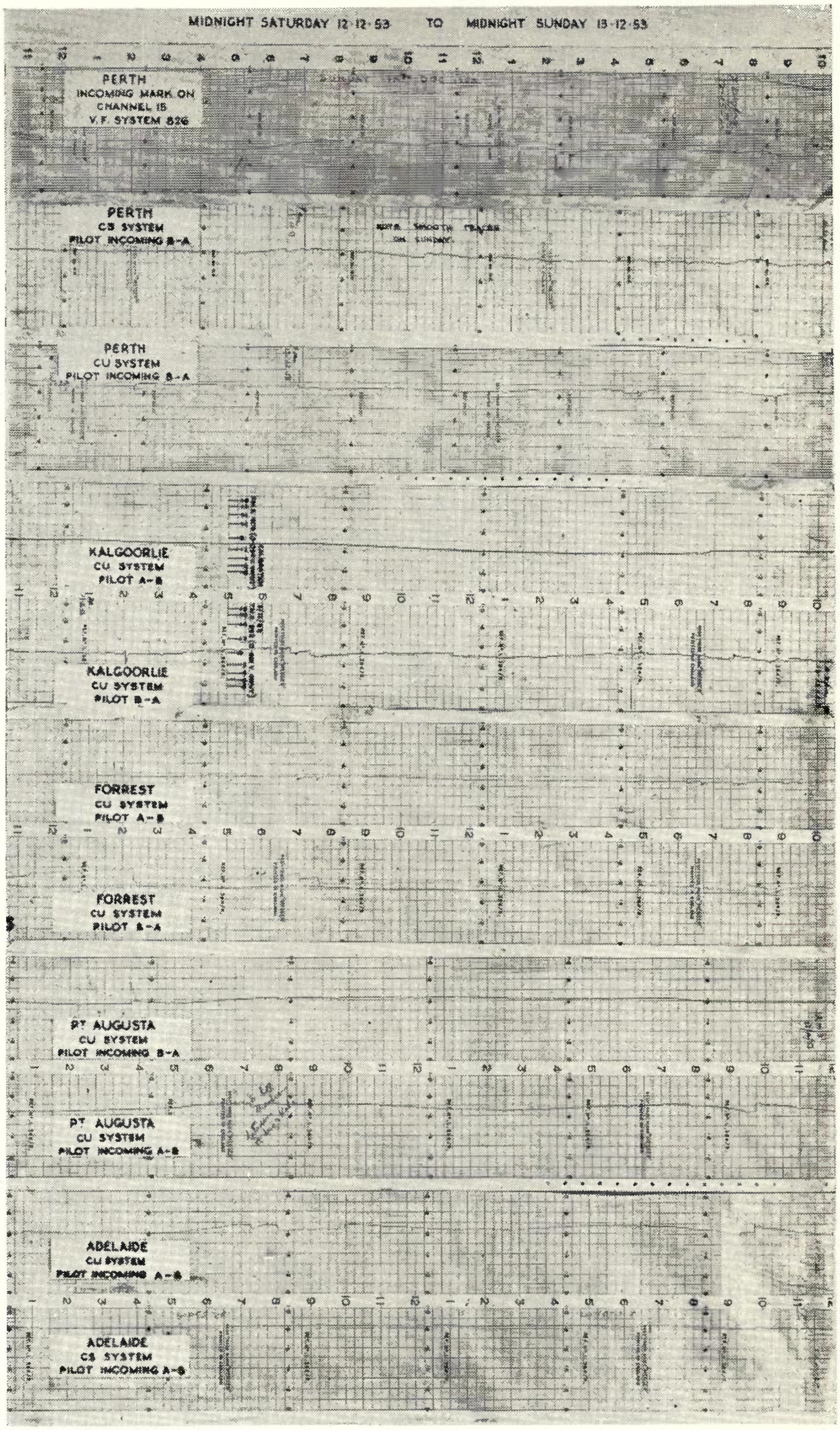


Fig. 18.—Level recordings on Perth (A)-Adelaide (B) 3-channel C.U. system, 12-13/12/53.

NOTES: (1) Sections (a) Adelaide-Pt. Augusta, (b) Pt. Augusta-Forrest, (c) Forrest-Kalgoorlie, (d) Kalgoorlie-Perth.

(2) Times shown on charts are local and are related to Adelaide time, shown on bottom trace.

(3) Level of incoming pilot on C5 system recorded at Perth and Adelaide for comparison.

(4) Calibration varies between instruments, but those shown for Kalgoorlie charts are typical.

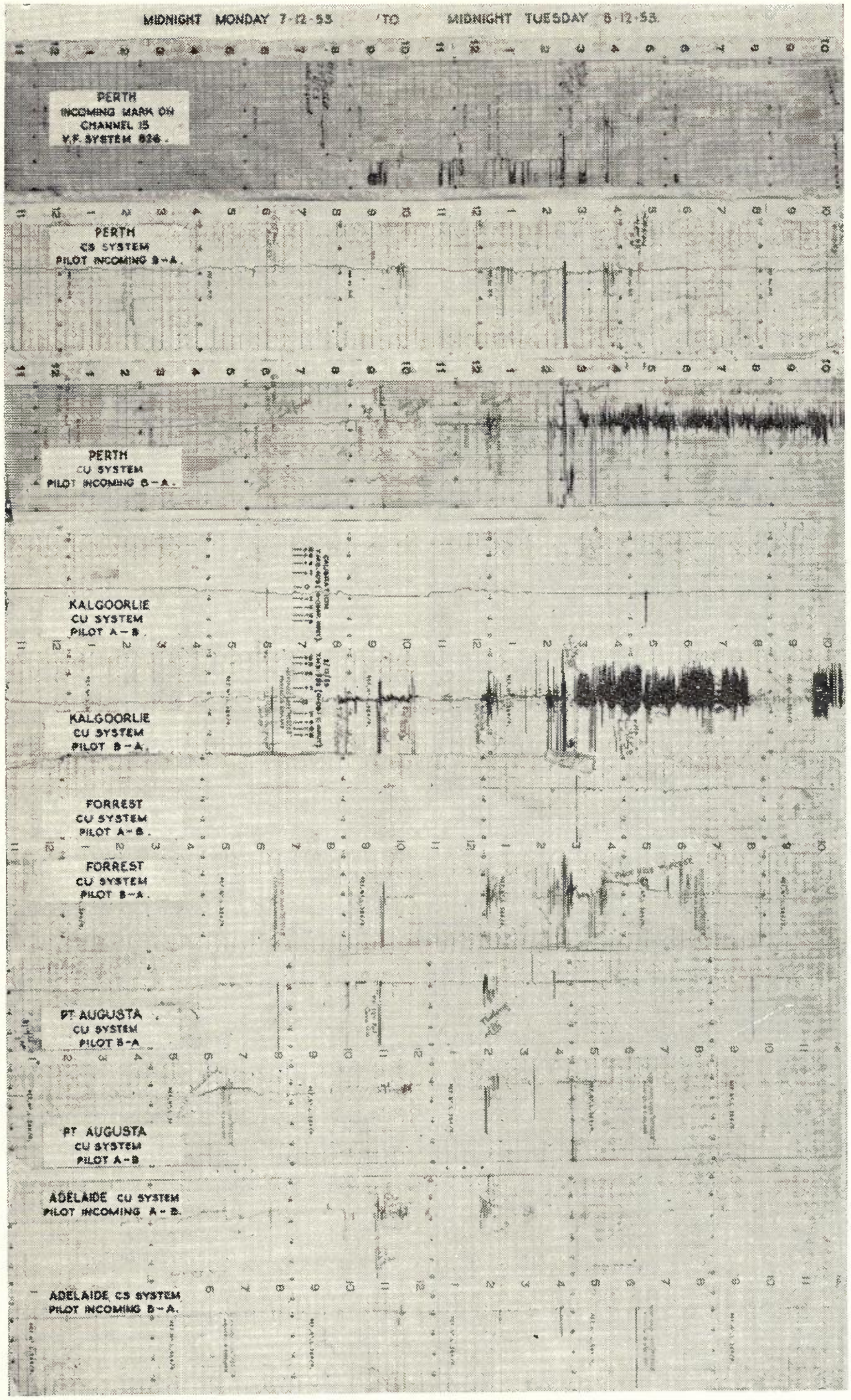


Fig. 19.—Level recordings on Perth (A)-Adelaide (B) 3-channel C.U. system, 7-8/12/53.

NOTES: (1) Sections (a) Adelaide-Pt. Augusta, (b) Pt. Augusta-Forrest, (c) Forrest-Kalgoorlie, (d) Kalgoorlie-Perth.

(2) Times shown on charts are local and are related to Adelaide time, shown on bottom trace.

(3) Level of incoming pilot on C5 system recorded at Perth and Adelaide for comparison.

(4) Calibration varies between instruments, but those shown for Kalgoorlie charts are typical.

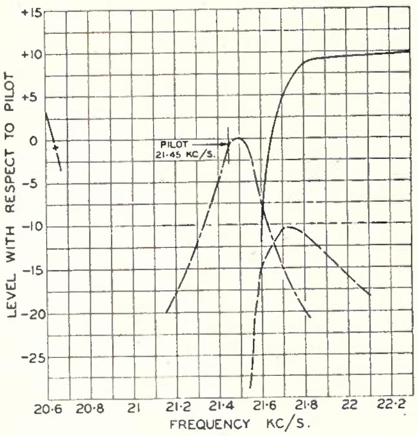


Fig. 20.—Pilot Selectivity of the Perth Terminal CU5 System, 6/12/53.

———— Channel 1.
—— + —— Channel 2.
—— – —— Pilot pick-off characteristics.
—— —— Tone level with respect to pilot in pilot pick-off circuit.

plugs be hung on strings as they are elsewhere and this was done where possible.

Final Traces: The traces received immediately following the clearing of the troubles at Rawlinna and Forrest indicated that a definite improvement had resulted. The completion of the lineup on 31/1/54, together with the completion of the "J" installation on 29/1/54 and the repairs at Loongana at about the same time resulted in traces which gave a fair picture of how the line would behave under traffic without linemen and installation parties working on the pairs. The traces for the week ended 6/2/54 were the smoothest yet obtained for a working week and showed that improvements had been made to the circuit.

Analysis of the C.S. System

Since the telegraph channel had the C.U. system as bearer, most of the effort was concentrated on this system. However, faults found on the C.U. system resulted in a check on the C.S. system to ensure that similar conditions did not exist there. It was generally acknowledged by the staff that the C.S. system was the more stable of the two, and the traces taken at each end of the C.S. system during the C.U. system tests indicated this.

Channel responses were taken on the C.S. system in the initial stages of the investigation, see Fig. 22. A study of these responses in the light of experience gained on the C.U. system indicated that a change of carrier frequency and a careful lineup would modify the channel responses to well within the limits and take out the hump in channel 2, in the B-A direction. Channel 3 in the B-A direction suffered, as did its counterpart on the C.U. system, from a lack of "J" filter equalizers.

The traces taken on this system at Adelaide and Perth during the work on the C.U. system showed the C.S. system to be more stable of the two. However, the small bump, hardly more than 0.5 db. during busy periods indicated that a reline, keeping the levels down to +18.5 db maximum, would be advisable.

After work on the C.U. system had finished, the recorders were placed on the C.S. system for one week in order to sectionalise its behaviour and for comparison with the C.U. system. These traces were similar to those shown in Fig. 21, and confirmed that the dynamic behaviour of the C.S. system was good.

Conclusion and Remarks

During the investigations, the interruption time on the high speed channel varied considerably but showed a general improvement. The best performance was five minutes per day in the Christmas week. The significance of this was that the installation parties and linemen were not working along the track during this period. The two minutes per day on the following week was not significant since it took into account only the period before a major breakdown. However, had all been well, the average for this week might well have been five minutes.

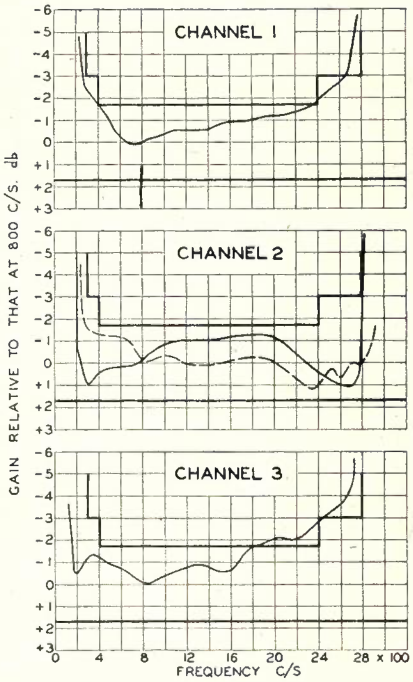


Fig. 22.—CS5 Three Channel System, Overall Channel Responses, Adelaide-Perth.

————— Adelaide —> Perth.

—— · ———— Perth —> Adelaide.

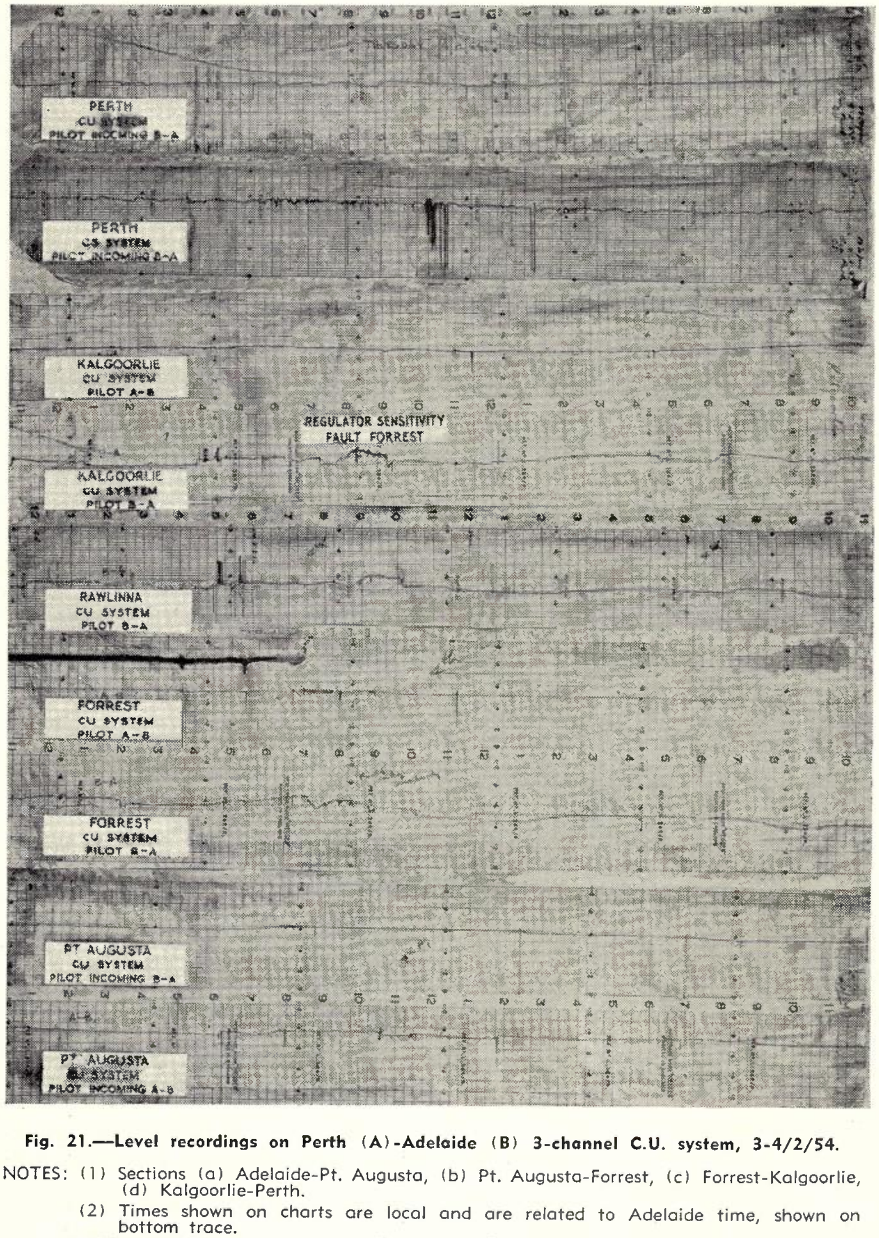


Fig. 21.—Level recordings on Perth (A)-Adelaide (B) 3-channel C.U. system, 3-4/2/54.

NOTES: (1) Sections (a) Adelaide-Pt. Augusta, (b) Pt. Augusta-Forrest, (c) Forrest-Kalgoorlie, (d) Kalgoorlie-Perth.
(2) Times shown on charts are local and are related to Adelaide time, shown on bottom trace.
(3) Level of incoming pilot on C5 system recorded at Perth and Adelaide for comparison.
(4) Calibration varies between instruments, but those shown for Kalgoorlie charts are typical.

The break at Loongana coupled with urgent work on the "J" system masked the effect of the improved service for the whole of January, the "J" system being completed on 29th January, 1954, and the break rectified by about the same date. Reference to Fig. 23 shows how the fault incidence on the circuit has decreased since the investigations on the channel began in August 1953. This graph also shows that following a serious break on the line the fault incidence increases, this being due to the subsequent repeated interruptions caused by the replacement of temporary circuits by the permanently repaired ones.

This investigation, as well as improving the grade of service on the high speed channel, resulted in a closer knowledge of the C5 type Western Electric three channel systems and their problems as single pilot regulated systems. They have virtually no "static" characteristics since the alteration of one manual control alters the equalization at that office, and hence changes both the high frequency response and the channel responses in the direction concerned. As a rule it has been found that channel 3 in the A-B direction has been high at 2000 c/s on most C5 systems examined and this is thought to be due mainly to the slope of the high frequency response at lineup and/or the lack of 5 kc/s filter equalizers. Care was needed to keep the manual control high in order to maintain the effectiveness of the building out networks for line equalization, and to provide an adequate margin of repeater gain for adverse line conditions. When lining the system up it was noted that several different combinations of building out networks, pads and manual control would yield the same net slope, but would vary between them the flatness or otherwise of the response. Any tendency to a positive hump in the centre needed to be avoided where possible. The pilot to sideband relativity of +1·0 db was a useful check on the slope of the high frequency response in this region.

The use of recorders has proved a powerful method of sectionalising a line, and as experience is gained with the traces more definite conclusions can be drawn from subsequent tests.

Finally the results obtained from these tests emphasise the necessity for keeping close control over the standard of operation of carrier telephone links, since they will not function satsifactorily unless they work under the conditions for which they were designed.

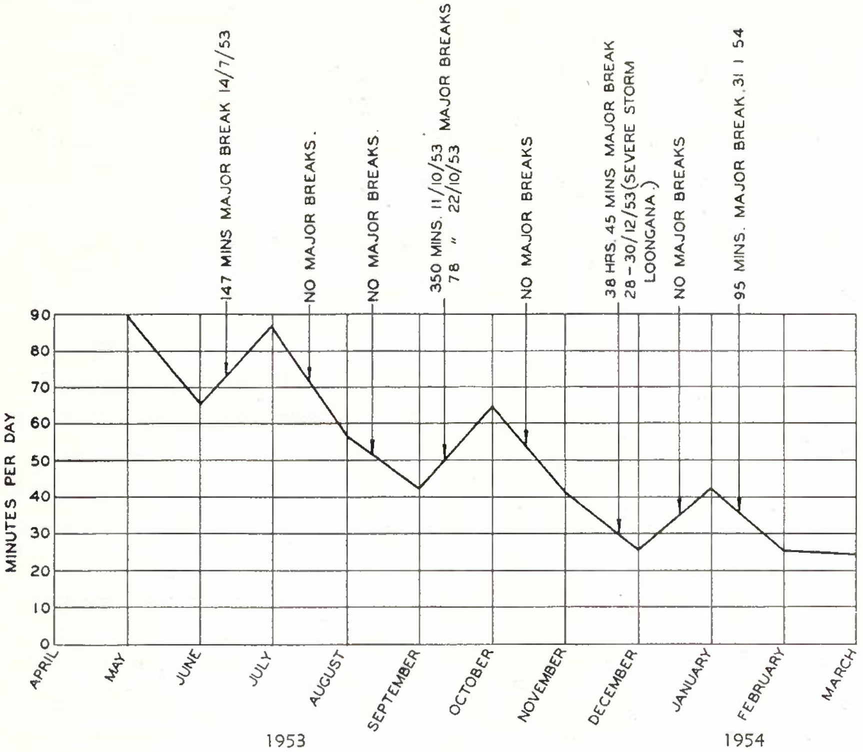


Fig. 23.—O.T.C. High Speed Telegraph Channel. Monthly average fault time in minutes/day due to P.M.G. plant, as reported by O.T.C.

MR. D. D. KNUCKEY

On 22nd July, 1953, Mr. D. D. Knuckey retired, at the age of 65 years, from the position of Superintending Engineer, N.S.W. Over his 42 years of outstanding service, Mr. Knuckey made his mark as an engineer of the highest grade and the Australian Post Office is much the poorer by the loss of his great engineering skill and executive ability.

Dick Denzil Knuckey—to give him his full name—was born in Port Lincoln, South Australia, on 23rd July, 1888. He is the son of another noteworthy postal officer, Richard Randell Knuckey, who was one of the supervisors under Charles (later Sir Charles) Todd, who erected the 1800-mile Overland Telegraph Line from Adelaide to Darwin, an early and magnificent achievement of the Post Office in Australia. Later, Richard Randell Knuckey supervised the construction of the first Trans-Continental Telegraph Line between Eucla and Norseman, and subsequently rose to the position of "Inspector of Lines" which was then the second highest rank in the South Australian Post Office.

Entering the Post Office in 1911 after passing through the Electrical Engineering course in the Adelaide School of Mines, D. D. Knuckey became an Engineer in 1915. In 1917 he joined the First A.I.F. and saw service in Mesopotamia with the First Australian Wireless Squadron. On promotion as Divisional Engineer, Sydney, in 1928, he transferred to New South Wales and steadily progressed until he occupied the top position of Superintending Engineer, Sydney, in 1946.

Throughout his career, Mr. Knuckey played a most active and effective part in developing the telecommunication services of New South Wales to their present stage. As Superintending Engineer he had the management and development of this large organisation throughout the difficult post-war years with their most extensive and unprecedented demands for more and more telephone services, against a background of shortages of buildings, materials and manpower. Some measure of the effect of his control is well illustrated by the number of telephone services installed during these years:—

1945	13,101
1946	15,782
1947	22,500
1948	20,557
1949	26,446
1950	33,120
1951	38,503
1952	29,508

The total effect of these connections was to increase the whole network by over 60 per cent. in eight years.

In outward appearance, Mr. Knuckey is of medium build, with keen bright eyes and a most incisive manner. On and off duty he presented two very different personalities. Normally a man of simple tastes, leading a relatively quiet life, very human, and possessing a quiet sense of humour, he became, in his official capacity, a dynamic executive, with the quick logical thinking necessary to make bold decisions and the perspicacity and will power to carry them into effective action.

He wasted no time on irrelevancies, combining great depth of technical knowledge with a marked ability to seize on to all essential facts, rapidly reduce the most complex problem to its fundamentals and arrive at its solution. From this personal efficiency he derived an immense capacity for the handling and control of all the multifarious activities of the organisation.

Despite the heavy and responsible burden of his position, he did not neglect the welfare of his staff and personally conducted a case which resulted in improved conditions and salaries for the professional engineering staff in all States of the Commonwealth.

Mr. Knuckey not only left behind him a record of high achievement, which has contributed greatly to the engineering development of Telecommunication services, but set a standard of personal efficiency which is an example to all who know him.

ANSWERS TO EXAMINATION PAPERS

The following answers generally give more detail than would be expected in the time available under examination conditions. The additional information should be helpful to students.

EXAMINATION No. 3106
SENIOR TECHNICIAN
RADIO AND BROADCASTING
RADIO II

Q.5.—Describe the construction of a tetrode tube and explain why its amplification factor is high as compared with a triode. Indicate any disadvantage of this type of tube and show how this may be overcome by the introduction of an additional electrode.

A.—The tetrode tube, as its name implies, is a four electrode tube which differs from the triode tube by having an extra grid, called the "screen grid", inserted between the control grid and the anode.

The amplification of a triode depends on the position of the anode relative to the control grid and the cathode, and for a given spacing between the control grid and cathode, the amplification is greater the further the anode is from the control grid, but there is a limiting distance as the accelerating effect of the anode potential on the electron stream decreases as the separation distance increases. In the case of a tetrode, the anode is some distance from the control grid whereas the screen grid is placed close to it. When the screen grid is connected to a potential similar to that on the anode it strongly attracts the electrons from the cathode. Most of the attracted electrons pass through the mesh of the screen grid and continue on to the anode. Thus the electrode spacing is favourable for high amplification and the accelerating effect is still high as the screen grid is relatively close to the cathode.

Due to the spacing of the electrodes in a tetrode, the main accelerating force evident on the electron stream is supplied by the screen grid and not by the anode. Hence, the anode has very little control on the anode current whilst the control grid still has the same control as in a triode. Consequently, the ratio of anode control to control grid control on the anode current is greater in a tetrode than in a triode. This ratio defines the amplification factor of a tube.

The main disadvantage of the tetrode is that secondary emission can occur from the anode. This is due to some of the electrons rebounding after striking the anode and forming a space charge of electrons between the anode and the screen grid. The space charge tends to repel electrons approaching the anode and so reduces the anode current.

Greatest secondary emission occurs when operating at a certain anode potential less than the screen potential. Under these conditions a small increase in anode voltage causes a decrease in anode current. This is sometimes referred to as "negative resistance" as an increase in voltage causes a decrease of current.

The secondary emission effect is minimised in the pentode tube by having another grid placed between the screen grid and the anode, and connecting it to the cathode. This grid is called the "suppressor grid" as its potential is negative relative to the anode and it repels the secondary emission electrons back to the anode thus suppressing secondary emission. The pentode has the high amplification of the tetrode without the negative resistance characteristic.

Q.6.—What are the desirable characteristics of an audio frequency test oscillator used for the testing of studio equipment? Explain briefly the operation of a beat-frequency oscillator.

A.—(a) Test Oscillator. The following list shows the desirable characteristics of a test oscillator used in conjunction with studio equipment—

1. The frequency range should be from 15 c/s to a minimum of 20 kc/s, preferably to 50 kc/s.
2. The amplitude of the output voltage should remain constant over the whole range.
3. The harmonic distortion should be very low, preferably below 0.1 per cent.
4. The noise level should be low.
5. Output leakage voltage should be very low.
6. A negligible frequency drift with time should exist.
7. The frequency calibration should be accurate and capable of being reset within close tolerances.
8. All the above characteristics should be independent of line voltage fluctuations both in amplitude and frequency.
9. The output sources should be of high and low impedances both balanced and unbalanced. They should be constant over the whole frequency range.
10. An accurately calibrated output level control is an advantage.

(b) Beat Frequency Oscillator. The beat frequency oscillator works upon the principle of mixing two signals of different frequencies (f_0 and f_1) and extracting the difference frequency (f_2). To give a variable frequency output one of the frequency sources (f_1) is made variable with a range of f_0 to $f_0 + f_{max}$; where f_{max} is the maximum frequency required from the output.

Hence, by varying f_1 over its range we get a difference frequency (f_2) variable from O c/s to f_{max} c/s; this range being indicated on a calibrated dial attached to the variable frequency control of f_1.

Calibration may be checked by noting on an indicating device (usually a magic eye tube) the output when the calibrated dial reads zero (that is, when $f_1 = f_0$). A trimmer attached to the f_1 circuit may be adjusted to give the desired condition at this point.

Q.7.—Describe the operation of an alternating current bridge suitable for the measurement of small inductances or capacities.

A. Description: An alternating current bridge of the type usually used for the measurement of small values of inductance or capacity takes the form of a simple Wheatstone Bridge with the following variations:

(a) The ratio arms are fixed and in some instruments are formed by the tapped secondary winding of a transformer.
(b) An alternating current source replaces the battery of the simple resistance bridge. A frequency of 1000 cycles per second is usual.
(c) The galvanometer is replaced by headphones, or by an amplifier detector unit tuned to 1000 cycles/sec. and offering both meter and headphone indications of balance.
(d) Highly accurate, stable and adjustable standard arms of inductance and capacity are provided. The range of values available in the standard arms covers the range of low values to be measured by the bridge.

Operation:

To measure the value of a small inductance or capacity, the component to be measured is connected to the "×" arm of the bridge while the standard arm is adjusted for balance. Balance is indicated by a "null" in the signal heard on the headphones or observed on the meter of the detector amplifier. If the frequency of the signal used with the bridge is constant the standard arm may be calibrated directly in micro micro farads or in micro henries. Similarly if equal ratio arms are used (a comparison bridge) the value of the unknown equals that of the standard at balance and direct reading is possible.

Q.8.—What performance would you expect from an outside broadcast amplifier used for broadcasting a programme from a hall remote from the main studio? Enumerate the main items of equipment which would be required for carrying out such a broadcast and indicate what tests should be carried out prior to the broadcast.

A. Performance

Frequency response: ∓ 1db 30 c/s—15 Kc/s.

Signal to noise ratio: 55 db for an input signal of −70 dbm.

Total harmonic distortion: 4% at max. power.

Maximum power output: + 21 db.

Maximum cross talk between channels: 60 db.

Equipment

4 channel outside broadcasting amplifier plus spare if necessary.

1 microphone complete with stand and cable for each position plus one spare of each type.

Intercommunication facilities from the outside broadcasting point to the studio, e.g., magneto telephone or microphone and amplifier depending on local conditions.

Headphones, power cable, etc.

Battery power supply and batteries if required.

Portable oscillator.

Tests:

1. equalise line,
2. test all pieces of equipment including cables and spares,
3. test by speaking and sending test programmes on both lines.

EXAMINATIONS Nos. 3819 and 3820 TECHNICIAN, TELEGRAPH MAINTENANCE

R. S. Butler.

Q.1.—Describe the construction and operation of the Model 14 Transmitter Distributor. (Teletype.)

A.—The Transmitter distributor is a motor driven device for converting code combinations (5 unit) perforated in a paper tape into electrical impulses and transmitting these impulses over a line. Except in special circumstances these signals will be single current, enabling direct operation into a Model 15 Teletype.

It consists basically of an electric motor (110 Volts A.C.) driving a vertical shaft through a felt clutch. To the upper end of this shaft is fitted a brush arm carrying 2 carbon brushes passing over a plateau of 2 concentric brass rings. The outer of these 2 rings is divided into 7 segments whilst the inner is solid. The brushes bridge together these 2 rings.

To the lower end of the shaft is fixed a cam which operates a lever riding on its periphery. This is known as the operating lever. This lever operates 5 contact levers and one feed lever.

These levers are held against the operating lever by spring tension, their design being as shown in Fig. I.

To the left hand end of the contact levers is fitted a contact tongue whilst the right hand end has a vertical needle attached to it.

The contact tongues move between Marking and Spacing contact bars mounted below and above the tongues respectively. Each tongue is insulated from its lever and is connected to its respective segments on the outer plateau ring.

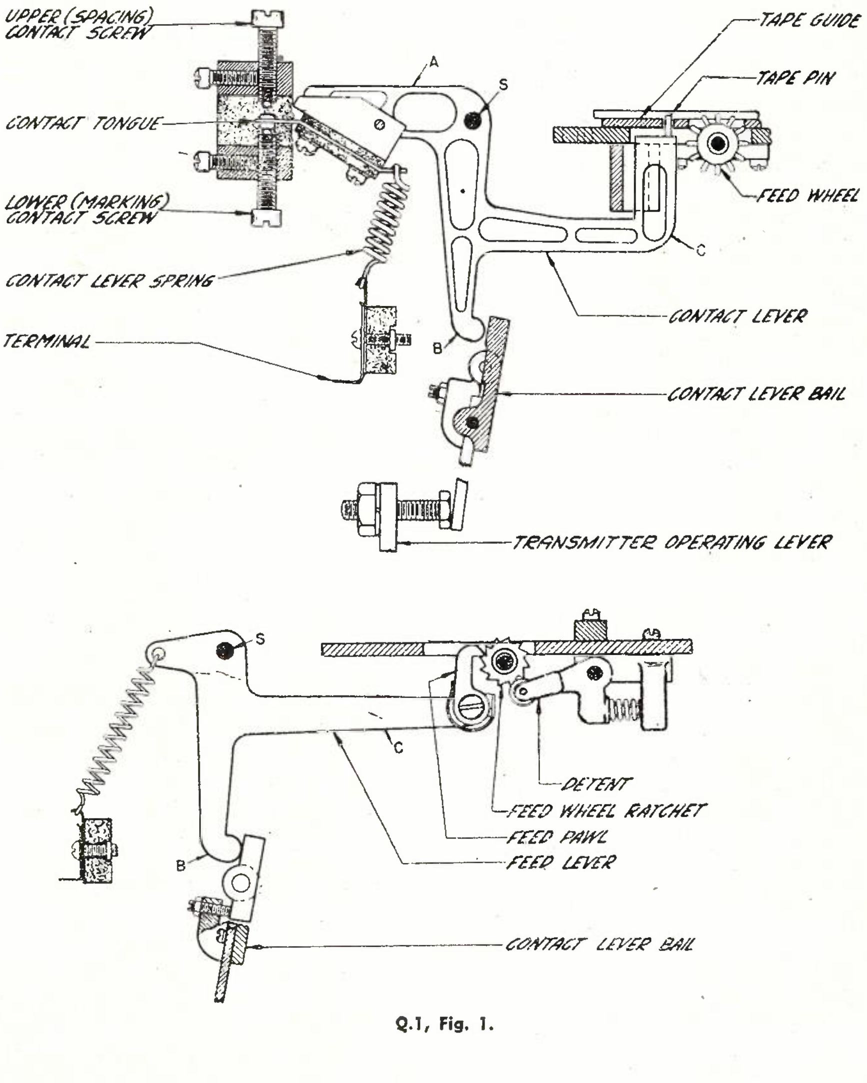
The feed lever is fitted with a pawl which engages with a feed ratchet on the tape feed shaft. A feed wheel on this shaft feeds the tape through the transmitter. A detent ensures evenness of tape feed.

A release is provided to permit the shaft to be driven from the motor as required. The armature of this magnet is in the path of a stop lug attached to the main shaft causing the clutches to slip. When energised the armature is attracted to the magnet and out of the path of the lug which will now revolve, driven by the motor through the clutches.

The motor speed is governed to 2308 R.P.M. by a centrifugal governor. Compensation is made for variations of motor speeds in the load and no-load conditions. A lever is provided to open the circuit to the release magnet should the tape to the transmitter become tight.

Operation. With the main shaft held at rest by the stop arm, the operating lever is resting on the peak of its cam, holding the needles out of the tape and the feed pawl at the bottom of its stroke. The contact tongues are resting on the Space contact bar and the brush arm and brushes are resting on the stop segment.

With the motor switched on power is provided to the release magnet control switch, which when closed operates



Q.1, Fig. 1.

the release magnet permitting the shaft to revolve. As the cam revolves the operating lever rides off the peak of its cam and the 5 contact levers and the feed lever rise under the influence of their springs. Should there be holes above any of the needles, the needles will pass through the holes, permitting the contact tongues to move to the Mark contact bar.

Where no hole is presented above the needle the upward movement of the needle is arrested, the controlling spring being of insufficient tension to force the needle through the tape. Due to this restricted movement of the levers concerned, their contact tongues do not move off the Space contact bar.

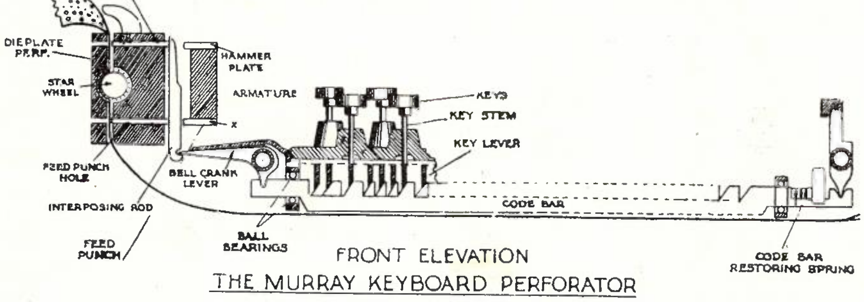
Simultaneously with this action, the feed lever has raised the feed pawl in readiness for it to feed the feed shaft one tooth when the feed lever and contact levers are withdrawn by the operating lever and cam.

This sequence of actions occur as the brushes are passing over the 'Start' segment (usually open) and now as the contact tongues are connected to their associated segments on the plateau, as the brushes pass over those segments to which a contact tongue on Mark is connected, the circuit is closed for the duration of that segment. If the contact tongue connected to the segment is on Space, the circuit will be opened for the duration of time as the brush passes over it. The brush arm takes 20 milli-seconds to pass over each segment, with the exception of the 'stop' segment which takes 28 milli-seconds to traverse.

In this manner a Start signal and 5 code signals are transmitted to the line in accordance with the code perforated on the tape.

As the brushes pass on to the Stop segment and complete the circuit again, the operating lever rides on to the peak of its cam, withdrawing the needles from the tape and then feeding the tape one hole.

When the release magnet is operated by the operation of the tight tape lever and tape stop switch (in series), the armature, besides controlling the starting and stopping of the shaft also opens a set of contacts which remove a short circuit from across a 20 ohm resistor in series with the motor. This slightly reduces the current to the motor, preventing it from gaining speed due to the removal of the load of the slipping clutches.



FRONT ELEVATION

THE MURRAY KEYBOARD PERFORATOR

Q.2, Fig. 1.

Q.2.—Describe the construction and operation of any keyboard perforator with which you are familiar. Name the perforator so described.

A.—The perforator to be described is the Murray keyboard perforator. This keyboard perforator employs five saw-toothed codebars mounted horizontally and parallel to each other on ball bearings. The codebars are spring loaded so that when in their normal position they are held to the right hand side of the keyboard.

Mounted between the 2nd and 3rd code bar is a bar of similar design, having uniform sawteeth cut upon its upper edge. This is known as the Universal bar.

Pivotally mounted above the codebars are the keybars, having knife shaped lower edges. Each keybar is depressed by its associated keystem mounted above it in the keydeck. The keybars are returned to their unoperated (upper) position by small coil springs mounted under the keybar.

The left hand end of the codebars are notched and a bellcrank is fitted into each codebar, the other end of the bellcrank fits into a vertical interposing rod, mounted in the punch-head of the perforator.

These interposing rods are mounted behind the punches and are the medium by which the punches are pushed through the tape by the punch hammer.

The movement of these rods is such that when a space is required for that particular element, the corresponding rod is pulled down by the codebar and bellcrank, from behind the punch. The stroke of the punch hammer is insufficient for it to strike the punch in question hence the punch is not forced through the tape.

If the element is mark, the rod is left behind the punch and the punch hammer will force the punch through the tape per medium of the interposing rod.

Fixed to the punch hammer is a feed pawl which engages with a feed ratchet on the feed shaft of the punch head. With every operation of the punch hammer the feed pawl operates the ratchet one tooth. On the same shaft as the ratchet is the feed wheel which feeds the tape through the punch head. To ensure evenness of tape feed a detent is provided on the feed shaft.

A backspace lever is also provided to enable the tape to be fed back through the head in the event of errors, enabling them to be erased or corrected.

There are 5 punches to conform to the 5 unit code, these are mounted horizontally in guides and are spring returned after being struck by the hammer. A smaller punch mounted beneath the code punches is struck by another hammer plate on the punch hammer lever to provide the centre line holes.

The universal bar, which operates with every depression of each key, terminates in a contact operating lever, which when operated by the depression of a key, closes a set of contacts, energising the punch magnet. A spark quench condenser is fitted across these contacts to prevent severe sparking, caused by the back e.m.f. of the magnet when the contacts are opened.

A letter counter is provided and operates with every operation of the punch hammer. It consists of a horizontally moving rack to which is fitted the pointer, the rack moves over a graduated scale. A feed pawl directly operated from the hammer operates the rack and it is held in its operated position by a retaining pawl.

As the rack is nearing the end of its horizontal movement it completes the circuit to a warning lamp via a set of contacts indicating to the operator that he is nearing the end of the line.

When 'Carriage Return' is depressed, apart from perforating the tape with the code for that function, an extension on the 'Car Ret' keybar disengages the feed and retaining pawls from the rack which returns to its starting point under the influence of its return spring.

Operation. Upon depression of a key, the keybar moves into the sawteeth of the codebars beneath it. Upon striking the sloping sides of the codebars in its path, those codebars which have teeth beneath the keybar are moved to the left, carrying with them their associated bellcranks. The bellcranks in turn pull down their interposing rods out of the path of the hammer. The universal bar operates closing the circuit to the punch magnet which operates the punch hammer. The hammer plate (attached to the punch hammer) strikes the back of the interposing rods not pulled down by the operation of the codebars and forces them and their associated punches forward, the punches passing through the tape and dieplates perforating the code for that letter. Simultaneously the centreline punch is operated to perforate another centreline hole.

Upon release of the depressed key the contacts are opened, and the magnet de-energises, allowing the punch hammer to return to normal under the influence of its restore spring, at the same time feeding the tape on one hole and the letter counter on one letter.

The codebars return to normal under the influence of their springs causing those interposing rods which were pulled down to rise to their normal or Marking positions.

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SPECIAL NOTICE

SIZE OF JOURNAL

In 1952 the subscription to the Telecommunication Journal was increased from 6/- per annum to 10/- per annum. Although substantial, this did not foresee the further major increases in costs which occurred subsequently. Notwithstanding the assistance of a subsidy from the Department, it has not been practicable to meet the increased cost of production and distribution from subscriptions to the Journal, and the Committee of the Postal Electrical Society of Victoria has given careful consideration to two courses of action:

(i) Increase the subscription rate,

(ii) Decrease the size of the Journal.

The decision has been made to decrease the size of the Journal and in this the Committee was influenced by the present difficulty being experienced by the Editors in obtaining an adequate supply of papers for publication.

It is planned that Issues, Vol. 9, No. 6 (February, 1954) to Vol. 10, No. 6 (February, 1956) inclusive, will be published in the reduced size of 32 pages in lieu of 48 pages. At the end of 1955 a review will be made in the light of the availability of papers, the costs of production and the desirability of an increased subscription rate.

The Committee of the Postal Electrical Society of Victoria and the Editors of the Journal regret the necessity for this action, but readers may rest assured that the earliest opportunity will be taken to restore the Journal to an issue of 48 pages.

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