RECURRENT - SURGE INVESTIGATIONS

A THESIS

FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

SUBMITTED BY

RONALD RUSSELL FINES, B.Sc.

THE ROYAL TECHNICAL COLLEGE, GLASGOW, JANUARY 1955

SUMMARY

This thesis concerns the design, construction and applications of two equipments, the Recurrent-Surge Oscillograph (R.S.O.), and the Recovery Voltage Indicator (R.V.I.) which rely on the recurrent injection of a suitable voltage or current waveform to an electrical network, and the oscillographic display of potentials across the whole or part of the network on a timebase synchronised to the injection waveform.

The R.S.O. is particularly useful in determining the voltage distribution in windings, especially transformer windings, when subjected to rapid rates-of-rise of voltage such as occur on transmission lines under fault conditions. Whereas the natural phenomena are of considerable magnitude and occurring at random, the instrument described generates typical surge waveforms of low amplitude ($<$ 1000 volts) repetitively at fifty times per second, so that resulting stresses may be investigated at will and without fear of damage to the winding. The equipment may also be used as a high-speed oscillograph for the recording of repetitive transient phenomena, a special feature being the time resolution afforded, of the order of ten millimicroseconds, during the period immediately following timebase triggering. Tests may also be made

to determine the characteristics (and certain faults to earth) of cables using reflected pulse techniques.

The R.V.I. is used to inject a current repetitively, again at fifty times per second, into an electrical system which ideally may be a uniform transmission line, but in practice consists more often of an inter-connection of cables, reactors and transformers. The injected current is of half-sine-wave form and represents the last half-cycle of line current (often a heavy fault current) before circuit breaker contacts open ideally, and the current ceases. Again the injected quantity is small (milliamperes) compared with the typical practical quantity (up to thousands of amperes), and the resultant recovery voltage across the circuit breaker contacts, which in the case of miniature simulation are represented by anode and cathode of a valve, is correspondingly small compared with the abnormally high potentials which may cause restriking of an arc between contacts in practice. These recovery voltages are due to the stored energy in the system at the time of rupture of current, and theoretical prediction of their severity is considered in various appendices.

Part 1 of the thesis refers particularly to the R.S.O., and Part 2 to the R.V.I.

RECURRENT - SURGE INVESTIGATIONS

CONTENTS

Page

PART 2: The Recovery Voltage Indicator

AUTHOR'S NOTES:

Especially in the chapters on Historical Surveys, use of the present tense has in some instances been made purposely to impart an air of freshness to the work of the past few years, that is roughly during the time when investigations were proceeding.

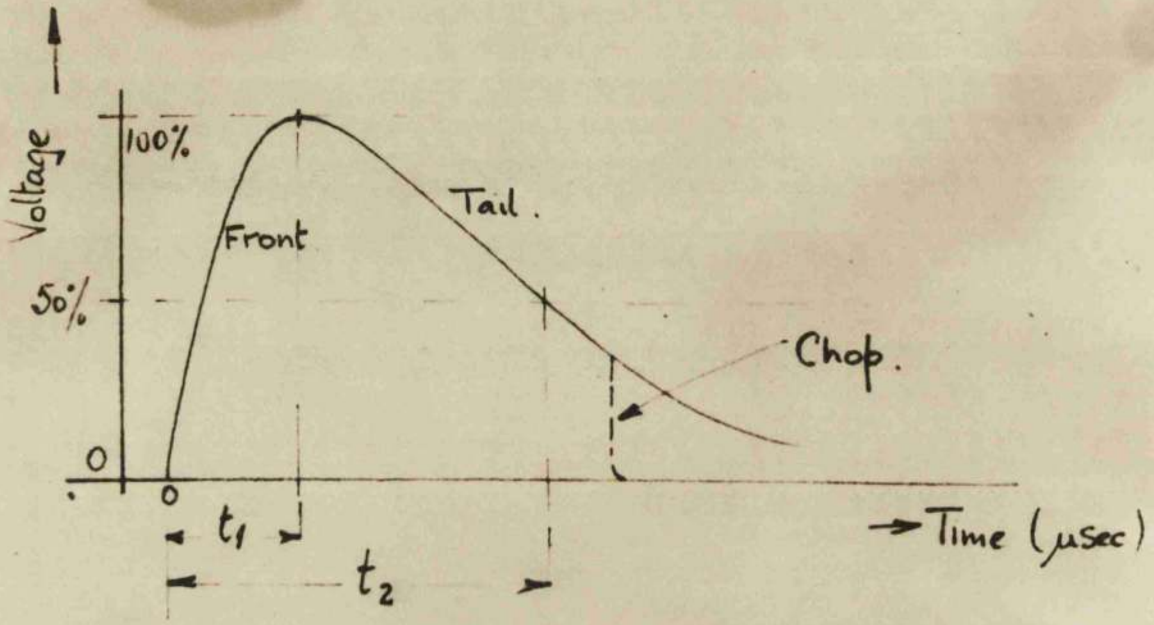
Due to the large number of oscillograms associated with Part 1, it has been considered desirable to enter them at appropriate places in the text (as has been done with all figures) for ease of reference. In Part 2, the limited number of oscillograms have been collected to form Appendix "D".

Figures will normally be found facing the page of text where reference to the figure first occurs.

PART 1

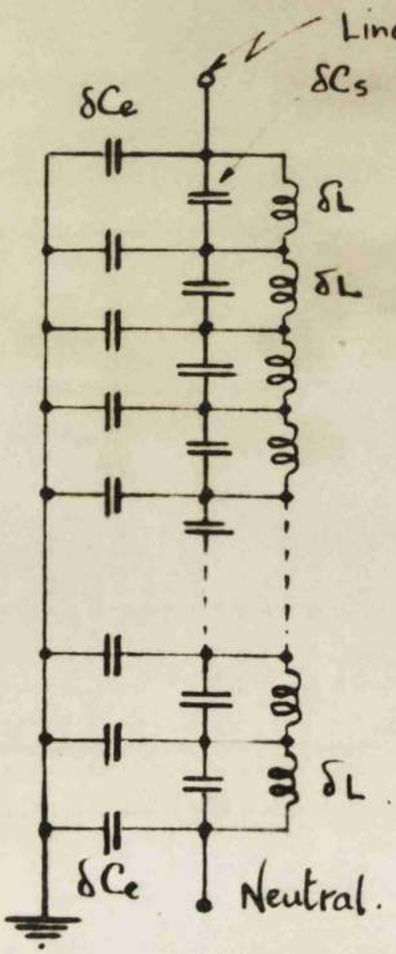
RECURRENT - SURGE OSCILLOGRAPH

LIST OF FIGURES



Wave shape specified as t_1/t_2 microseconds.

Fig 1.1 Standard form of test waveshape



δL = effective inductance per coil.

δC_s = series capacitance between coils

δC_e = capacitance to earth from each coil.

n = number of coils.

$$C_s = \frac{\delta C_s}{n-1}$$

$$C_e = n\,\delta C_e.$$

Fig. 1.2 Equivalent Circuit of a Uniform Winding.

PART 1. THE RECURRENT SURGE OSCILLOGRAPH

Chapter 1

An Introduction to the Problems and Applications

The Recurrent Surge Oscillograph (R.S.O.) is an instrument for generating impulse waveforms of some desired shape, and displaying the results of applying such waveforms to networks. The waveforms are normally the standard test waveforms as defined by the International Electrotechnical Commission (see Fig.1.1), i.e. the 1/5 and 1/50 waves, though many other variants have been used. The associated oscillograph should be capable of displaying the whole or part of such waveforms, preferably on a linear time base and repetitively (to give a steady trace for direct observation) at a frequency corresponding to that of the impulse repetition rate.

Impulse Testing of transformer windings has been common practice for many years, the object being to subject the winding to stresses in excess of those which would normally occur in practice due to lightning striking a transmission line, switching, or some other fault condition. Fundamentally the transformer winding may be represented as in Fig. 1.2 by an inductance having distributed capacitance to earth, and capacitance between successive turns. These capacitances are small and have negligible effects at power frequencies, but become all important when the initial voltage distribution in a winding subjected to a high rate-of-rise of voltage is considered. For a rectangular waveform (unit function) applied to the winding, the initial voltage distribution will be determined solely by the winding capacitances, with the result that a large proportion of the applied voltage appears across the first few turns from the line end of the winding. Subsequently, the inductances and resistances of the winding must be considered during the oscillatory transition period before a uniform voltage distribution is obtained. At any point in the winding therefore, decaying oscillations of a fundamental plus other (often harmonic) frequencies occur which may result in over-stressing the main insulation of the winding. So far, the effects of a rectangular wave applied to a simple uniform winding have been mentioned, but in practice the rate-of-rise is not infinite, the winding may not be uniform, there may be coupled windings, and the impulse may not appear directly across the winding but in series with some other impedance, for example, an inductive neutral-to-earth connection.

Two points emerge: firstly, a rigorous mathematical treatment becomes very laborious if not almost impossible with the result that experimental investigation gives a quicker and possibly more accurate solution; secondly, that as long as linear circuit elements are considered, the use of high voltage tests are unnecessary, for the same phenomena may be observed with a waveform whose amplitude is but a small fraction of the typical practical value. This should not be taken to infer that an approximate mathematical solution is difficult or useless, or that such complete satisfaction is obtained as when a winding successfully withstands a high voltage test.

With the extension of impulse testing to machine windings, cables and other networks, and the investigation of faults and irregularities in transmission lines by reflected pulse techniques, the usefulness of a mobile apparatus generating miniature test impulses and displaying the results will be appreciated. The idea is not new, having been used by various workers 103, 104, 105, 108, 109, 110, 111 in many parts of the world for the last twenty years. This present work concerns the design, construction and application of a Recurrent Surge Oscillograph, incorporating the refinements of a modern equipment, for the Royal Technical College, Glasgow.

Versatility has been kept in mind, and in addition to producing smooth waveshapes in the normally desired range, a pulse generator having a low impedance output and an oscillograph capable of displaying very high writing speeds have been specified.

The problems involved in the design of such apparatus are not very apparent. Firstly, for a steady repetitive display, the time of triggering of the impulse generator with respect to the timebase must be constant and accurate, especially when it is desired to display an impulse rise-time of 0.1 microsecond on a 0.5 microsecond time sweep; and further, very few thyratrons have a rate-of-rise of current characteristic to permit such a fast impulse front. Secondly, stray wiring inductances and capacitances, and inter-circuit coupling, may produce unwanted oscillations or distortion of the desired waveshape, especially considering the component frequencies of certain wave shapes. Thirdly, the conventional high-voltage cathode ray tube necessary for obtaining a sufficiently bright and fine trace at high writing speeds has intrisically low deflection sensitivities, so requiring a very high speed repetitive timebase producing an equivalent peak-to-peak sawtooth voltage of nearly 2000 volts. Fourthly, in order to reduce fogging of the cathode ray tube screen and to eliminate initial spot halation due to the relatively long inter-impulse periods, beam modulation for predetermined and precise time periods must be provided; also a means must be found of accurately calibrating vertical deflection (in volts) and horizontal deflection (in millimicroseconds or microseconds). Fifthly and lastly, the construction must allow all necessary changes in circuits to be made quickly, and provide facilities for modifying the existing circuits easily for special research purposes.

The individual applications present further problems, though relatively small compared with those of the main equipment. These include tests on various types of winding, the tapping of waveforms from points on the winding, and the simulation of static-end-ring conditions and protective schemes. In the case of cable pulse-testing, matching must be considered, and for impulse testing of machine windings, the question of removing the rotor or armature for experiment.

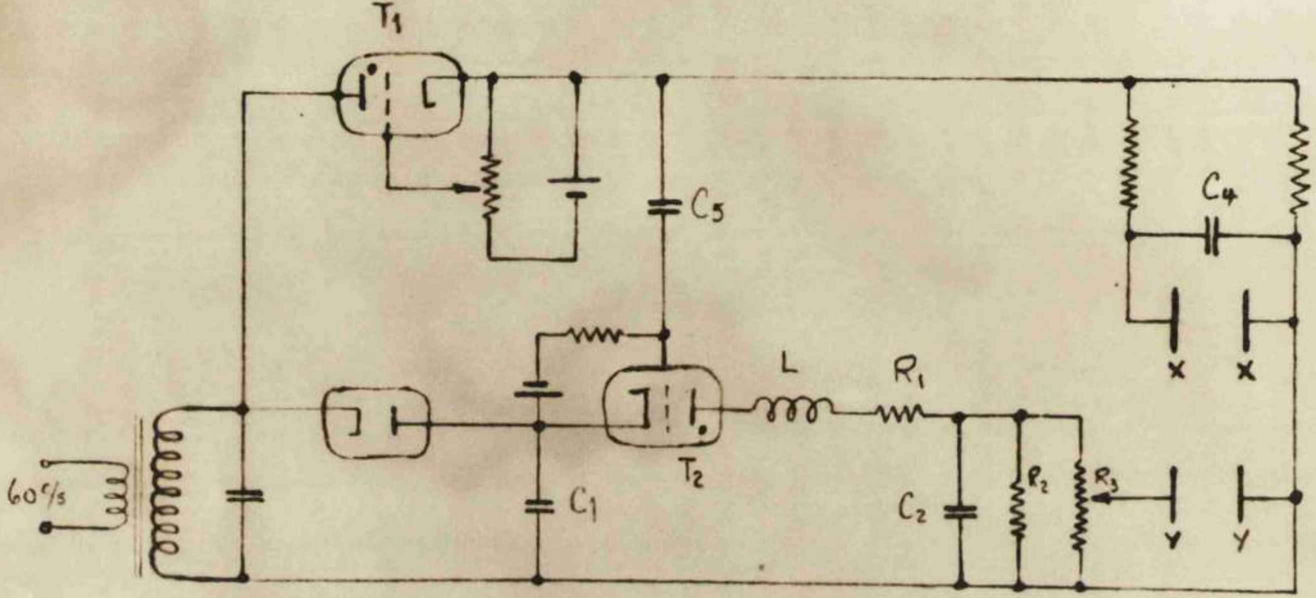


Fig 2.1 Circuit diagram of Rohats' Oscillograph Electric Transient Analyzer

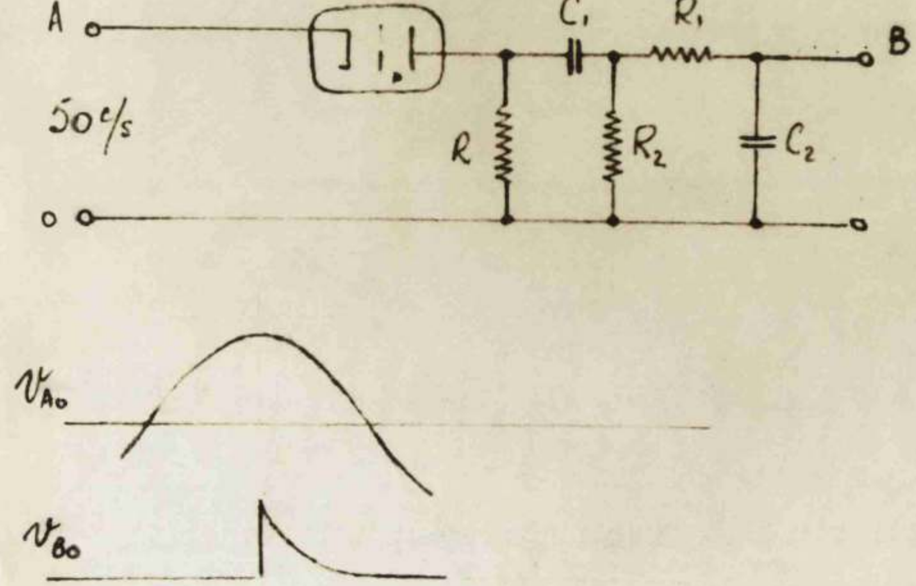


Fig. 2.2 Wilkinson's circuit for the generation of Impulses from cosine-form voltages

Chapter 2

An Historical Survey

Recurrent - Surge Oscillographs and Associated Circuits:

In 1924, Turner (Trans. A.I.E.E. 43, p.805) described a technique for superimposing images of transients, using a vibrating-mirror oscillograph and a rotating contact system, so that observation and recording of the images was facilitated. Such an equipment has distinct limitations in practice, and the development of the cathode ray tube in the 'thirties made available a vastly superior method of display.

It was not until 1936 however that papers on Recurrent-Surge Oscillographs using high-vacuum sealed-off cathode ray tubes appeared, one by Rohats(103) of the General Electric Company of America and one by Wilkinson of the British Thomson-Houston Company (B.T.H. Activities 12, p.64, 1936). Rohats(103) used a simple circuit (Fig. 2.1) in which negative half-cycles from the transformer secondary charged the capacitor C_1 through the rectifier diode. The thyratron T_1 was biased so that striking occurred only at the crest of the positive-going half-cycle from the transformer secondary after which the charging of capacitor C_4 provided a time-sweep potential to the X deflection plates. Simultaneously with the start of the time-sweep, a positive-going waveform coupled to the grid of thyratron T_2 through capacitor C_5 "fired" this thyratron and discharged capacitor C_1 through the remainder of the wave-shaping circuit L, C_2, R_1, R_2 and R_3. The full output across capacitor C_2 could then be applied to the transformer winding or other network under test. To provide a calibrating oscillation, Rohats loosely coupled a "wavemeter", presumably a parallel tuned circuit with suitably calibrated variable elements, to the inductance L of the waveshaping circuit and observed the resultant decaying oscillation from the wavemeter on the oscillograph. This "Electric Transient Analyzer" was used for the surge analysis of machine and transformer windings and for demonstrating the effect of terminating impedance on reflections of impulse waves in lines or cables.

Though Wilkinson published a paper on his instrument in 1936, the more classical paper(110) did not appear till early in 1938. Whereas Rohats(103) had used a thyratron as a switch to discharge a capacitor through a waveshaping circuit during a convenient half-cycle, Wilkinson(110) suggested the use of the thyratron for the sudden

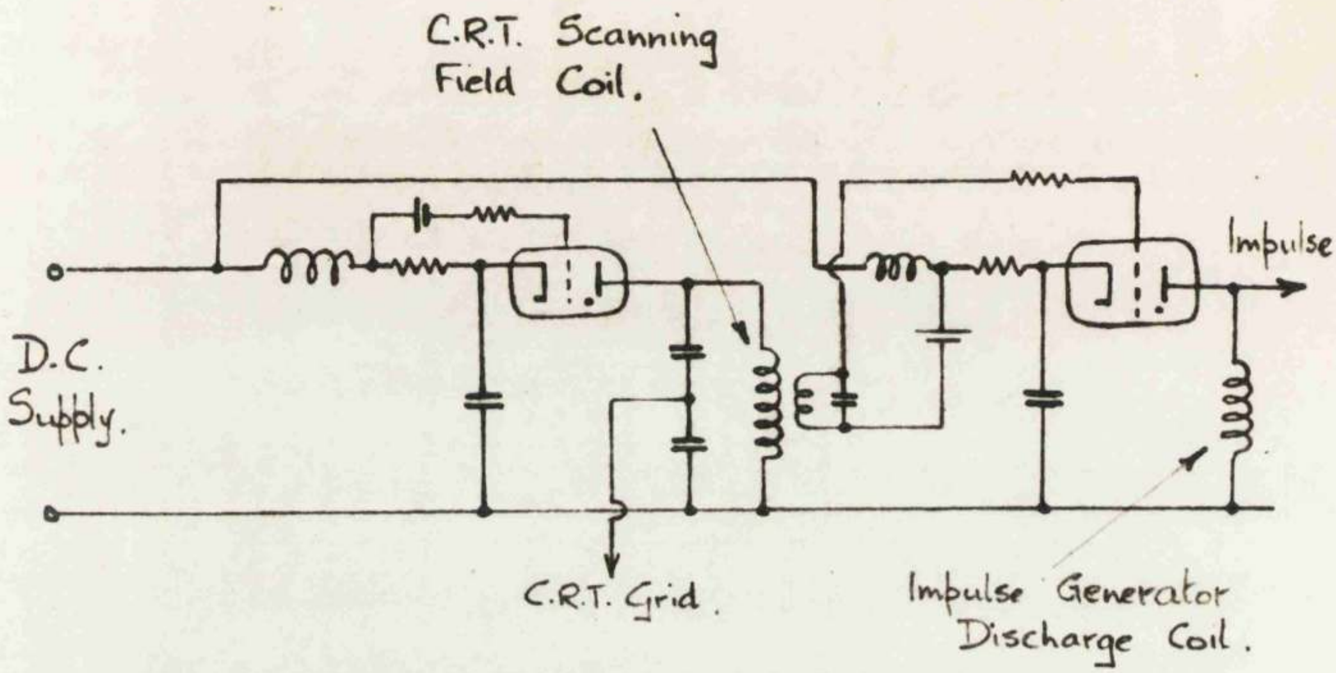


Fig. 2.3. Wilkinson's circuit for electromagnetic scanning, and for synchronized impulse generation at recurrence frequencies about 1000 c/s.

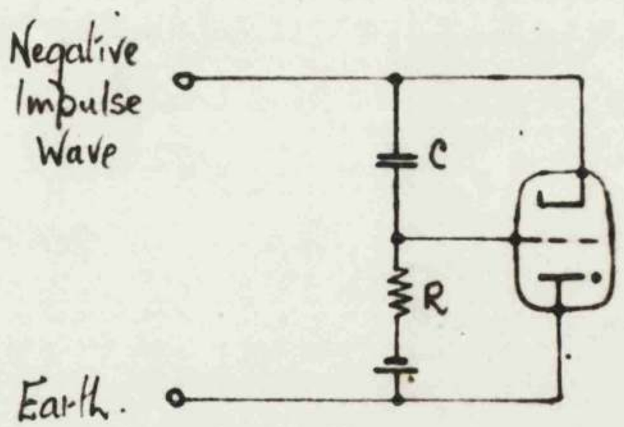
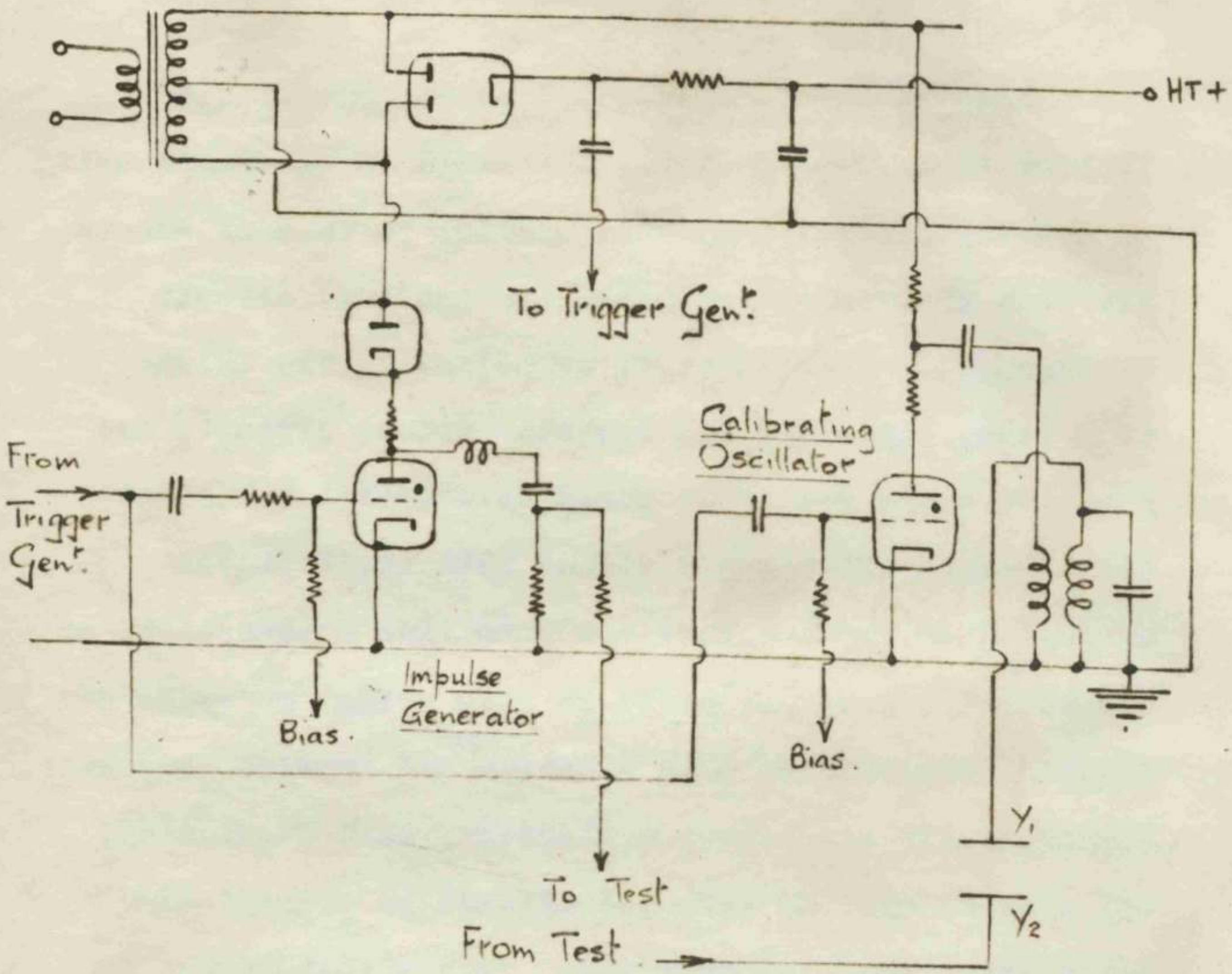


Fig. 2.4 Scoles' Circuit for producing chopped waves.

application of a sinusoidal waveform from the mains at voltage maxima, i.e. a cosine-form (equals 0 at t < 0) followed by a suitable waveshaping network (Fig. 2.2). The advantage of this latter method is in dispensing with the charging rectifier. Both Rohats and Wilkinson had used the mains frequency (60 c/s and 50 c/s respectively) as their repetition frequency source, but by 1938 Wilkinson had developed a circuit operating from a D.C. source having a repetition frequency of about 1000 c/s so giving a brighter trace at higher writing speeds (Fig. 2.3). Wilkinson used electromagnetic deflection for the timesweep, biasing coils for X-shift, and directly coupled oscillatory circuits to provide a timing oscillation. Cathode ray tube beam modulation was introduced to suppress the spot during the relatively long idle periods, a fraction of the potential across the time-sweep coils being applied to the cathode ray tube cathode for this purpose. As regards superimposition of successive traces, a constancy of image position of only 0.5 microsecond was claimed, while impulse wavefront times of 0.1 microsecond were not unusual. One further feature of Wilkinson's later instrument was its application to circuit interruption problems, i.e. as a Recovery Voltage Indicator (R.V.I.). (See Part 2).

Also in 1938, Scoles(105) of the Metropolitan-Vickers Electrical Co.Ltd., described an equipment using an impulse generator circuit similar to that of Rohats, but with an original tripping (triggering) circuit arrangement. Effectively, by adjusting the balance of a neon, capacitor and resistor bridge circuit, two positive peaks per cycle could be obtained to actuate the timebase 100 times a second with the Y-plates producing an impulse wave and zero line alternately, or one positive peak per cycle to give normal 50 cycle per second repetition of both timebase and impulse generator. Electrostatic time-sweep deflection, beam modulation, and a shock excited resonant circuit to provide time calibration were incorporated. A new feature was an additional circuit for producing chopped impulse waves, using a charging network and a thyratron (Fig. 2.4), to simulate breakdown of insulation at the crest or on the tail of the impulse waveform, and so producing a waveform having a very high rate-of-change of potential.

In 1942 Rohats produced a paper(104) written, partly it would seem for the layman, in which he described a more compact and finished instrument. Fundamentally, there was nothing new except that he used a thyratron push-pull timebase and beam modulation.



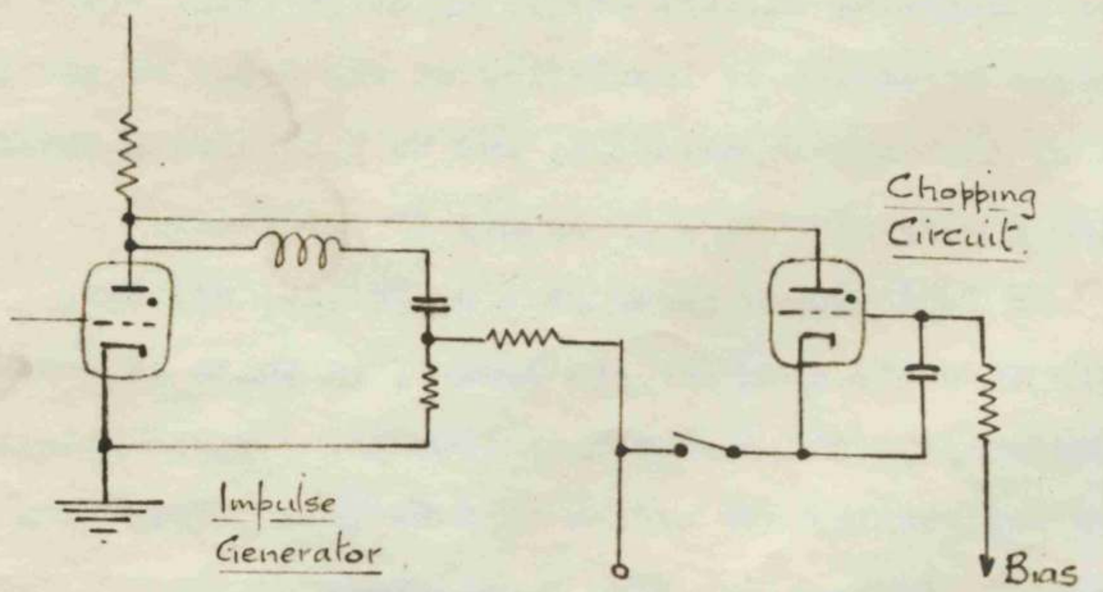


Fig. 2.5 Circuits for White's R.S.O. (1943)

About the same time, White(108) of the E.R.A.* was developing a new high-speed R.S.O., which was to be the basis of several constructed in this country during the subsequent decade. White used a poorly smoothed full-wave rectifier the output from which gave 100 unidirectional pulses per second, which in turn "fired" a simple triggering circuit (Fig. 2.5). The timebase was of a push-pull variety in which capacitors were charged relatively slowly (flyback) from positive and negative D.C. supplies, and discharged more rapidly through two thyratron switch circuits tripped 100 times a second. The impulse generator and timing oscillator circuits were tripped alternately, each 50 times a second, the common 100 c/s tripping pulse being effective only when the respective thyratron anode was positive with respect to its cathode. A slightly different chopping circuit was used so that the impulse generator valve did not have to carry an additional current due to the chopping thyratron. White's R.S.O. was also designed to display externally generated transients, and to give single-stroke operation of the timebase as a result of a positive trip signal also from the external source; in such cases, a 0.8 microsecond cable was to be inserted to delay

---

* British Electrical and Allied Industries Research Association.

the arrival of the transient phenomenon at the deflection plates.

The circuit of D'Heckenbrugge(112) added little to the techniques already described, except perhaps the (rather crude) use of a high-voltage A.C. cathode ray tube supply so that the beam was effectively "on" only during negative half-cycles at the cathode.

In 1949, White and Nethercot(109) of the E.R.A. published a comprehensive paper on the most recent developments of the E.R.A. Recurrent-Surge Oscillograph. This paper and the subsequent discussion may be acknowledged as the most recent survey published on the technique, and give several indications of design trends and applications. White and Nethercot emphasize the need for a balanced time-sweep circuit in order to avoid undue distortion and astigmatism especially when highly unsymmetrical potentials are applied to the vertical deflection plates. The performance of their cathode ray tube was improved by using rectangular modulating pulses instead of the exponential forms which appear to have been acceptable to previous designers, and by using a hard valve timebase so eliminating a possible cause of trace jitter due to mercury-vapour thyratrons. Judging by comments of many authors and contributors to discussion

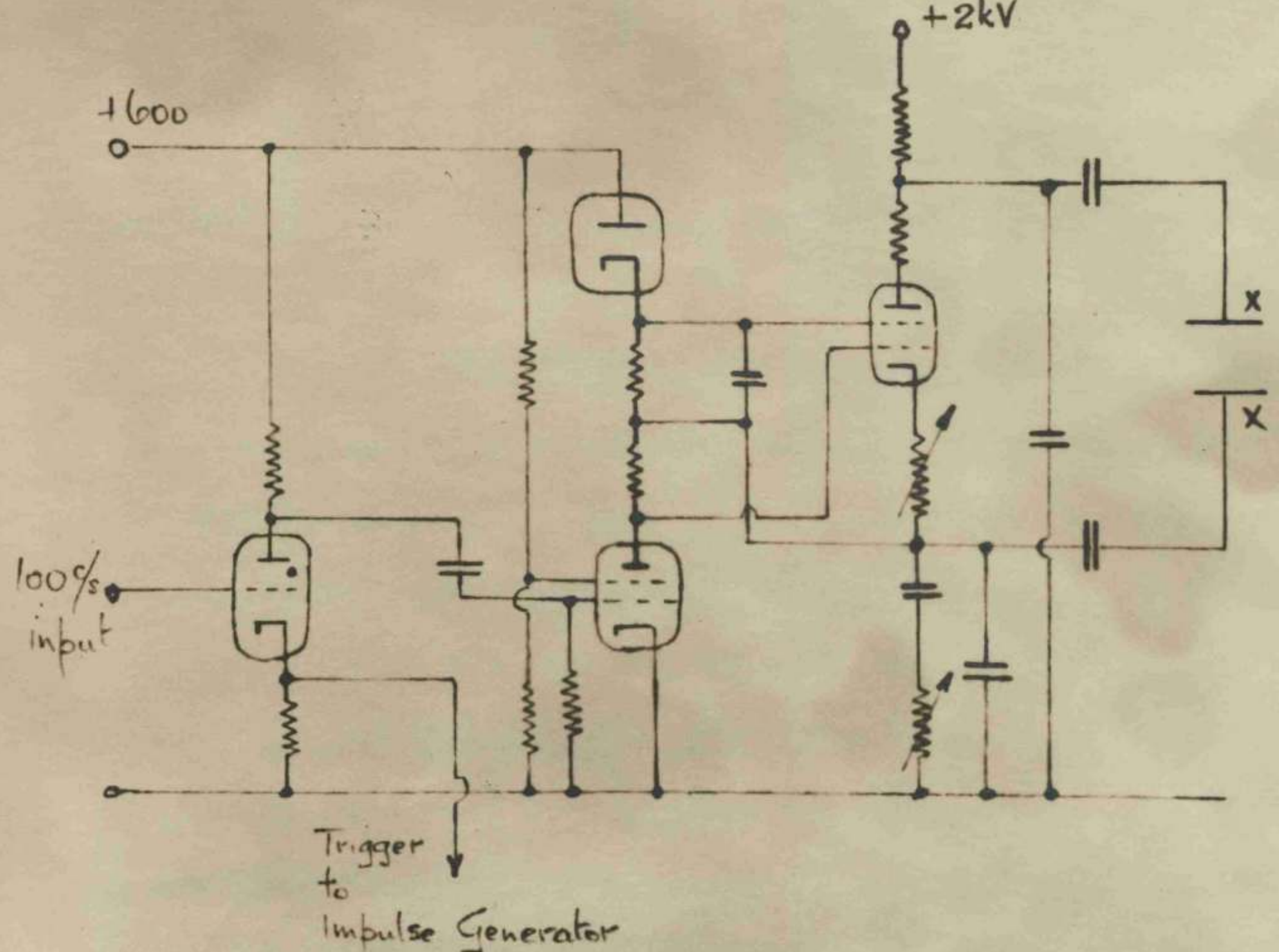


Fig. 2.6 Timebase of White and Nethercot's R.S.O. (1949)

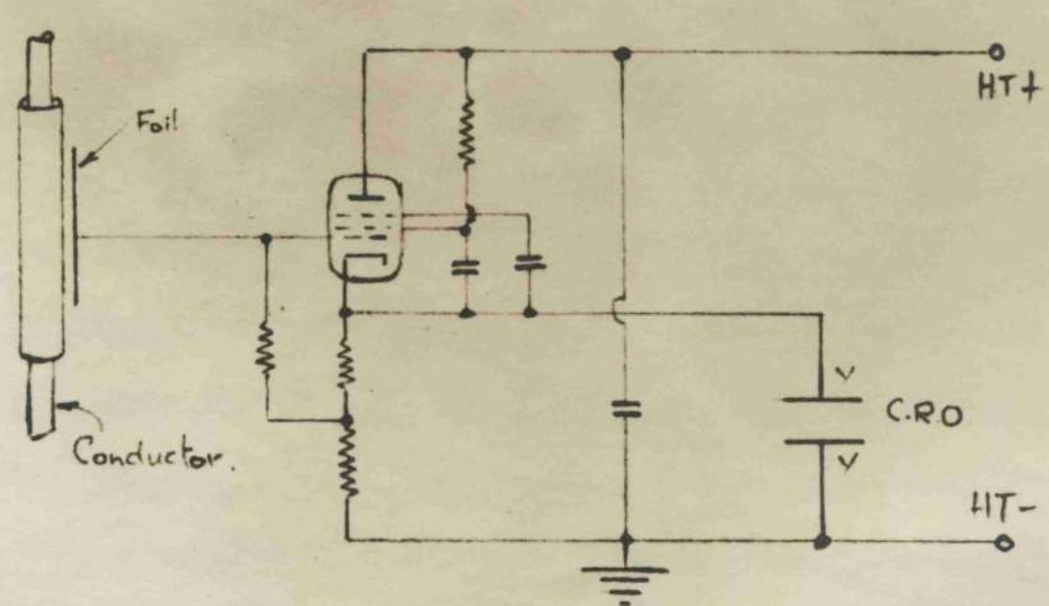


Fig. 2.7. Robinson and Gray's Capacitance tapping and Cathode-follower circuit.

through the years, trace jitter was one of the most virulent problems of the technique.

The current E.R.A. instrument (109) used much the same arrangements for the timing oscillator and impulse generator as mentioned previously(108), the outputs being applied to each of the deflection plates, it being accepted that the other plate was at earth potential during a particular function and vice-versa. The timebase (Fig. 2.6) employed the discharge of one capacitor to charge another in a circuit containing a hard valve (electronic switch) of high A.C. resistance and gave a reasonably linear sweep waveform having durations of 0.5 to 250 microseconds. The use of the hydrogen-filled thyratron in generating impulse wavefronts shorter than 10^{-7} second was forecast and indeed had been experimentally included, and for even high wavefront speeds (c. 0.03 μsec.) triggered spark-gaps had been successfully utilized. An additional external feature was the development of a generator for investigating the reaction of a transformer to the type of relaxation oscillation voltage which sometimes arises between contacts of a circuit breaker on breaking an inductive circuit: this comprised eight thyratrons having inter-valve RC timing circuits so as to produce a form of saw-tooth voltage which under certain conditions could cause the build up of forced oscillations in a winding followed by free oscillations decaying exponentially after the saw-tooth had ceased; so far as is known, the incidence of suitable critical conditions in practice is still unassessed.

In the discussion on White and Nethercot's paper, Wilkinson, who pioneered the R.S.O. in Great Britain said: "If the recurrent-surge oscillograph is like a tutor with whom problems can be discussed, the single-record oscillograph is to be compared with a system of correspondence by field postcard". Bowdler commented on the use of screened or unscreened leads from the R.S.O. to the transformer, finding screening unnecessary when the connecting leads were kept short. Perry and Page mentioned the possibility of the impulse wave shock-exciting the timing oscillator, and resulting in the superimposition of low amplitude oscillations on the record trace, but the authors discounted this. Hammarlund (Sweden) considered that the importance of impulse wave-front times shorter than 0.5 microsecond should not be over-estimated, but this did not necessarily apply to transition times of chopping on the wave-tail. Hammarlund also stressed the need of care with leads, but suggested that errors using unscreened leads were quite small at least for routine tests with 1/50 waves; also for routine work, tests of transformer windings in air instead of oil gave sufficient accuracy. Page described an equipment having a maximum timebase speed of 0.5 microsecond and minimum impulse wavefront times of 0.05 microsecond, observing that hydrogen thyratrons seemed the ideal switch for impulse generators, and satisfactory in timebases if spurious oscillations at the higher speeds were not encountered. In measuring inter-turn voltages, Clarke suggested that the impulse generator and transformer be allowed to take up any potential, and that an earth be applied at one of the tappings considered, so as to avoid defocussing effects due to highly asymmetric voltages (Wilkinson had earlier suggested insulating the core and tank of a transformer from earth, applying the impulses to the (normally earthed) tank, and earthing the line terminal so that inter-turn voltages at the line end would be less asymmetrical). Buttrey and Wilkinson both raised the question of the transformer winding behaving linearly during the first several hundred microseconds, and White and Nethercot agreed that while the iron core of a transformer will carry magnetic flux during this period, the leakage path is in air very largely, whether or not the transformer windings are effectively open-circuited,

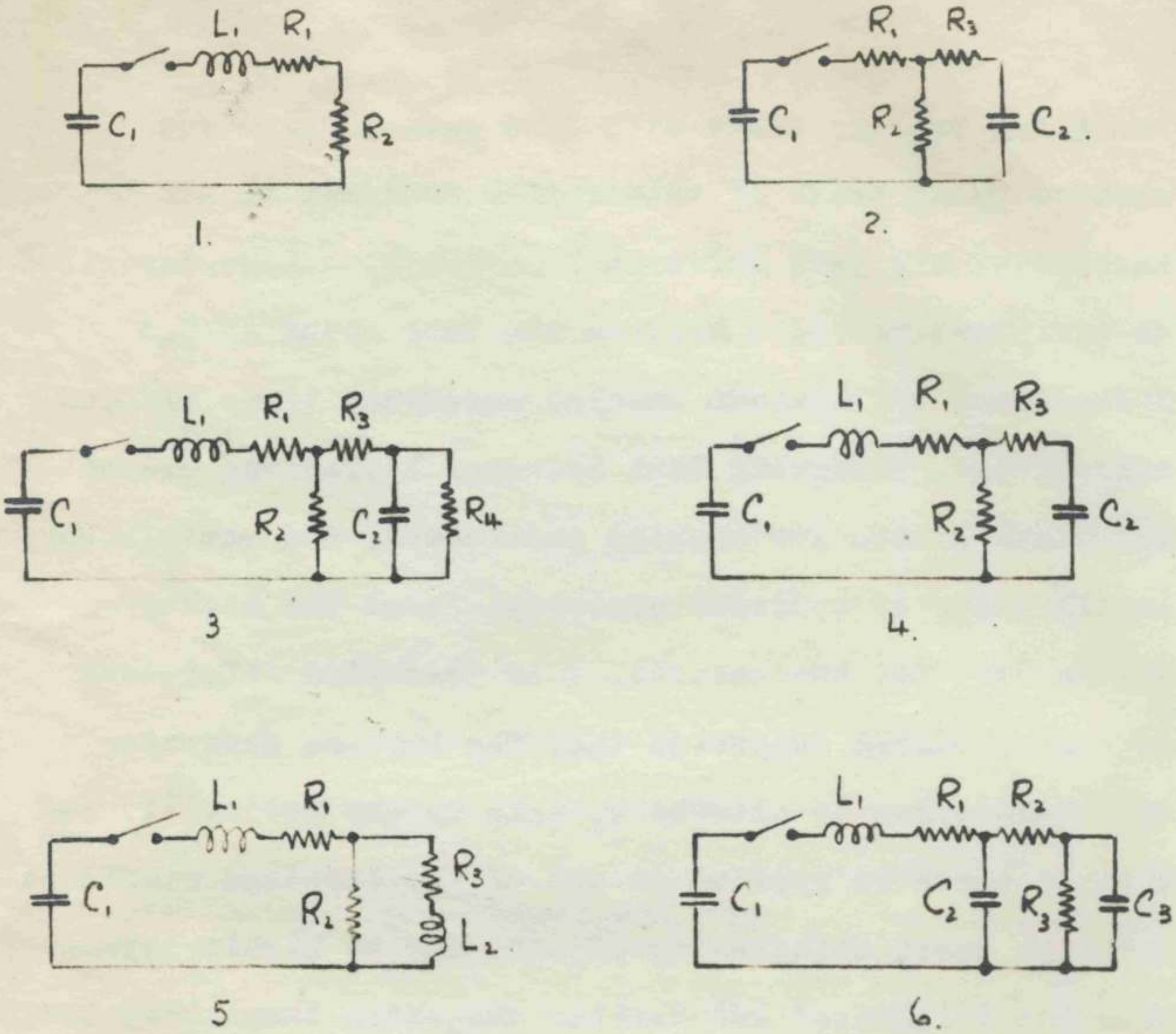


Fig. 2.8. Some of the Impulse Generator Circuits for which formulae concerning waveshaping were given by Thomason (1934).

that variations in the reluctance of the iron circuit would be negligible, and that low flux-density and eddy-currents substantiate the presumption of linearity. At that time the authors of the paper did not know of any method of tapping an existing transformer without piercing the insulation; however, in 1953 Robinson and Gray(102) described a suitable method using a capacitive coupling to some metal foil wrapped round a conductor and a cathode follower circuit between the "pick-up" and the oscillograph plates (Fig. 2.7).

The subject of waveshaping to obtain impulses of the various standard forms was treated by various authors, one of the earliest being Thomason(102) who in 1934 published a fairly complete set of formulae for the solution of the more common circuits (Fig. 2.8). The analysis of some of the circuits suggested would be rather tedious, and it is not surprising that Thomason confined his comparisons to the simplest circuits. Nevertheless he did show effectively the results of varying the parameters of circuits on the waveshapes. Later, in 1937, Thomason produced a series of charts(107), for two particular circuits recommended as basic by the International Electrotechnical Commission, so that circuit constants could be easily selected. A further paper(101) by Eaton and Gebelein in 1940 presented a series of graphs from which circuit parameters to give a particular waveform might be determined; in this paper three of the most common circuit arrangements were considered including the one(2b) used by the present author.

Oscillography:

Progress in oscillography and in high-speed recording in particular, from the early instruments of Dufour, Wood, and Rogowski was traced in a paper presented in 1935 by Miller and Robinson(204). For high speed recording, continuously pumped tubes with very high accelerating potentials were the rule and (in Germany) recording speeds of the order of one fifth of the velocity of light were reported. Hot and cold cathode structures were in use, and gas focussing common, with magnetic focussing and (even more so) electrostatic focussing considered as interesting novelties. Sealed-off tubes were not mentioned in this paper except in regard to their considerable inferiority. Post-deflection acceleration systems were used as early as 1928.

From 1935 onwards, the development of the high-vacuum sealed-off tube proceeded rapidly. Rohats(103), Wilkinson(110), McGillewie(210) and others described equipments for recording recurrent or single-stroke transients using sealed-off tubes with final accelerating potentials of up to 5kV. Forrest(203) in a 1943 paper quoted a classification of oscillographs in three categories: (a) the continuously evaucated type having a final anode voltage of about 50kV and writing speeds up to 50,000 Km/sec; (b) high-vacuum sealed-off tube type having final anode voltages of about 5kV; and (c) the lower voltage types, also sealed-off, with final anode voltages not exceeding 2kV. By this time therefore, the high-voltage high-vacuum sealed-off tube was established as a practical tool and research into screen phosphors and construction techniques led to such developments (1948-50) as the 908 BCC and 1608 BCCA tubes (G.E.C. Ltd.) having effective writing speeds of 3000 and 20,000 km/sec respectively with appropriate optical arrangements.

Many of the wartime developments are described in the book "Cathode Ray Tube Displays"(1) and in a paper by Bartlett and Davies(201) on the design of high-speed oscillographs. This latter paper discusses succinctly the problems of high-speed oscillography such as trace brightness with timesweeps of the 1μsec order and low repetition frequencies. The cathode ray tube screen may receive energy only for about 0.05% of the total time and this may be countered by increasing the beam current with degradation of focus, or by increasing the final anode accelerating voltage with consequent loss of deflection sensitivity. Post-deflection-acceleration cathode ray tubes as considered by White(209) have been designed to overcome this last problem but although available in the United States for a number of years now, these have been slow to gain popularity in this country, as the accelerator rings can act as a lens distorting the image and reducing the effective screen area. Further, beam modulation is essential in high-speed oscillography since otherwise the normally long periods when the spot is stationary would cause intense light to be produced at one point with consequent general illumination, lack of contrast, and damage to the screen. If the timebase and modulation pulse are initiated simultaneously then there is an inherent delay, typically about 0.005 μ sec, before the trace comes up to the desired brightness. The effect of such modulation on focus should be small. Bartlett and Davies(201) also discussed the deflection arrangements with particular reference to design for minimum input capacitances and lead inductances by bringing connections to the deflection plates directly out through side arms instead of by long leads and base contacts, small plate separation and long plate length to obtain high sensitivity without "shadowing" effects, avoidance of transit time effects, and minimizing "crosstalk" by screening the pairs of X and Y plates from each other and by equalizing the plate-to-earth impedances. Screen phosphors having a high resistance to electron burn, and giving a highly actinic blue colour with negligible afterglow (less than 1 μsec) were recommended for high-voltage tubes and photographic recording of the trace.

A desirable feature of high-speed (and other) oscillographs is simple calibration facilities. Calibration of the vertical or Y-deflection is easily accomplished by measuring, on a suitable voltmeter, the difference in shift potentials corresponding to the movement of the desired ordinate through a chosen point. Time calibration is more difficult, and for a repetitive timebase, it is necessary at least to shock excite a tuned circuit of known frequency and small decrement repetitively also. A continuously running oscillator is never used due to the difficulty of locking together the calibration frequency and the timebase repetition frequency. Bartlett and Davies(201) considered it difficult to shock excite a tuned circuit or produce time markers (reflections from a pulsed interminated line) for frequencies much above 10 Mc/s.

During the last decade a number of papers have been published(202, 205, 208, 211) concerning the recording of single-stroke transients. Compared with repetitive transient display, the technique is very similar except that writing speed and photography are more exacting requirements, while timebase design (due to the long recovery times permissible) and calibration oscillators (which may be of the continuously-running type) are simpler. In the three British papers(202, 205, 211) the cathode ray tube employed was the G.E.C. type 908 BCC having a final anode accelerating potential of 10kV. Maximum timebase speeds vary from 1 microsecond (White 208) to 10 millimicroseconds(Hardy 211), this latter figure being about the limit for the cathode ray tube even with special attention to photographic details. Rohats(207), and Prime and Ravenhill(206) have described equipments which could be used for single-stroke or repetitive operation, the latter equipment(206) using a hydrogen thyratron timebase having a minimum sweep time of 100 millimicroseconds. In all these papers, the general principles as mentioned by Bartlett and Davies have been accepted viz. a push-pull timebase, beam modulation, short leads and low input capacitances, and negligible trace jitter in repetitive cases.

Timebase Circuits for high-speed oscillography require particular consideration. The use of high-voltage oscillograph tubes, with consequent low deflection sensitivities, requires timebase waveforms of large amplitude, often as much as 1600 volts (800 volts amplitude for each phase of the balanced input). Further, obtaining a push-pull signal often necessitates an inverting amplifier, and either this valve or the timebase generator valve itself will carry a high quiescent current. The push-pull waveforms should be carefully balanced, and although 5 to 10 per cent unbalance is permissible with low voltage timebases, a better matching is desirable when the horizontal and vertical deflection voltages are large(2). Linearity is a most desirable feature, for although non-linearity is theoretically tolerable when a calibration oscillation or marker is available, the assumption of a linear time-sweep aids the understanding of oscillograms very considerably.

The requirements noted in the last paragraph have been satisfied by several authors in whole or in part. Bartlett and Davies(201) describe a simple exponential timebase generator with linearizing feedback followed by two valves in parallel with split anode and cathode loads, the outputs being taken from the anode of one valve and the cathode of the other (this does not give the outputs equal impedances to earth, but may be acceptable if the output impedances are both low). Prime and Saxe(214) used two Miller Integrator circuits, one of which passed a heavy current in the quiescent condition, to provide simultaneous "run-down" and "run-up" voltages; in this way a minimum sweep-time of 2 microseconds was obtained. Miller Integrator and similar feedback timebases have been fully considered by Briggs(212), Puckle(2), and in the books "Cathode Ray Tube Displays"(1) and "Waveforms"(3) by the M.I.T. staff. Timebases for shorter sweep-times, but less (though adequately) linear traces, are mainly of the capacitor-discharge-to-charge-another-capacitor-through-resistance type such as those by White(208) (using a hard-valve switch), and by Prime and Ravenhill(206) (using a hydrogen thyratron switch). Hardy(211) uses the same basic circuit as Prime and Ravenhill, but suggests different beam modulation arrangements for the highest speeds. The circuits of Prime and Saxe, White, Prime and Ravenhill, and Hardy all give a high-voltage push-pull output suitable for 5 to 10 kV oscillograph tubes. For use with a post-deflection-acceleration tube such as the G.E.C. 1608 ABCA, Moody and McLusky(213) have employed inductive linearization and a paraphase circuit to give 250-volt waveforms as short as 0.1 microsecond.

The hydrogen thyratron has been mentioned as a suitable switch, both in impulse generator and timebase circuits, due to the extremely high rate-of-rise of current possible (750 A/ μsec for BT79) and for the high peak current rating (35A for BT79). Such thyratrons are however rather more critical in their operation than mercury vapour types, especially in regard to the triggering pulse, which should be of at least 250 volts amplitude from an impedance less than 2000 ohms. Knight and Hooker(215) have described the main operating characteristics, while Germeshausen in a Section(8.11) of the book "Pulse Generators"(4) gives a more comprehensive survey of their properties.

Surge Phenomena and Impulse Testing, etc.

A large number of papers have been written on surges in transformer windings, and the section of chapter 10 (Bibliography) concerned with this subject lists only the more classical or notable papers. Of these, a representative selection will be considered in this present survey, since few of the papers refer directly to recurrent-surge testing; nevertheless, the principles behind high-voltage impulse testing of windings are equally applicable in most cases to low-voltage repetitive testing.

The initial distribution of potential due to capacitances between turns, coils and core, the subsequent oscillations, and the final or dying-away distribution in a winding subjected to impulse waveforms, was described in full detail by Weed(327) as early as 1915. The extensive practical application of such principles did not develop until the late nineteen-thirties largely due to the lack of suitable impulse generators and high-speed oscillographic equipment. Over the years, qualitative understanding developed, and a fair amount of work on surge prevention, or winding protection, was undertaken as instanced by papers from Weed(317) in 1921 and Norris(311) in 1935.

The more modern advances and quantitative approach were heralded by Foust, Kuehui and Rohats(306) (U.S.A.) in 1932, and by Allibone, Hawley and Perry(301) (Gt. Britain) in 1934. By quantitative approach is meant simply the knowledge of the amplitude and characteristics of the waveform used for testing, and not a comparison between practical and theoretical investigations; hitherto, testing with impulse plant had been unaccompanied by oscillographic observation and the effect of various test loadings on wave shape had not been fully appreciated(301).

In 1935 and 1936, Allibone and Perry(302, 303) virtually campaigned for some standardization in impulse test methods as applied to transformers, generators and insulators, and for some standard forms of test waveform. This latter point did achieve international approval, at least in the method of specifying the wave shape, and the 1/50 and 1/5 impulse waveforms have been used extensively since. Other features requiring standard practice included the polarity of the test wave, circuit aperiodicity, fatigue tests, cascading (insulators), and transformer winding connections.

A most comprehensive paper was presented in 1937 by Allibone, McKenzie and Perry(318), and provoked an equally comprehensive discussion. The authors surveyed the theoretical treatment of the effects of impulse waves on windings, assuming the applied wave firstly as of unit impulse form and then as of the standard double-exponential form. The effect of winding resistance in introducing a damping factor was also briefly considered. Initial and subsequent voltage distributions, and the effects of wave-front and wave-tail durations were also dealt with; and in addition remarks concerning the following features of impulse testing: removal of transformer from its tank, addition of a series of capacitances, earthing through impedance, applying impulses to both ends of the winding simultaneously, discontinuities at tap-changing points, re-inforced coils and static end rings. Testing practice for three-phase transformers is also given.

Thomas(316) discussed insulation stresses in transformers, the use of a calculating board (setting up an equivalent simplified network to represent coil-to-coil and coil-to-earth capacitances) and in particular "non-resonating" transformers with electrostatic shielding. Comparison of high-voltage and R.S.O. tests on shielded windings showed good agreement.

A paper by Foust and Rohats(307) in 1940 surveyed American developments in Impulse Voltage Testing, giving the latest form of their Electric-Transient Analyzer (R.S.O.), and also detailing some of the techniques employed in high-voltage work, especially in regard to earthing and obtaining smooth impulse waves with front durations as low as 0.02 microsecond. Reference has been made previously to the difficulty of recording voltages between tappings on a winding due to the considerable asymmetry of the potential applied to the oscillograph plates, and to overcome this, Foust and Rohats devised a Subtractive Voltage-divider which essentially divided the tapping potentials (with respect to earth), inverted one of them in an amplifier stage, and added them so that the resultant (with respect to earth) could be applied to the oscillograph plates in much the same way as for single tap-to-earth recording.

Hagenguth(319) and Stewart and Holcomb(315) in 1944 and 1945 respectively described an interesting method of fault detection. This is known as the Neutral Current Method, and in practice the potential across a resistance connected between the "neutral end" of the winding and earth is recorded. Differences in wave shape between the unfaulted winding oscillogram and an oscillogram taken with only one shorted turn are stated to be discernible. For larger failures or for shorted coupled turns the differences may be even more pronounced.

Rippon and Hickling(313) (Gt. Britain) presented the first paper on the Neutral Current Method in this country in 1949. The basis of the method is the demagnetization, by short-circuited turns, of the main core flux set up by impulse voltage. The short-circuited turn or coil produces an effect equivalent to a substantial reduction in inductance, and the inductive current through the winding is therefore increased. Theoretically, the method does not apply to chopped waves since $\int E.dt$ (which is proportional to the inductive current in the winding if E is the peak impulse voltage) is zero from the instant of chop onwards, when faults are most likely to occur. Rippon and Hickling give a variety of test circuits and methods of application, including the use of an R.S.O. when earthing resistances on the two phases (of a three-phase transformer) not being immediately investigated may be dispensed with, so giving increased sensitivity of fault indication in many cases.

Papers relating to impulse testing of machine windings are few, the two main ones by Friedländer(322), and by Robinson(314) referring to high-voltage alternator windings. The other rotating machines most prone to the effects of lightning surges are probably series-wound motors for railway traction where overhead conductors are used for power supply to the locomotives. Otherwise, several more theoretical papers such as those by Bewley, Hagenguth and Jackson(320), and Rudenberg(325, 326) deal with surges and oscillations in windings generally.

A comprehensive treatise on transformer high-frequency transients, recognised as a reference work for a number of years (first edition), is Part Two of a book by Bewley(5), who has been responsible for numerous papers on transient phenomena. A detailed survey of research on phenomena associated with lightning particularly, and many high-voltage measurement techniques, is contained in the book on "Surge Phenomena"(7) published in 1941 by the E.R.A.

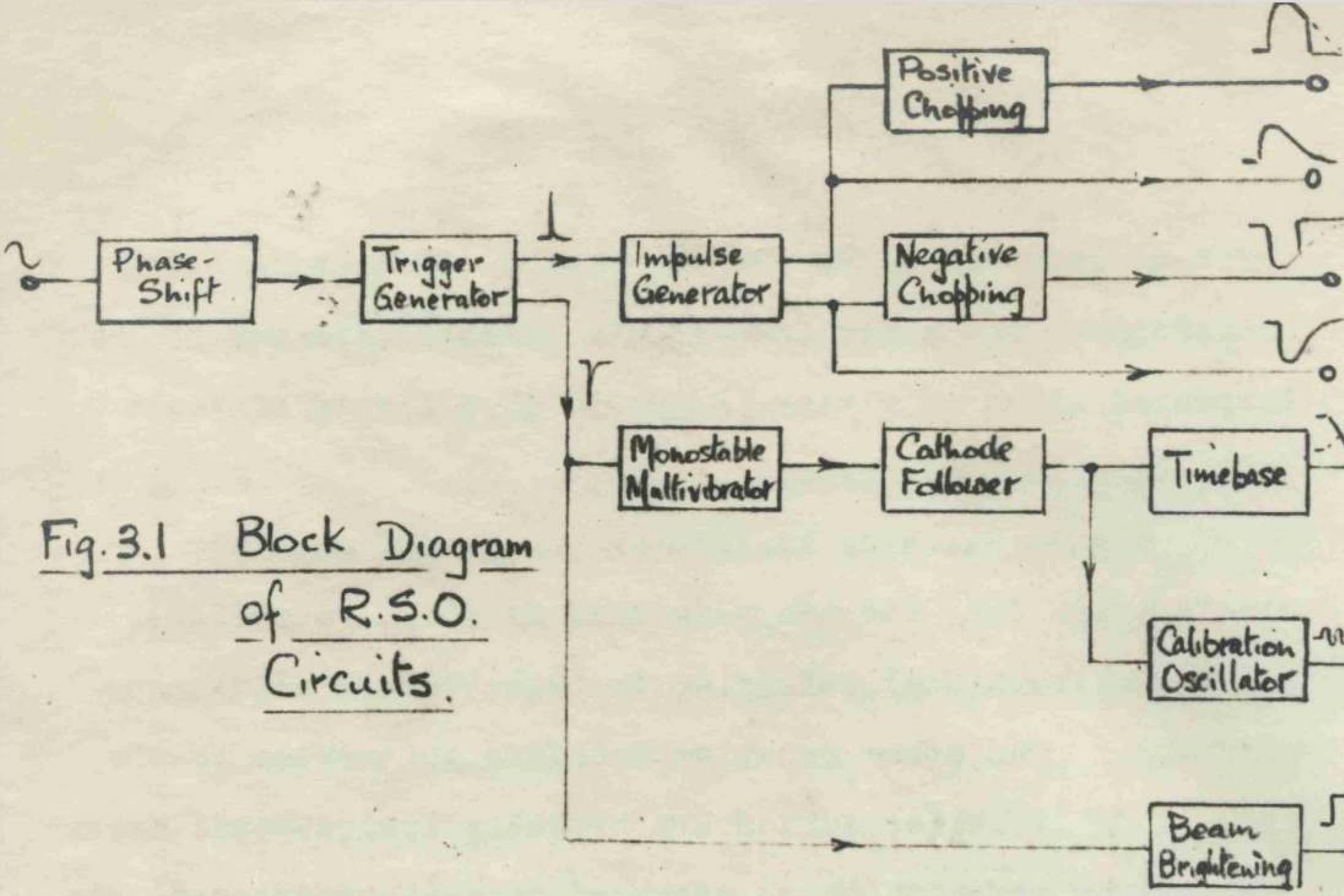


Fig. 3.1 Block Diagram of R.S.O. Circuits.

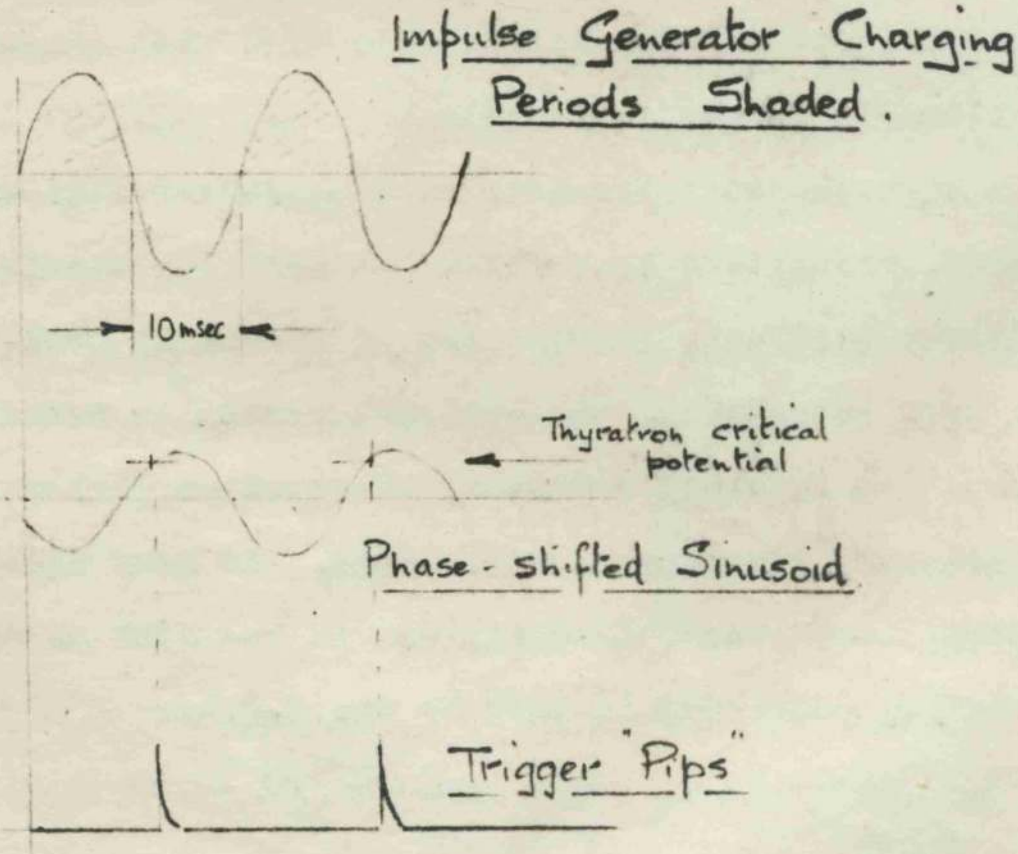


Fig. 3.2. Relative phasing of Waveforms.

Chapter 3

The Present Approaches

The original specifications for a R.S.O. were drawn up as a result of the previous work of Wilkinson(110), Rohats(103, 104) Scoles(105) and White(108). One of the first decisions was the choice of cathode ray tube, for this would affect the required time sweep amplitude. Of four types, the S.T.C. 4063YB tube was selected, this requiring a 5kV accelerating potential and having two side arms so providing a very low input capacitance to the Y-plates; furthermore, White(108) of the E.R.A. had used this tube. Otherwise the specifications called for a push-pull timebase having time-sweeps in the range 1 to 200 microseconds, a calibration oscillator, and an impulse generator producing negative-going (and positive-going if possible) wave shapes variable at least within the limits of the most standard 1/5 and 1/50 forms. Beam modulation was a highly desirable feature. Chopping of the negative-going (and positive-going) impulse waves over a wide range of tail amplitudes was also required.

As a result, the operations as shown in the block diagram (Fig. 3.1) were necessary as an absolute minimum, and on this basis, prototype circuits were developed and built into a DEXION framework. This particular design in the

DEXION framework (known hereafter as Model "A") served as an experimental assembly of the complete apparatus and much useful information was gained, especially in respect of stray magnetic fields in the vicinity of the cathode ray tube. Practically, however, it was never very satisfactory, due to the lack of fine focus of the spot, and severe astigmatism despite the inclusion of correcting circuits. Consequently, it was decided to build an instrument in finished form, using chassis fitting a standard rack. This new design employed a G.E.C. 908 BCC tube requiring 10kV accelerating potential; the deflection sensitivities were therefore lower and a new timebase design was required. The main features of the equipment (known hereafter as Model "B") were the same as before, but many minor improvements to facilitate operation and give a first-class oscillographic display were incorporated.

Since the block diagram of Fig. 3.1 applies equally well to Models "A" and "B", the sequence of operations will now be described. It was decided to use an impulse generator circuit in which a capacitor charged up during the long inter-impulse period and then was discharged through a shaping network, rather than by waveshaping a cosine form impulse as was done by Wilkinson(110). For a 50 c/s repetition frequency, which was accepted as most convenient, this meant using a rectifier diode to allow the charging of a capacitor during the positive half-cycles of the supply, and to cut off the capacitor from the supply during the negative half-cycles during which triggering of the impulse generator thyratron to produce an impulse waveform would take place (Fig. 3.2). In view of the relative powers involved, it is much better to phase-shift the triggering waveforms for impulse generator and timebase relative to the impulse generator charging supply than vice-versa. The first block of Fig. 3.1 therefore represents a phase-shift circuit giving an output of about 60 volts R.M.S. shifted through angles of 90^{o} to 180^{o} from the input. The positive-going half-cycles of this phase-shifted signal fire a thyratron trigger generator which produces very sharp positive- or negative-going "pips" to time the impulse generator or timebase operation. The impulse generator has already been described briefly; chopping arrangements for positive and negative waves require separate circuits, which were similar in operation to that of Scoles(105) i.e. time to chop was controlled by an integrating circuit with a variable element.

Many triggered timebase circuits require external "gating", and a necessary pre-requisite to the timebase circuit proper is therefore a monostable multivibrator (flipflop) to generate a "gating" pulse of duration at least as long as the longest time-sweep. The "pips" from the thyratron trigger generator initiate this multivibrator which is followed by a cathode follower circuit to give stability, and reduce interaction between the driven circuits. In Model "A", the push pull time-sweep was provided by a Miller Integrator(212) and an invertor stage working as a cathode-coupled see-saw circuit; in Model "B" the time-sweep was obtained from the split anode and cathode loads of a bootstrap circuit(2, 3). The calibration oscillator is also "gated" by this same pulse, and the oscillation, which in all circuits used could be adjusted to give constant amplitude, lasts at least as long as the longest time-sweep.

Various authors have derived a beam brightening pulse from the timebase circuit, and this may be simple and convenient for some cases; however, it lacks flexibility in that the pulse amplitude, and especially the pulse duration which may be required to be less than the time-sweep, are not generally independently controllable. A satisfactory arrangement is to trigger a monostable multivibrator (having stepped or continuously variable control of pulse duration) which exists purposely for generating a beam brightening pulse (See Fig. 3.1).

A further feature which is not indicated in the block diagram is Impulse Delay. This facility is most desirable as the front of the impulse wave would otherwise start roughly coincident with the time-sweep (or earlier in cases of inherent delay of the timebase triggering "pip" as occur in certain commercially made oscillographs); also it may be desired to shift the interesting phenomena clear of the initial spot halation, if any. In Model "A", such delay was accomplished using an integrating network with a variable element (this may also affect the amplitude of the triggering "pip" however), and in Model "B" by a multiple-tapped delay line followed by delayed-trigger generator to give stability and a lower output impedance than was available from the delay line itself.

It will be appreciated that in the simple block diagram shown, jitter in the thyratron trigger generator stage is unimportant, and that the impulse generator switch valve itself is the inherent source of jitter trouble, since thyratrons are normally used in this purpose. Jitter from hard valve circuits is negligible.

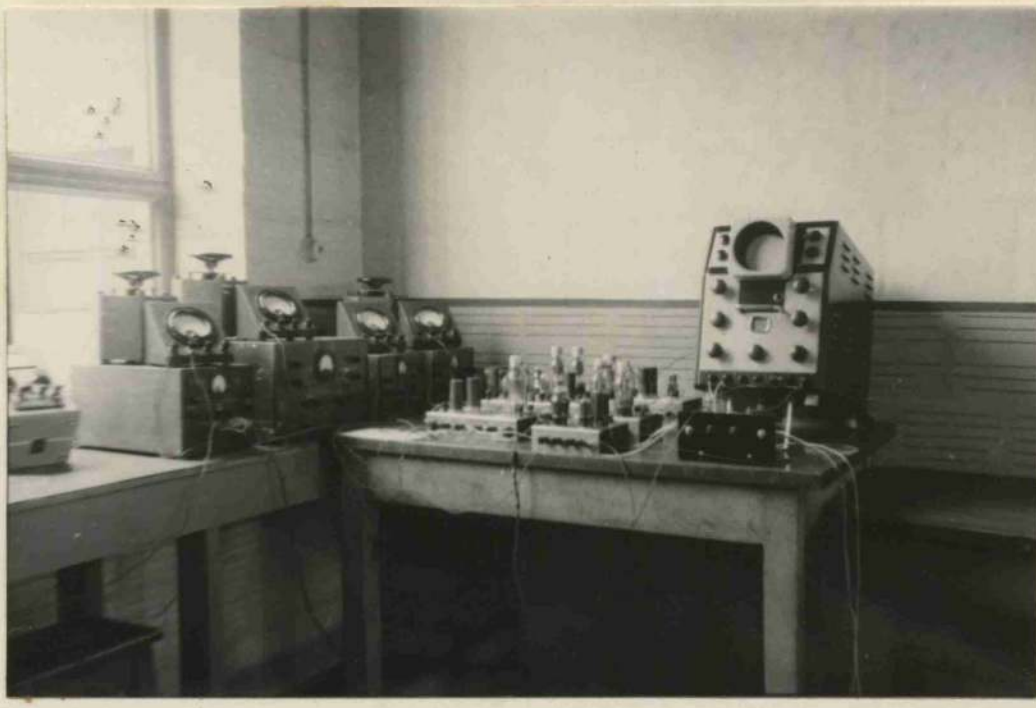


Fig. 4.1. Experimental Bench Layout.

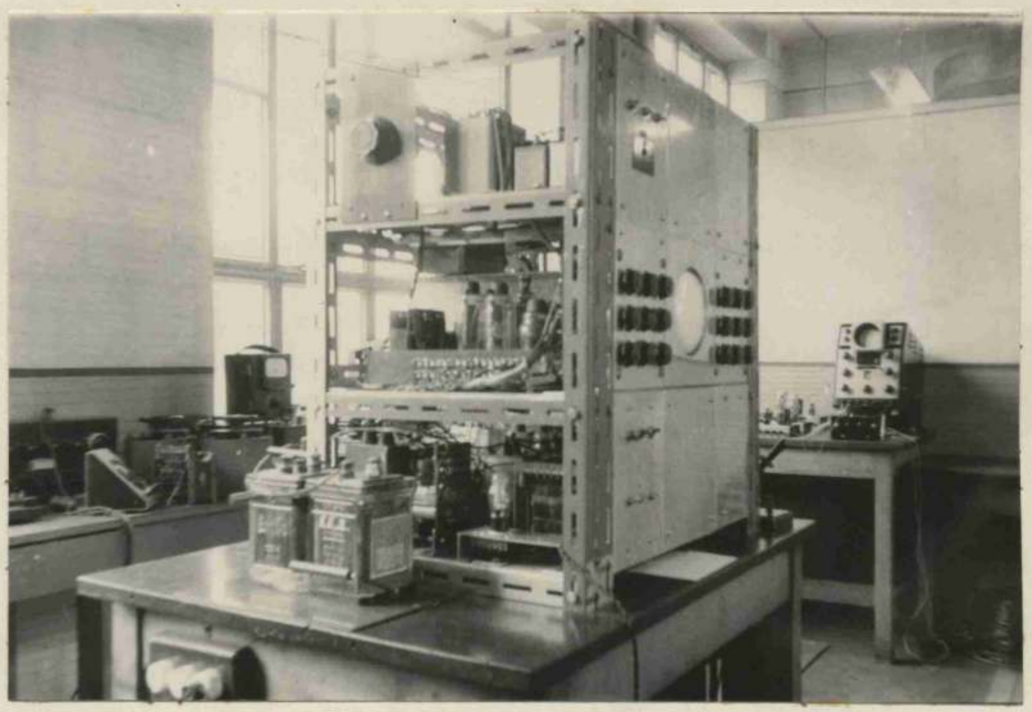


Fig. 4.2. General view of Model "A".

Chapter 4

Circuit Design and Arrangement - Model "A"

Experimental circuits were constructed on small chassis, temporarily wired together, and supplied from standard laboratory power packs (Fig. 4.1). Under such circumstances, a laboratory oscillograph was used for display of waveforms, but it must be pointed out that many such oscillographs have a limited writing speed, and minimum sweep-times of the order of tens of microseconds; for the examination of a repetitive 1/50 wave they are quite suitable, but do not give a very fine trace nor are they necessarily amenable to external beam modulation.

Fig. 4.2 shows Model "A" completed. There are three levels, the lower one accommodating the instrument's own power supplies; the middle one the phase-shift, triggering, impulse and chopping circuits on one side, the cathode ray tube in a galvanized-iron box in the centre, and the timebase, modulation and calibration oscillator circuits on the far side; and the top level carrying an additional power pack. Two accumulators on a bakelite board provide the cathode ray tube heater supply temporarily, in the absence of a heater transformer with suitable winding insulation.

The main circuits for Model "A" are shown in Fig. 4.3. They will be described very briefly as considerable

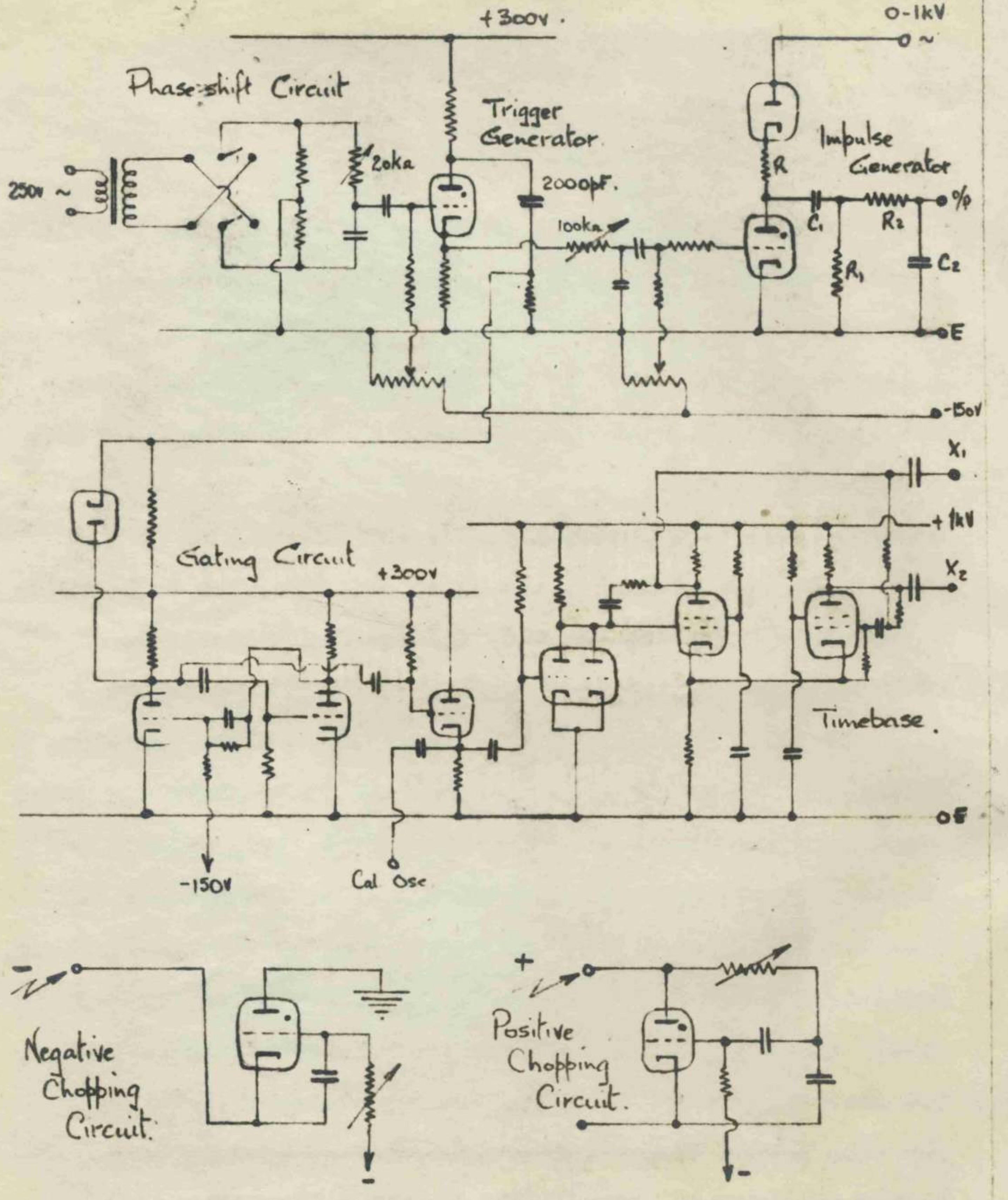


Fig. 4.3. Circuits for Model "A".

improvements were effected in Model "B", but nevertheless as an introduction to the technique they are interesting.

The Phase-shift Circuit is a well-known arrangement (see Reference 3, section 4.12), which in theory affords a constant voltage output with no loading and provides a phase-shift between 0° and 180°. A change-over switch facilitates phase inversion should transformer connections cause the variability to be between 180° and 360°. Once set to the desired phase-shift by the pre-set 20-kΩ variable resistor, no further alteration is required.

The Trigger Generator uses an argon-filled GT1C thyratron, which is fired by the positive-going sinusoid on the grid so discharging the 2000 pF capacitor previously charged from the D.C. supply. The capacitor discharge rate is limited by two series resistors, from across which are obtained positive- and negative-going triggering "pips". During the latter part of this capacitor discharge the current through the thyratron is so small that deionisation of the gas filling takes place if the grid voltage goes negative. The capacitor recharges and the cycle repeats approximately 20 milliseconds later in the 50-c/s repetition case.

The positive-going trigger "pip" from the cathode of the thyratron trigger generator is integrated, i.e. has the sharp initial rise rounded off, so that by varying this degree of rounding off by the 100 - kΩ variable resistor, the instant at which the critical grid potential of the impulse generator thyratron is attained may be varied. The Impulse Generator stage is shown in diagrammatic form only: as drawn in Fig. 4.3 only negative impulses could be produced; but if the right-hand side of C_1 is earthed, and the π-network consisting of R_1, R_2 and C_2 included in the cathode circuit of the thyratron, by means of suitable switching, then reasonable positive impulses may also be produced. In either case C_1 charges via R and R_1 during positive half-cycles of the supply, and discharges through the π-network when the thyratron is fired. C_1, C_2, R_1, R_2, the parameters of the wave-shaping circuit, may each be varied in steps; continuous variability of R_1 and/or R_2 is not possible because of the inductance associated with suitable high wattage components, and series of composition resistors are used instead.

The negative trigger "pip" from the thyratron trigger generator actuates the anode-to-grid coupled monostable multivibrator to give a timebase "gating" pulse. Negative pulses from the cathode follower stage turn on the calibration oscillator as well as the time-sweep. The first valve of the timebase proper conducts only slightly during quiescent periods, since the grid is at a low potential due to heavy conduction by the previous double-triode. A negative "gating" pulse turns off this double-triode, and a large positive pulse is applied to the grid of the Miller Integrator valve. A typical "run-down" then occurs and is applied to X_1, the only difference from other Miller Integrator circuits being perhaps the effect of the common cathode resistor which introduces degeneration so that a slightly less linear forward stroke may be expected than otherwise. The invertor stage is coupled by the cathode resistor, and by a see-saw circuit between the valve anodes thus ensuring symmetry of the push-pull outputs. Such a scheme is described in Reference 3, section 7.11.

Although a calibration oscillator and a beam modulation circuit were available for use with Model "A", final ideas on these details were not at the time established, and the development of calibration oscillators especially will be considered in the next chapter.

The chopping circuits are shown separately in Fig. 4.3. The positive impulse version uses a typical integrating circuit by which the applied wave is further rounded off to delay firing of the chopping thyratron. In the negative chopping circuit, the grid is initially biased negatively with respect to both anode and cathode, and an incident negative wave takes the cathode and grid equally negative so that the thyratron does not fire immediately; however the capacitor starts charging and when the capacitor potential is sufficient to overcome the initial bias, the thyratron fires and chopping takes place.

Fig. 5.1. General view of Model "B"

Chapter 5

Arrangement, and Additional Technique - Model "B"

Fig. 5.1 shows Model "B" in completed form. There are in all six large chassis, and a small panel at the bottom which carries the main switch and the main fuzes. The chassis are housed in an enclosed rack provided with opening side doors and a back door. The inter-chassis wiring connections are made at the back of each chassis so facilitating disconnection before withdrawing any particular chassis for examination; with the exception of very high potential leads and leads carrying trigger and pulse signals between co-axial sockets, multi-core cables and connectors are used. The whole equipment is mounted on a heavy base with casters so that it may be moved quickly on any one level, but for transpot over some distance in a vehicle, say, it is usual to remove all chassis from the rack.

The chassis are numbered from the top:

No.1 - Y-shift calibration

No.2 - Cathode ray tube, timebase, calibration oscillator, beam modulation

No.3 - Impulse (and pulse) generator, and trigger generators

No.4 - Calibration oscillator gating multivibrator; additional smoothing for timebase H.T.

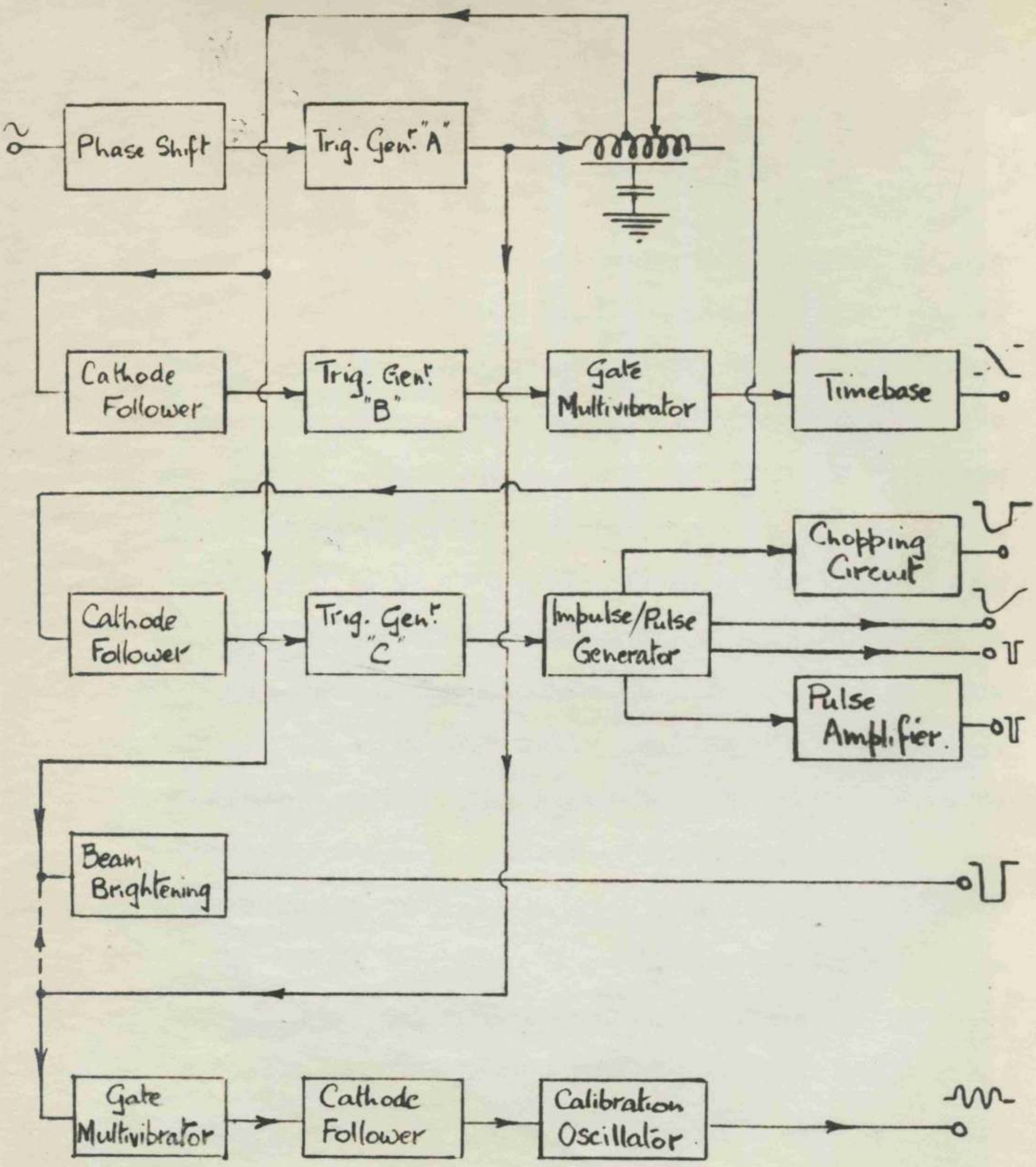


Fig. 5.2. Block Diagram for Model "B".

No.5 - High voltage power supplies

No.6 - Low voltage power supplies

(No.7 - Switch panel).

Chassis No.1 contains only the Y-shift calibration voltmeter, and its associated range switch with series resistors. This instrument measures the D.C. shift potential between the Y-plates of the C.R. tube, so that a series of horizontal lines, recorded on film, and corresponding to successive Y-shift control positions, may be simply related to a vertical voltage scale.

The second, third and fourth chassis contain the circuits relating to the oscillograph and generation of the test pulses or impulses. Fig. 5.2 shows the block diagram for Model "B". The important feature not included in Model "A" is the timing sequence for the initiation of calibration oscillator, timebase and beam modulation, and impulse (or pulse) generator. Trigger Generator "A" actuates the calibration oscillator "gate" multivibrator and hence the oscillator itself so that the oscillation can build up to constant amplitude (time < 3 μsec.) before other circuits function. The necessary delay till the next initiation is effected by an artificial delay line using lumped constants. From a tapping on this delay line is taken a delayed trigger which is fed via a cathode follower stage to Trigger Generator "B". A cathode follower buffer stage is necessary here as when the trigger generator thyratron fires, a low impedance would otherwise be presented at the delay line tapping so upsetting matching conditions; incidentally, bias control on such a cathode follower gives a very fine control on the triggering time of the following Trigger Generator. The output of Trigger Generator "B" actuates the "gate" multivibrator for the timebase and the beam brightening multivibrator; alternatively, beam brightening may be initiated earlier from the output of Trigger Generator "A" giving a small initial spot but a guarantee of brightening for the whole of the time-sweep (in practice this not normally necessary even on the fastest sweeps). From a variable tapping on the delay line, a timing signal is fed via a cathode follower stage, similar to that just described, to Trigger Generator "C" which in turn fires the impulse generator thyratron, this last action normally being the third distinct timed initiation of the sequence.

In Model "B" the positive impulse output (with associated chopping circuit) was dispensed with since the negative impulse case was more convenient from the circuitry point of view (the impulse generator thyratron cathode could be semi-permanently earthed), and in any case there was no difference in the useful information obtained by using the opposite polarity of wave with linear systems. A pulse generator facility was added, partly for the possible study of reflections from cable terminations. Instead of the four main components of the impulse wave-shaping circuit, a pulse-forming-network (or artificial line) with matching resistance was substituted. A negative 1½ microsecond pulse could be obtained from the matching resistance, or by inserting a resistance in the thyratron cathode circuit a positive pulse for further squaring and amplification in a hard-valve amplifier could be produced.

The fifth chassis houses the high voltage power supplies. These are two identical shift power packs (one for Y-shift, one for X-shift), the timebase H.T. supply of approximately 100mA at 2kV, and the E.H.T. power supply for the C.R. tube of 2mA at 10kV. The heater transformer supplying the C.R. tube heater requires a winding insulated for 10kV and is also included in this chassis. There are no interlocks associated with these supplies and the switching sequence is left to a competent operator.

The sixth chassis contains several heater transformers; a bias power pack with neon stabilizer (- 150 volts); a general H.T. power pack with electronic stabilizing having a maximum output of 350V, 75mA and giving voltage regulation better than 1% and a hum level better than 0.02%; an auxiliary H.T. power pack to supply 60 to 80mA at 400V; a transformer and phase-shift circuit for triggering purposes; and the high voltage A.C. supply (1000 to 1500 V) for the charging of the impulse generator. The general H.T. supply has a valve delay switch giving 45 seconds delay, and the impulse (or pulse) generator supply a similar device affording a delay of 2 minutes, this latter arrangement to protect the hydrogen thyratron of the impulse generator from premature application of H.T. These delay circuits are not meant to be foolproof and the normal switching sequence is determined by the operator.

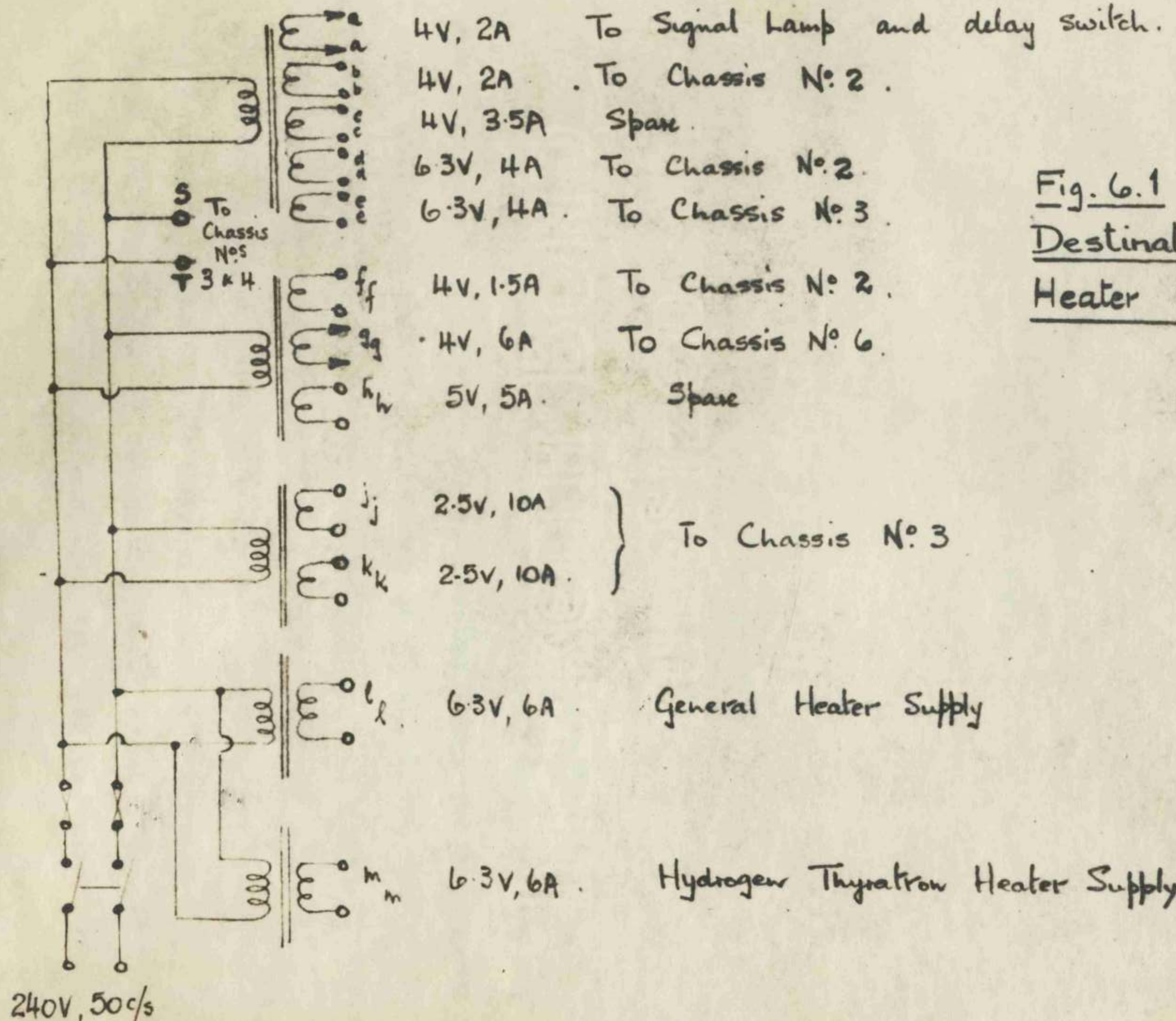


Fig. 6.1
Destinations of Heater Supplies.

Chapter 6

Circuit Design - Model "B"

A more detailed treatment of Chassis Nos. 2 to 6 will now be given. Chassis No.1 contains only a large panel-mounting 1500-0-1500V voltmeter with mirror scale and a knife-edge pointer, so that Y-shift potential differences may be accurately measured; switching of various series resistor banks permits full-scale deflections of one-half, one-quarter, or one-tenth of the normal value so that shift potentials about the centre of the C.R. tube face may be even more carefully determined. Panel No.7 has channeling behind it which carries the 240V 50 c/s supply terminal block and the main fuzes; all mains supplies for power packs and transformers throughout the equipment are protected by these fuzes and controlled by the Main Switch, but with each individual switched supply on Chassis Nos. 5 and 6 there are lighter fuzes for normal protection.

Chassis No.6:

Chassis No.6 carries the General Power Supply packs for the equipment, controlled by six individual switches each with a pair of fuzes and an indicator lamp.

Fig. 6.1 shows the arrangement for valve heater supply. Five transformers are mounted on Chassis No.6

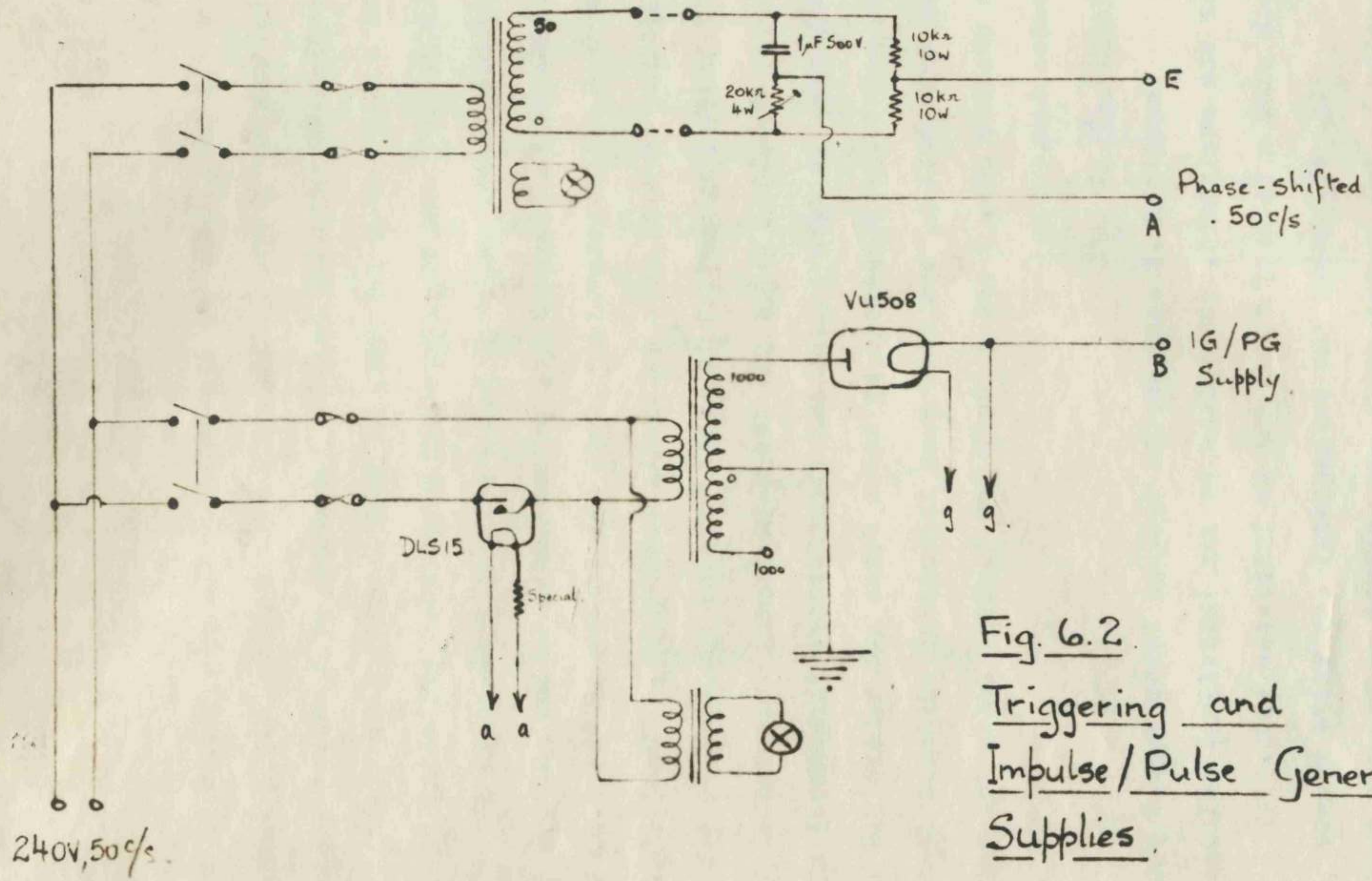


Fig. 6.2

Triggering and Impulse/Pulse Generator Supplies.

and most of the secondary windings supply the requirements on other chassis through International Octal plugs and sockets and multi-core cables. The supplies aa and gg are used on Chassis No.6 itself. In addition one transformer is situated on Chassis No.3 and one on Chassis No.4 to supply special (more recent) needs on these chassis and a switched mains supply for these two "external" transformers is fed via the plug and socket connections denoted by ST. In the original design it was considered desirable to keep bulky and weighty articles such as transformers as low as possible, and also as far as possible from the C.R. tube, so that 50 c/s magnetic field effects on the tube would be minimised. The secondaries ff, gg, hh, and jj, kk have special insulation for potentials to earth of 1.5kV. Heavy gauge wiring is used for heater supply purposes in order to reduce line volt-drop.

Two separately switched supplies are shown in Fig. 6.2. The upper circuit uses a conventional phase-shifting arrangement so that the triggering sequence may occur correctly within the negative half-cycle from the transformer of the lower circuit, i.e. when the impulse/pulse generator circuit has been charged and the VU508 charging rectifier is cut off. The supply to the transformer for the impulse/pulse generator is closed by contacts in a valve delay

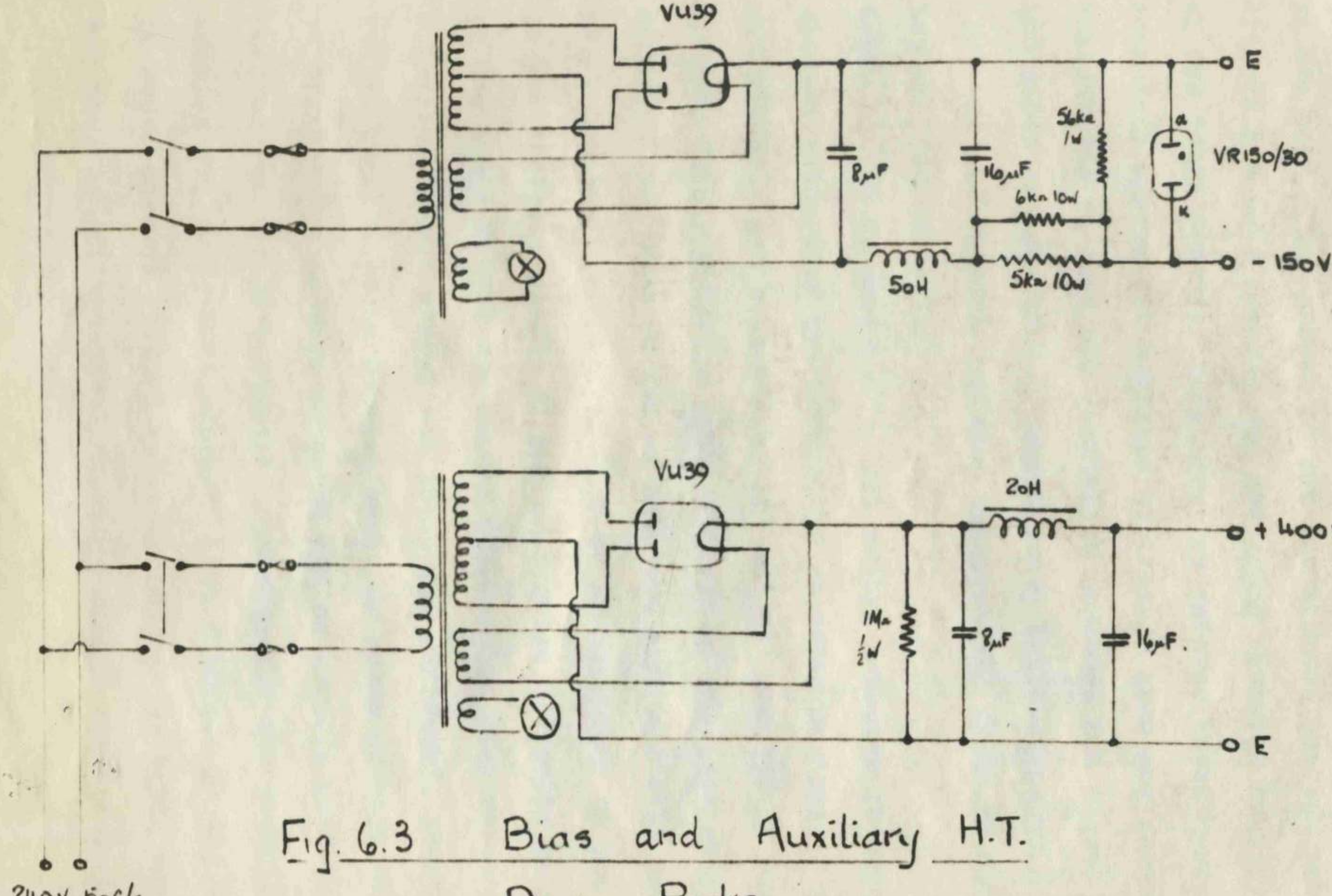


Fig. 6.3 Bias and Auxiliary H.T. Power Packs.

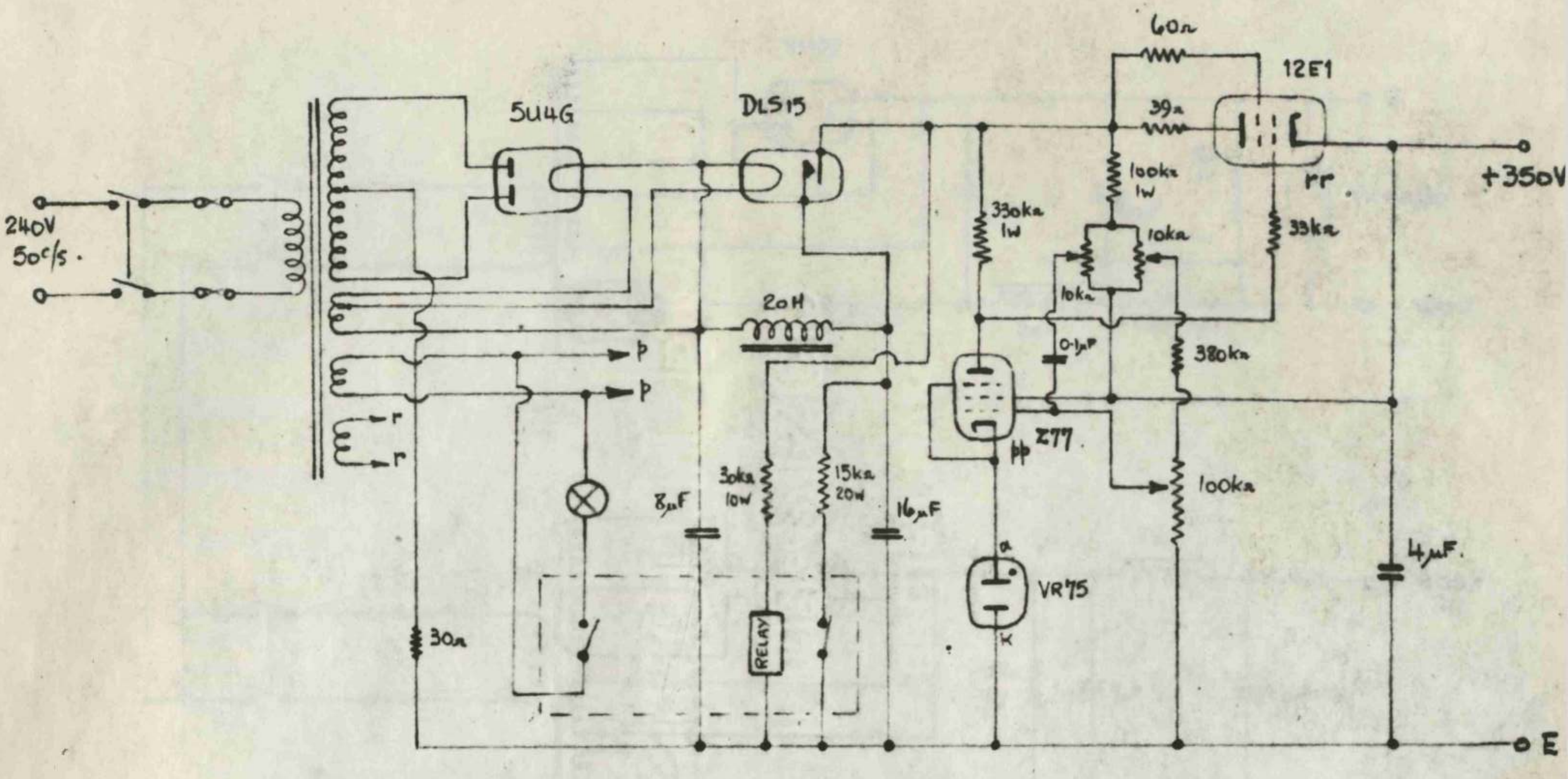


Fig. 6.4 General H.T. Power Pack.

switch DLS15, that is if the manual control switch is itself already closed. By adjusting the value of the resistance in series with the DLS15 heater, the switching delay may be varied from about half-a-minute to several minutes - the desired delay in this case should be greater than two minutes.

Fig. 6.3 shows the Bias and Auxiliary H.T. Power Packs, both of which are quite conventional. The Bias Power Pack has a VR 150/30 neon stabilizer to assist in maintaining stable operating points both in hard valves and thyratrons; not all the H.T. power packs are stabilized, and such supplies are used for the less critical circuit operations, or where front panel manual controls may be quickly re-set.

The General H.T. Power Pack is shown in Fig. 6.4. The circuit is typical of series-valve stabilized power packs, with a parallel feed via a 0.1 μF capacitor to the grid of the Z77 to give increased control on hum (100 c/s) rejection. A valve delay switch DLS15 is incorporated, and a relay circuit, which provides artificial loading to restrict the H.T. voltage before the normal load is applied and which closes the indicator lamp circuit when the delay switch closes, is included as a desirable extra.

Chassis No.5:

Two Shift Power Packs are desirable so that X and

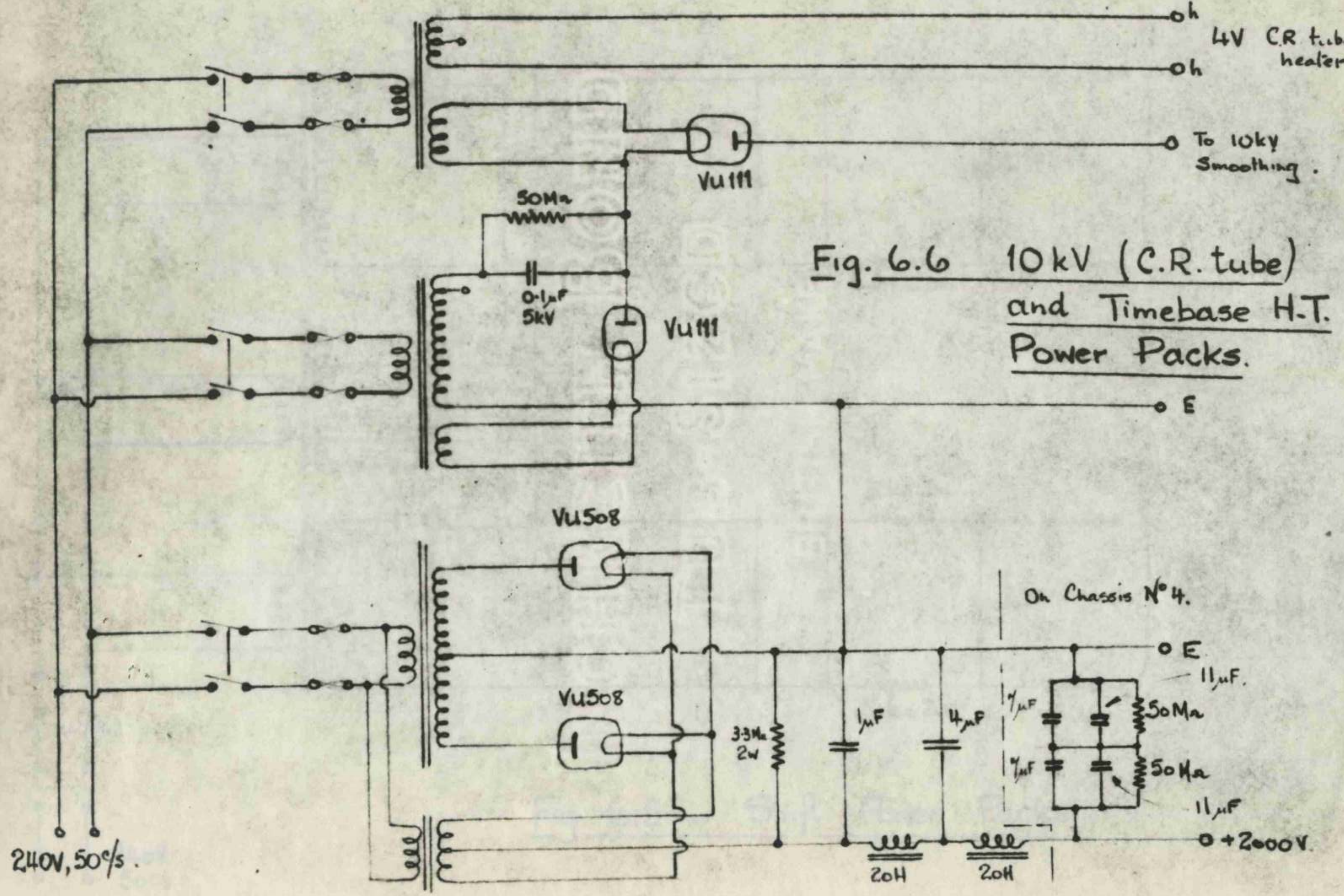


Fig. 6.6 10kV (C.R. tube) and Timebase H.T. Power Packs.

Y-plate anti-astigmatism circuits may be independently adjusted, and due to the appreciably different deflection sensitivities for each pair of deflection plates, one power pack is for 3kV and the other for 2kV. The actual shift and anti-astigmatism controls are mounted on Chassis No.2, and since the anti-astigmatism circuit depends on varying the mean potential of the pair of deflection plates with respect to earth, the supplies from the Shift Power Packs themselves must be "floating" or unearthed. Fig. 6.5 shows the two power packs, half-wave rectification and resistance-capacitance smoothing being adequate in view of the small steady currents taken.

Three switched supplies are shown in Fig. 6.6. Firstly, a heater transformer having highly insulated secondary windings (one for 10kV) supplies the 4V. C.R. tube heater and also the filament of one of the E.H.T. rectifier/doubler valves; if the C.R. tube heater supply is not "on", then only a fraction of the full E.H.T. potential will be applied to the C.R. tube. Secondly, a step-up transformer feeds the Cockroft-Walton voltage-doubler circuit which provides the 10kV accelerating voltage for the C.R. tube, a 50 MΩ resistor acting simply as a bleeder across the 0.1 μF capacitor. Thirdly, a conventional full-wave rectifier circuit gives a 100 mA, 2kV output primarily for Timebase H.T., but small currents

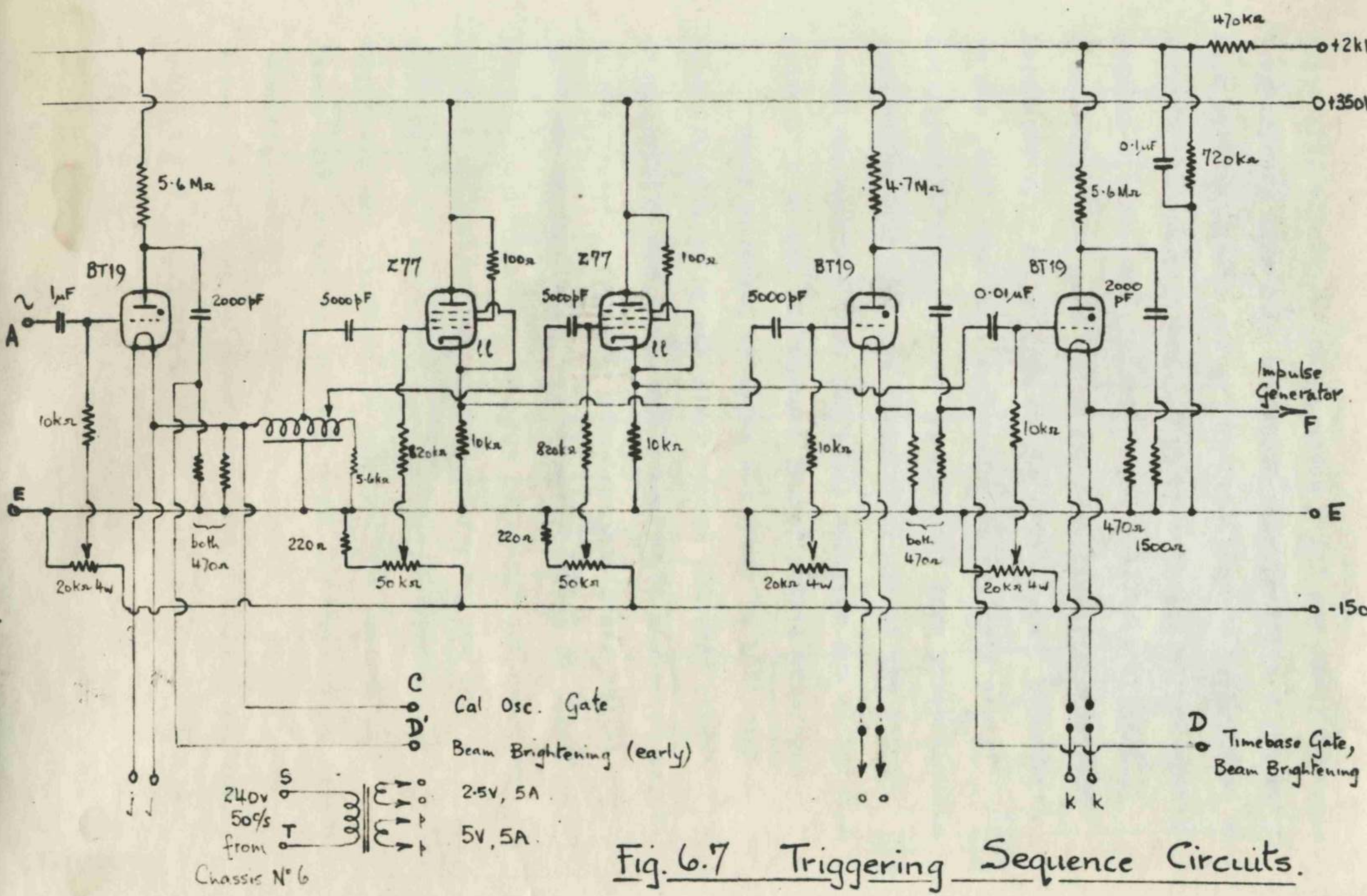


Fig. 6.7 Triggering Sequence Circuits.

are also taken by the trigger generators and the pulse amplifier on Chassis No.3. The smoothing of this high power supply is rather more elaborate than usual consisting of a double-section filter, with the chokes mounted on bakelite legs so as to be electrically isolated from the chassis, and the final capacitor bank effectively of 9 μF mounted separately on Chassis No.4.

Chassis No.3:

In Fig. 6.7, the first trigger generator, the delay line from tappings on which are taken appropriately timed "pips" to cathode follower stages, and a further two trigger generators are shown. The three trigger generators are almost identical, and use a well-known arrangement already described for Model "A". Although large in size, the BT19 mercury vapour thyratrons have proved eminently suitable especially in regard to the trigger "pip" amplitudes of several hundred volts which may be generated from both of the series resistors in the discharge circuit; also the BT19 may be slightly more reliable than the smaller GT1C. The anode resistors must be of high value (4 to 6 MΩ) so that after the discharge of the 2000 pF capacitors, the thyratron grid may regain control due to the very limited standing current still flowing to earth. The discharge circuit resistors are not critical in value except that they must limit the initial discharge current to within the capacity of the thyratron and yet provide as low an output impedance as may be desired. The grid circuit resistance of 10 kΩ to 15 kΩ is typical of the value suggested by the manufacturers.

The tapped delay line has fourteen tap points, eleven of which may be selected by a wafer switch which also has an "off" position. The line is terminated by a suitable resistance (5.6 k). From one fixed tapping and from the selected variable tapping, triggers are fed to the two Z77 cathode follower stages, which are quite conventional. The 50-kΩ bias potentiometers act to considerable extent as fine delay controls, so much so that the one associated with the second Z77 (Impulse/Pulse Generator timing) is mounted on the front panel. This variable delay property is due to varying the instant at which the rising front of the trigger from the delay line crosses the cut-off threshold for the valve and initiates conduction. The 100-Ω screen-grid "stopper" resistances are included as a precautionary measure. In the filament supply leads to the second and third BT19 trigger generators there are terminals which normally allow for an A.C. supply, but links can be removed so that a D.C. supply from accumulators may be substituted for jitter comparison tests; since the

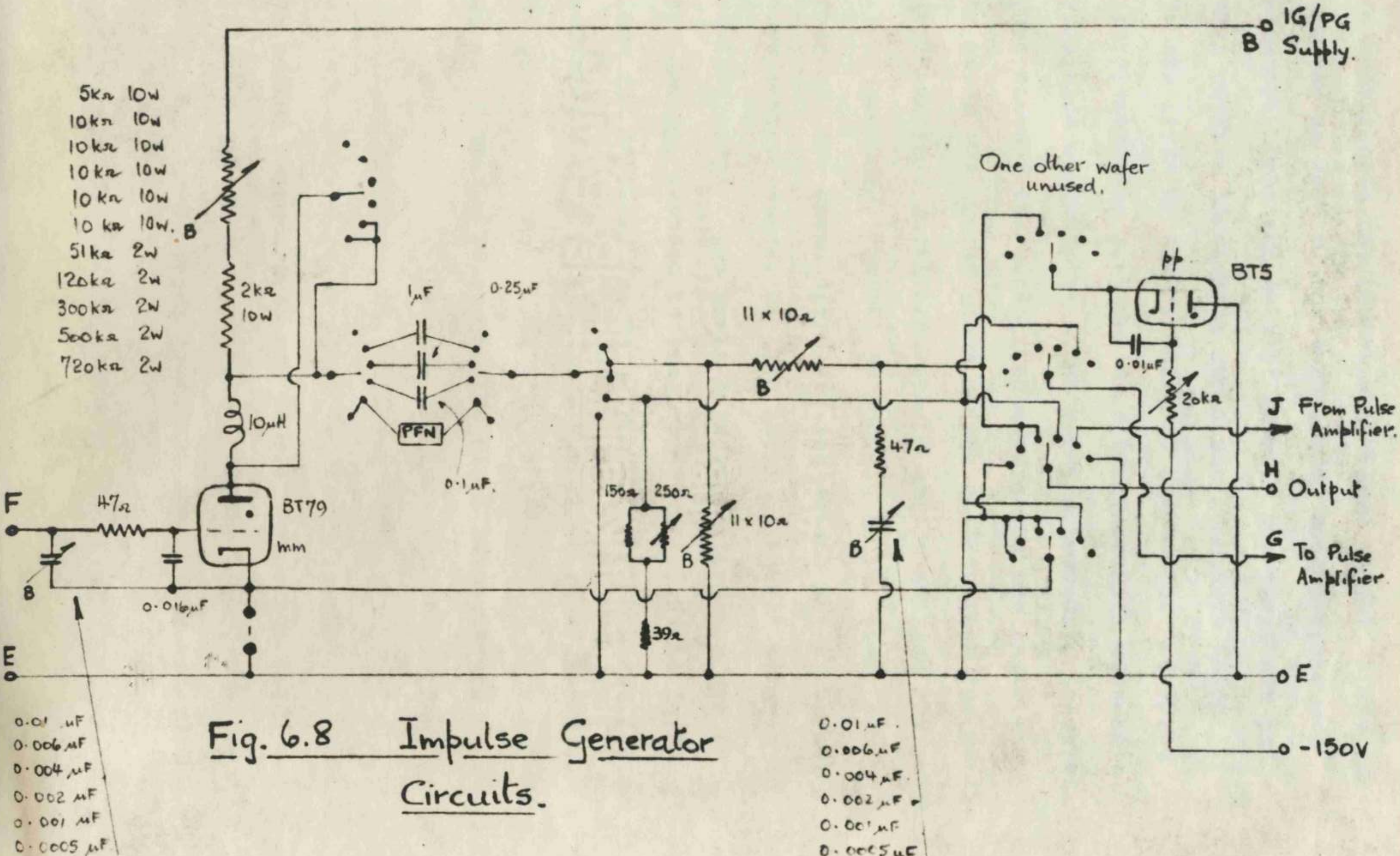


Fig. 6.8 Impulse Generator Circuits.

first trigger generator jitter is common to both timebase and impulse timings, no such provision was made as regards its filament supply.

Fig. 6.8 shows the Impulse/Pulse Generator and Chopping circuits, with the associated system switches. The positive trigger to the BT79 grid is fed via a 47Ω resistor with capacitor loadings ~~loadings~~ to the cathode so that oscillations of high frequency attributed to the grid potential immediately after firing may be reduced. It is also true that the trigger as generated and without the loading network has a very rapid rate-of-rise whereas the manufacturers of the hydrogen thyratron suggest a more moderate rate-of-rise. The loading network produces this more moderate rate-of-rise and may also act as a store of energy to be released automatically when the grid-cathode "arc" initiates before the main "arc" is struck. One of the capacitors of this loading network is in fact a switched bank, but various capacitor selections should have negligible effect on impulse shape except to vary initiation delay.

The impulse circuit proper consists of a switched bank of charging resistors which vary the potential to which the tail capacitor (1μF, 0.25μF or 0.1μF) or the pulse forming network charges from the half-wave supply at B. The 10 μH inductor, which is short-circuited on pulse generator operation, is included in the impulse discharge circuit to smooth the rise and crest of impulse wave-forms for otherwise extremely rapid rates-of-rise which appear distorted (partly due to inter-modulation on the time-sweep), and crest oscillations occur; consequently, the maximum rate-of-rise is limited to about 0.2 μsec, but faster transitions are possible with deterioration in shape. Heavy terminals with a copper link are provided for connecting the cathode of the BT79 solidly to chassis (a common earth point is in fact chosen) except for "Amplified Pulse" operation when a 150 Ω resistor in parallel with a variable 250-Ω resistor are inserted by appropriate switching to match the pulse forming network. The rest of the impulse waveshaping circuit consists of a switched bank of 10-Ω resistors to earth, these acting as tail shaping resistors; another switched bank of 10-Ω resistors (front shaping resistors, and alternative higher values may be substituted if desired); and a switched bank of front shaping capacitors to earth with a small waveshape "smoothing" resistor in series. The matching resistors already mentioned take the place of the π shaping network on pulse operation, being connected between the pulse forming network and earth for "Direct Pulse" operation and in the thyratron cathode circuit for "Amplified Pulse" operation.

There are two system switches: the first, having four poles, primarily selects the tail capacitor, or alternatively the pulse forming network; the second

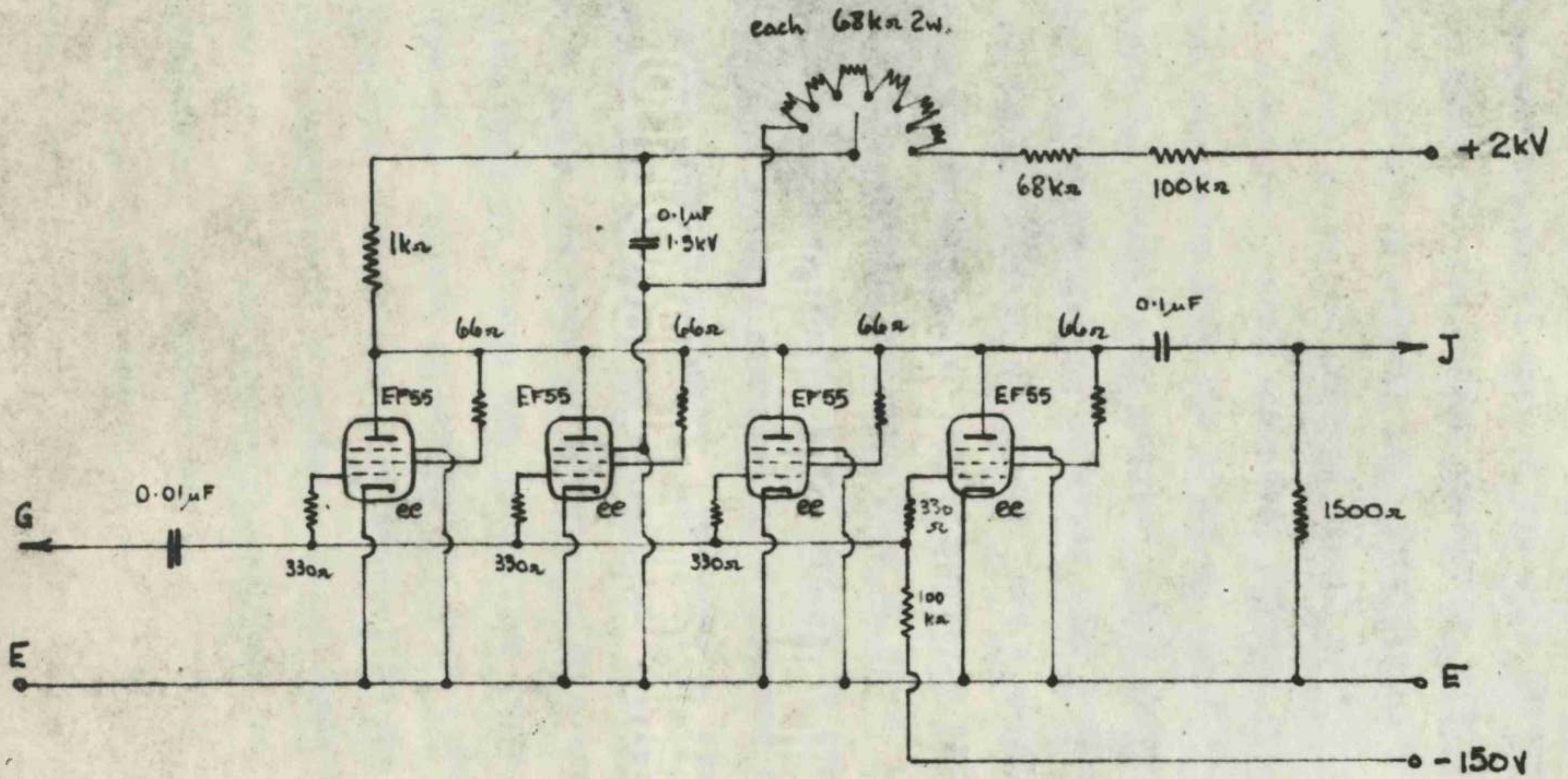


Fig. 6.9 Pulse Amplifier Circuit.

having six poles (two being unused) selects in turn Off, Negative Impulse, Negative Impulse with chopping, "Direct Pulse" operation, "Amplified Pulse" operation, and Off. The second system switch functions are as follows (going from top to bottom as in Fig. 6.8): to connect the chopping circuit on the appropriate switch position; to connect the positive pulse output from the thyratron generator circuit to the pulse amplifier; to select the appropriate signal for connection to the output terminal socket of the instrument; to apply an earth to the thyratron cathode (in the absence of the copper link already mentioned) except on "Amplified Pulse" operation. The chopping circuit is very simple, consisting of a mercury-vapour thyratron BT5 connected across the impulse generator output and with a bias and capacitor charging circuit similar to that of Scoles(105). The chopping circuit is most effective with a high front shaping resistance ($> 200\Omega$) and the longer wave-tails (e.g. 1/50 type), when wide variation in the time-to-chop is obtainable and a chop transition of less than 0.5μsec.

The pulse amplifier circuit is shown in Fig. 6.9. This is in effect four stages in parallel with "stopper" resistances on screen and control grids to prevent spurious oscillation. A positive pulse of about 1½ microseconds duration is applied to the control grids which are

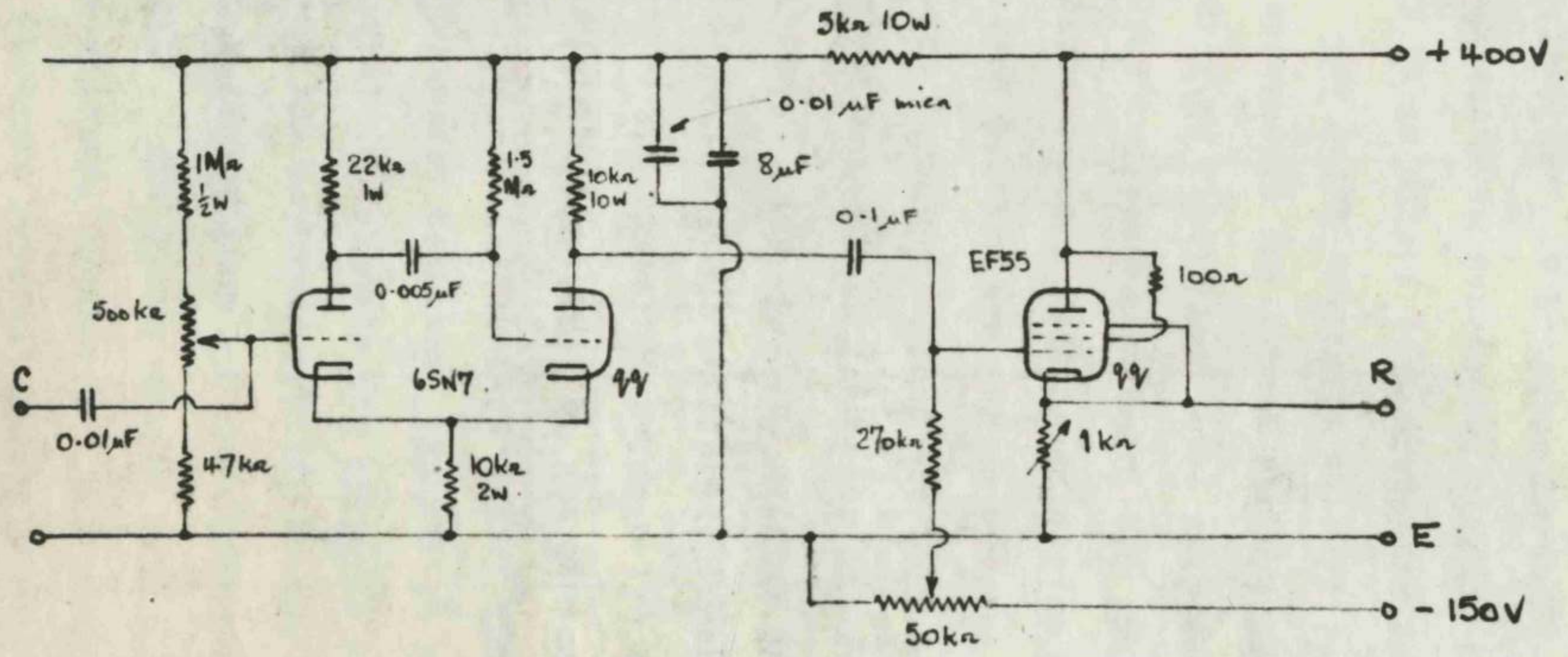
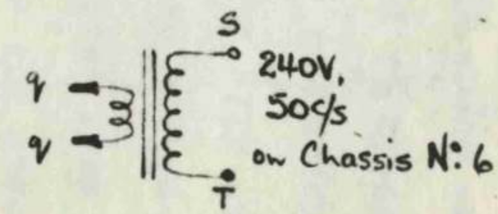


Fig. 6.10 Gating multivibrator etc. for Calibration Oscillator.



normally biased well beyond cut-off. A negative pulse of low output impedance (about 175Ω), and of amplitude controlled by the switched resistor bank in the H.T. line, is obtained from the anodes.

Chassis No.4:

This chassis is considered out of numerical sequence intentionally so that it may be understood how the trigger "pips" at terminal C are obtained (from trigger generator No.1, Fig. 6.7). Fig. 6.10 shows how these triggers, which are the first in the timing sequence of triggerings, are used to actuate a 6SN7 cathode-coupled monostable multivibrator. The action of this multivibrator is quite well-known, and is described in slightly more detail in Part 2, Chapter 4, but it will suffice here to say that a positive pulse, of duration controlled by the grid potential of the first section of the 6SN7, is available at the anode of the second section for pulsing the EF55 cathode follower stage which is normally biased well beyond cut-off. The duration of the pulse, which is used to "gate" the calibration oscillator circuit, must be adjusted so that an oscillation continues at least for the sweep time of the slowest timebase. A very low output impedance is desired from this circuit so that the calibration oscillator is turned quickly from the cut-off quiescent condition to that producing a constant amplitude oscillation of usable magnitude.

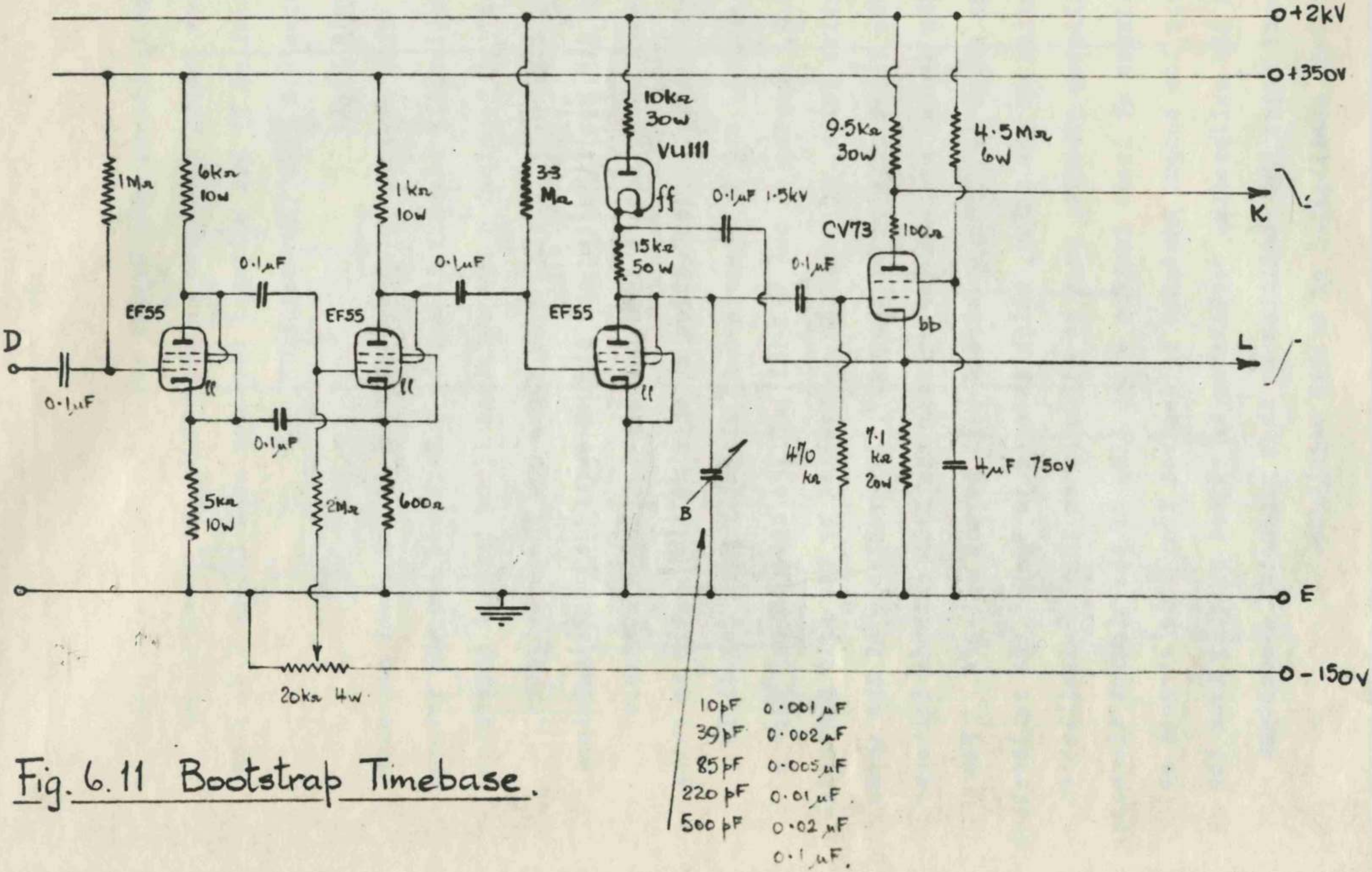


Fig. 6.11 Bootstrap Timebase.

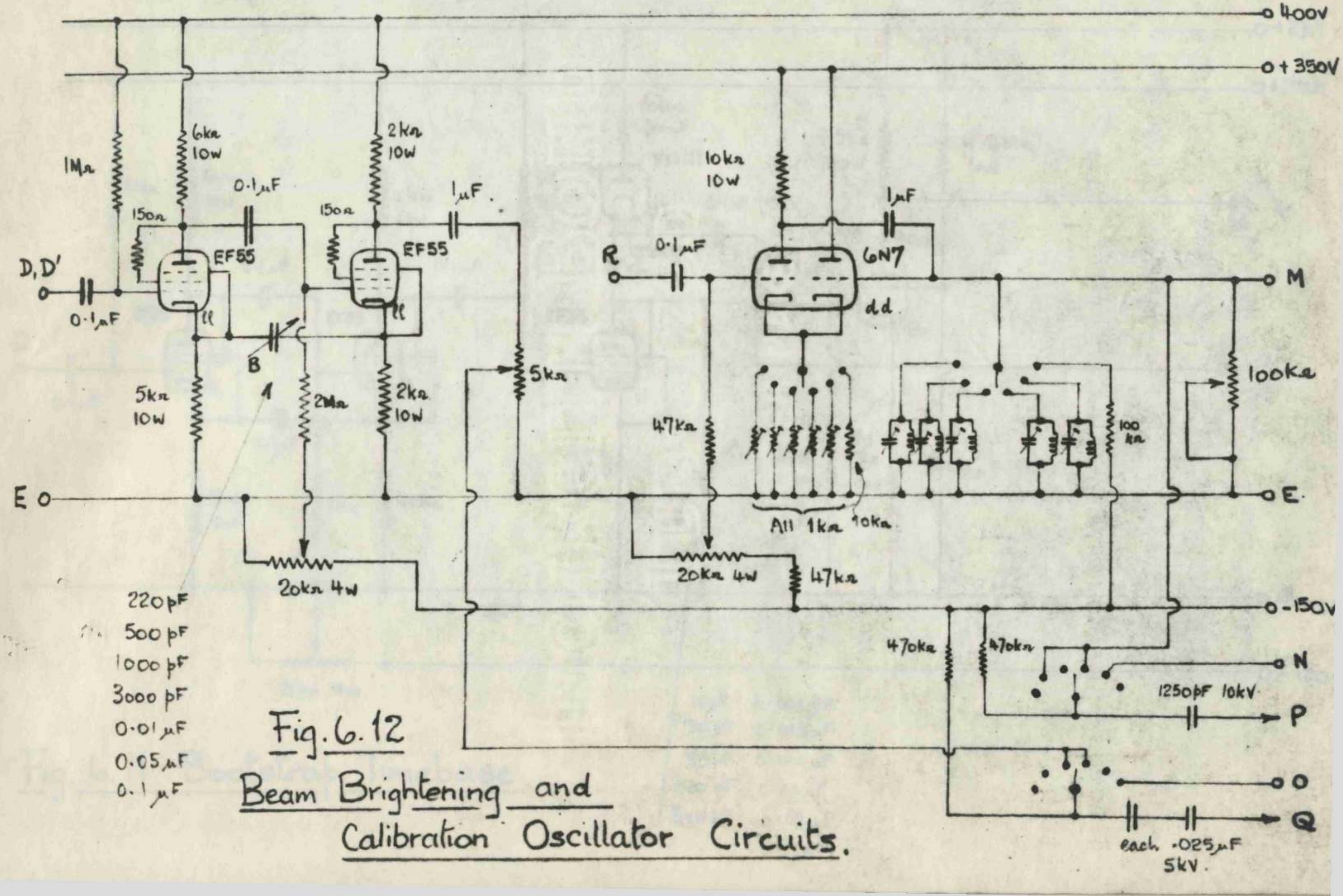


Fig. 6.12

Beam Brightening and

Calibration Oscillator Circuits.

Chassis No.2:

Fig. 6.11 shows the timebase "gate" multivibrator and the bootstrap timebase*. Negative triggers are available at D to actuate the monostable "gate" multivibrator which is rather unusual in having the cathode coupling and timing circuits combined. The particular advantage of this circuit is in the generation of very short pulses (often <1 μsec), and although this feature is relatively unimportant here, the circuit is uniform with that used for beam brightening (Fig. 6.12) where short pulses may be required. The stable state is with the first of the EF55s conducting and the other cut-off. Negative triggering causes the first anode and consequently the second cathode to rise in potential, the cathode coupling to the first valve providing the regenerative path. The capacitor coupling the cathodes now charges, current flowing through the second valve and the cathode resistor of the first, causing the cathode potential to fall exponentially towards earth potential until the first valve is no longer cut off and the second regenerative transition takes place. The

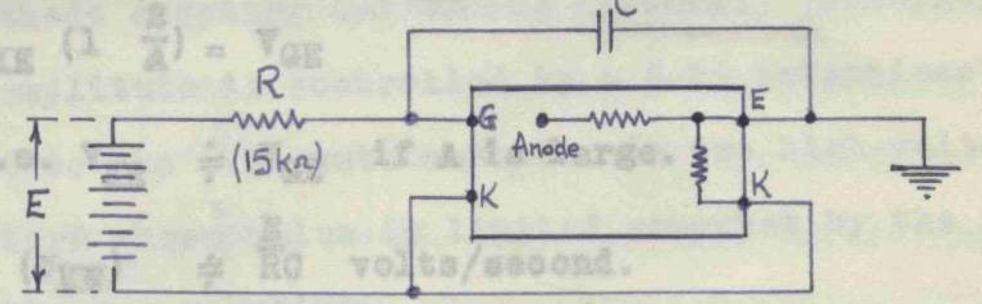
---

* See Reference 2, pp. 131 to 136 ; Reference 1, page 135 et seq.; Reference 3, pp. 35, 267 ; and Reference 216.

exponential timing action is largely a function of the values of the capacitor coupling the cathodes and the cathode resistor of the first valve. EF55 valves are used due to their exceptionally high mutual conductance and their heavy pulse current rating (about 1.5 amps.).

From the anode of the second EF55, a negative pulse, of low impedence, is obtained which cuts off the EF55 switch valve (otherwise held conducting by the 3.3 MΩ resistor to the 2kV supply) of the timebase proper. Before the negative gating pulse is applied the EF55 switch valve is conducting heavily so that there is a very small potential across the capacitor in parallel with the switch valve; the VU111 diode is conducting and the 0.1 μF capacitor between the VU111 cathode and the CV73 cathode charges to the diode-earth potential. When the "gate" pulse cuts the switch valve off, the selected capacitor of the bank in parallel with the switch valve begins to charge, but as this happens the cathode potential of the CV73 rises also (cathode follower effect) taking the cathode of the VU111 diode more positive than previously and cutting off current through it. The 0.1 μF capacitor, which is fully charged, now acts as a battery, providing the potential for the charging of the smaller capacitor of the bank through the 15 kΩ resistance.

In the conventional bootstrap circuit, the anode of the CV73 would be connected directly to the H.T. supply line, that is effectively to A.C. earth potential, and the output may be taken from the CV73 cathode say. The effect of adding an anode load resistor from which an inverted time-sweep waveform may be derived to give a push-pull timebase, is to reduce somewhat the effect of negative feedback in linearizing the waveform. Considering the block representation of the amplifier as follows:



Initially $V_{GK} = V_{GE} = V_{KE} = 0$

and E is ineffective

When circuit is gated, E is effectively applied and C begins to charge at a rate of E/RC volts/second. The potential of G with respect to earth tends to differ from that of K with respect to earth so producing an input to the amplifier as follows:

$$V_{KE} = V_{GE} - V_{KE}$$

and $V_{KE} \doteqdot \frac{A}{2} V_{GK}$ say, if the anode and cathode load resistors are of similar value. A, the stage gain, is taken positive here.

$$\therefore V_{KE} = V_{GE} - V_{GK}$$

$$= V_{GE} - \frac{2V_{KE}}{A}$$

or $V_{KE} \left(1 \quad \frac{2}{A}\right) = V_{GE}$

i.e. $V_{KE} \doteqdot V_{GE}$ if A is large.

and $\frac{d}{dt} (V_{KE}) \doteqdot \frac{E}{RC}$ volts/second.

For the conventional boots-trap circuit, an analysis may proceed on similar lines leading to the expression:

$$V_{KE} \left(1 + \frac{1}{A} \right) = V_{GE}$$

so that V_{KE} more nearly follows V_{GE}.

One assumption which has been made is that E is constant, and to ensure as far as possible that this is so, the capacitor between the diode and CV73 cathodes should be large compared with C, i.e. the capacitor of the switched bank, if linear time-sweeps are to be obtained. In the actual circuit (Fig. 6.11) some departure from linearity and reduction in timebase waveform amplitude is to be expected on the slower timebase ranges.

In Fig. 6.12, the beam modulation multivibrator and calibration oscillator circuits are shown. The monostable multivibrator which provides negative pulses of selected durations to the C.R. tube cathode is similar to the timebase "gate" multivibrator already described, except that a switched bank of capacitors is used in the cathode coupling and timing network. Modulation pulse amplitude is controlled by a 5-kΩ potentiometer and fed to the C.R. tube cathode via two high-voltage capacitors whose value is limited somewhat by the space available for mounting.

The circuit associated with the 6N7 double-triode in Fig. 6.12 is the Calibration Oscillator providing five frequencies of constant amplitude pulsed oscillations. In the quiescent (non-gated) condition, the second half of the 6N7 is conducting heavily and the first half is cut off. The tuned circuit selected by the frequency selection switch is effectively damped by the low grid-to-earth impedance of the second section of the valve. A positive "gate" pulse turns the first section "on", and tends to turn the second section "off" but this latter action is not completely successful. Due to the pulse on the grid of the second section, the selected tuned circuit "rings", and sufficient regeneration may be obtained by adjustment of the common cathode resistance of the 6N7 to causing this "ringing" oscillation to maintain its amplitude. It will be noted that there are separate regeneration adjustment controls for each frequency range. In practice, this circuit requires careful setting up as the amplitude of the gated pulse (controlled by the cathode resistance of the EF55 cathode-follower driver stage), the bias on the first section of the 6N7, and the regeneration adjustment are inter-related. However, of many pulsed oscillator circuits investigated, this particular variety has given the most satisfactory service at frequencies up to 12Mc/s. Examples of pulsed oscillators and the theory associated with the oscillation are considered in Reference 1; Reference 2, page 146; Reference 3, page 140; and Reference 6 page 191.

Also in Fig. 6.12, the Modulation Selection switching is shown in the lower right hand corner. The line P goes to the C.R. tube grid and the line Q to the cathode. The selector positions are: Off; Calibration Oscillator only; Modulation (brightening) Pulse only; Calibration Oscillator and Modulation Pulse simultaneously; External Modulation

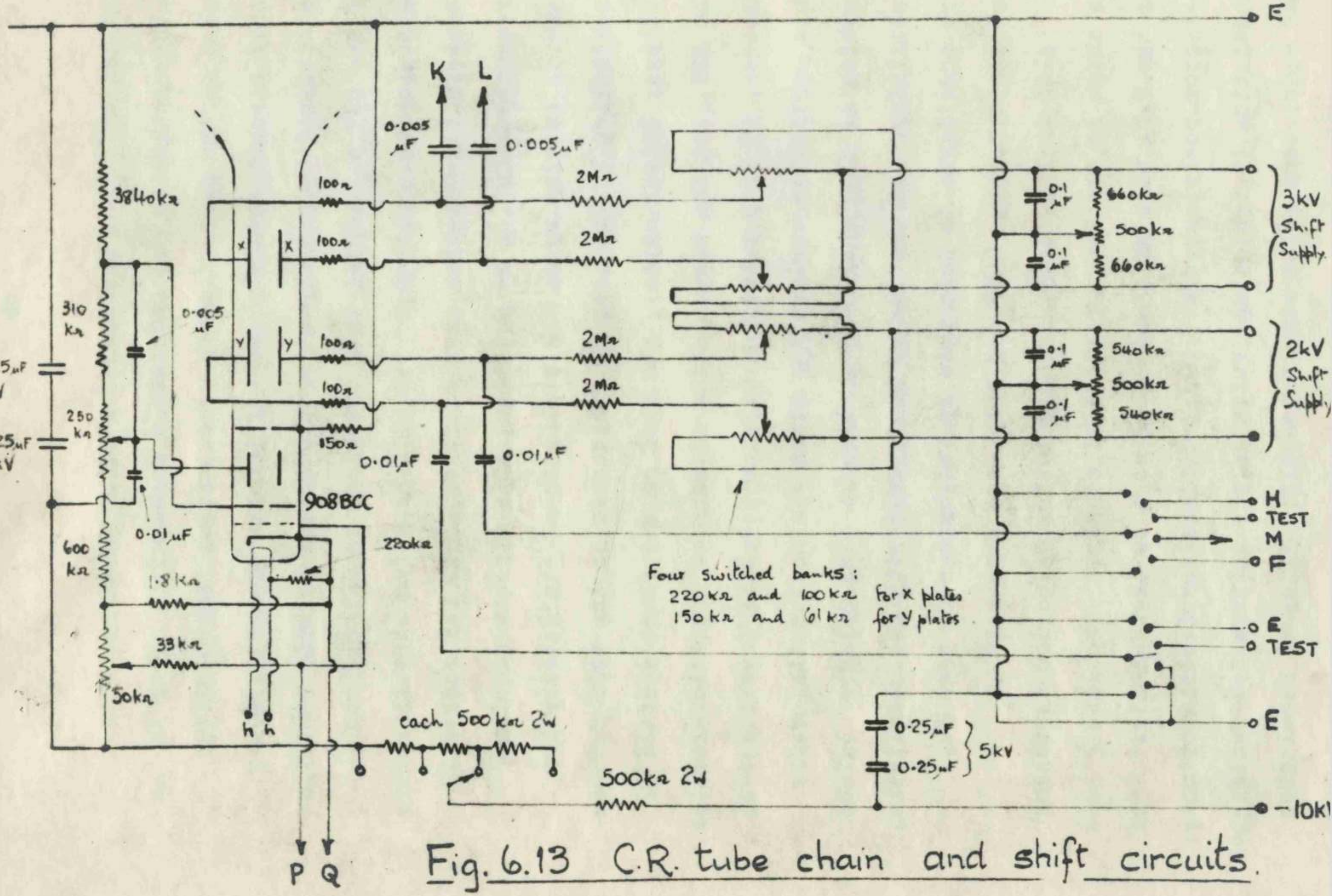


Fig. 6.13 C.R. tube chain and shift circuits.

to C.R. tube grid; and External Modulation to C.R. tube cathode. The last two positions are included for convenience for some future use if desired.

Fig. 6.13 shows the circuits associated with the C.R. tube itself. The supply chain is designed for the full 10kV across it, and to give the potentials at various electrodes as recommended by the manufacturers of the tube. Extra series resistance can be inserted to reduce the overall potential slightly. Smoothing of the 10kV supply is accomplished by a π-network, the capacitor arms each consisting of two 0.25μF, 5kV working capacitors in series, and the resistive arm of at least 500 kΩ. The shift arrangements for X and Y plates are fundamentally similar, though different resistor values are used due to the difference in supply potentials. The shift and astigmatism correction circuits are similar to those suggested by Puckle (Reference 2, page 236) for push-pull working, the shift ganged-potentiometers varying the potentials on any pair of plates symmetrically, and the astigmatism correction setting the mean level of the plates with respect to earth. "Stopper" resistors are mounted immediately at each deflection plate terminal to damp any resonances due to wiring inductances and inter-plate or wiring capacitances.

The Y-selector switching is shown in the lower right-hand corner of Fig.6.13. The consecutive positions are: Off; Impulse/Pulse Generator output (H and E); any two associated Test Points external to the apparatus (these are connected to the Y-plates without application of an "earth"); Calibration Oscillator; Impulse/Pulse Generator triggering waveform; Off. It will be noted that the time calibration of a waveform may be made either by modulating the waveform by the positive peaks of the calibration oscillation to give a dotted trace, or in the case of photographic records by exposing first to the waveform, and secondly to the oscillation applied to the Y-plates instead of the waveform. The latter method is normally used when making oscillograms, further exposures enabling amplitude calibration bars to be recorded as well. For visual adjustments, e.g. to the waveshape, and direct observation generally, the dotted display is desirable.

Fig. 7.1. Close-up view of controls on Chassis 1, 2 and 3.

Chapter 7

Operation of Model "B"

This chapter is concerned with the normal operation of the equipment, and also with the setting-up procedure for various circuits. With the Main Switch "on", the first five individual switches on Chassis No.6 are closed (working from left to right), followed by the first two individual switches on Chassis No.5. When the "General H.T." indicator lamp lights up after approximately 45 seconds, the third and fourth switches on Chassis No.5 may be closed and the timebase and calibration oscillator circuits adjusted.

With the timebase range (TB) control on position 6 say (see Fig.7.1), the Calibrator Frequency (CF) control on position to (i.e. "off"), and the 'Modulation Selector (MS) control on MP, the Main Trigger (MT) control is rotated clockwise until a steady 50 c/s repetitive time-sweep is observed on the C.R. tube face. To position this time-sweep, adjustment may be required to the shift controls (X and Y); and to obtain correct setting of the brightness the general brightness level (B) control should be set so that only the initial "dot" of the time-sweep is visible, further adjustment being by the Modulation

Amplitude (MA), Modulation Duration (MD) and Focus (F) controls. The anti-astigmatism pre-set controls are to be found on the chassis brackets supporting the panel of Chassis No.2 and access is obtained by opening the side doors of the enclosed rack (the Y astigmatism correction control is most effective).

There are five calibration oscillator ranges, position 6 being "Off". The frequencies chosen at present are 250 kc/s, 1 Mc/s, 5Mc/s and 12 Mc/s, selected by the Calibration Frequency Control (CF), and of amplitude determined by the Calibration Amplitude (CA) knob. At the rear of Chassis No.4 there are three pre-set controls, one without a knob affecting the "gate" multivibrator duration, and one also without a knob next to the first the bias potential on the EF55 cathode-follower. A third spindle, with a knob, controls the value of the EF55 cathode resistor and hence the "gate" pulse amplitude. With the highest frequency range selected, this latter control is adjusted in association with the 6N7 bias potentiometer (next to the valve) and the appropriate regeneration control to obtain an oscillation of maximum constant amplitude. Adjustment for the other four frequency ranges is made using the regeneration (cathode coupling resistance) control only. The calibration oscillator circuitry with plug-in coils, pre-set capacitors and cathode coupling resistors is at the right-hand side of Chassis No.2 (looking at front of equipment).

The frequency of any selected range may be checked by link coupling the chosen inductance with the plug-in coil of a Marconi Instruments Absorbtion Wavemeter type TF975, and tuning the wavemeter until a small deflection is observed. This method is effective despite the relatively small duty ratio of the oscillator, but the link coupling must be very loose otherwise loading may affect the frequency of oscillation. An alternative method is to tune a nearby radio receiver over the range of frequencies expected, so that the energy radiated "closes" a tuning indicator display or gives maximum volume of the 50 c/s component.

When the timebase, modulation and calibration circuits are operating satisfactorily, attention may be given to the Impulse/Pulse Generator. The sixth switch on Chassis No.6 is not normally closed until the valve heaters have been "on" for three to five minutes (the delay switching here is really a protective arrangement, and is not normally required to close the circuit, especially on full load). The Generator Trigger (GT) control is normally set ~~fully clockwise~~ at mid-position, the trigger shaping network control (WC) to position 7, the System Switch (SS) to -I, the Generator

Amplitude (GA) control to position 4, and the waveshaping controls on the front and tail capacitors and resistors (C_F, C_T, R_F and R_T) to any desired positions. There are two knobs marked GD (Generator Delay), the twelve position switch selecting delay line tappings, and the continuously variable control affecting the bias of one of the Z77 cathode-follower-stages. The latter control should initially be fully anti-clockwise, and the step-by-step selector altered until the approximate positioning of the trace is obtained, whereafter fine control of positioning is made using the bias potentiometer.

Desired waveshapes are set up quite quickly by modulating the C.R. tube grid with a suitable calibration frequency to give a dotted trace. In this way the time to half amplitude of the tail may be quickly assessed, and also in most cases an approximate estimate of the front rise time. For general work, the tail capacitor (C_T) is set to position 1 for 5 μsec tails and position 3 for 50 μsec tails, the fine adjustment being made by the tail resistance (R_T) control. Front times less than 1 microsecond are usually desirable and the front capacitor (C_T) control is commonly at position 7, i.e. with no intentional capacitance included. Again, fine control is obtained using the front resitor (R_F) selection. Chopped waves require setting the System Switch (SS) to

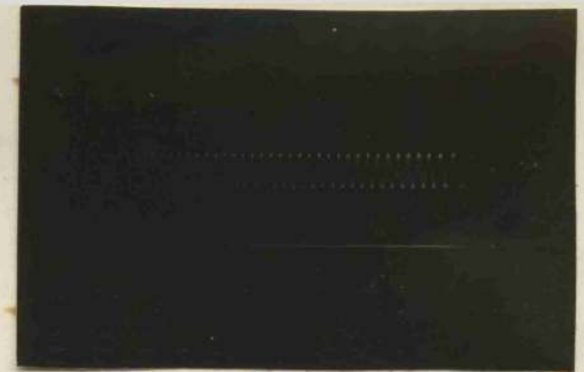
-IC, and time-to-chop is then varied using the Chop Delay (CD) knob.

There are various pre-set potentiometers mounted on Chassis No.3. The second and third trigger generators have bias potentiometers similar to that of the first trigger generator (the Main Trigger control, MT), and these are adjusted to give 50 c/s firing under all conditions of delay circuit settings. The Z77 cathode-follower stage associated with the timebase triggering also has a bias potentiometer which admits positioning of the displayed waveform in a similar manner to the front-panel control, but once set to give stable triggering of the second trigger generator, no further variation is normally made. On the right-hand chassis bracket is mounted a small variable resistance which permits matching of the effective load on the pulse generator ("Direct Pulse" operation) to the pulse forming network to avoid reflections beyond the injected pulse.

Operation of the pulse generator facilities is as follows: "Direct" or "Amplified Pulse" operation must first be selected by moving the tail capacitor (C_T) and System Switch (SS) controls in unison to the correct positions The Generator Amplitude (GA) knob affects the pulse amplitude when utilizing the "Direct Pulse" facility, and the pulse shape slightly when on "Amplitude Pulse" working (GA positions 2 to 4 are considered best in this latter case). The Pulse Amplitude (PA) switch varies the amplitude only on "Amplified Pulse" operation.

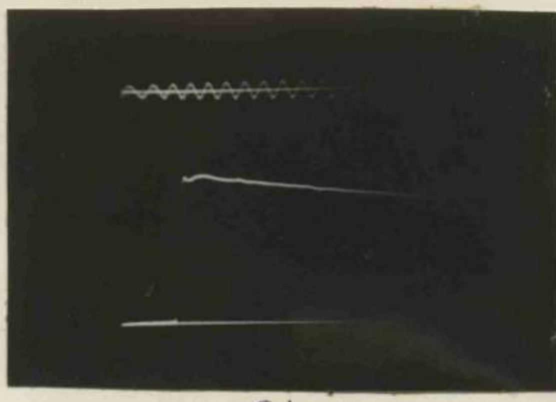
Other pre-set potentiometers are found on Chassis No.2 controlling the bias for the beam brightening multivibrator (under the C.R. tube base cap), and for the timebase "gate" multivibrator (on the left-hand side of the chassis); also on Chassis No.6 associated with the General H.T. valve stabilizer circuit where the settings are determined for minimum hum, and stable operation under conditions of varying load and/or mains voltage.

Should it be desired to check the symmetry of the push-pull timebase waveforms the following procedure may be adopted using a Cossor Model 1035 Double Beam Oscillograph. Two identical resistive dividers are made up which do not effectively load the timebase outputs, but which have fairly low value lower arms (e.g. 47 kΩ/10 kΩ) and the divided timebase outputs are fed directly to the Y-plates of the oscillograph. A shift circuit will be operative in the case of the Y_2 beam, but an external shift circuit will be required for the Y_1 beam. Since the deflection sensitivities for both beams are equal, and since there is a natural inversion effect on one of the inputs due to the earthed beam splitter plate being between the signal plates, the traces appear to be of the same sense, and should be coincident for symmetrical operation,

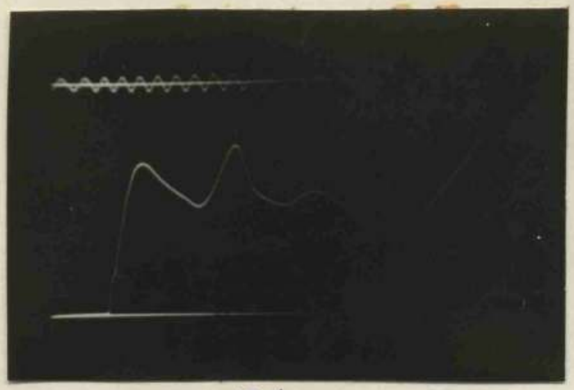


8.1a

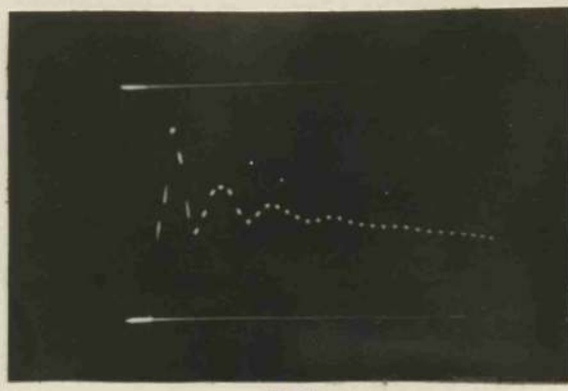
8.1b



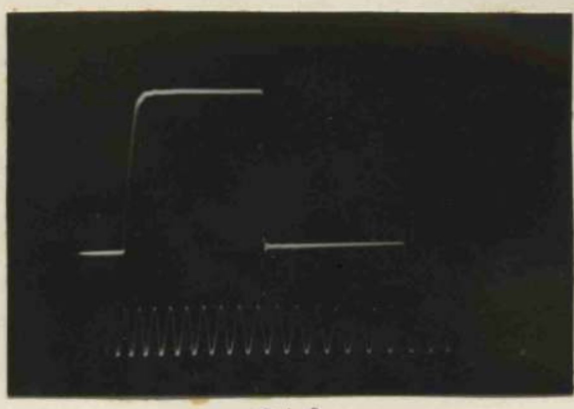
8.1c



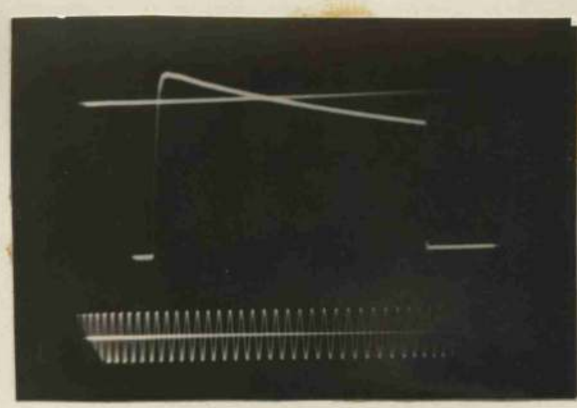
8.1d



8.1e



8.1f



8.1g.

Fig. 8.1 Various Oscillograms
(see text)

Chapter 8

Proving Tests and Methods

In many cases, the applications of the R.S.O. are such that it is difficult to "prove" the working of the equipment in the truest sense, since mathematical or alternative experimental analyses of windings, etc., are difficult to carry out. The series of tests described in this chapter are therefore rather more demonstrations of the applications and the versatility of the equipment. In fact, it is difficult to imagine where errors might occur, except perhaps due to the wiring and deflector plate capacitances and at very high frequencies.

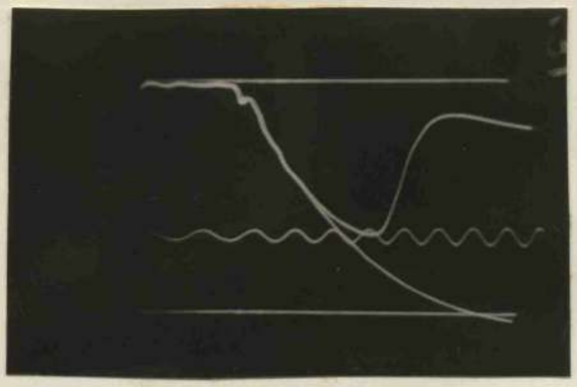
Typical display:

Firstly, the performance of the instrument itself will be considered. Fig. 8.1a shows a medium speed timebase (TB6) with a 2.5 Mc/s calibration wave and it will be observed that except at the start of the time-sweep, reasonable linearity is obtained. The vertical calibration bar is displaced 75 volts from the axis of the sinusoid. Fig. 8.1b illustrates the fastest normal rise of front obtainable displayed on the fastest time-sweep (TB1), about 0.3 μsec, with the highest frequency calibration wave - 12 Mc/s. The crest amplitude of the impulse, 510 volts, was measured from a separate vertical calibration oscillogram. An exposure of about ½ second (25 superimposed traces) was used, and it will be noted the jitter is completely unobservable. Fig. 8.1c and 8.1d show typical waveforms obtained when testing a disc winding (see Appendix A) having 22 tappings, the oscillograms referring to tap 22 (full wave) and tap 19 respectively, and the latter one showing a second crest of amplitude in excess of the applied wave.

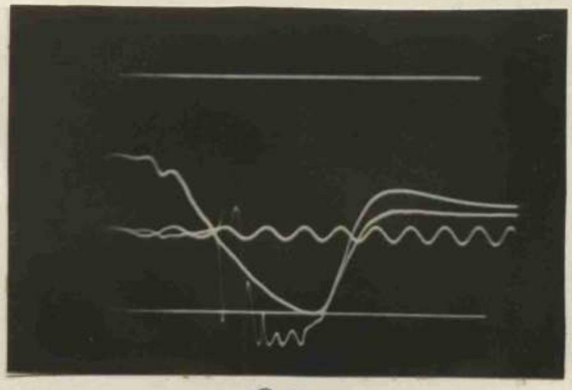
The dotted (calibration modulated) display is featured in Fig. 8.1e, the oscillogram indicating the waveform at tap 12 of the disc winding with a 1/50 wave applied, and with a calibration frequency of 250 kc/s. Figs. 8.1f and 8.1g illustrate 1/50 waves chopped after 8 and 24 microseconds respectively, the chopping transition time being very much less than 1 microsecond. Under short time-to-chop conditions, the front transition is lengthened slightly due to the loading of the chopping thyratron.

Hydrogen Thyratron Tests:

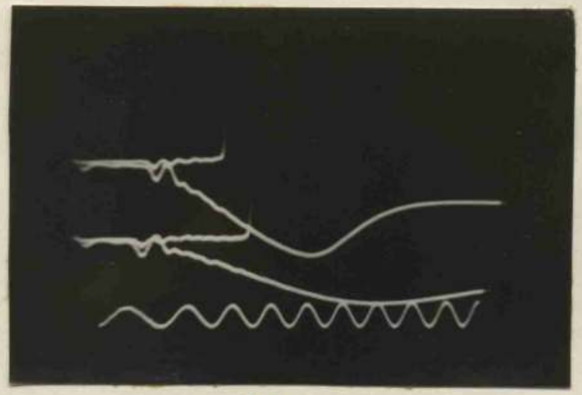
One of the most interesting studies made possible using the R.S.O., was that on the firing characteristics of a BT79 hydrogen thyratron. For this, the normal impulse generator circuit was temporarily modified to give positive impulse waves by including a 600-Ω resistor between the thyratron cathode and earth, and so firing a further experimental hydrogen thyratron having its own charging circuit. The discharge circuit of this second hydrogen thyratron comprised simply a 0.1 μF capacitor, two 600-Ω



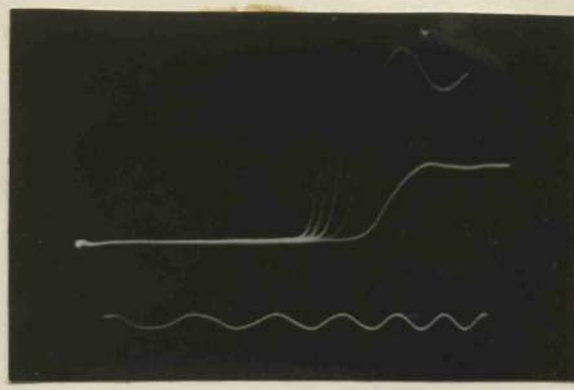
8.2a



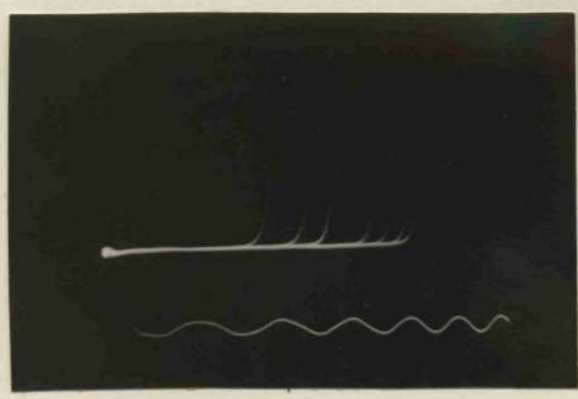
8.2b



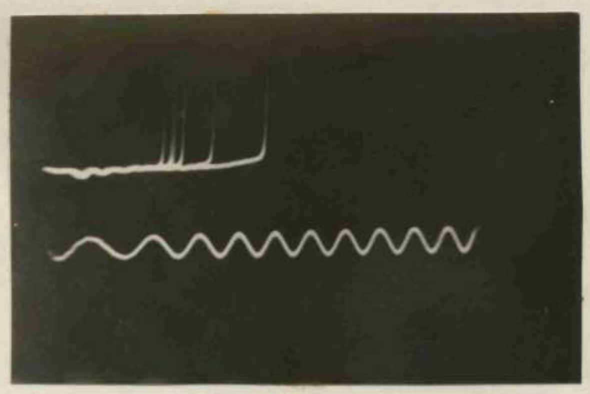
8.2c



8.2d



8.2e



8.2f.

Fig. 8.2. Oscillograms relating to Hydrogen Thyratron tests.

resistors in series and the valve itself. Oscillograms of the main discharge current could be obtained by tapping across the two 600-Ω resistors.

Information on hydrogen thyratrons is rather limited, being confined to the papers of Heins(218), Grolleau(219), and Knight and Hooker(215). Experiments on thyratron firing characteristics have not received wide publicity either, the most applicable papers being by Webster(217), and Germeshaüsen (Section 8.11 etc. of Reference 4) of which the results of the latter author are comparable with those of the present investigation.

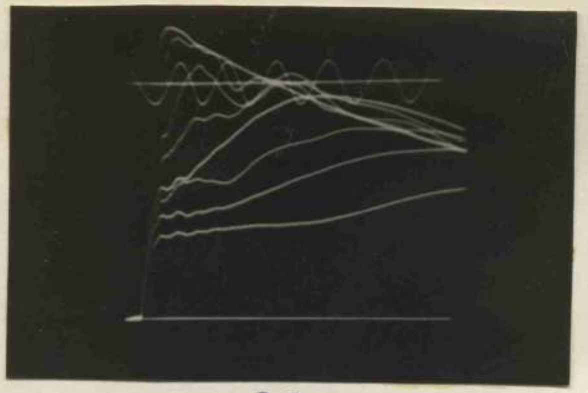
Fig. 8.2a shows the rise of the triggering pulse with the hydrogen thyratron grid disconnected, and with the grid connected but the charging circuit inoperative - the breakdown of the grid-cathode space is clearly indicated. Fig. 8.2b shows the grid waveforms with and without the charging circuit operative, and also the rise of anode current (rather faint) with the charging circuit operative, the typical grid oscillation at breakdown being most evident. Hydrogen thyratrons are generally designed with a positive grid-control characteristic, and to trigger the valve,the grid must be driven sufficiently positive to draw grid current between grid and cathode so that the grid-cathode space ionizes after which the main anode-cathode conducting path is established within about 50 millimicroseconds.

Grid-cathode ionization occurs at a certain grid voltage (which is lowered slightly by the presence of anode voltage), and the delay to firing therefore depends on the rate-of-rise of grid voltage. Fig. 8.2c illustrates this effect which is not necessarily a linear one (Germeshausen). The effect of anode voltage on delay time to firing is demonstrated in Fig. 2d in which the successive charging circuit variac settings were 230(maximum), 190, 150, 110, 70.

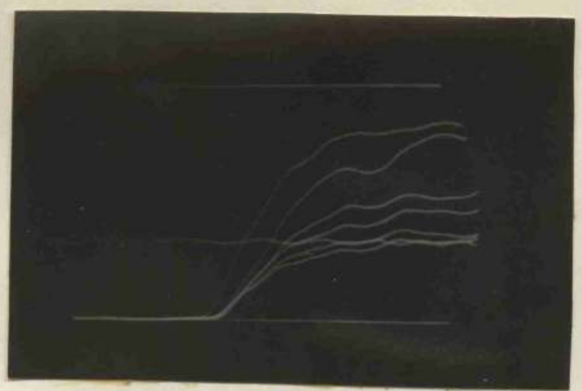
Two further tests concern the effects of the grid circuit resistance and heater current. Unfortunately it was most difficult to measure the actual value of grid circuit resistance under operating conditions, and Fig. 2e therefore shows the delay to start of anode current proportional to grid circuit variable resistance set at 100, 300, 500, 1000, 1500, 2000, and 2500 ohm steps. So far results had merely confirmed Germeshausen's earlier work, but Fig. 2f which shows the delay to start of anode current for heater currents of 2.80, 2.75, 2.70, 2.65, 2.60 and 2.55 amperes seems to contradict his statement that neither hydrogen pressure nor cathode temperature have much effect on the time delay or jitter so long as they are kept within the normal operating range. Knight and Hooker(215) prescribe a tolerance of ±5% in heater voltage, and the variable delay to firing due to changes in heater current well within $\pm 5\%$ is quite noticeable. Indeed, slow drift of an impulse waveform (not a quick jitter) was considered to be due to slow changes in mains voltage, and on some occasions it was necessary to resort to a separately generated stabilized supply when recording high-speed traces.

Transformer Winding Tests:

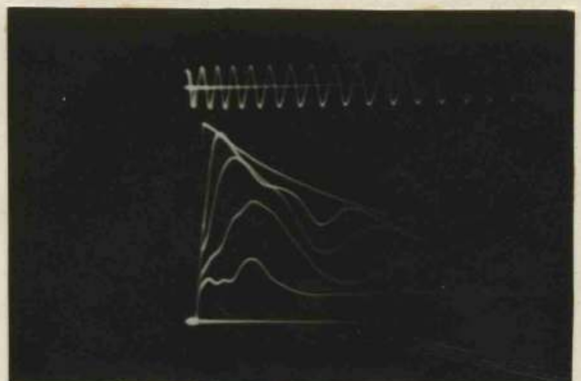
These tests were performed on a small two-limbed transformer having a low voltage winding, and three interchangeable high voltage windings which individually could be slipped co-axially over the low voltage winding before the iron circuit was closed by replacing the top section of the iron path (see Appendix "A"). The three high voltage windings were of the layer (spiral), cross-over, and disc types, all provided with tappings the majority of which were nearer the line ends, Transformer winding tests fall generally into three classes; to find the initial voltage distribution; to find the maximum voltage envelope; and to find any abnormally high potentials between roughly adjacent turns or coils (this latter operation is, of course, giving direct information which might otherwise be obtained indirectly from the first two classes of test, and is rather more amenable to low voltage recurrent-surge testing than to high voltage testing). (See also Reference 308).



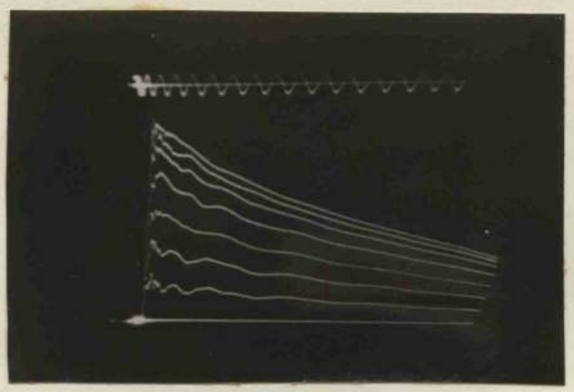
8.3a



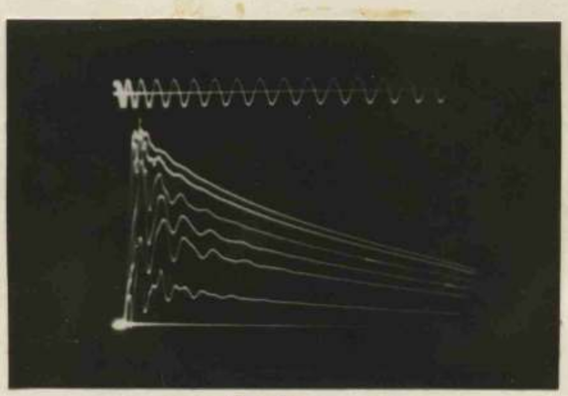
8.3b



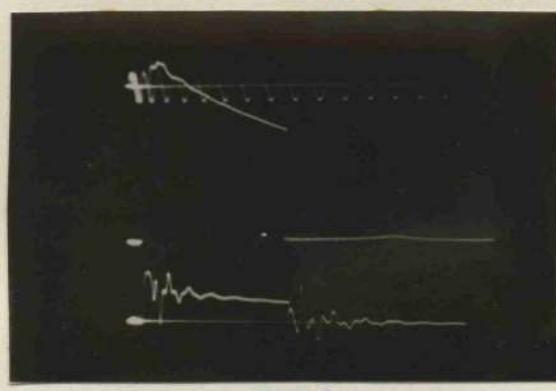
8.3c



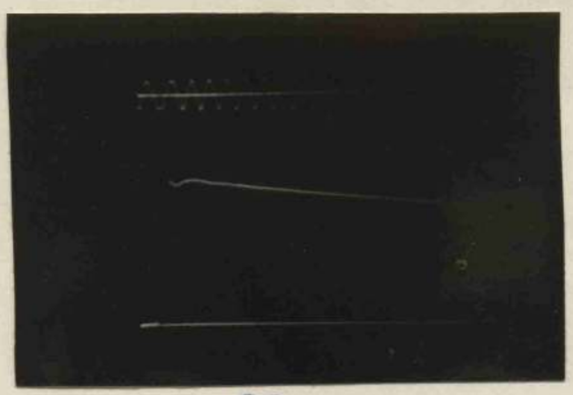
8.3d



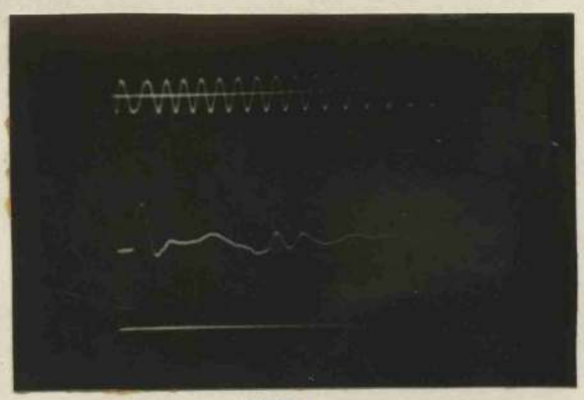
8.3e



8.3f



8.3g



8.3h.

Fig 8.3. Oscillograms relating to Winding Tests.

Examples of oscillograms taken to find the initial voltage distribution in the cross-over type winding are shown in Figs. 8.3a and 8.3b. The former illustrates fairly clearly the kinks (on the waveforms relating to the various tappings) where the initial voltage distribution gives place to the oscillatory condition, while the latter oscillogram uses an expanded timebase to facilitate measurement.

Fig. 8.1d has already indicated that the initial crest value may not be the largest, this being quite a typical condition in the disc winding available. Other tests to obtain maximum voltage envelopes were made with 1/50 waves on a cross-over winding (Fig. 8.3c) and a layer (spiral) winding (Fig. 8.3d). While the oscillogram for the cross-over winding shows very marked oscillations, some of considerable amplitude and therefore requiring adequate turn-to-earth insulation, the layer winding results in practically no oscillation. Fig. 8.3e shows a comparable oscillogram for the disc winding. The mode of connection can affect the oscillograms for maximum voltage envelope derivation very considerably, for example in the case of an isolated neutral, but all the demonstration traces illustrated in Fig. 8.3 are for impulses applied directly across the winding with secondary open-circuited and isolated.

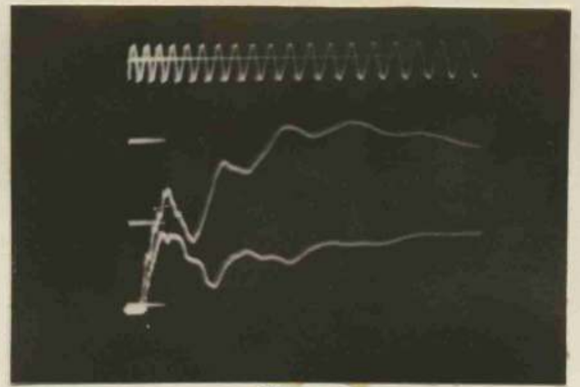
For examples of inter-turn or inter-tapping voltages

Fig. 8.3f is typical and shows a chopped 1/50 wave and the resulting voltage between tappings 22 and 18, i.e. across the first two discs of the disc winding. Fig. 8.3g shows a waveform having a very fast front applied across the whole of the disc winding with an experimental stress control ring very close to the line end disc, and Fig. 8.3h indicates the voltage across the first half-disc only, i.e. between tappings 22 (line end) and 21. The applied impulse has a crest amplitude of 300 volts, and the maximum value of the potential across tappings 22 and 21 is 111 volts so that it is evident that this particular stress control ring is ineffective.

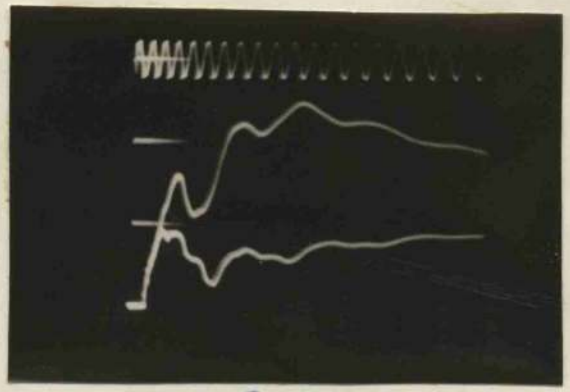
<u>Neutral-Current Tests:</u>

Neutral-current tests have already been described in Chapter 2, and are in effect special impulse tests with the object of fault detection. The efficiency of the method has been considered by several authors, especially Hagenguth(319), and Rippon and Hickling(313), and the purpose of the present investigation was merely to confirm the main features of the previous work as applied to the small experimental transformer available.

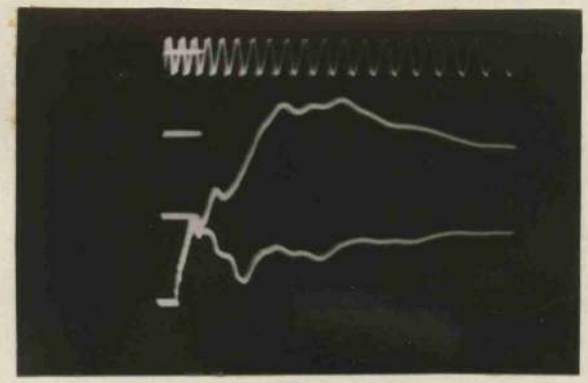
All the neutral-current tests were carried out with a 10-kΩ resistor connected between the winding end remote from the line end, and earth. The impulse waves were applied between the line end of the winding and earth, and the neutral-current oscillograms were recorded from the



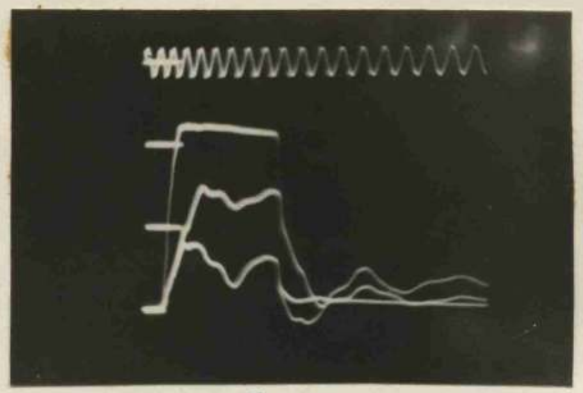
8.4a



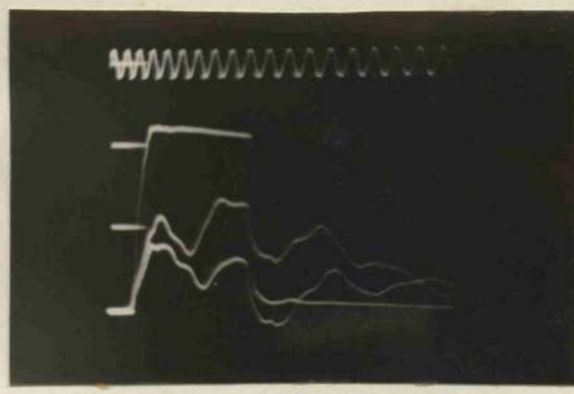
8.4b



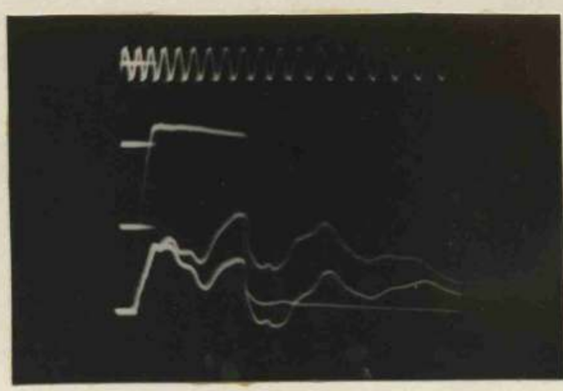
8.4c



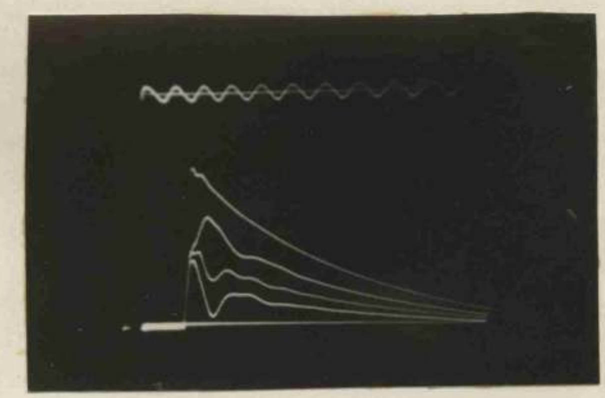
8.4d



8.4e



8.4f



8.4g.

Fig. 8.4. Oscillograms relating to Neutral Current Tests (a to f) and Machine Winding Test (g).

potential across the 10-kΩ resistor. The disc winding was used in all cases.

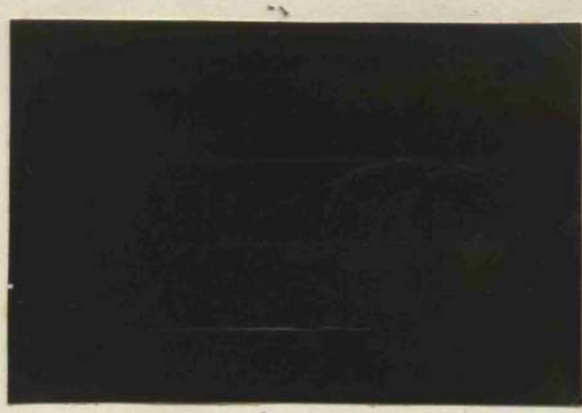
Fig.8.4a shows the waveform (lower of the two traces) of neutral-current with no fault applied as a result of a 0.2/50 wave. The upper waveform is that of neutral-current when a direct short-circuit is applied between tappings 21 and 20. The appreciable indication of fault is very evident. The ability to detect the position of the fault by neutral-current methods has been debated by the main investigators, and in general no reliance is put on results beyond fault indication, and not always to that extent. However, Figs. 8.4b and 8.4c show faults applied between tappings 12 and 13, and between 4 and 5 respectively with obvious differences; to be of use, such records would necessarily require to be compared with a standard set made at the time of manufacture of the transformer.

Figs. 8.4d and 8.4e illustrate the ineffectiveness of applying chopped waves for neutral-current detection work. Fig. 8.4d shows the neutral-current for no fault and the secondary unloaded (lower waveform), while for the secondary loaded by a resistance of 600Ω the middle waveform is obtained, and it will be noted that after chopping the relative effectiveness of the indication is not nearly so marked. Fig. 8.4e indicates the change by inserting a 3-Ω resistance between tappings 21 and 20, but here the post-chop differences are slightly more illuminating. The effect of a coupled short-circuited turn at the bottom end of the winding is demonstrated in Fig. 8.4f, and in this case, moving the turn to the top of the winding gave no appreciable change of indication.

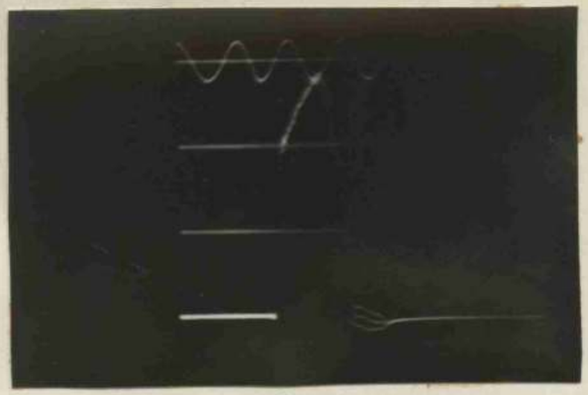
Machine Winding Tests:

Probably the most representative cases for investigation would be those of a D.C. series-field traction motor or a high-voltage alternator. Impulse testing of traction motors has received little publicity, if attention, and it may be that in most cases part of the field winding, of which the insulation might be re-inforced more easily than for the armature, may act as an effective modifier to rapid rates-of-rise. High voltage alternators have been considered recently by Robinson(314, 328) in particular, rather more from a theoretical stand-point than as a testing technique.

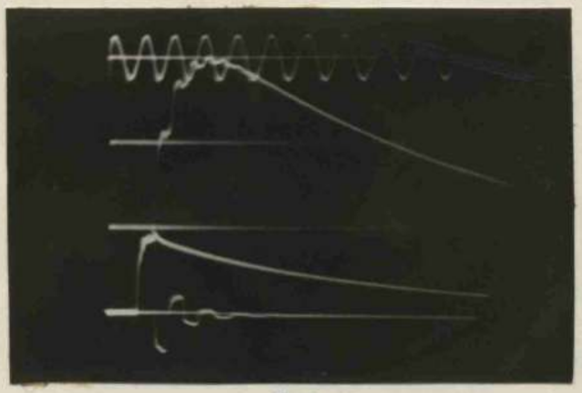
The author had available a small motor-alternator convertor set, and it was decided to withdraw the armature completely for test (for convenience and since the absence of the yoke would make little difference at least to initial distribution). The brush-gear was adjusted for normal operation on the commutator, and impulses applied at the normal terminals. Tappings were made on various commutator segments. Fig. 8.4g shows the result of applying a 1/5 wave to adjacent brushes centred on commutator segments 0 and 19(earthed), with tappings on segments 6, 11 and 14. The



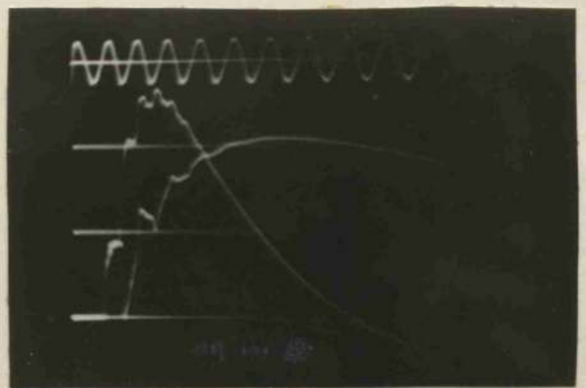
8.5a



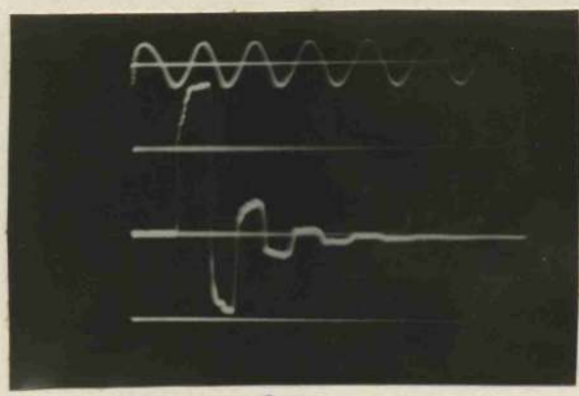
8.5b



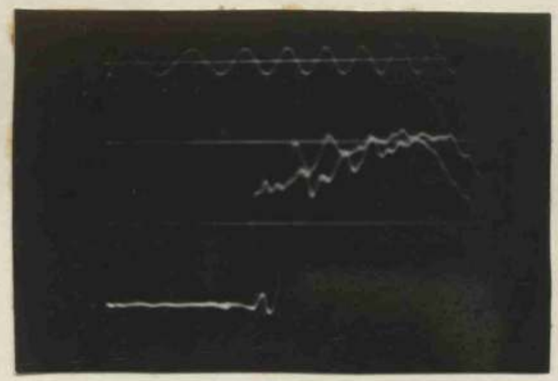
8.5c



8.5d



8.5e



8.5f.

Fig. 8.5. Oscillograms relating to Delay Cable Tests.

inference is that this simple retrogressive wave winding is subject to similar effects as occur in transformer paths despite the alternative paths in the armature, but that in practice, shunt or series elements would modify the severity of the conditions.

Delay Cable Tests:

A further application of the R.S.O. is to the testing of cables, for considerable impedance irregularities or fault location, or in the case of good specimens to determine characteristic impedance and transit time. The properties of various terminations at the far end of a cable in giving significant reflections which may be recorded at the near end are well-known, and it is this technique which applies to the present study.

Three co-axial cables of slightly different characteristics were available: a lead covered solid-dielectric type; a braided-sheath air-space dielectric type; and a braided-sheath solid dielectric type. The first oscillogram, Fig. 8.5a, illustrates the delay (about 0.35 μsec) and front distortion effects of the lead-sheathed cable, the traces being taken at the near and far ends with a terminating resistance of 72 Ω (= Zo) at the far end. The calculated delay time for the 80 yards of cable, using manufacturer's data, is 0.37 μsec. Fig. 8.5b shows how the "Amplified Pulse" facility may be used to determine the characteristic impedance of the air-spaced cable even though the pulse duration is considerably in excess of twice the cable transit time. The three traces, taken at the near end, are taken with "matching" resistances of 97Ω, 102Ω, and 107Ω at the far end, and from which the 102Ω condition is accepted as best. This is also closest to the manufacturer's specification of approximately 100Ω. For the solid-dielectric cable with braided sheath, Fig. 8.5c shows the effect of applying an impulse waveform to the near end with the far end short-circuited (lower squarish waveform), matched (middle impulse waveform), and open-circuited (large stepped waveform), the oscillograms being taken at the near end and with a sending-end impedance somewhat greater than the characteristic impedance. Fig. 8.5d illustrates the result of terminating the line with an inductance of 3mH (stepped wave), and a capacitance of 0.01 μF (waveform with longer front). Fig. 8.5e shows the short-circuited termination case of Fig. 8.5c on a larger scale.

An artificial line was available which had been constructed earlier for experimental purposes, and which consisted of sixteen inductance and capacitance sections ($L = 1.82\ \mu H$, $C = 82\text{pF}$), there being no intentional coupling between inductors. For this line the approximate properties are: $Z_o \doteq \sqrt{L/C} = 150\Omega$; Cut-off frequency $\doteq \dfrac{1}{\pi\sqrt{LC}} = 26.1$ Mc/s; and delay per section $\doteqdot \sqrt{LC}$ = 12.2 mμsec. The overall delay should therefore be 0.195 μsec. Fig. 8.5f shows the input and output (delayed) waveforms, the pulse being generated using the "Amplified Pulse" facility. The most suitable terminating resistance for matching was found by experiment to be approximately 130Ω, while the delay as measured from the oscillogram 0.18 μsec., agrees closely with the theoretical figure.

Reflection tests were also performed on one phase of a three-phase 132-kV pipe-line compression cable as described in Part 2, Chapter 8. Impulse waveforms were found to be most satisfactory in this case, the first in which the transit time was considerably in excess of the impulse/pulse duration. Typical results are discussed in Part 2 and are compared with results obtained by other methods. Some oscillograms are included in Part 2, Appendix D (Nos. D7, D8 and D9).

Chapter 9

Conclusion

A self-contained equipment has been designed for the impulse testing of transformer and machine windings in particular, but as has been indicated, many other high speed repetitive transient phenomena can also be investigated. Compared with previous equipments(103, 104, 105, 108, 109, 110), it is considered that this new instrument, though perhaps larger in physical size, is more comprehensive and versatile than its predecessors: a pulse generator facility is provided for the investigation of networks; calibration facilities for both X and Y axes are directly available; almost continuous variation of impulse wave shape within the normally accepted limits is possible, and other specific requirements can be met by the insertion of suitable circuit elements; the timing sequence associated with trace initiation permits photographic recording of high quality; the 10-kV C.R. tube gives a high-definition trace of adequate brightness for direct visual observation of the fastest time-sweeps in daylight; and unsymmetrical voltages with respect to earth may be displayed with good overall focussing.

The design of such an equipment has introduced several problems, viz. the high-speed high voltage push-pull timebase for repetitive working, the pulsed calibration oscillator for high frequencies, and the impulse generator which will give smooth waveforms and at the same time an exceptionally high rate-of-rise of front. These problems have been successfully solved. Jitter, which was the main obstacle to progress by earlier investigators, has been almost eliminated as a difficulty by the use of the hydrogen thyratron switch, which apart from being a precision timing device, has the added advantage of handling large peak currents though of small physical size. Not only has the hydrogen thyratroh been used in the production of waveforms, but using the R.S.O., its firing characteristics have been superficially investigated, sufficiently it is felt to indicate that a more detailed study of batches of thyratrons (having a variety of gas fillings) working under different circuit conditions might be of value.

Other specialized applications in which the R.S.O. might be utilized, as a complete instrument using the impulse generator or as a repetitive high-speed oscillograph, are photo-electric studies, micro-gap studies in vacuum or in gases under various pressures (some work concerning automobile sparking plugs has been undertaken by the E.R.A. (108)), and indeed any subject where repetitive operation is possible and where, for example, de-ionization and similar after-effects are complete before the next cycle commences. Originally, it had been intended to incorporate a single-stroke facility, and such working is still possible in some cases by injecting positive triggering signals to the first trigger generator; the timebase circuit however, being designed for repetitive operation, may give distorted displays under such circumstances.

The equipment was designed at the time when the normal sized valve was beginning to be replaced for many purposes by the miniature valve, and in any future designs it is likely that much space could be saved in this way. Typical changes in valves which might be made would be the Mullard 2D21 for the B.T.H. BT19 thyratron, the Mullard ECC82 for the 6SN7, and the Brimar 6CH6 for the Mullard EF55. For the 10-kV supply to the C.R. tube, a high-frequency oscillator/rectifier arrangement, now accepted as fully reliable and commercially obtainable, would probably realize a saving in space, but it is doubtful if the other power packs could be appreciably reduced in size or weight. The bootstrap timebase circuit herein described has proved very reliable but it requires a considerable power supply; also, it was designed before confidence had been established in hydrogen thyratron operation, and the author now considers that a timebase such as that described by Hardy(211) would probably be less bulky and require less power. The 908BCC C.R. tube has been most satisfactory and so far the only advance which might be suggested is the use of one of the high-speed multi-beam tubes which are becoming available. For fine focus, and low repetition frequencies, the seemingly high accelerating voltage of 10kV is fully justified, and the author sees little advantage in the use of post-deflection acceleration tubes in an R.S.O., except perhaps for the examination of small inter-turn voltages, a requirement which could be equally well catered for using a good pulse amplifier.

With regard to repetition frequency, experiments were undertaken to produce an impulse generator circuit working at 250 c/s. The arrangement comprised an astable multivibrator operating at the desired recurrence frequency, gating two Mazda 12E1 tetrodes in parallel to allow impulse generator charging during one half of the cycle from a D.C. supply, and permitting timebase and impulse generator triggering during the other half-cycle. The limit of this arrangement seems to be the convenient power which may be switched by the 12E1 valves, so that impulse amplitude is restricted. The maximum recurrence frequency desirable is about 500 c/s in the author's opinion, and an equipment designed to operate from a 500 c/s supply would differ little from the 50 c/s design herein described, except that a small alternator set would be required additional to the equipment. Taking these factors into account, and in view of the satisfactory performance of the 50 c/s design, it is considered that the lower acceleration potential allowable in obtaining adequate trace brilliance with a 500 c/s design is not sufficient to justify a recommendation for a higher repetition frequency. The method of displaying impulse waveforms and calibration oscillations alternately, each 50 times a second, on a 100-c/s repetitive timebase is however considered commendable.

An experimental Subtractive Voltage Divider similar to that described by Foust and Rohats(307), and with a pulse amplifier, has been built, but for most purposes, direct recording of voltages between tappings removed from earth has been satisfactory, provided astigmatism correction is available. The conclusion is that the additional complication of the Subtractive Voltage Divider is not generally warranted. No capacitance tapping circuits similar to those described by Robinson and Gray(102) have been investigated.

For all normal purposes, the range of time-sweeps from about 0.3 to 150 microseconds has proved adequate, but for certain windings having low natural frequencies and for long cables, say of three or four miles in length, the extension of time-sweep ranges beyond 150 microseconds would be desirable. This could be attained by modifying the timing circuit of the bootstrap timebase, or by extending the ranges of, say, Hardy's circuit if a new design were contemplated. A corresponding increase in modulation pulse duration would also be necessary, but then such operation is equally within the field of many commercially made oscillographs whose attributes the present R.S.O. was never intended to have.

Chapter 10

Bibliography

Textbooks:

1. Cathode Ray Tube Displays - M.I.T. Radiation Laboratory Series No.22. (McGraw Hill, 1948)
2. Puckle, O.S. - Timebases. (Chapman and Hall, 2nd Edition, 1951)
3. Waveforms - M.I.T. Radiation Laboratory Series No.19 (McGraw Hill, 1949).
4. Pulse Generators - M.I.T. Radiation Laboratory Series No.5 (McGraw Hill, 1948).
5. Bewley, L.V. - Traveling Waves on Transmission Systems. (Chapman and Hall, 2nd edition, 1951).
6. Zeluff, V., and Markus, J. - Electronics Manual for Radio Engineers - (McGraw Hill, 1949),
7. Surge Phenomena - Seven years research for the Central Electricity Board (ERA Reference S/T35, 1941).

<u>R.S.O. and Impulse Generator Circuits:</u>

101 Eaton, J.R. and Gebelein, J.P. - Circuit Constants for the Production of Impulse Test Waves
(Gen. Electric Rev. 43, p.322, 1940)

102 Robinson, B.C. and Gray , A.- A new Method for the Measurement of Surge Voltages in Windings.
(Proc. I,E.E. Part II, 100, p.38, 1953)

103 Rohats, N. - The Oscillograph Electric Transient Analyzer. (Gen. Electric Rev. 39, p.146, 1936)

104 Rohats, N. - A New Instrument for analyzing Electric Transients. (Gen. Electric Rev. 45, p.121, 1942)

105 Scoles, G.J. - A Recurrent Surge Oscillograph.
(Jour Sci.Insts. 15, p.201, 1938)

106 Thomason, J.L. - Impulse Generator Circuit Formulas.
(Electrical Engineering, A.I.E.E. 53, p.169, 1934)

107 Thomason, J.L. - Impulse Generator Voltage Charts for Selecting Circuit Constants. (Electrical Engineering A.I.E.E., 56, p.183, 1937)

108 White, E.L. - A New High-speed Recurrent Surge Oscillograph. (Jour.Sci.Insts. 20, p.125, 1943)

109 White, E.L. and Netheroot, W. - The Recurrent - Surge Oscillograph and its application to the study of Surge Phenomena in Transformers.

(Proc. I.E.E. Part II, 96, p.269, 1949)

110 Wilkinson, K.J.R. - Recurrent-Surge Oscillographs, and their application to short-time Transient Phenomena. (Jour.I.E.E. 83, p.663, 1938).

110 Ducastel, G. - Recurrent - Surge Generator and Oscillograph for the study of Transformers under surge conditions, (IN FRENCH)

(Rev. Jeumont 43, p.15, 1950)

112 D' Eeckenbrugge, G.C. - L'oscillographe cathodique à récurrence; son application à l'étude des phénomènes ultrarapides.

(Rev.Gen.Elect. 53, p.159, 1944)

Oscillography:

201 Bartlett, J.G. and Davies, G.T. - The Design of High-Speed Oscillographs. (Jour.I.E.E. Part IIIA, 93, p.1304, 1946)

202 Bauer, R.E. and Nethercot, W. - A New Oscillograph for recording very fast Electrical Transients (E.R.A. Report U/T 115, 1949)

203 Forrest, J.S. - Applications of the Cathode-Ray Oscillograph to Electric Power Systems. (Jour.Sci.Insts. 20, p.69, 1943)

204 Miller, J.L. and Robinson, J.E.L. - The High-speed Cathode-Ray Oscillograph (Reports of Progress in Physics, 2, p.259, 1935)

205 Nethercot, W. and White, E.L. - High-speed transient recording with the sealed-off glass Cathode-Ray Oscillograph (CIGRÉ Report No.126, 1946)

206 Prime, H.A. and Ravenhill, P. - The Design of a High-speed Oscillograph (Jour.Sci.Insts. 27, p.192, 1950).

207 Rohats, N. - High Speed Oscillograph. (Electronics 19, p.135 of No.4, 1946)

208 White, E.L. - The Design, Construction and Performance of a New High-speed Cathode Ray Oscillograph for Recording High-Voltage surges. (E.R.A. Report S/T 70, 1950)

209 White W.G. - Cathode-Ray Tubes with Post-Deflection Acceleration (Electronic Engineering 21, p.75, 1949).

210 McGillewie, D.I. - The Use of the High-vacuum Cathode-Ray Tube for recording high-speed Transient Phenomena. (Jour.I.E.E. 83, p.657, 1938)

211 Hardy, D.R. - A high-speed transient recorder. (Jour.Sci.Insts. 29, p.241, 1952)

212 Briggs, B.H. - The Miller Integrator (Electronic Engineering 20, p.243, 1948, et seq.)

213 Moody, N.F. and Maclusky, G.J.R. - Millimicrosecond Pulse Techniques (Part 2); A High Speed Oscillograph (Electronic Engineering 24, p.287, 1952).

214 Prime, H.A. and Saxe, R.F. - The Recording of Optical Transients (Proc. I.E.E. Part II, 96, p.662, 1949).

215 Knight, H. de B. and Hooker, O.N. - The Hot Cathode Hydrogen Filled Thyratron. (B.T.H. Research Laboratory Report RLP203).

216 Sowerby, J. - The Bootstrap Circuit. (Wireless World, 55, p.92, 1949).

217 Webster, E.W. - Note on the Ionization Time of an Argon-filled relay. (Jour.Sci.Instrs. 24, p.299, 1947).

218 Heins, H. - Hydrogen Thyratrons. (Electronics 19, p.96 of No.7, Jul. 1946).

219 Grolleau, M.J. - Les Thyratrons à Hydrogène. (Bull.Soc. Fr. Elect. 9, p.525 , 1949).

Surge Phenomena and Impulse Testing, etc:

301 Allibone, T.E., Hawley, W.G., and Perry, F.R. - Cathode - Ray Oscillographic Studies of Surge Phenomena (Jour.I.E.E. 75, p.670, 1934)

302 Allibone, T.E. and Perry, F.R. - Standardization of Impulse - Voltage Testing. (World Power 24, p.287, 1935)

303 Allibone, T.E. and Perry, F.R. - Standardization of Impulse - Voltage Testing. (Jour.I.E.E. 78, p.257, 1936).

304 Chadwick, A.T., Ferguson, J.M., Ryder, D.H., and Stearn, G.F. - The Design of Power Transformers to withstand surges due to Lightning, with Special Reference to a new type of winding. (Proc. I.E.E. Part II, 97, p.737, 1950)

305 Edwards, F.S., Husbands, A.S., and Perry; F.R. - The Development and Design of High-Voltage Impulse Generators. (Proc. I.E.E. Part I, 98, p.155, 1951).

306 Foust, C.M., Kuehni, H.P., and Rohats, N. - Impulse Testing Technique (Gen. Electric Rev. 35, p.358, 1932)

307 Foust, C.M., and Rohats, N. - Some Recent Developments in Impulse - Voltage Testing. (Trans. A.I.E.E. 59, p.257, 1940).

308 Husbands, A.S. - Surges in Transformer Windings. (Bull.Elect.Eng.Education No.5, p.6, 1950)

309 Miller, J.L. and Thomson, J.M. - The Surge Protection of Power Transformers. (Jour.I.E.E. 84, p.187, 1939).

310 Monahan, T.F. - A note on the Impulse Testing of Power Transformers (Proc.I.E.E. Part II, 100, p.35, 1953)

311 Norris, E.T. - Protection of Electrical Apparatus from High Voltage Surges. (World Power 24, p.67, 1935).

312 Provoost, P.G. - Detection of Insulation Faults in Transformers by Tests with Chopped Waves (IN DUTCH) (Elektro-Techniek 29, p.48, 1951)

313 Rippon, E.C. and Hickling, G.H. - The Detection by Oscillographic Methods of Winding Failures during Impulse Tests on Transformers. (Proc.I.E.E. Part II, 96, p.769, 1949).

314 Robinson, B.C. - The Propagation of Surge Voltages through High-Speed Turbo-Alternators with Single-Conductor Windings. (Proc. I.E.E. Part II, 100, p.453, 1953)

315 Stewart, H.C. and Holcomb, J.E. - Impulse - Failure - Detection Methods as Applied to Distribution Transformers (Trans.A.I.E.E. 64, p.640, 1945)

316 Thomas, H.L. - Insulation Stresses in Transformers, with special reference to Surges and Electrostatic Shielding. (Jour.I.E.E. 87, p.427, 1940).

317 Weed, J.M. - Prevention of Transient Voltages in Windings. (Trans. A.I.E.E. 41, p.14, 1921).

318 Allibone, T.E., McKenzie, D.B., and Perry, F.R. - The Effects of Impulse Voltages on Transformer Windings. (Jour. I.E.E. 80, p.117, 1937)

319 Hagenguth, J.H. - Progress in Impulse Testing of Transformers (Trans. A.I.E.E. 63, p.999, 1944)

320 Bewley, L.V., Hagenguth, J.H., and Jackson, F.R. - Methods of determining natural frequencies in coils and windings. (Trans. A.I.E.E. 60, p.1145, 1941)

321 Boyajian, A. - Oscillations of a High-voltage Secondary Winding. (Trans. A.I.E.E. 64, p.1010, 1946)

322 Friedländer, E. - Travelling Waves in High-Voltage Alternator Windings (Jour. I.E.E. Part II, 89, p.492, 1942)

323 Norris, E.T. - The Lightning Strength of Power Transformers (Jour.I.E.E. Part II, 95, p.389, 1948)

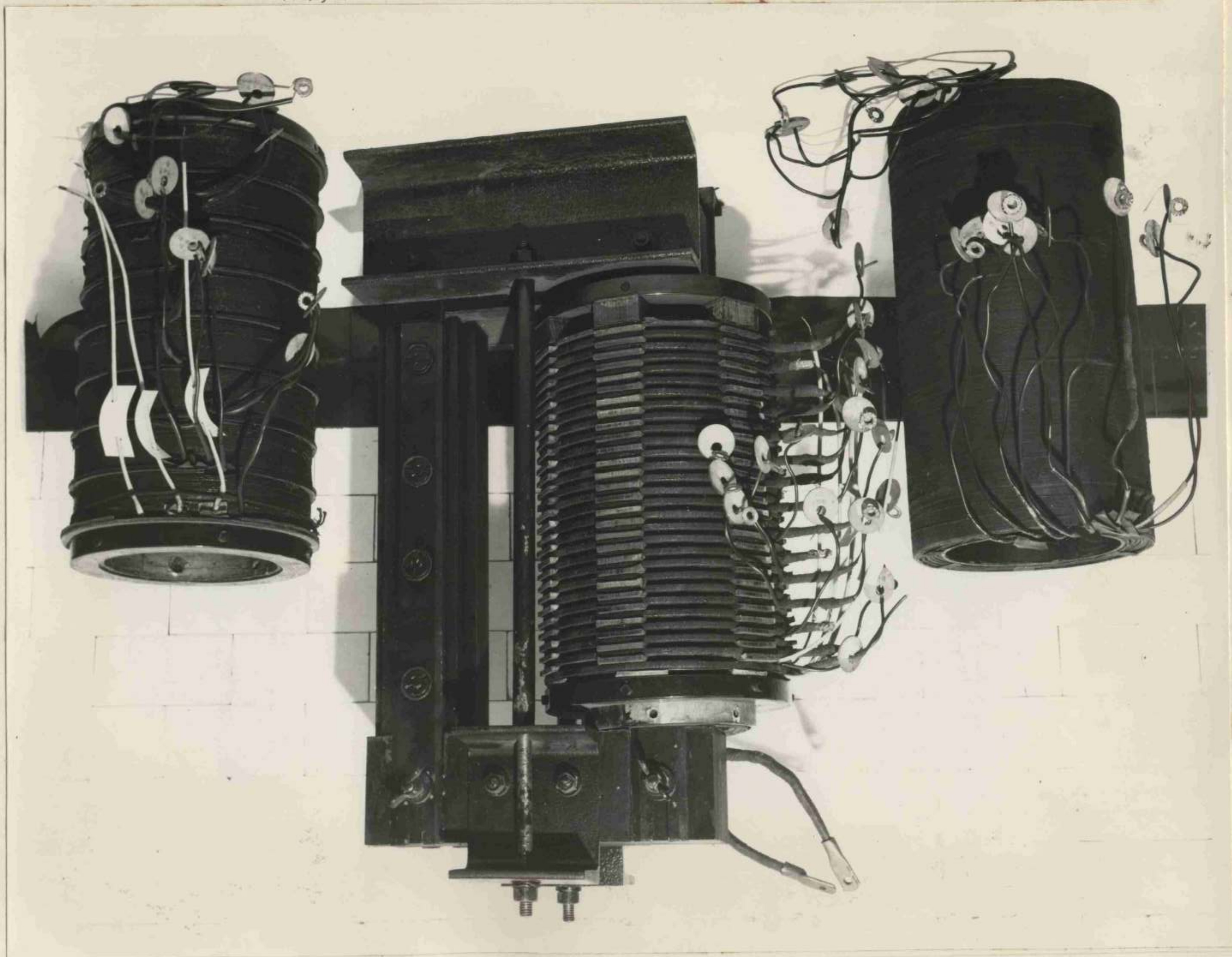
324 Makin, A.W. - Surges in Transformer Windings. A New Theoretical Analysis and Experimental Investigation. (London Univ. Ph.D. Thesis, 1953).

325 Rudenberg, R.- Electric Oscillations and Surges in Subdivided Windings (Trans. A.I.E.E. 59, p.1031, 1940)

326 Harvard University Graduate School of Engineering Publications Nos. 306, 343, 310, 479.

327 Weed, J.M. - Abnormal Voltages in Transformers. (Trans. A.I.E.E. 34, p.2197, 1915)

328 Robinson, B.C. - The Propagation of Surge Voltages through Large Turbo-Alternators with two Parallel Windings. (Proc. I.E.E. Part II, 101, p.335, 1954)



APPENDIX "A"

Small Demonstration Transformer

Fig. 11.1 opposite shows the transformer core, of the two limb type, having interleaved bottom yoke and top butt joint, complete with frame and two cross-channel mounts. The transformer is approximately two feet high. A low-voltage coil, wound on insulating tube, slips over one of the limbs, and has short copper bars with bolting holes for connections. There are three high-voltage windings, any one of which may be slipped over the low-voltage coil already in position.

One high-voltage winding is of the cross-over type, consisting of eight coils of approximately 250 turns each assembled on insulating tube. Tappings are provided on the coils, two in each of the first two coils, and one in each of the remainder, and also at the series joints between half-coils giving eleven tappings in all. Three extra tappings have been inserted near the line end for special experimental purposes. The total D.C. resistance of the winding is 15 ohms.

The second high-voltage winding is of the disc type, consisting of fourteen double-section disc coils, assembled on insulating tube with spacers between coils and sections. All the outside joints are tapped and also the inside joints over the first half of the stack giving 22 tappings in all. Five extra tappings have been inserted near the line end, The total D.C. resistance is 0.6 ohms.

The third high-voltage winding is of the layer or spiral type, consisting of about 2040 turns wound in eleven layers on insulating tube. Two tappings are provided on the outer layer and one on the next-to-outer layer, also twelve other tappings at layer ends making fifteen tappings in all. The total D.C. resistance is 15 ohms.

PART 2

THE RECOVERY VOLTAGE INDICATOR

LIST OF FIGURES

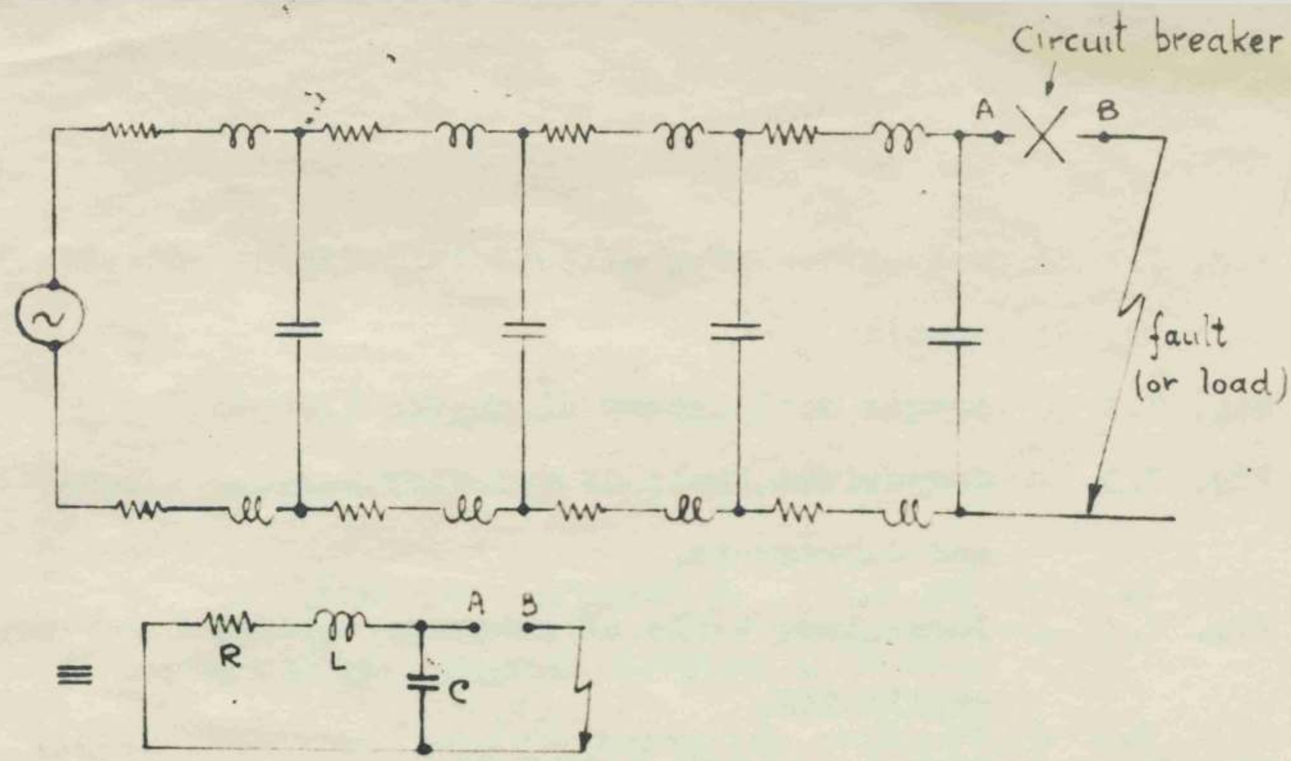
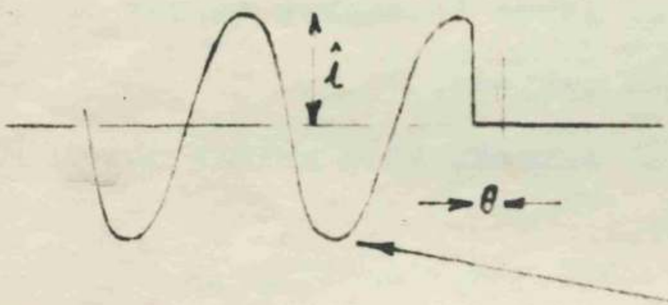


Fig 1.1 Diagram showing how transmission line and alternator distributed constants may be represented, in the simplest case, by a tuned circuit.



θ = angle-of-chop

Last cycles of "fault" current.

Fig. 1.2

With no damping, i.e. $R = 0$, then for the simplest case as above, and θ small,

$$\text{Recovery Voltage} \doteqdot \hat{i}\left\{-\sqrt{L/C}\,.\sin\theta\,.\sin\frac{t}{\sqrt{L.C}} + \omega.L\left(1-\cos\frac{t}{\sqrt{L.C}}\right)\right\}$$

and $\hat{i} \doteqdot \hat{e}/\omega L$ where $\hat{e}$ is the peak value of the system voltage.

PART 2 - THE RECOVERY VOLTAGE INDICATOR

Chapter 1

An Introduction to the Problem, and General Requirements

Recovery voltages occur between the opening contacts of a circuit breaker which has been caused to operate due to overload or in the course of normal switching procedure. Especially due to the previous fault conditions, or to inopportune interruption of light currents, these recovery voltages may be very considerable and often capable of causing the restriking of an arc after an initial clearance. Such voltages are oscillatory in nature, decaying and having fundamental and other component frequencies dependent on the parameters (inductance, capacitance and resistance) of the system to which the circuit breaker is connected.

Due to the current flowing before a circuit breaker opening operation takes place, energy is stored in the system inductance and capacitance (which are represented for simplicity by the single elements in Fig. 1.1)and it is this energy which, after circuit breaking has taken place, dissipates itself as an oscillatory current in the system and produces recovery voltages at the circuit breaker(D1, D2, D3,D6*)

---

* These numbers refer to oscillograms in Appendix D.

Ideally, circuit breaker contacts would open quickly and precisely as the alternating current flowing through the circuit breaker was passing through a zero value (Ref.108, Chapter 3), but in practice this is seldom the case. Current interruption at instants successively earlier than that corresponding to the current zero, gives rise to increasingly severe recovery voltages, and a consequent increased probability of a restrike (for a constant value of system current)(D3). Under certain conditions, for a circuit breaker operated to clear a normal light system current, interruption may sometimes take place near the peak value of system current resulting in a large angle-of-chop (i.e. degrees before current zero) and dangerous recovery voltages. Fig. 1.2 illustrates the above conditions and notes some simple mathematical relationships; see also Appendices A and B.

While the possible danger from large angles-of-chop has been stressed, certain designers confidently expect chopping of appreciable currents followed by restriking, clearing, restriking etc., in the form of a relaxation oscillation of current until a final clearance is attained. The rather random nature of such relaxation oscillations, and the present difficulty of defining the exact conditions for the arc to be sustained or extinguished, make the experimental representation (especially in miniature) of a certain particular set of circumstances in a given circuit breaker connected to a system of known characteristics will nigh impossible. Fortunately, it is not a particular set of circumstances which matters, but the most extreme conditions for the production of dangerous recovery voltages.

Circuit severity is the term given to the conception by which various systems including circuit breakers can be compared. It is of rather doubtful value, since not only are the system parameters involved, but also the circuit breaker characteristics and the protective devices, such as ohmic or non-ohmic resistive shunts, associated with the circuit breaker. From the analytical and experimental points of view, only the system parameters and, say, an ohmic shunt at the circuit breaker which may be considered as a system parameter, afford reasonable comparisons. It is to the investigation of these parameters that the experimental and analytical techniques herein developed are confined, little cognizance being taken of relaxation oscillations, arc conditions, or the design of individual circuit breakers. This limition is not only prudent but satisfactory, since the information obtained assists designers in that the most severe service conditions may be predicted and suitable factors of safety allowed.

The mathematical analysis for chopping at any instant in the appropriate quarter-cycle of current, to produce a single frequency recovery voltage from a simple system of lumped parameters, is given in Appendix B. An experimental apparatus, using a miniature technique, which injects into the system under investigation what is supposedly the last half-cycle of current (or part thereof due to current chopping) repetitively fifty times per second, and oscillographically displays the voltages produced by the system after cessation of the current (i.e. recovery voltages) is described in Chapter 3 et seq. This apparatus uses what may be described as "The Extended Half-Wave Injection Method", following on the work of S.Y. King who suggested the simple Half-Wave Injection Method which was restricted to zero-pause recovery voltages.

Chapter 2

An Historical Survey

When reviewing past work on Recovery Voltage Indicators, it is desirable to consider also the background which led to their development - a background, which by virtue of the many types and operating conditions of circuit breakers in use, is necessarily of wide extent. The Bibliography (Chapter 10) therefore contains a selection of the more important papers on arc gap conditions, methods of predicting recovery voltages for practical systems, circuit breaker testing, some protective devices, and theory, as well as the comparitively few papers concerned with a practical miniature technique.

Serious research on various aspects of switchgear, especially arc rupture, began in Great Britain in 1922 under the auspices of the E.R.A.*. The paper by Widmore, Whitney and Bruce(1) is concerned mainly with arcing and the necessity for avoiding restriking, while little or no mention is made of recovery voltage. In the United States, Slepian(2) was carrying out investigations into the A.C. arc and suggested that events near a current zero were due to a race between rise of voltage and a property of the

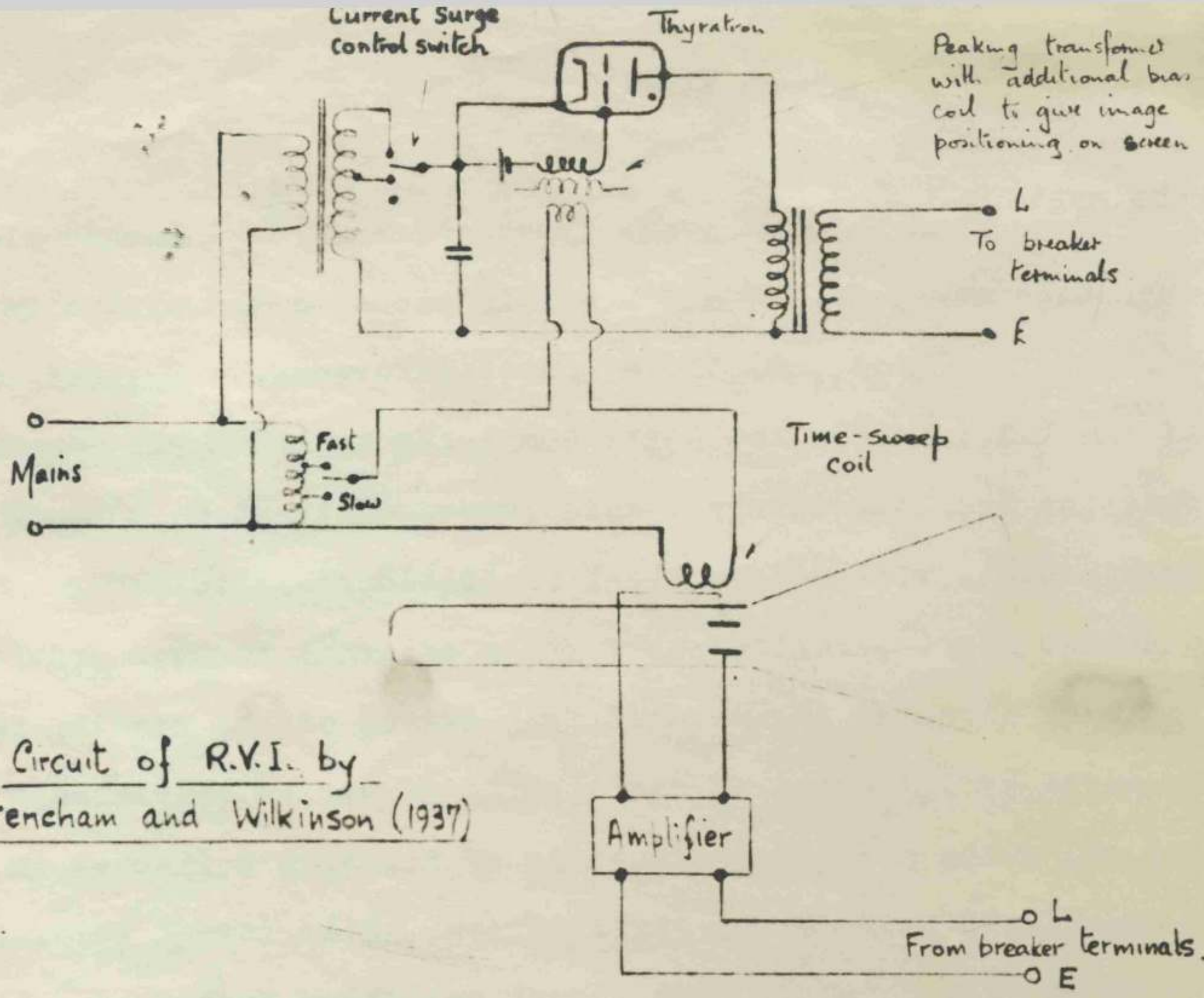
---

* The British Electrical and Allied Industries Research Association.

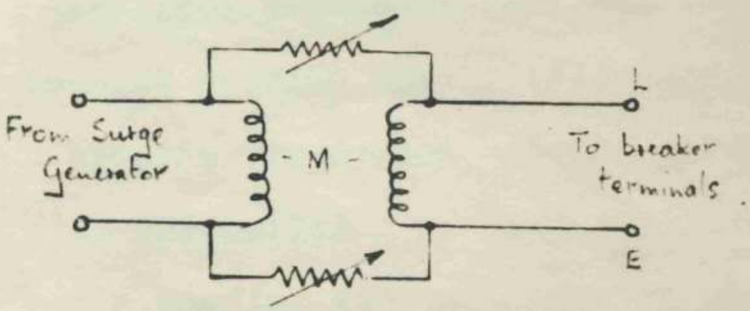
arc-path changing with time. The advent of improved cathode ray oscillographs accelerated the study of restriking and recovery voltages. No simple theory, however, was forthcoming and although a large amount of research has been carried out on the physical mechanism of arc extinction in circuit breakers, no complete theory has yet been produced. Cassie(4,7,19,20) of the E.R.A. propounded an energy balance theory (CIGRE paper No.102 of 1939) which applies in part to certain arc conditions especially near current zero, while for other conditions, results tend to bear out Slepian's rate-of-rise theory, or a combination of both theories. What seems fairly certain is that a complete theory will have to take into account the many circuit breaker characteristics. An up-to-date account of the work on this subject is given in the book on Circuit Breakers edited by Trencham(101).

The evaluation of recovery voltages was considered in papers by Park and Skeats(3) in 1931, Boehne(6), Dannatt and Goodall(8), and Gosland(10) in 1935 with the object of using rate-of-rise of recovery voltage (r.r.r.v.) in some measure as a criterion of circuit severity. The knowledge of such rates-of-rise was at least a method of specifying testing station conditions for circuit breakers. Boehne(6) introduced a further idea, that of circuit recovery impedance as a "true measure of circuit severity"; for a single frequency case this recovery impedance was $\sqrt{\frac{L}{C}}$. Boehne also suggested various L, C and R combinations as the equivalent circuits for lines, machines and transformers. Gosland(10) of the E.R.A. conducted tests comparing experimental recovery voltages from relatively simple lumped-constant L, C and R combinations with mathematical predictions; alternator windings short-circuited through an external reactor provided the test circuit, the natural frequencies of the reactor being measured by injecting an oscillation of variable frequency and observing phase-relationships by Lissajou's figures on a sealed-off cathode ray oscillograph, while actual recovery voltages were obtained from normal switching tests.

The first paper on "The Restriking-Voltage Indicator" (more correctly a Recovery-Voltage Indicator) was published in 1937 by Trencham and Wilkinson(14) of the British Thomson-Houston Company. The apparatus used a sealed-off cathode ray tube, the time-sweep being obtained by a deflection coil excited from a 50 c/s supply, and the recovery voltage, amplified, was applied to a pair of deflection plates. By modern standards the timebase and some other circuit arrangements appear a little crude, but they seem to have been effective enough. Dannatt and Goodall(8) had earlier suggested that instead of simulating an ideal switching operation, i.e, removing a current of sinusoidal form from



Circuit of R.V.I. by Trencham and Wilkinson (1937)



Modification to allow current chopping - Wilkinson (1938)

Fig. 2.1

the system, an injection method using a current of similar form injected into the system whose terminals were the open breaker, might be feasible. This latter method required access to the system at one point only and was adopted by Trencham and Wilkinson for their apparatus. The principle of the current surge generator is illustrated opposite (Fig.2.1). Instead of injecting a sinusoidal current, a linearly rising current, which approximates to the sinusoid over the first several hundred microseconds, was used and generated in a high impedance circuit so that the effects of load impedance would be unimportant. This injection was repetitive, fifty times a second, and the time-sweep was synchronised with the current injection so that the recovery voltage could be observed on the cathode ray tube screen. An alternating voltage at crest value (i.e. a step-function of potential) suddenly applied to a perfect inductor causes a linearly rising current to flow and also can have the "constant current" or high impedance generator characteristic. Unfortunately, the self-capacitance of a suitable inductor distorts the current waveform, and a mutual inductance was used instead, the surge current being obtained from a secondary winding carefully screened electrostatically from the primary. The authors state that the instrument is suitable for application to system impedances (at 50 c/s) of 0.05 to 20 ohms, various windings being provided for the mutual inductance of the generator circuit to cover this range; departure from a linear current rise due to eddy currents in the mutual coupling was also encountered but a measure of correction was provided. Gosland, in the discussion consequent on the above paper, gives details of a number of comparitive tests with recovery voltages obtained from fault tests, using a breaker with very little arc voltage and negligible transient post-arc conductivity, and displayed on a cathode ray oscillograph. The comparison is fairly good, though the R.V.I. records exhibit the effects of some inherent damping. Other contributions to the discussion made mention of the desirability of applying the apparatus to live networks, since large parts of a system, with interconnections, could rarely be made dead for test purposes.

A different approach was considered by Evans and Monteith(13) in a paper also published in 1937. Their method has since been described as the Current Removal Method in which faults and circuit breaking are simulated by a synchronously driven commutator consisting of three elements each of which has two brushes. Systems were set up using lumped constants and the desired fault conditions applied. The records were taken by rotating the recording film synchronously and recording the moving cathode ray tube spot (deflected in one axis only) through a lens system,

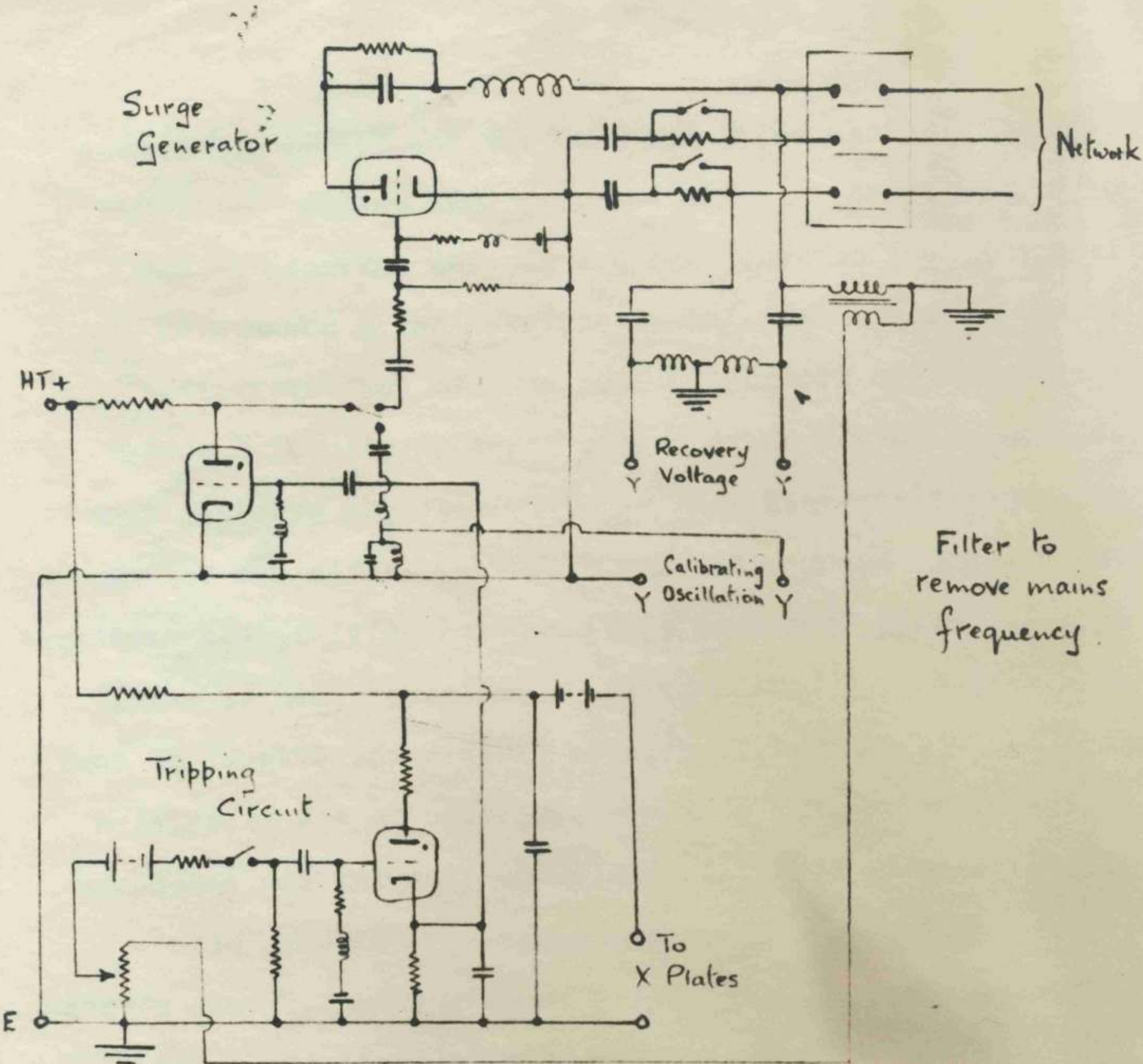


Fig. 2.2

Essentials of Dannatt and Polson's Method for Determining the Restriking Characteristics of Power Networks whilst in Service.

so giving an oscillogram, of uniform time scale, in the polar form. This may be unique, but would require practice for the rapid interpretation of results.

In 1938, Wilkinson(16) in a paper devoted primarily to Recurrent-Surge Oscillographs, describes an extension to the R.V.I. technique which allows current chopping - this is accomplished by adding resistors between the ends of the primary and secondary windings of the mutual inductance, thereby adding a negative step function to the linear injection current (Fig.2.1).

Dunlap(25) of the General Electric Company in the United States, developed an instrument known as a Recovery-Voltage Analyzer using the same principles as Trencham and Wilkinson. The timebase and amplifier circuits were somewhat more elaborate than those of Trencham and Wilkinson, but little was contributed to the technique.

Dannatt and Polson(24) described a method (called the Parallel Injection Method) in 1941 whereby a recovery voltage could be obtained from live systems operating at up to 33kV. A single-stroke recording was taken, the comparatively low system frequency being rejected by means of a high-pass filter inserted between the system and the C.R.O. deflection plates; no amplifier was required. The injection circuit consisted of a thyratron or three-ball spark-gap to give the switch action producing a potential step-function, a series circuit of capacitance and the current-linearizing inductance having a natural resonant frequency about 500 c/s, and various other capacitors according to the fault conditions which it was desired to simulate. In spite of the presence of the series capacitor in the injection circuit and the natural frequency of about 500 c/s, the first few hundred microseconds of injection current were substantially linear. A series of tests were carried out on practical systems; measured and calculated results compared quite favourably - at least to within ±10% which is an acceptable figure in this type of work.

Gosland and Dunne(26) had also carried out tests about this time to determine recovery voltage on 132-kV overhead-line systems. These tests were carried mainly at full voltage at a 132-kV Grid substation. This paper(26) was one of a series by Gosland in an E.R.A. survey of transients of recovery voltage relating to switchgear on cable networks, transformer-substation busbars, and generating-station busbars (E.R.A. Reports G/T 86, G/T 89, G/T 100, G/T 102, and G/T 104).

In a paper by Wilkinson and Mortlock(28), the synthetic testing of circuit breakers is discussed, in which a recovery voltage is obtained from one source and the arc current from another source. Compared with full scale test, the paper concludes that synthetic testing on a big scale cannot generally be justified economically. Though only of indirect importance here, this paper is of interest in illustrating possible test methods on the circuit breakers themselves as distinct from systems. The papers by Cox and Wilcox(30), and Harle and Wild(31) presented in 1944, with the ensuing discussion, indicate that the problem of defining circuit severity was still elusive.

The evaluation of system recovery voltages was the subject of two papers, one by Adams, Skeats, Van Sickle and Sillars(27) in the U.S.A. and one by Mortlock(32) some three years later in Great Britain. Both papers present equivalent circuits for alternators, transformers, reactors, transmission lines, etc. and consider various fault conditions. Mortlock tabulates the basic circuits and the corresponding expressions for the zero pause recovery voltage, natural frequencies, and constants, and the mathematics is reduced to routine evaluations.

Hoover(35) in 1946 discusses the recording of transients by high speed film methods, or by using a high voltage (15 kV) sealed-off cathode ray tube. The best results are mainly from the systems of American power companies for voltages above 110 kV.

Also in 1946, Hammarlund(34) published his work on Transient Recovery Voltage with special reference to Swedish Power Systems. The treatise covers interruption tests, measurement without breaker action (with information on a Swedish built "current surge injector similar to Wilkinson's

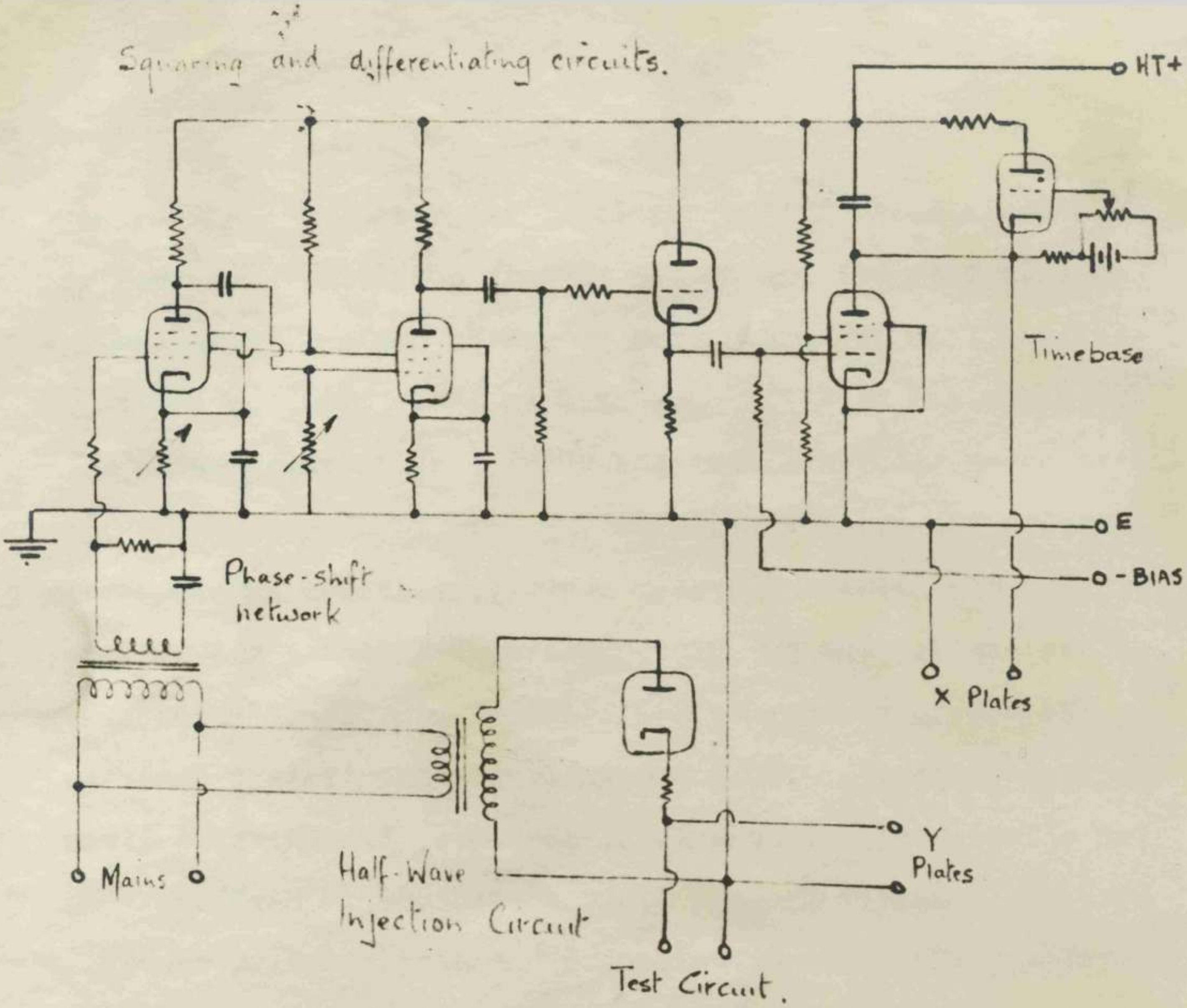


Fig. 2.3

Essentials of the R.V.I. by S.Y King (1949) showing the Half-Wave Injection Circuit.

R.V.I.), investigations purely by calculation, and the use of miniature systems. The influence of the breaker on the recovery voltage, the interruption ability of circuit breakers, and circuit severity, are also discussed fully, and the results of many measurements and calculations are given. There is an extensive bibliography.

Consequent upon work in Imperial College, London, King(38) described a further miniature technique of obtaining recovery voltages from systems. King called this a Half-Wave Injection Method since alternate half-cycles of current from a 50 c/s supply were injected into the system. A simple diode rectifier with a large series resistor (to make the diode dynamic characteristic as linear as possible) served to remove the unwanted half-cycles from the sinusoidal supply, so leaving the other half-cycles to represent, repetitively, the last half-cycle of fault current before breaker operation (Fig. 2.3). The recovery voltage obtained was that due to zero pause interruption and it was shown that the diode characteristic had negligible effect on the slope of the "fault" current just before current zero. A synchronised timebase was included in the equipment so that the repetitively obtained recovery voltage appeared as a steady trace on the cathode ray tube screen. King also describes a method (similar to that of Dammatt and Polson(24)) whereby recovery voltages may be obtained from a live system, though repetitively instead of for single injections as before. The same limitations apply, for example distortion of low frequency recovery voltages by the high-pass filter, but the method has the advantage of simplicity. King did not suggest in his paper the extension of the method to include chopping, i.e. current interruption before a zero.

Of recent years, Satche and Grosse(40) in 1950 gave an interesting paper on the calculation of recovery and other voltages using a graphical method (with voltage and current as axes, instead of the more usual voltage/time or current/time plots) developed in France by Bergeron(107) more particularly for hydraulic problems. The method is being developed in the Royal Technical College by Mr. J. McGregor. Mortlock(41) and Mortlock and Jones(42), of the B.T.H. Company have presented papers, the first commenting on the interruption of capacitive and magnetizing currents with mention of the relaxation voltage due to repeated current suppression, and the second on the effect of linear resistors in reducing the r.r.r.v. or the distribution of voltage across interrupting structures.

Young(43) in a paper primarily devoted to current-chopping in high-voltage circuit-breakers reviews the chopping mechanism for air-blast and oil-break circuit breakers, and the use of switching resistors. The breaking of small magnetizing currents, as considered in sections of this paper, suggests one field of application where a miniature technique may be invalid due to the non-linear effects of an iron circuit, especially with low values of current flowing in the windings.

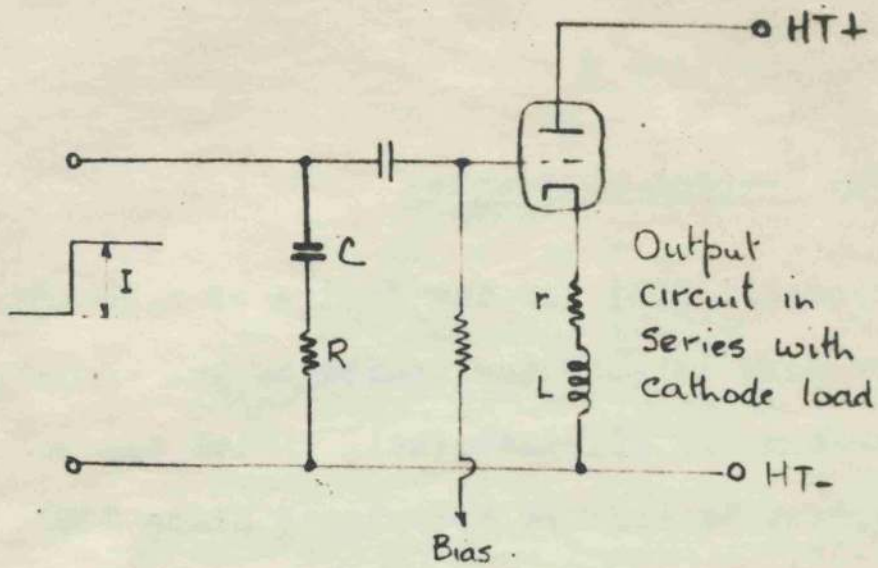
Mention should also be made of the relevant chapters in some text-books. Bewley(102) (Chapter 13, Sections 9, 10) considers a general mathematical approach for a simple lumped-constant circuit, with shunt resistance if desired. He also indicates how problems involving a non-linear shunt resistance (less common) may be approached. The second section mentioned (Section 10) deals with restriking phenomena: arcing conditions, the effect of the dielectric recovery rate, relaxation oscillations, and the effect of shunt capacitance. Gerszonowicz(104) in a book describing many varieties of circuit breaker, sums up the attitude in various countries towards the definition of recovery voltages experienced under certain conditions, breaking capacity, and rated breaking capacity (p. 53, p.328). The book edited by Trencham(101) and based on a series of lectures given by the staff of the E.R.A. on circuit breakers, is full of interesting material, and gives a very fair account of the rival theories and practices which have developed over the last twenty-five years.

Chapter 3

The Present Approaches

The early proposals(1950) for the design of a Recovery Voltage Indicator were largely influenced by the technique developed by Trencham and Wilkinson(14), With the considerable development in circuit techniques since 1937, it was felt that the generation of a linearly rising current using vacuum valves would be possible and that the addition of a step-function to simulate current chopping would follow as a matter of course. Some early experiments were therefore devoted to the linear current injection method, the simple specification being that (a) the rise of current should have a variable slope to represent various valves of fault or interruption current; (b) the injection be repetitive, fifty times a second, this being an easily obtained repetition frequency; and (c) the test system should affect the performance of the current generator as little as possible.

While the generation of a linear voltage rise is a reasonably simple matter, the generation of a linear current rise in a system one side of which might be solidly earthed proved quite a problem at the time. Thought developed from the magnetic deflection arrangements for a cathode ray tube where, to provide a linear time sweep, a linear rise of current in the deflection coils is required. At about



Input : Step-function of current (say from pentode stage).
Output : Linear rise of current in cathode circuit of valve.

Operationally $I \times R\left(1 + \frac{1}{pRC}\right) \times \frac{1}{pL}\left(\frac{1}{1 + \frac{r}{pL}}\right)$

$$= I \times \frac{R}{pL} \quad \text{or} \quad I \times \frac{1}{prC} \quad \text{if } RC = \frac{L}{r}$$

$I \times \frac{1}{prC}$ represents a linear rise of current at the rate of I/rC amps/second.

Fig. 3.1 Suggested "Linear Current" Generator.

the same time, however, interest in the Half-Wave Injection Method was growing, partly due to its simplicity and partly due to the projected extension to simulate current chopping, with the result that the linear current injection method was eventually dropped.

More recently, information on linear current generators has been better appreciated, and the author feels certain that a waveform shaping technique to provide a trapezoidal waveform on the grid of a vacuum valve in whose anode or cathode circuit is included the "linearizing" inductance or mutual inductance, could provide the basis of a recovery voltage indicator. One advantage of such an arrangement is that the unavoidable resistance of the inductance can be counteracted by choosing a suitable step-to-triangle proportion in the trapezoid. So far as is known, this idea has not been applied to the determination of system recovery voltages. (See Fig.3.1 opposite; also M.I.T. Radiation Laboratory Series Textbooks: No.19, Waveforms - Sections 2.3, 8.13, 8.14; No.22, Cathode Ray Tube Displays - Chapter 10).

A circuit using King's Half-Wave Injection Method was easily set up for preliminary investigations, especially as trigger circuits used in the experimental development of the Recurrent-Surge Oscillograph were available, and as a result it was decided to incorporate certain additional

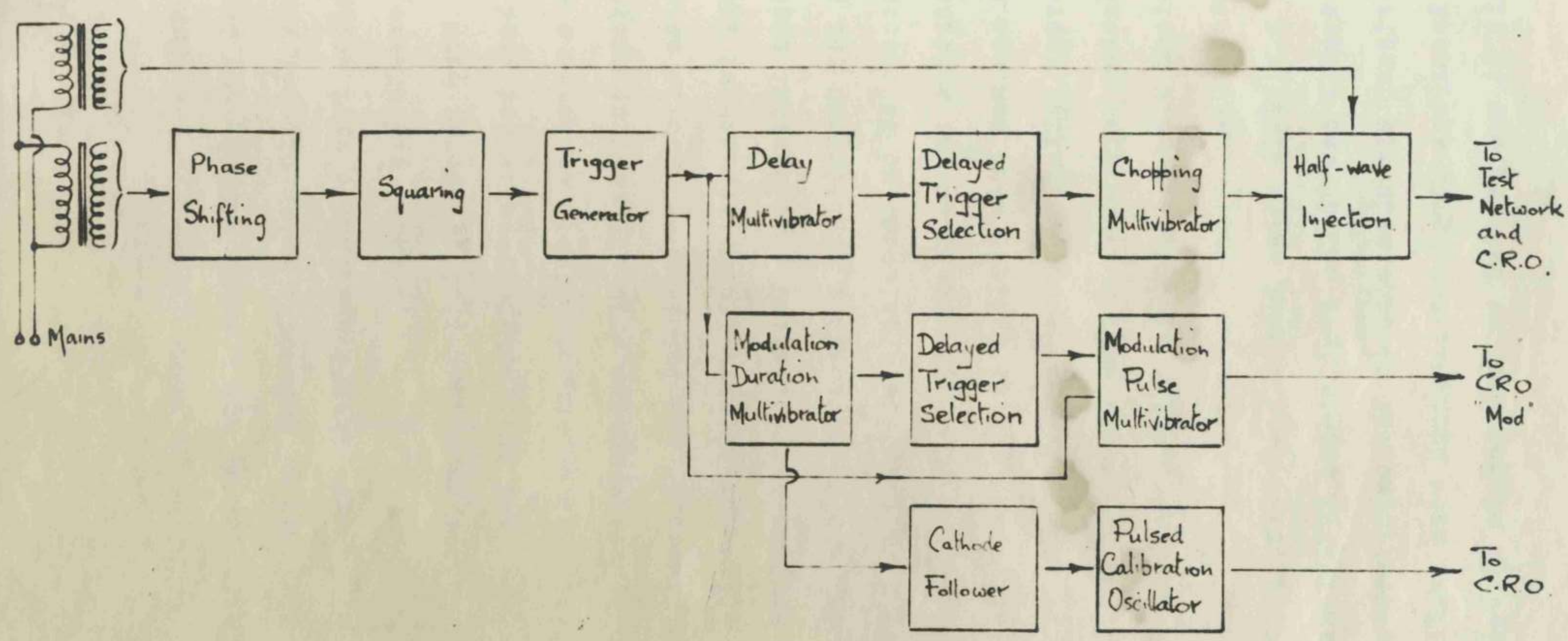


Fig. 3.2 RVI Block Diagram

features in the design for a recovery voltage indicator. These features were (a) delay of the initiation of the recovery voltage from the time of triggering the oscillograph timebase so as to avoid initial spot halation (if any) and any timebase irregularities near the commencement of the time-sweep; using such delay one is certain that the timebase is initiated before the recovery voltage and not vice-versa: (b) production of a modulating pulse to "black out" the timebase fly-back and initial spot (which can be very bright due to the relatively long periods of no deflection between successive transients in a fifty-cycles-per-second repetition arrangement) and "brighten up" the trace for the time immediately prior to and during the recovery transient: (c) provision of say three calibrating oscillation frequencies, the oscillations to be of reasonably constant amplitude and of necessity pulsed "on" with successive time-sweep triggerings so as to give superimposition of successive traces: (d) incorporation of a selection switch to allow the observation of waveforms at various critical parts of the circuit, and of an artificial test network to permit checking of complete operation of the instrument without requiring access to an external system.

A block diagram of the finalized circuit arrangement is shown opposite (Fig.3.2). A normal 240V. 50 c/s supply goes to two transformers, one to provide a half-sinusoidal injection current, and the other by suitable waveform manipulation to provide the repetitive triggers etc., required for various circuit functions. Considering zero pause current interruption, the trigger to the oscillograph timebase must be suitably phased to initiate the time-sweep in advance of current zero, this phase depending on the amount of delay desired from time-sweep to recovery voltage initiation; also if current chopping, caused by applying a negative pulse to the grid of a triode valve which replaces King's rectifier diode, is to be simulated, then the timing of the negative pulse must be controlled by some variable phase-shift circuit, that is with reference to the injected (part) half-wave. The first block fulfils these functions, and a phase-shifted sinusoid is then available for squaring, the process of converting the sinusoid into quasi-rectangular pulses, which are then differentiated and used for the accurate firing of a thyratron trigger generator.

The trigger generator provides outputs of both polarities, the positive trigger actuating the delay monostable multivibrator, from which a pulse is taken, differentiated, and the "pip" corresponding to the pulse trailing edge selected. This "pip" actuates a further monostable multivibrator, a negative pulse from which causes chopping of the half-wave current. A positive trigger also actuates a similar circuit sequence, this time to provide a beam modulation pulse, but instead of the monostable chopping multivibrator, a bistable multivibrator is used - here the delayed "pip" is used to turn the beam "off", and the negative trigger from the trigger generator turns the beam "on".

The pulse from the Modulation Duration monostable multivibrator is also used to "gate" the calibrating oscillator, which is therefore pulsed "on" only when the beam is brightened.

Power supplies required are stabilized H.T. (280 V.) with a higher voltage unstabilized H.T. line to the trigger generator thyratron, a bias supply also stabilized (- 150V.) and heater supplies to the valves. The oscillograph was to be a standard commercially available type, the Cossor Model 1035 with suitable camera for photographic recording of traces.

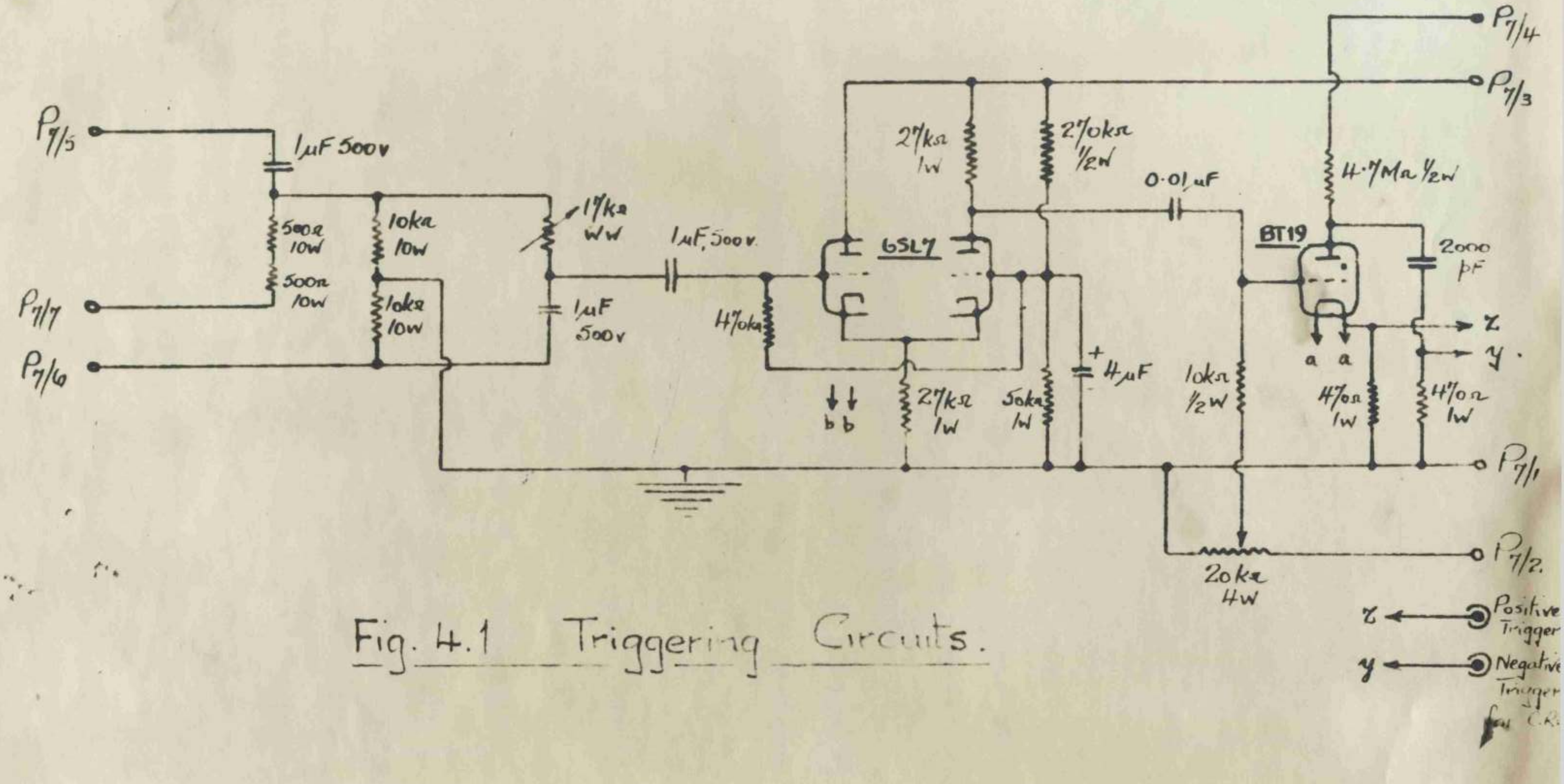


Fig. 4.1 Triggering Circuits.

Chapter 4

Circuit Design and Arrangement

Referring to Fig. 4.1

A 120-0-120 volt supply from a suitable mains transformer is available at plug pins $P_{7/5}$, $P_{7/6}$, $P_{7/7}$; $P_{7/6}$ is the centre-tap connection. Phase shift is accomplished in a two-stage network, each section being of the resistance/ reactance type fed from a centre-tapped source. (Bibliography 106, Section 4.12). The first section gives a fixed phase-shift of about 35°, assuming no loading, while by varying the resistance element of the second section (a 17 kΩ wire-wound potentiometer) a phase-shift over a wide range may be obtained. A phase-shifted sinusoid of slightly varying amplitude, somewhat over 50V r.m.s., is therefore available for "squaring".

"Squaring" is accomplished in the cathode-coupled limiter circuit (after Sowerby, Wireless World 54, p.283) which has the advantage over the pentode-with-grid-resistor limiter circuit of being independent of the signal source impedance. The first section of the 6SL7 operates as a cathode-follower, and the second section as a grounded-grid amplifier. On the positive peaks of input voltage the second half cuts off, while on negative peaks the first section tends to cut off and the second half conducts heavily; thus a rectangular output waveform is available at the anode of the second section.

The circuit values are similar to those suggested by Sowerby, the design requiring a suitably large cathode resistor to limit current flow on positive input peaks.

The square waveform is next differentiated, the positive impulses triggering the BT19 mercury thyratron trigger generator. The half-period of the square waveform will be approximately 10 milliseconds and for appreciable differentiation the product CR must be less than 0.1T where T is the half-period.

i.e. $\quad CR < 0.1 \times 10$ msec

and if $C = 0.01\mu F \quad R < \dfrac{0.1 \times 10 \times 10^6}{10^3 \times 0.01}$

$< 10^5$ ohms.

The value chosen is between 10 kΩ and 15 kΩ, it being desirable to keep the grid circuit resistance of the thyratron fairly low.

The thyratron trigger generator is of a type found very suitable by the author for developing sharp trigger impulses from a very low impedance source. The 4.7 MΩ charging resistor is made as large as possible so that the 2000 pF capacitor charges to almost the full H.T. line voltage in the time between successive triggerings (here CR = 10 msec approx.). A positive impulse on the thyratron grid permits discharge of the capacitor, the maximum current being limited to less than ½ amp. by the two 470Ω resistors in series; a positive trigger is made available at z and a negative trigger at y. The

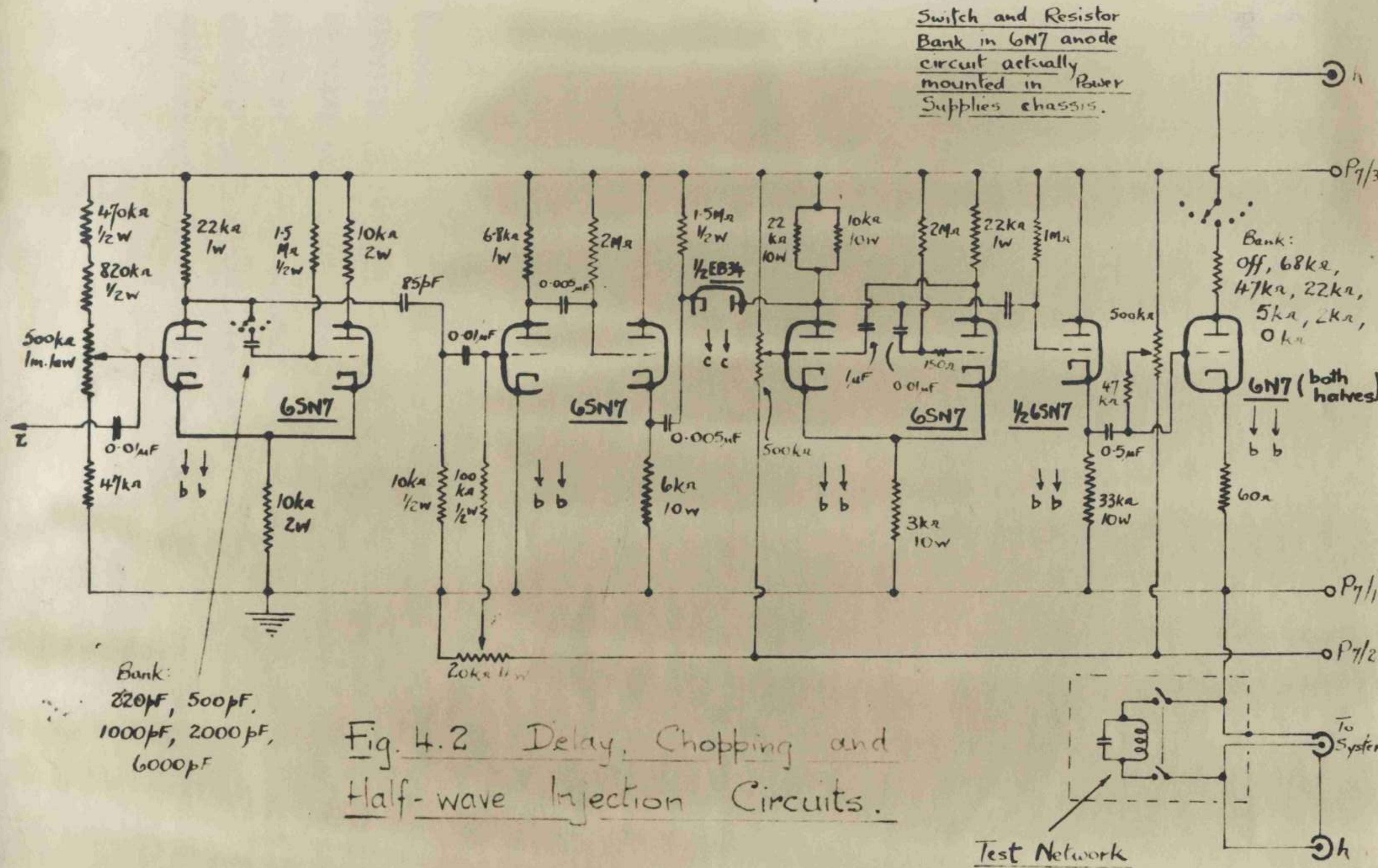


Fig. 4.2 Delay, Chopping and Half-wave Injection Circuits.

thyratron current rapidly falls to a negligible value and the discharge is no longer self-maintaining, this process being known as current limiting extinction, i.e. when the negative grid bias voltage regains control at low values of anode current(45).

Referring to Fig. 4.2

A positive trigger from z actuates the cathode-coupled monostable multivibrator which delays the initiation of the recovery voltage. Initially the second section of the 6SN7 double triode is conducting due to the 1.5 MΩ resistor tending to take the grid positive, and a voltage at the cathodes sufficient to cut-off the first section is produced, no matter the adjustment of the grid voltage of the first section by the 500 kΩ potentiometer. Positive triggering causes the first section to conduct, generating a negative-going pulse at the anode; thus the grid of the second section is taken negative cutting off the second section, the timing capacitor discharges at a rate mainly controlled by the 1.5 MΩ resistor, and the grid of the second section becomes more positive eventually causing this section to conduct and raise the cathode potential. The instant when the first section cuts off can be controlled by the grid potential, and the 500 kΩ potentiometer therefore may be used as a fine delay control, coarser control being accomplished by capacitor switching; in fact, the fine control is so effective that all desired delays may be obtained using it in conjunction with the largest timing capacitor.

The negative pulse from the delay multivibrator is differentiated by the 85 pF and 10 kΩ coupling circuit to the next valve, which is normally biased beyond cut-off. Only the "pips" resulting from the differentiation of the trailing edge of the multivibrator pulse drive this valve to the conducting condition. These delayed "pips" are amplified and inverted and fed to a cathode follower stage (second section of this 6SN7) which affords a low impedance output, and which is normally conducting by the 2 MΩ grid resistor connected to the H.T. line.

Negative delayed triggers from the cathode follower actuate a cathode-coupled monostable multivibrator similar to that already described except that triggering is by diode injection (the diode having an individual heater supply) to the anode of the first section of the 6SN7. This multivibrator is used for chopping the injected half sine wave of current, and for chopping at a current maximum a chopping pulse duration of at least 5 msec is required, that is the time for a quarter cycle of a 50 c/s sinusoid, after which the unidirectional properties of the triode in the current injection circuit become operative. In order to achieve stability in the time of the trailing edge transition, a large capacitor is connected from the anode of the second section to the grid of the first section so accelerating the switch action. The 500 kΩ potentiometer setting the first section grid voltage is pre-set to give a fixed desirable pulse duration. Since, when the first section of the valve is conducting the anode to earth impedance is only a few thousand ohms, the desirability of the cathode follower buffer circuit will be appreciated.

The negative chopping pulse, having been fed through another ½ 6SN7 cathode follower stage, produces the necessary switching action in the 6N7 injection circuit valve. Both halves of the double-triode 6N7 are used, "strapped" together, to permit injection currents up to 60 mA to be employed. A most serious objection to the use of a vacuum valve for chopping and rectifying purposes is the non-linearity of the anode characteristics at low anode voltages. For many triodes, the anode characteristic for approximately zero grid bias is nearly straight however, and this property is utilised in this particular application; in the conducting condition the grid-cathode impedance is small and hence the use of the cathode-follower driver stage for injecting the chopping pulses is justified. Additionally, the anode circuit of the 6N7 contains a bank of resistors, the higher values of which give the circuit

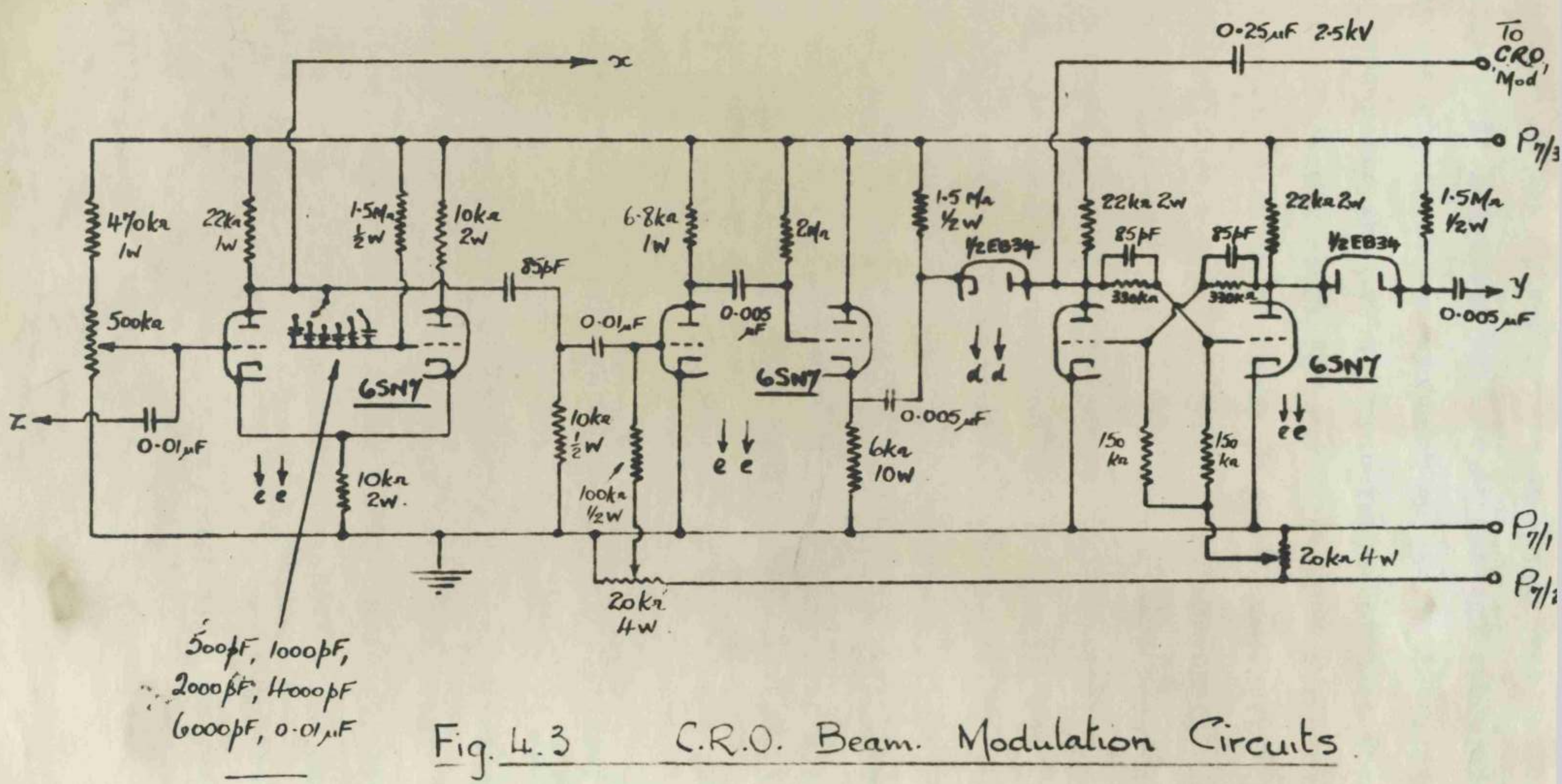


Fig. 4.3 C.R.O. Beam. Modulation Circuits

a very linear dynamic characteristic, but unfortunately also reduce the injected current amplitude. The 60 Ω cathode resistor with the 6N7 provides a means of checking the injected current waveform, and a simple tuned circuit may be switched in to act as a test network when no external system is convenient.

Referring to Fig. 4.3

The circuits concerned with the first two 6SN7 valves in this figure are identical to those described in the last section, with the addition that a negative pulse is made available at x to actuate the calibrating oscillator. Instead of the chopping multivibrator circuit, a bistable multivibrator to produce a modulation pulse is included. A delayed negative trigger from the cathode follower stage (second section of the second 6SN7) is diode injected to the bistable multivibrator to cause one transition and produce a negative-going or "blacking out" pulse at the oscillograph modulation terminal, while a negative trigger at y (coincident with the start of the time-sweep) causes the other transition and allows the beam to come up to the brightness set by the manual control on the oscillograph. (This particular arrangement is necessary because of the circuits in the commercially made oscillograph). The modulation pulse is fed to the oscillograph modulation terminal via a 0.25 μF, 2.5 kV working, capacitor, the mean level of the pulse at the cathode ray tube grid being such as to give the desired effect on all commonly used time-sweep ranges.

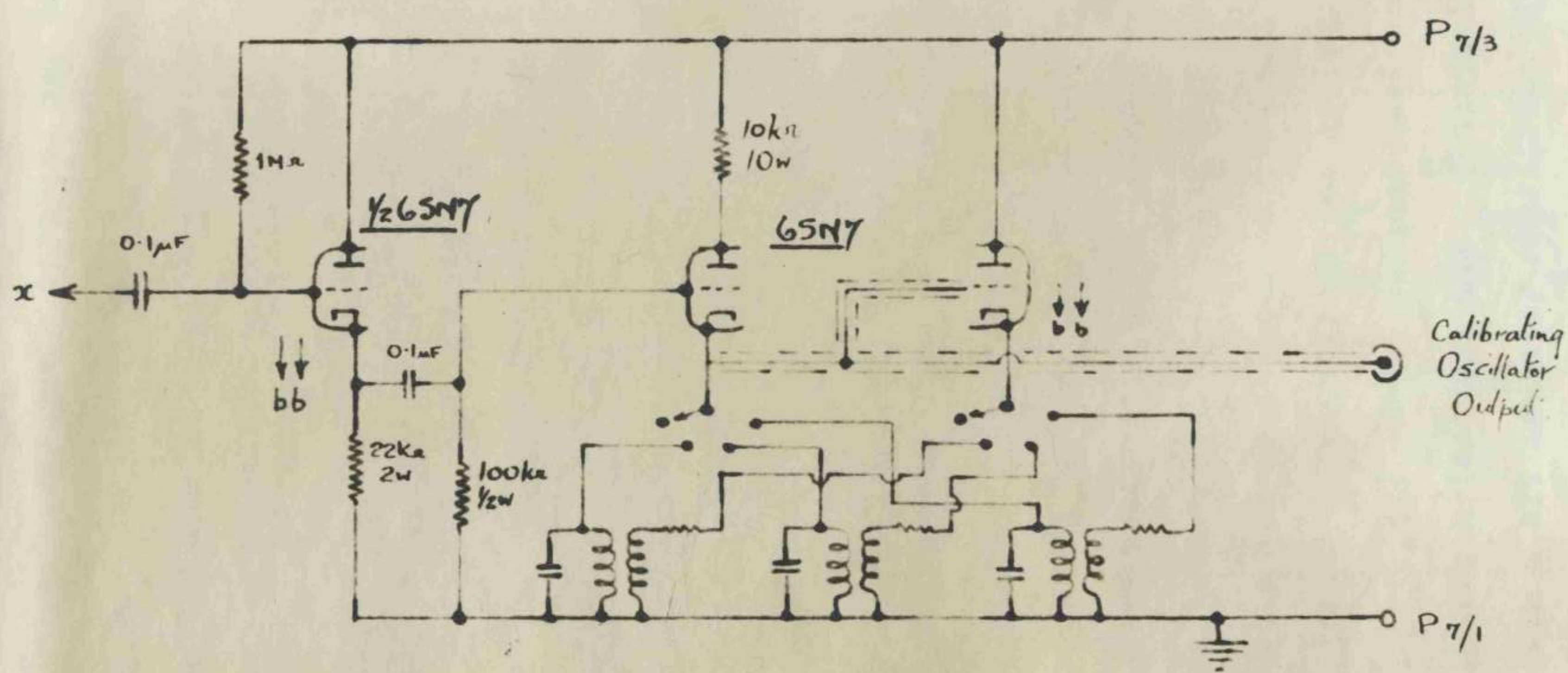


Fig. 4.4 Calibration Oscillator Circuits

Referring to Fig. 4.4

A negative pulse from x having the same duration as the brightening pulse passes first through a cathode follower stage which acts as a buffer stage between the modulation duration multivibrator and the calibrating oscillator. In the absence of this negative pulse, the first valve of the calibrating oscillator (Bibliography 108, Section 4.14) is conducting and current flows through the inductance of the cathode tuned circuit. The negative pulse causes sudden cessation of this current and a decrescent sinusoidal voltage is obtained across the tuned circuit. The second section of the 6SN7 acts as a cathode follower whose cathode circuit contains a resistance between 5kΩ and 10 kΩ and an inductance mutually coupled to the tuned inductance so that positive feedback is applied. By varying the cathode circuit resistance, feedback sufficient to overcome losses and produce a pulsed oscillation of constant amplitude may be obtained(B4). This is a variation (due to the author) of the pulsed Hartley oscillator in which the feedback path is taken to a tapping on the tuned inductance. Three calibrating frequencies, 25 kc/s, 50 kc/s and 150 kc/s, are available.

Referring to Fig. 4.5

The power supply requirements for the complete instrument are approximately 240 volts, 1 amp. The power

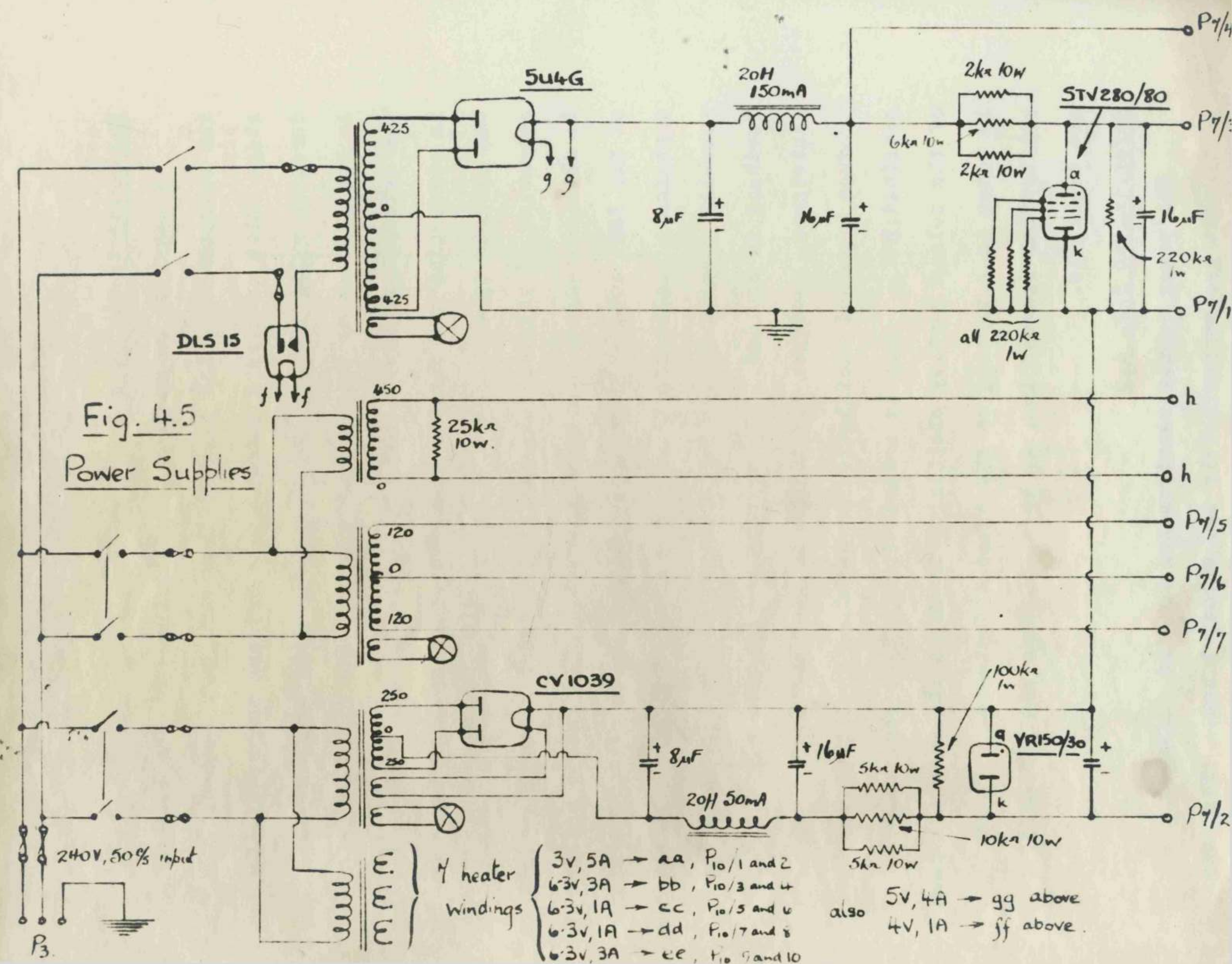


Fig. 4.5
Power Supplies

packs are controlled by three double-pole switches with associated fuzes, and switching should be carried out in a natural sequence (left to right looking at the front panel).

The first circuit controls the heater transformer, seven windings supplying all valve heaters except those of the bias power pack rectifier, and the bias power pack which is of conventional design with full-wave rectification, π-section filter, and a VR 150/30 neon valve stabilizer.

The second switch controls two transformers, one providing the 120-0-120 volt supply to the phase-shift circuit and the other the injection current. It was found undesirable to combine these two transformers as certain mutual inductive and capacitive effects between windings caused additional damping of the recovery voltage. The 25-kΩ resistor across the 450 volt injection current winding takes a steady alternating current and reduces the possible effects of winding oscillations, etc. when the injection current is chopped.

The third switch controls the H.T. power pack which is conventional and has a STV 280/80 Stabilivolt added to give a constant voltage supply to all the vacuum valves. The H.T. supply to the BT19 thyratron is unstabilized, since variations may be counteracted simply by resetting a front panel control. H.T. may not be applied before the heater and bias supplies have become operative, due to a thermal delay valve DLS15 whose heater supply is switched with the other heater supplies; the 5U4G full-wave rectifier similarly affords some protection.

Some General Design Principles:

In choosing the values of components for multivibrators, pulse amplifiers, and cathode followers, consideration must be given firstly to valve ratings, particularly the average and pulse anode current ratings. For example, resistive anode loads are made as small as possible, consistent with the desired pulse amplitude, so that valve and stray capacities may have little effect on fast transitions. For valves pulsed "on" for very short times the resistive loads may be quite small and the resistor wattage rating also reduced. In many cases, the nearest 20% tolerance resistor valve is used, the only very critical values in the equipment being the feedback-control resistors in the calibrating oscillator which were made up to suit by paralleling several standard value resistors. Pulse circuit impedances are kept as low as possible throughout to minimise the effects of inter-modulation and interaction due to stray capacities.

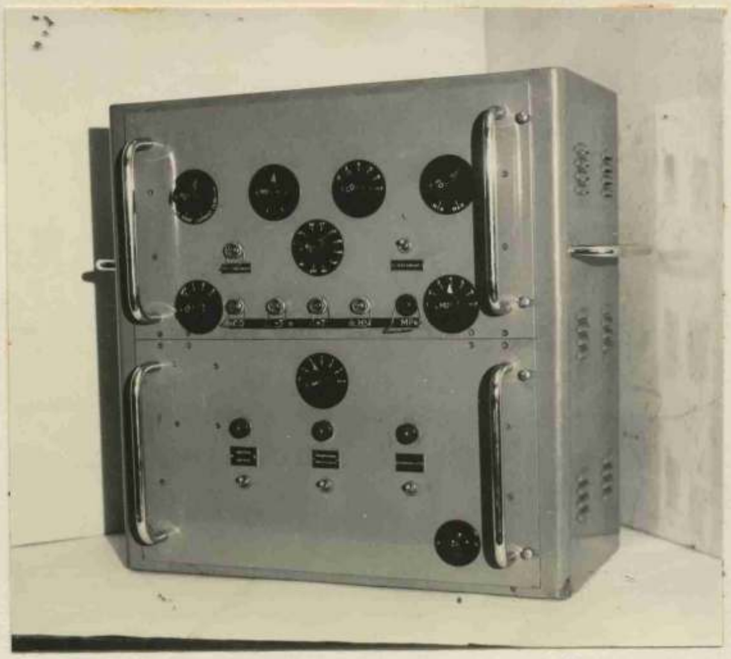


Fig. 5.1. R.V.I. viewed from the front.

Fig. 5.2. R.V.I. viewed from behind.

Chapter 5

Constructional Details

Fig. 5.1 shows the instrument in finished form viewed from the front. There are two panels corresponding to the two chassis of the equipment, the upper containing the trigger, delay, injection, modulating and oscillator circuits, and the lower chassis the power supply units.

The top panel controls are: Phase-Shift (PS) which controls the angle-of-chop - the delay controls also affect this but to a lesser extent; Main Trigger (MT) which is the bias control on the thyratron trigger generator and is set just to cause tripping of the thyratron; Coarse Delay (CD) which selects the timing capacitors of the delay multivibrator and Fine Delay (FD) controlling the 500 kΩ linear law potentiometer and therefore the grid voltage of the first section of the 6SN7 multivibrator; Waveform Selector (WS) which selects the waveform at one of eleven points throughout the circuit as indicated by the numbered arrows on the circuit diagrams; Calibrating Frequency (CF) selecting one of three frequencies already mentioned; and Modulation Duration (MD) switching the timing capacitors of the modulation duration multivibrator. Pye male sockets provide the following outlets: Waveform Check; Calibrating Oscillator (CO); Negative Trigger from y (-T); Positive Trigger from Z (+T);

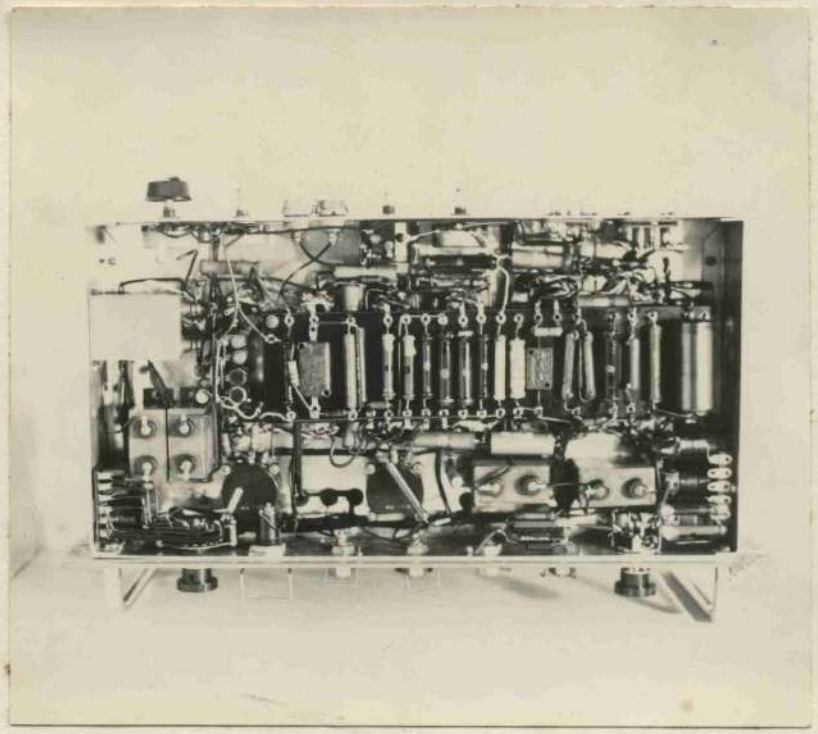


Fig. 5.3. R.V.I. – Underside of upper chassis.

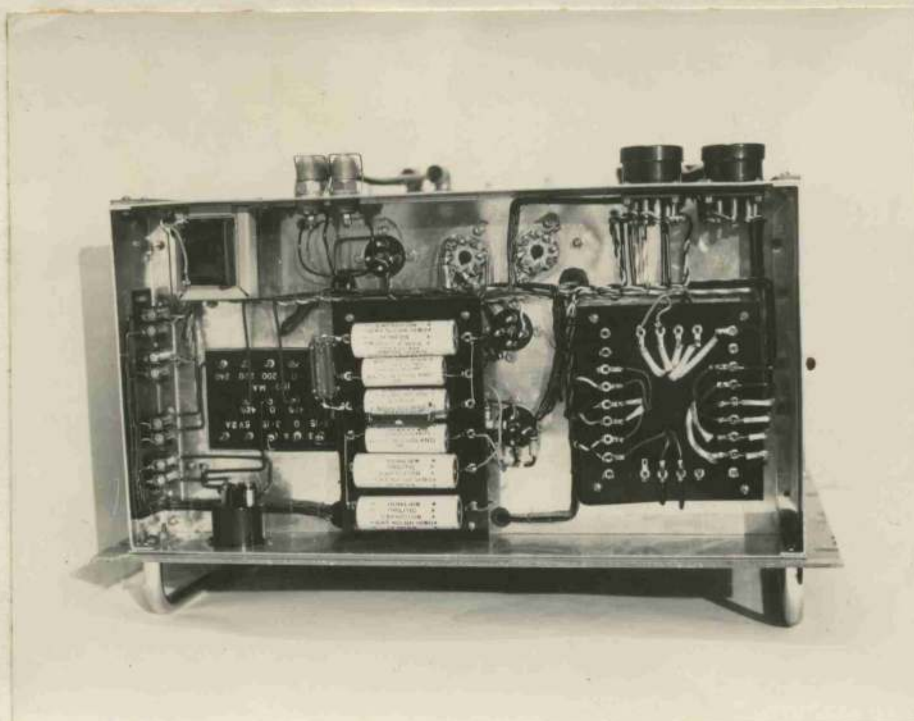


Fig. 5.4. R.V.I. – Underside of lower chassis.

Half-Wave Injection Current to system under test (HW); and Modulation Pulse (MP). There is also a toggle switch by which the test network may be switched in when an external system is doubtful or unavailable.

The bottom panel controls are Waveform Amplitude (WA) switching the various resistors in the 6N7 anode circuit and thereby altering the amplitude of the injected current, and three toggle switches for the power units with their respective indicator lamps. There is also a socket for the mains input to the equipment.

Fig. 5.2 shows the chassis removed from the case and viewed from the rear. Except for major adjustments, the chassis remain strapped together as a single unit by means of the brass strips at the corners, so permitting all normal adjustments to be made with the minimum of inconvenience. Most of the preset potentiometers are located on theback flange of the upper chassis, and with the aid of the Waveform Check switch and outlet the desired circuit functions may be quickly set up. Figs. 5.3 and 5.4 show the undersides of the upper and lower chassis respectively.

Chapter 6

Operation of the Instrument

Preliminary Adjustments:

Before switching on and setting up the correct operation of the circuits, the Phase Shift control should be set to "current zero", the Main Trigger control to maximum negative bias (fully anti-clockwise), the Coarse Delay to position 1 and the Time Delay to the centre of its travel; pre-set potentiometers fixing the bias voltages to the various valves must be set to give maximum negative bias as in some cases grid bias voltages which are considerably positive may otherwise be applied. The beam modulation circuits may be ignored temporarily after the above precautions have been taken, and the oscillograph operated without external modulation.

The oscillograph may be triggered from the positive or negative outputs, there being little to choose between them, and the output from HW taken to the deflector plates through an amplifier if desired. The Test Network should preferably be used in these initial stages. The setting up procedure depends on use of the Waveform Selector facility and waveforms from the Waveform Check output should be applied to the other set of oscillograph deflector plates. The oscillograph is normally used with the "triggered timebase" arrangement, but for check purposes the "repetitive timebase" is useful as this allows several injected half-cycles to be observed although the recovery voltages are very small and cramped.

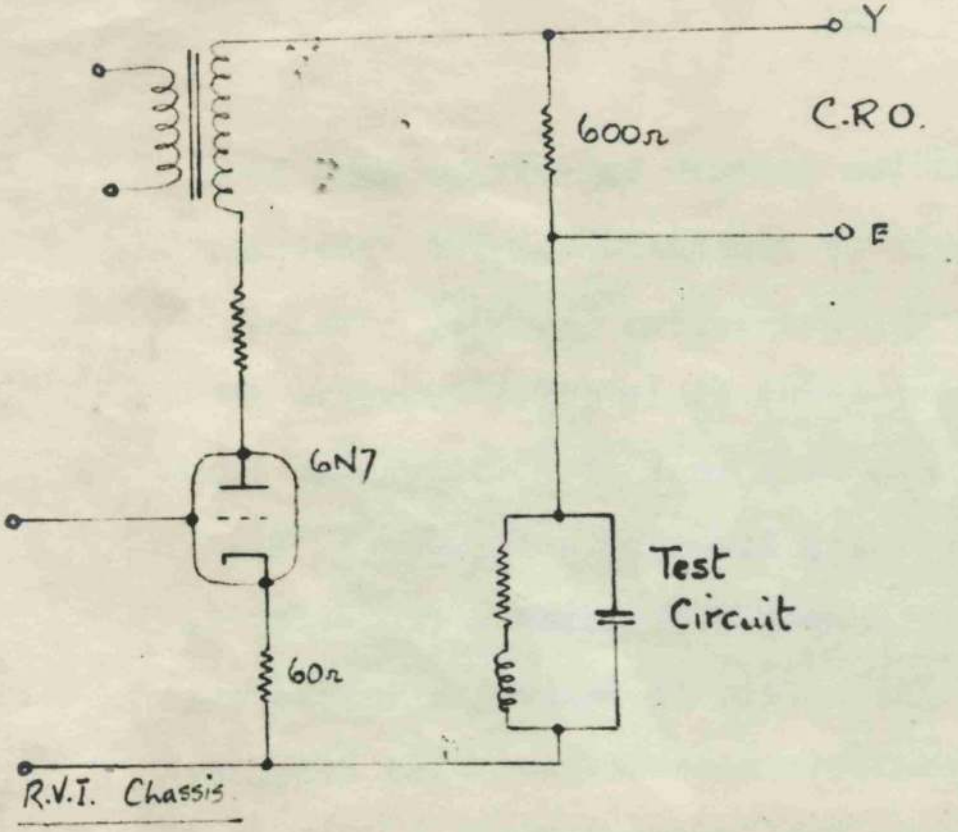
Using the Waveform Selector facility, the phase-shifted (PS) and squared (SQ) waveforms are checked with a "repetitive timebase". The Main Trigger front panel control is then adjusted to give large single equi-spaced triggers (selector position -T or + T) and thereafter the "triggered timebase" should operate satisfactorily. Correct operation of the thyratron trigger generator can also be judged by observing the glow from the BT19 valve. The delay multivibrator pulse is next observed and the delay duration (DD) varied by the Coarse or Time Delay controls. A pre-set potentiometer (20 kΩ, 4W) controls the bias on the delayed trigger selection amplifier and the resulting chopping circuit trigger (CT) should be negative-going only. Another preset potentiometer permits adjustment of the chopping pulse (CP) so that it is of suitable duration and stability. Finally in this sequence, the shape of the half-wave (HW) of current may be observed on another selector position. By turning the Phase Shift control, current chopping may now be produced and the desired recovery voltages obtained; further, the amplitude of the recovery voltages will depend on the amplitude of the injected current which is controlled by a seven position switch on the lower panel. A compromise may be necessary here, for when an accurate current waveform is desired, the recovery voltages will be smaller (due to larger value of injection circuit resistance) and more amplification will be required.

The modulation circuits may be similarly set up, the waveforms being initially observed using the Waveform Selector switch, and then by removing the link behind the side panel of the oscillograph, the modulating waveform may be applied to the appropriate terminal and the result observed. The modulation duration (MD) is controlled by the pulse from the monostable multivibrator for which a 500-kΩ preset potentiometer provides adjustment. The modulation trigger (MT) is the delayed and selected trigger which terminates beam brightening, and which causes one transition of the modulation pulse (MD) bistable multivibrator, which in turn has a preset adjustment of bias to the grids of the valves.

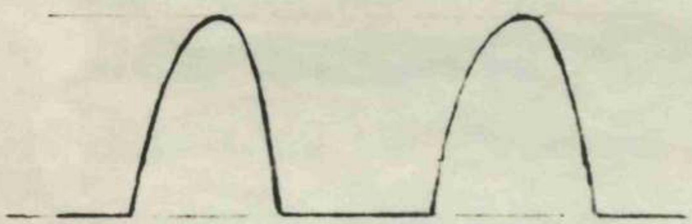
The calibrating oscillator circuit requires little adjustment. The feedback circuit resistors are chosen to give a pulsed oscillation of approximately constant amplitude, a process of trial and error, which, should the present values drift, is easily repeated. The tuned circuit values also have been suitably chosen: the inductors are identical but across the trimmer capacitors have been added fixed capacitors to bring the desired frequency within the range of the respective trimmer. Though the oscillations are pulsed, it is quite possible to compare their frequency with that of a continuous (sub-standard) oscillator using Lissajou's figures. The adjustment of the continuous oscillator's frequency is rather critical but the method is otherwise simple and efficient. Other possible methods have been described elsewhere (Bibliography 106, Section 20.6).

Routine Measurements:

Distinct from setting up procedure and checks on operation of the instrument, there are certain measurements on recovery voltage waveforms which are regularly desired, such as fundamental frequency, decrement, and amplitude of the first voltage crest, the latter being a function of the injected waveform as well as of the system. It is usual to record the recovery voltages on 35 mm. photographic film which may be fed through a projector, thus enabling measurement of enlarged traces to be made from a graph paper screen. Time calibration in the horizontal axis is readily achieved using one of the three calibrating frequencies available. Voltage calibration in the vertical axis is best made by taking a special oscillogram of a continuous oscillation obtained from a signal generator of a frequency



Method 1



Method 2

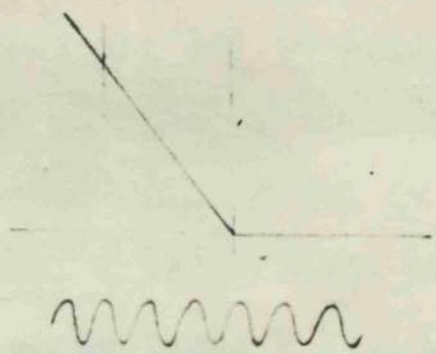


Fig. 6.1

Methods of determining the amplitude of the injected current.

For injected current

$$i = \hat{i}.\sin\omega t$$

$$di/dt = \omega.\hat{i}.\cos\omega t$$

$$= -\omega\hat{i} \text{ at } \omega t = \pi$$

similar to that of the recovery voltage, and amplified by the same amplifier as the recovery voltage; knowledge of the amplitude of the continuous oscillation from valve voltmeter measurement gives the vertical scale for a series of oscillograms.

The amplitude of the injected half-waves of current may be found in two ways (D5). Both require the insertion of a resistor, usually 600Ω, on the non-earthy side of the system under test, i.e. in series with the system, and the measurement by oscillograph of the voltage across the resistor (the oscillograph chassis "floating" with respect to earth). The amplitude of the injected current may then be found (Fig. 6.1) directly by using the "repetitive timebase" of the oscillograph to display several cycles, or by using the "triggered timebase" and a long delay from time-sweep initiation to current zero thereby displaying the slope of the current wave before the zero - this slope in amperes per second is simply related to the peak value of the current. This latter method is somewhat more accurate and also provides an excellent check on any departure from the almost linear law desired at this point for the injected current. The voltage across the 60-Ω resistor in the cathode circuit of the 6N7 chopping valve of the injection circuit is not so desirable for this current measurement since a small steady grid current may also be flowing through the 60-Ω resistor.

Chapter 7

Proving Tests and Methods

With such a simple injection circuit, it might be thought that there was no possible cause for error in recordings made using the instrument. The Proving Tests showed otherwise, for natural frequencies, decrement, and amplitude of first recovery voltage peak all differed considerably at first from the mathematically predicted results.

Simple parallel tuned circuits, the parameters of which were accurately known, were used as test systems. Natural frequencies were all lower than expected and measurement of the capacitance between the output terminals of the injection circuit by 1000 c/s Impedance Bridge revealed an inherent output capacitance greater than 2000 pF. Removal of the screened wire from the injection circuit and its replacement by ordinary wire has produced no ill effects, and the output capacitance is now approximately 540 pF which, compared with typical system capacitances of over 0.1μF, gives negligible change from the true natural frequency. If low capacitance systems are to be tested, then the instrument output capacitance can be allowed for.

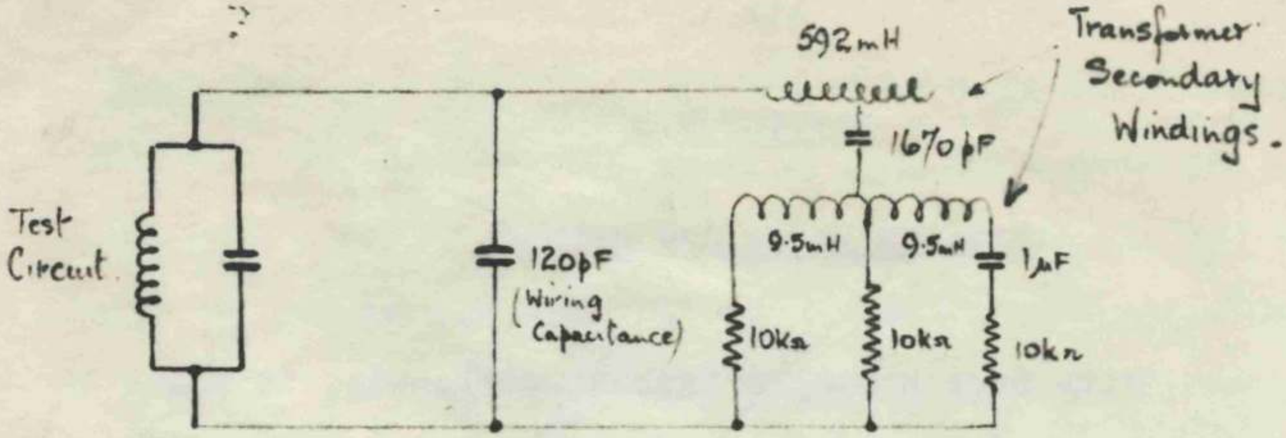


Fig. 7.1

Diagram showing how mutual coupling between the secondaries of the injection current transformer and the triggering circuit transformer may introduce damping across the test circuit.

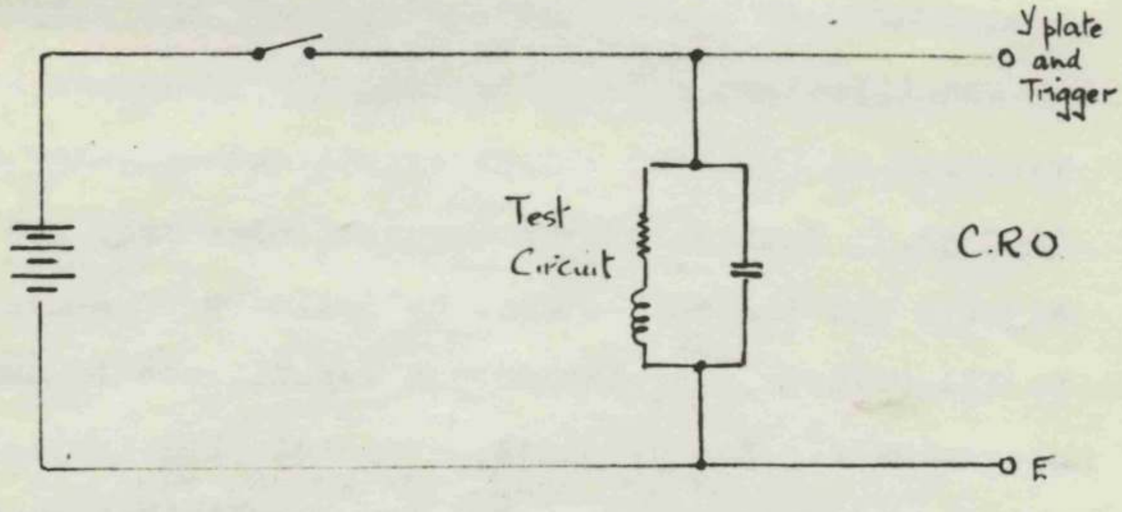


Fig 7.2

Circuit producing single oscillatory discharges when switch is opened

Discrepancies in decrement values gave rise to considerably more trouble. After examining oscillograms obtained from single oscillatory discharges in the test circuit (See Fig.7.2) where no additional damping could possibly exist, it was found that the resistance of the test inductor varied considerably with frequency even at the low frequencies (C. 10 Kc/s) involved, and the d.c. resistance value was useless. This was confirmed later by other investigators in the Royal Technical College. Taking this increase of resistance with frequency into account gave closer agreement with the mathematical predictions, but not close enough for normal working. Finally it was resolved that a constant resistance of about 19 kΩ was effectively across the tuned circuit and this was eventually traced to the mutual inductive and capacitive effects in the injection circuit transformer already referred to (Fig. 7.1). By using separate injection circuit and trigger circuit transformers instead of separate windings on the same core, this error was reduced to small proportions.

The error in the amplitude of the first recovery voltage peak was initially due to a non-linear dynamic characteristic of a 6J5 chopping valve which was overcome by increasing the series resistance in the injection circuit, increasing the injection circuit transformer secondary

L mH	C nF †	Frequency kc/s				Decrement/10^3 *	
↓	↓	R.V.I.	Single Discharge	Signal Generator	By Calculation	R.V.I.	Single Discharge.
16.4	11.48	10.9	11.7	11.4	11.5	0.93	0.96
16.4	4.45	17.3	18.8	18.8	18.5	1.89	1.75
16.4	6.17	15.0	15.8	16.0	15.8	1.54	1.45.
9.05	500	2.3	2.3	2.4	2.4	0.75	0.76
9.05	11.48	14.7	14.7	15.6	15.6	1.39	1.39
9.05	4.45	22.5	23.8	24.7	25.0	2.59	2.75
0.46	750	8.3	8.7	8.7	8.7	1.69	1.70
0.46	500	10.0	10.3	10.5	10.5	1.29	1.30
0.46	150	19.3	19.2	19.3	19.3	4.0	3.93
0.46	98	23.4	24.3	23.9	24.2	5.11	5.24
0.46	47	34.5	36.7	36.1	36.3	8.26	8.33
150	1.7	8.3	8.9	9.0	9.1	–	–

† 1 nanofarad (nF) = 10^{-9} Farad ; this unit is used for convenience in printing.

Fig. 7.3 Table comparing frequencies and decrements as obtained by various methods from various test circuits.

* Logarithmic decrement = $\frac{Rt'}{2L} = \frac{\pi . R}{\omega' L}$ where ω' = (angular) natural frequency.

L mH	C nF	θ°	FPA Calc. Volts	FPA R.V.I. Volts	% Difference from Calc. value
150	250	0	0·78	0·71	−8·5
150	250	19·8	2·7	2·5	−10
150	250	45	5·0	5·5	+8·9
150	250	90	7·0	7·0	−0·4
9·05	11·48	0	0·054	0·053	−0·8
9·05	11·48	5·3	1·51	1·54	+2·0
9·05	11·48	32·5	0·79	0·80	+1·9
9·05	11·48	80	0·65	0·62	−4·6
0·46	500	0	0·0024	0·0026	+9
0·46	500	42	0·55	0·50	−9·2
0·46	500	60	0·71	0·68	−4·2
0·46	500	90	0·82	0·79	−2·5

Fig. 7.4

Table comparing values of first peak amplitude (FPA) obtained by calculation, and by measurement from R.V.I records voltage to 450 volts and substituting both halves of a 6N7 working in parallel. By observing the linearity of the injection current near current zero as described in the last chapter, and adjusting the 6N7 grid bias voltage, and the aforementioned series resistance, satisfactory results were achieved.

In all, agreement to within ten per cent on these three features of the recovery voltage compared with results obtained by calculation, the single oscillatory discharge method, or resonance with an applied signal from signal generator, has been proved (Figs. 7.3 and 7.4), and in many cases agreement is much closer.

Additionally, comparison was possible with the results obtained by other investigators, Messrs. Pender and Srivasteva, who have used a high current test circuit (Fig. 7.5). The 12,000μF capacitor bank is charged to 1000 volts, and discharged through the test circuit which has a resonant frequency of approximately 50 c/s. Such a discharge may be initiated either by closing the switch and firing the arc at the test contacts by an impulse generator, or by connecting fuze wire across the contacts and then closing the switch. The arc so struck at the contacts has a duration of several half-cycles and a maximum current of 3000 amperes to simulate fault current can flow. The interesting feature of this comparison

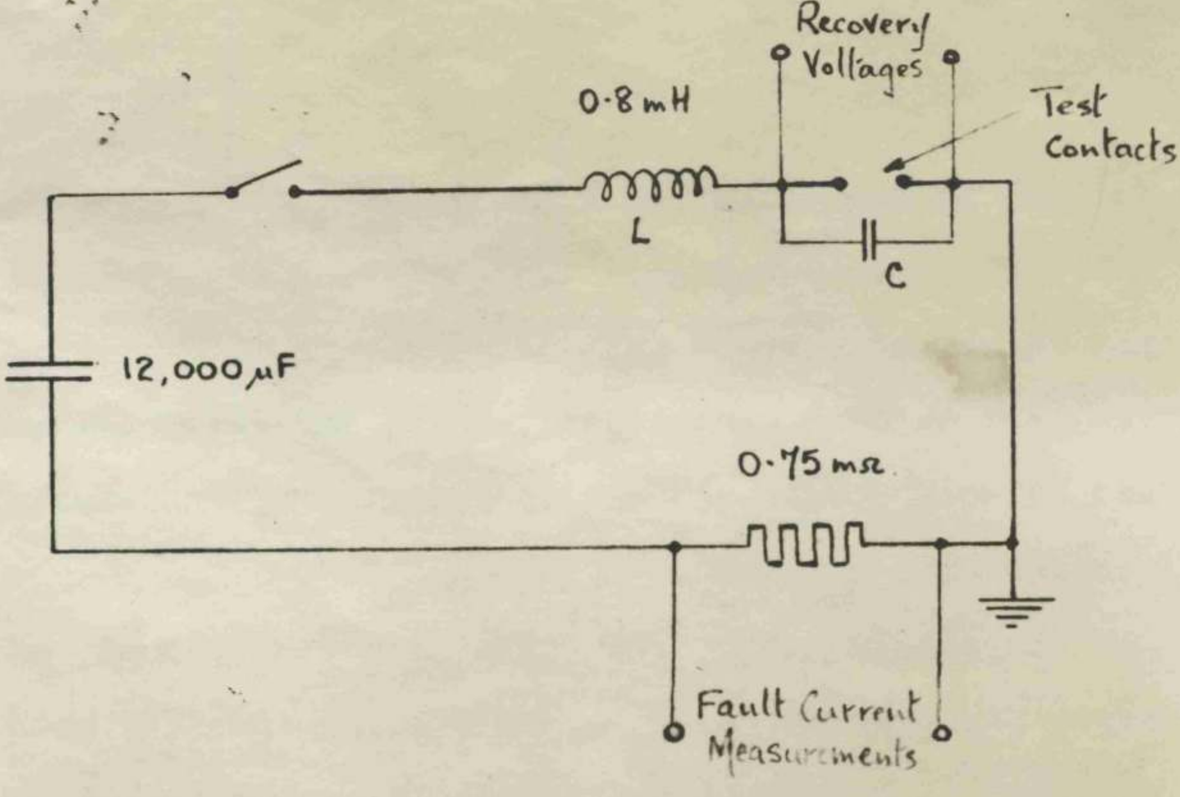


Fig. 7.5 High Current Test Circuit.

L mH	C μF	Frequency kc/s				Decrement 10^3	
↓	↓	R.V.I	High Current	Signal Gen^r	By Calc	R.V.I	High Current
0·8	0·105	17·7	17·4	17·8	17·4	1·35	1·28
0·8	0·05	25·0	25·5	26·8	25·1	3·71	5·26
0·8	0·5	7·6	7·8	7·9	7·9	5·26	5·55.

Fig. 7.6 Table comparing frequencies and decrements with special reference to the results from the High Current Test Circuit above.

is that this high current circuit represents the more typical practical case where additional damping of the recovery voltage might be caused by post-arc conductivity between the test contacts. (See Fig. 7.6) (Also D6).

The possibility of using the R.V.I. on an un-earthed (i.e. floating) system has also been investigated, since the unavoidable capacitances from the output terminals of the R.V.I. to earth (supply neutral) mainly via the mains transformers might affect the frequencies of recovery voltages recorded. Using a 1000 c/s Impedance Bridge these capacitances were found to be 2150 pF from R.V.I. chassis to earth and 320 pF from injection circuit transformer to earth, which again would normally be small compared with system capacitances, but which could be allowed for if necessary. The core of the injection circuit transformer is isolated from the chassis to reduce such capacitances and their effects.

Fault Condition	By R.V.I	By Calculation (a)	(b)	Mean of (a) & (b)	By R.S.O
Phase to phase	71.6	78.4	58.2	69.4	60
Phase to phase, to earth	36.1	39.2	29.1	34.7	34
Phase to earth	36.4	39.2	29.1	34.7	34
3 - phase, first phase to clear	51.2	58.8	43.6	51.2	49
3 - phase to earth	18.4	19.6	14.6	17.1	—
3 - phase to earth thro' 10Ω	18.44	19.6	14.6	17.1	—
Phase to phase, to earth through 10Ω	—	39.2	29.1	34.7	—

Fig. 8.1 Comparison table of surge impedance (in ohms) obtained from R.V.I records; R.S.O. (matching reflection technique) records; and by calculation of $\sqrt{L/C}$ (a) taking the inductance as the (star reactance) × $1/\omega$, (b) taking the inductance as from core to sheath neglecting losses.

By R.V.I	By Calc. (a)	By Calc. (b)	By R.S.O.
28	40	30	25

Fig. 8.2 Comparison table of transit times (in microseconds) obtained by various methods as in Fig 8.1. The transit times are the same for all connections

Chapter 8

Field Tests

To date, field tests using the R.V.I. have been made by Mr. J. McGregor, of the Royal Technical College on various features of a power system at Haggs Road Sub-Station, Glasgow. In particular, recovery voltage tests have been carried out on over two miles of 132-kV gas-filled cable between Haggs Road and Govan Sub-Stations of the British Electricity Authority, and on two large 132 kV/33kV transformers. The R.V.I. has also been used, in preference to a Q-meter or other methods, to measure the self-capacitance to earth of a transformer winding by adding a small additional capacitor and noting the difference in natural winding frequencies recorded; the test being made at more typical frequencies for the transformers than would be otherwise convenient.

Comparison of the test results, in the case of the 132-kV gas-filled cable, with those obtained by calculation or by R.S.O. impulse tests (q.v.) has shown reasonable agreement (Figs. 8.1 and 8.2). In the case of a cable or transmission system having branches or interconnections, the R.V.I. would give the most direct prediction of likely recovery voltages, since mathematical analysis could be most involved, and impulse/pulse testing might give evidence difficult to interpret. Having been proved reliable on such a simple system, there are no grounds for expecting other than reliable results from more complicated networks, especially when the choice from a selection of mutual inductances, and doubts regarding damping introduced by the instrument are avoided (cf. the R.V.I. of Wilkinson(14)) in this new apparatus.

Cable Tests:

The tests were made on a three phase 132-kV pipe-line compression cable, 4452 yards long. The cable is a three core paper insulated type with oval conductors and individual lead sheaths, the latter being bound with non-ferrous tapes. There are additionally at each end 17.5 yards of single core cables trifurcating to the sealing bells. The effects of these has been neglected in calculations. The test connections represent the following faults: phase to phase; phase to phase, to earth; phase to earth; three phase fault; three phase to earth; and three phase to earth through 10Ω.

Calculation of the relevant inductances and capacitances in order to find the surge impedance, or the transit time of a cable can only be approximate. Skin and proximity effects were ignored in the calculation of inductance, and cores and sheaths were considered circular. Gosland(46), and McGregor(47) have compared calculated and experimental results and have noted the factors which must be taken into account to obtain agreement. Figs. 8.1 and 8.2 show such a comparison, calculation (a) using the value of star inductance at 50 c/s, and calculation (b) the inductance from core to sheath neglecting losses and based on the inside diameter of the sheath. In Figs. 8.1 and 8.2 it will be noticed that there is a considerable discrepancy in the results of calculations (a), i.e. using a value of inductance obtained from the star reactance as used in steady state calculations. This value of inductance is not truly applicable to transient conditions, and the value used in calculations (b) is a better approximation. The true inductance values associated with the steep-fronted R.S.O. impulse wave (having a high-frequency component) and the R.V.I. half-wave and ensuing oscillation are also likely to be different. Measurements of inductance and capacitance using a 1000 c/s Impedance Bridge have also shown good agreement with the core to sheath values. Hence $Zo \doteqdot \sqrt{L/C}$ and the transit time $T \doteqdot \sqrt{L.C}$.

The surge impedence may be found from R.V.I. records by noting that, up to the time of the first reflection $v = i.Z_o$ where $i = k.t$ and k is the slope of the injected current. If then k is measured just before current zero, and the recovery voltage has a value v at time t before the first reflection, $Z_o = V/k.t$ may be found. The transit time is measured with the far end of the cable short-circuited, from the interval between successive maxima (opposite polarities) of the recovery voltage; accurate measurement of this time may be difficult due to the rounded form of the peaks.

Best results with the R.S.O. have been obtained using an impulse waveform rather than a pulse waveform, and by arranging for control of the load impedance at the far end of the cable, suitable reflections may be displayed at the sending end. Twice the transit time is directly measurable (D7, D8) while, by arranging for the load resistance (a H.F. decade resistance box) to be varied in one ohm steps near the matching value, the minimum reflection value can be judged to within two per cent of the correct matching value (D9). This process can be quite rapid and gives a virtual direct reading, as compared with the examination of records and subsequent calculation necessary using the R.V.I.

Transformer Tests:

So far, tests have been made on two transformers, a Metropolitan-Vickers 60 MVA, 132/33 kV design, and a Parsons 45 MVA 132/33 kV design, to compare particularly the amplitudes of the transient oscillations obtained using the R.V.I. with those computed from winding tests and data.

First, it was necessary to find the variation in winding inductance with frequency, and the self-capacitance of the winding. In both cases, approximate results were obtained using the R.V.I. itself to determine natural frequencies with and without added capacitance (similar to a Q-meter technique). The amplitude of the transient oscillations may then be calculated from $i\omega h$ (zero pause condition) or $\hat{I}c\sqrt{L/C}$ (current chopping condition), as indicated in Appendix A.

Good agreement has been achieved in the preliminary analyses for the zero pause condition, but not for the current chopping case due, it is suggested, to the assumed winding inductance value being incorrect for the chop waveform having a high-frequency component. For the Parsons transformer, a double frequency transient has complicated the comparison of amplitudes.

Chapter 9

Conclusion

A new instrument has been described which uses an extended technique to allow current chopping of the injected half-wave of current. Though system analysis may be carried out using the simple zero pause recovery voltage, the more severe voltage transients due to chopping may be readily simulated and analysed. Also, while the circuitry is more extensive than that of the R.V.I. pioneered by Wilkinson, the principle is simpler and the oscillograph technique should be equally good (it must be remembered that Wilkinson used his own timebase and cathode ray tube circuits, thereby making the overall design simpler). Tests, both on artificial and practical systems, have shown the instrument to be adequately accurate and sound in practice. Compared with the technique using large and various mutual inductances, the present instrument is probably lighter and more universally applicable; in fact, no practical case has yet been encountered where the apparatus is unusable.

It is perhaps pertinent to compare the information obtained by the R.V.I. with that of other testing methods. The R.V.I. gives direct information on natural frequency, decrement, and first-peak-amplitude, the latter being the only factor affected by injected current amplitude in a linear system. The R.S.O. impulse or pulse tests give information on transit time and surge impedance from which may be derived the values for system natural frequency and cut-off frequency. A third method, which has only been used by the author in the single-stroke form, would be the repetitive charging of the system capacitance by a constant voltage pulse followed by free oscillations of the system at open terminals with the pulse removed, to give information on system frequency and decrement. This method is similar to that of the R.V.I. except that the chopping component is recorded without the normal recovery voltage component (See Appendix A).

Previous authors have given prominence to the testing of live networks, but there are few, if any, records of the continued satisfactory application of such equipments to a variety of systems. Quite apart from the vital question of safety, the modern requirements of supply continuity, at least on the more important parts of a transmission network, have led to circuit duplication or alternative routeing so that during periods of light loading the necessity to work on a live system may often be obviated. An equipment which would operate successfully on live systems is still desirable however.

One feature of the Extended Half-Wave Injection Method which gives some trouble, is the operation of the instrument from mains subject to continuous rapid changes of load e.g. due to welding plant. In such cases, the rate of change of current with time at zero pause or the time of chop fluctuates sufficiently to produce a considerable amplitude jitter of the recovery voltage. This is inherent in an equipment using the mains as the injection current source, and no such trouble would be expected where the injected current was locally generated. There are two solutions to the problem however: one is to use the R.V.I. during light load periods when the inteference is negligible; the other is to generate a 50 c/s supply locally for the R.V.I. alone. In practice, the majority of mains supplies seem to be satisfactory for normal purposes, and only where specially steady traces were required say, to obtain higher accuracy, would the corrective measures be necessary.

As with the R.S.O., the most recent practice would favour the use of miniature valves almost throughout the equipment with a possible saving in space. A considerable reduction in overall size would not be expected, since for ease of maintenance, reasonable access must be provided for the large number of components associated with the valves (see Fig. 5.3), and in any case the power packs would remain roughly the same size.

Two improvements in design are suggested. The first concerns the magnitude of the injected current, which in a number of cases has been found to give a very small and almost unmeasurable recovery voltage. A larger injection current, say up to 250 milliamperes, would require a much larger rectifier/chopping valve, but this would be worthwhile. Secondly, the Phase Shift (PS) and Delay (FD and CD) controls are inter-related in as much as all three can affect the angle-of-chop. Though this is not very inconvenient, provided the necessary measurements to determine angle-of-chop are made for each oscillogram, it precludes the calibration of any one control in "degrees of chop". A solution is to derive a triggering pulse for the oscillograph, and for the modulation and calibration circuits from a duplicate chain of phase-shifting, squaring and trigger generation stages (see Fig. 3.2), so that a delay multivibrator would be unnecessary (delay would be obtained by correct phasing of timebase initiation) and the normal Phase Shift (PS) could be calibrated confidently.

Chapter 10

Bibliography

1. Wedmore, E.B., Whitney, W.B. and Bruce, C.E.R. - An Introduction to Researches on Circuit Breaking, (J.I.E.E. 67, p.557, 1929)
2. Slépian, J. - Extinction of an A.C. Arc. (Trans. A.I.E.E. 47, p.1398, 1928; and 49, p.421, 1930)
3. Park, R.H. and Skeats, W.F. - Circuit Breaker Recovery Voltages (Trans. A.I.E.E. 50, p.204, 1931)
4. Cassie, A.M. - Arc Gap Conditions. (Electrician 111, p.771, 1933; also E.R.A. Report G/XT46)
5. Van Sickle, R.C. and Berkey, W.E. - Arc Extinction Phenomena in High Voltage Circuit Breakers (Trans.AI.E.E. 52, p.850, 1933)
6. Boehne, E.W. - The Determination of Circuit Recovery Rates. (Electrical Engineering 54, p.530, 1935)
7. Cassie, A.M. - Some Aspects of the Problem of the Calculation of Transients of Restriking Voltage in Single Phase Networks. (World Power 24, p.13, 1935).
8. Dannatt, C. and Goodall, S.E. - Circuit Breaker Operation. (Electrician 114, p.539, 1935)
9. Flurscheim, C.H. - Some Notes on Rates of Rise of Restriking Voltage Subsequent to Interruption of A.C. Power Circuits. (J.I.E.E. 76, p.323, 1935; also M.V. Gazette 15, pp.348, 367, 400)

10. Gosland, L. - Characteristics of a Single-Phase Switchgear Test Circuit. (World Power 23, p.118, 1935; also E.R.A. Report G/T 66)

11. Van Sickle, R.C. - Breaker Performance Studied by Cathode Ray Oscillograms. (Electrical Engineering 54, p. 178, 1935)

12. Skeats, W.F. - Special Tests on Circuit Breakers. (Electrical Engineering 55, p.710, 1936)

13. Evans, R.D. and Monteith, A.C. - System Recovery Voltage Determination by Analytical and A.C. Calculating Board Methods. (Electrical Engineering 56, p.695, 1937)

14. Trencham, H. and Wilkinson, K.J.R. - Restriking Voltage and its Import in Circuit Breaker Operation. (J.I.E.E. 80, p.460, 1937)

15. Evans, R.D. and Monteith, A.C. - Recovery Voltage Characteristics of typical transmission systems and relations to Protector-Tube Applications. (Electrical Engineering 57, p.433, 1938)

16. Wilkinson, K.J.R. - Recurrent - Surge Oscillographs, and their application to short-time transient phenomena. (J.I.E.E. 83, p.663, 1938)

17. Bewley, L.V. - Travelling Waves initiated by Switching. (Trans. A.I.E.E. 58, p.18, 1939)

18. Bresson, C. - La Coupure des Lignes a vide par les Interrupteurs (CIGRE paper No. 109 of 1939)

19. Cassie, A.M., Mason, F.O. and Orton, L.H. - Measurement of Rapidly Varying Resistance in an Arc Gap near Current Zero (Electrician 122, p.206, 1939)

20. Cassie, A.M., Mason, F.O. and Orton, L.H. - Application d'une tension de choc à un arc dont l'intensité est sur le point de s'annuler. (Rev.Gen. d'Electricité 45, p.877, 1939; also E.R.A. Report G/XT 83)

21. Concordia, C. and Skeats, W.F. - Effect of Restriking on Recovery Voltage (Trans. A.I.E.E. 58, p.371, 1939)

22. Orton, L.H. and Mason, F.O. - Measurement of transient resistance of arc gaps near zero pause. (E.R.A. Report G/XT 78 of 1939)

23. Peterson, H.A. - Power-System Voltage-Recovery Characteristics. (Trans. A.I.E.E. 58, p.405, 1939)

24. Dannatt, C. and Polson, R.A. - A Method of Determining the Restriking Characteristics of Power Networks whilst in service. (J.I.E.E. Part II, 88, p.41, 1941)

25. Dunlap, G.W. - The Recovery - Voltage Analyzer for Determination of Circuit Recovery Characteristics. (Trans. A.I.E.E. 60, p.958, 1941)

26. Gosland, L. and Dunne, W.F.M. - Transients of Restriking Voltage on Overhead-Line Systems. (J.I.E.E. Part II, 88, p.121, 1941)

27. Adams, J.A., Skeats, W.P., Van Sickle, R.C., and Sillars, T.G.A. - Practical Calculation of Circuit Transient Recovery Voltages. (Trans. A.I.E.E. 61, p.771, 1942)

28. Mortlock, J.R. and Wilkinson, K.J.R. - Synthetic Testing of Circuit Breakers. (J.I.E.E. Part II, 89, p.137, 1942)

29. McCann, G.D. and Clark, J.J. - Dielectric-Recovery Characteristics of Large Air Gaps. (Trans. A.I.E.E.62, p.45, 1943)

30. Cox, H.E. and Wilcox, J.W. - The Influence of Resistance Switching on the Design of High Voltage Air-blast Circuit-breakers. (J.I.E.E. Part II, 91, p.483, 1944)

31. Earle, J.A. and Wild, R.W. - Restriking Voltage as a Factor in the Performance, Rating and Selection of Circuit Breakers. (J.I.E.E. Part II, 91, p.469, 1944)

32. Mortlock, J.R. - The Evaluation of Restriking Voltages. (J.I.E.E. Part II, 92, p.562, 1945)

33. Browne, T.E. - Dielectric Recovery by an A.C. Arc in an Air Blast. (Trans. A.I.E.E. 65, p.169, 1946)

34. Hammarlund, P. - Transient Recovery Voltages subsequent to short circuit interruption with special reference to Swedish power systems. (Ingervetensk Akad Handl. No.189 1946 - in English)

35. Hoover, W.G. - An Oscillograph for Recording Transient Recovery Voltages. (Trans. A.I.E.E. 65, p.1086, 1946)

36. Johnson, I.B. and Wilson, J.R. - Switching High Voltage Transmission Lines. (Trans. A.I.E.E. 66, p.1552, 1947)

37. Herrington, E.J. and Starr, E.C. - Deionisation Time of High Voltage Fault-Arc Paths. (Trans. A.I.E.E. 68, p.997, 1949)

38. King, S.Y. - The Determination of Restriking Transients on Power Networks by a Half Wave Injection Method. (Proc. I.E.E. Part II, 96, p.700, 1949)

39. Witzke, R.L. - Voltage-Recovery Characteristics of Distribution Systems. (Trans. A.I.E.E. 68, p.172, 1949)

40. Satche, P. and Grosso, V. - Calculation of Recovery Voltage and Internal Voltage Surges by means of Bergeron's Method. (CIGRE Paper No.128 of 1950)

41. Mortlock, J.R. - Initiation and Interruption of A.C. Arcs. (B.T.H. Technical Monograph TMS 756, 1951)

42. Mortlock, J.R. and Jones, K.M. - The Effect of Linear Resistors inserted during the interruption of current on A.C. circuits. (B.T.H. Technical Monograph TMS 758, 1952)

43. Young, A.F.B. - Some Researches on Current Chopping in High-Voltage Circuit Breakers. (Proc. I.E.E. Part II 100, p.337, 1953)

44. Butterworth, S. - Electrical Characteristics of Overhead Lines. (E.R.A. Report O/T 4)

45. Knight, H. de B. - Hot-Cathode Thyratrons: Practical Studies of Characteristics. (Proc. I.E.E. Part III, 96, p.361, 1949)

46. Cosland, L. - Measurement and Calculation of Restriking-Voltage Transients at a Substation Fed by Single-Core Cables. (J.I.E.E. 84, p.269, 1939)

47. McGregor, J. - Power System Transient Investigation. (Royal Technical College, Glasgow; Department of Electrical Engineering Research Report No. R26, Jan.1954

<u>Bibliography - Text Books:</u>

101. Trencham, H.(editor) - Circuit Breaking. (Butterworth, 1953)

102. Bewley, L.V. - Travelling Waves on Transmission Systems. (Chapman & Hall, Second Edition 1951)

103. Peterson, H.A. - Transients in Power Systems. (Chapman & Hall, 1951)

104. Gerszonowicz, S. - High-Voltage A.C. Circuit Breakers. (Constable, 1953)

105. Tropper, H. - Electric Circuit Theory (Longmans Green, 1949)

106. Various Authors - Waveforms (M.I.T. Radiation Laboratory Series Volume No.19) (McGraw-Hill, 1949)

107. Bergeron, L. - Au Coup de Bélier en Hydraulique au Coup de Foudre en Electricité. (Dunod, 1950)

108. Flurscheim, C.H., Meldrum, J.P.A., and Pilcher, E.E.I. - The Switchgear Handbook. Volume 1. (Pitman, 2nd Ed^{n} 1953

APPENDIX 'A'

A SUMMARY OF A SIMPLE MATHEMATICAL APPROACH TO THE DETERMINATION OF RECOVERY VOLTAGE

Using the approximation suggested by Dannatt and Goodall(8):

For zero pause recovery voltage, assume current injected to be:

$$i = \omega.\hat{i}.t.$$

For small angles-of-chop (θ small) where wt $\doteqdot$ sin wt, assume current injected to be:

$$i = \omega.\hat{i}.t. - Ic.$$

where $Ic = \hat{i}.\sin\theta$.

For the simplest parallel tuned circuit, the operational impedance may be written:

$$Z(p) = \frac{p + 2b}{C\ (p^2 + 2bp + a^2)}$$

where $2b = R/L$; $a^2 = 1/LC$; also let $x^2 = a^2 - b^2$, and ϕ arctan x/b.

Obtaining partial fractions, applying inverse transformations, and noting that when R is small, $a >> b$, $x \to a$, and arctan $x/b \to 90^0$, the total recovery voltage with damping is:

$$v(t) = -\frac{\hat{i}.\sin\theta}{C}\left\{\frac{\varepsilon^{-bt}}{x}.\sin xt + 2b\left[1 - \frac{a}{x}.\varepsilon^{-bt}.\sin(xt+\phi)\right]\right\}$$

$$+ \frac{\omega.\hat{i}}{a^2.C}\left\{\left(1 - 4\frac{b^2}{a^2}\right)\left[1 - \frac{a}{x}.\varepsilon^{-bt}.\sin(xt+\phi)\right] + 2bt - \frac{2b}{x}.\varepsilon^{-bt}.\sin xt\right\}$$

or without damping, i.e. R 0:

$$V(t)_{R=0} = -\sqrt{L/C}.\ \hat{i}.\sin\ \theta.\ \sin\frac{t}{\sqrt{LC}} + \omega.L.\hat{i}\ (1 - \cos\frac{t}{\sqrt{LC}})$$

This latter expression is well-known, but the former case (with damping) is not often quoted.

The first term on the right-hand side of this latter equation is due to current chopping, while the second term is the zero-pause recovery voltage. It will be noted that the sense of the initial rise of recovery voltage changes as chopping begins to occur. When θ, the angle-of-chop, is greater than a few degrees, the second term above becomes negligible compared with the first.

APPENDIX 'B'

A GENERAL MATHEMATICAL APPROACH TO THE DETERMINATION OF RECOVERY VOLTAGE

The method shown, using Heaviside's Expansion Theorem, is an elaboration on the working given by Bewley (Ref. 102). The author has independently obtained a similar result, differing only in small detail, using a p-multiplied Laplace Transform method; the working is heavy, and many simplifications (though justifiable) are required to reach an understandable result.

Consider the application of a chopped sine-wave of current applied to a simple parallel tuned circuit but with a further damping resistance represented by the conductance G connected across the tuned circuit. This conductance may represent the leakance of the system or a protective resistor connected across the breaker contacts, or both. The circuit breaker is assumed to have opened, and the arc across the contacts extinguished at an angle θ before a current zero, or at $t = 0$ for the current $\hat{i}\sin(\omega t - \theta)$.

The operational form of the current is:

$$i\,(p) = \hat{i}.\ \frac{p.\omega\cos\theta - p^2\sin\theta}{p^2 + \omega^2}$$

The relevant operational impedance of the circuit is:

$$Z(p) = \frac{1/G \cdot 1/pC \cdot (R+pL)}{\frac{1}{G \cdot p \cdot C} + \frac{1}{G}(R+pL) + \frac{1}{pC}(R+pL)} = \frac{p+b}{C(p^2+2ap+A^2)}$$

where
$$b = \frac{R}{L}\,; \quad a = \frac{1}{2}\left(\frac{R}{L}+\frac{G}{C}\right)\,; \quad A^2 = \frac{(RG+1)}{LC}$$

Now
$$\begin{aligned} v(p) &= i(p) \cdot Z(p) \\ &= \frac{\hat{i} \cdot p\,(\omega\cos\theta - p\sin\theta)(p+b)}{C \cdot (p^2+\omega^2)(p^2+2ap+A^2)}. \end{aligned}$$

Taking the normal steps of Heaviside's method:

(1) Put $p=0$ in the above expression for $v(p) = \frac{M(p)}{N(p)}$

$$\frac{M(0)}{N(0)} = 0, \qquad \text{i.e. no steady state terms.}$$

(2) Solve $N(p)=0$ and obtain the n roots $p_1, p_2 \ldots p_n$ if $N(p)$ is of the n^{th} degree.

i.e. Solve $(p^2+\omega^2)(p^2+2ap+A^2) = 0$

Hence $p_1 = +j\omega\,; \quad p_2 = -j\omega.$

$p_3 = -a+jx\,; \quad p_4 = -a-jx.$

where $x^2 = A^2 - a^2.$

(3) Form $N'(p)$ by differentiating $N(p)$ with respect to p.

$$\begin{aligned} N'(p) &= C\left\{(p^2+\omega^2)(2p+2a) + (p^2+2ap+A^2)2p\right\}. \\ &= 2C\left\{2p^3 + 3ap^2 + (\omega^2+A^2)p + a\omega^2\right\}. \end{aligned}$$

(4) Write the expression for $\frac{M(p) \cdot \varepsilon^{pt}}{p \cdot N'(p)}.$

$$\frac{M(p) \cdot \varepsilon^{pt}}{p \cdot N'(p)} = \frac{p \cdot \hat{i}\,(p+b)(\omega\cos\theta - p\sin\theta) \cdot \varepsilon^{pt}}{p \cdot 2C\left\{2p^3 + 3ap^2 + (\omega^2+A^2)p + a\omega^2\right\}}$$

(5) Substitute the values of p_1 to p_4 found in (2) in the expression written in (4).

The working may be reduced by noting that p_1 and p_2, and p_3 and p_4, are two sets of conjugates, and it is necessary only to consider one root of each set.

Taking p_1 and substituting:

Expression
$$= \frac{\hat{i}\cdot(j\omega + b)\cdot(\omega\cos\theta - j\omega\sin\theta)\,.\,\epsilon^{j\omega t}}{2C.\left\{-2j\omega^3 - 3a\omega^2 + (\omega^2 + A^2)j\omega + a\omega^2\right\}}$$
$$= \frac{\omega.\hat{i}\;(b/\omega + j)\,.\;\epsilon^{j(\omega t-\theta)}}{2.C.x^2\left\{-\frac{2a\omega}{x^2} + j\left(1 + \frac{a^2}{x^2} - \frac{\omega^2}{x^2}\right)\right\}}$$

Taking p_3 and substituting:

Expression
$$= \frac{\hat{i}\;(b-a+jx)\left[\omega\cos\theta + (a-jx)\sin\theta\right]\,.\,\epsilon^{(-a+jx)t}}{2C\left\{2(-a+jx)^3 + 3a(-a+jx)^2 + (\omega^2+A^2)(-a+jx) + a\omega^2\right\}}$$
$$= \frac{\omega.\hat{i}\;\left(\frac{b-a}{x} + j\right)\left[\cos\theta + \frac{a}{\omega}\sin\theta - j\frac{x}{\omega}\sin\theta\right]\,.\,\epsilon^{(-a+jx)t}}{2.C.\,x^2\left\{2a/x - j\left(1 - \omega^2/x^2 - a^2/x^2\right)\right\}}$$

The expressions taking p_2 and p_4 are not evaluated since a result can be obtained by adding twice the real parts of the expressions due to p_1 and p_3, or $2j$ times the imaginary parts of the expressions.

The terms may also be written having sine-of-multiple-angle factors where:

$$\phi_1 = \arctan \omega/b\,.$$

$$\phi_2 = \arctan\left\{\frac{2a\omega}{a^2-\omega^2+x^2}\right\}$$

$$\phi_3 = \arctan\left\{\frac{x}{b-a}\right\}$$

$$\phi_4 = \arctan\left\{\frac{x.\sin\theta}{\omega\cos\theta + a\sin\theta}\right\}$$

$$\phi_5 = \arctan\left\{\frac{2ax}{a^2+\omega^2-x^2}\right\}$$

Hence

$$v(t) = \frac{\omega.\hat{i}}{C.x^2}\left\{\sqrt{\frac{(1+b^2/\omega^2)}{(1+a^2/x^2-\omega^2/x^2)^2+4a^2\omega^2/x^4}}\times\sin(\omega t-\theta+\phi_1-\phi_2) + \sqrt{\frac{\left[1+\left(\frac{b-a}{x}\right)^2\right].\left[(\cos\theta+\frac{a}{\omega}\sin\theta)^2+(\frac{x}{\omega}\sin\theta)^2\right]}{(1-\frac{a^2}{x^2}-\frac{\omega^2}{x^2})^2+4a^2/x^2}}\times\varepsilon^{-at}.\sin(xt+\phi_3-\phi_4+\phi_5)\right\}$$

This complicated expression may be reduced considerably by noting that normally $x \gg a$, b and ω, and $\omega > b$; and therefore $\phi_1 \doteqdot 90^o$, $\phi_2 \doteqdot 0^o$, $\phi_3 \doteqdot 90^o$, $\phi_5 \doteqdot 180^o$ and $x^2 \doteqdot 1/LC$ (see Appendix "C")

Also $\frac{\omega^2.\hat{i}}{C.x^2} \doteqdot \omega.L.\hat{i} \doteqdot \hat{e}$ where $\hat{e}$ is the peak value of the system voltage.

Hence $v(t) \doteqdot \hat{e}\left\{\cos(\omega t-\theta) - \sqrt{(\cos\theta+\frac{a}{\omega}\sin\theta)^2+(\frac{x}{\omega}\sin\theta)^2}\times\varepsilon^{-at}.\cos(xt-\phi_4)\right\}$

Provided G is small, this expanded becomes

$$v(t) \doteqdot \hat{e}\left\{\cos(\omega t-\theta) - (\cos\theta+\frac{a}{\omega}\sin\theta)\varepsilon^{-at}.\cos xt - (\frac{x}{\omega}\sin\theta)\varepsilon^{-at}\sin xt\right\}$$

The recovery voltage has therefore the following components:

(a) A power-frequency term

(b) A high-frequency term due to the capacitor voltage at the instant of chop.

(c) A high-frequency term due to the inductor current at the instant of chop. This term results in the high voltages produced by current chopping.

Now $\frac{\hat{e}.x.\sin\theta}{\omega} \doteq I_c\sqrt{\frac{L}{C}}$; so that the higher the system natural frequency (x , angular), the higher the recovery voltage; also the addition of capacitance will reduce x and the amplitude of the recovery voltage.

At current zero, $\theta = 0^{\circ}$ and expression becomes

$$v(t)_0 = \hat{e}\left(\cos\omega t - \varepsilon^{-at}\cos xt\right)$$

APPENDIX "C"

EVALUATION OF SOME TYPICAL CONSTANTS USED IN APPENDIX "B"

Taking $R = 0.5\,\Omega$; $L = 2\text{mH}$; $C = 1\mu\text{F}$; $G \doteq \frac{1}{10^4}\,\mho$;

Then $b = \frac{R}{L} = 250$

$$a = \frac{1}{2}\left\{\frac{R}{L} + \frac{G}{C}\right\} = 175.$$

$$A^2 = \frac{(RG + 1)}{L.C.} \doteq 5 \times 10^8$$

$$x^2 = A^2 - a^2 \doteq 5 \times 10^8 \quad \therefore \quad x \doteq 2.2 \times 10^4$$

$$\omega = 2\pi f = 314.$$

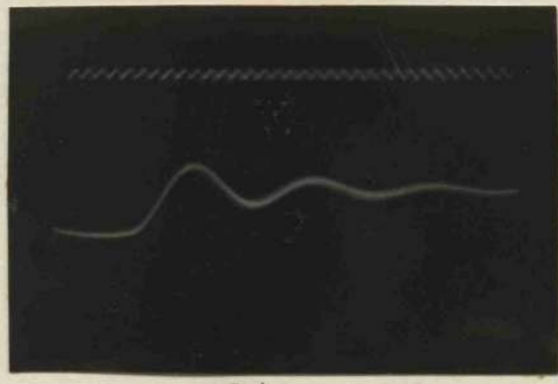
This justifies the following assumptions made in Appendix "B", viz.:-

$$x \gg a,\ b,\ \text{and}\ \omega.$$

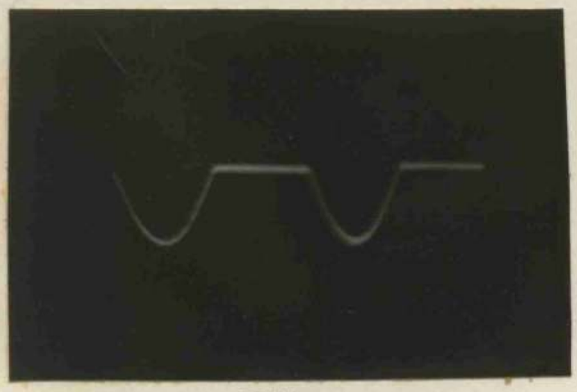
$$\omega > b.$$

APPENDIX "D"

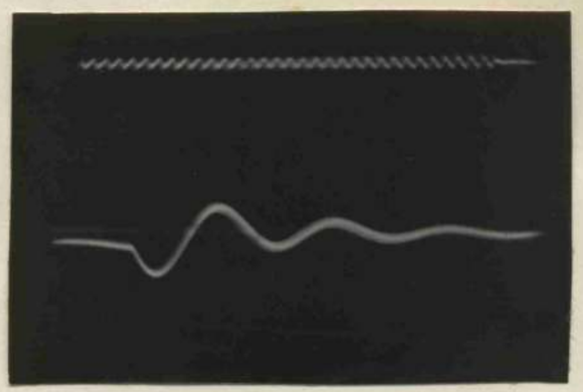
OSCILLOGRAMS RELEVANT TO PART 2



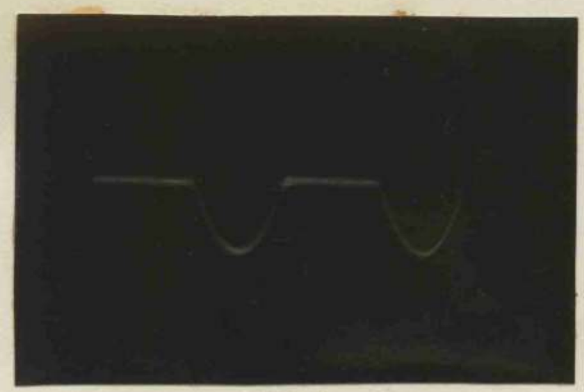
D1a



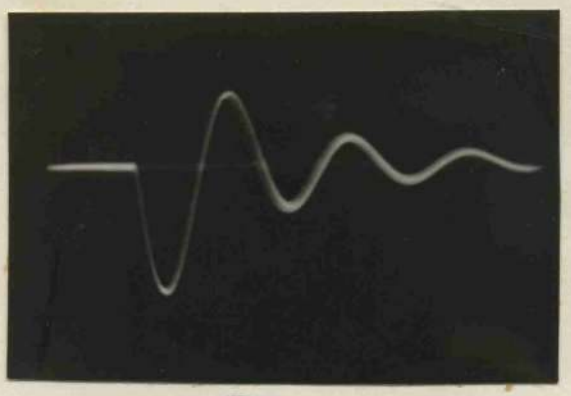
D1b



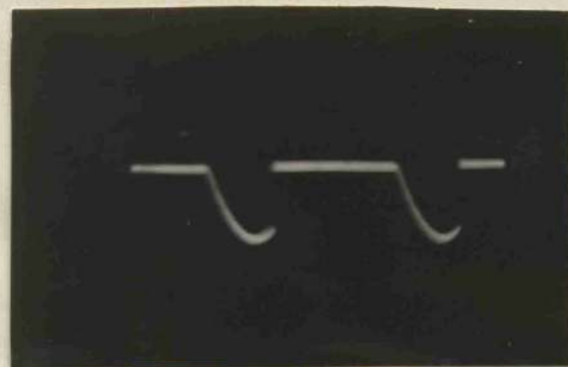
D2a



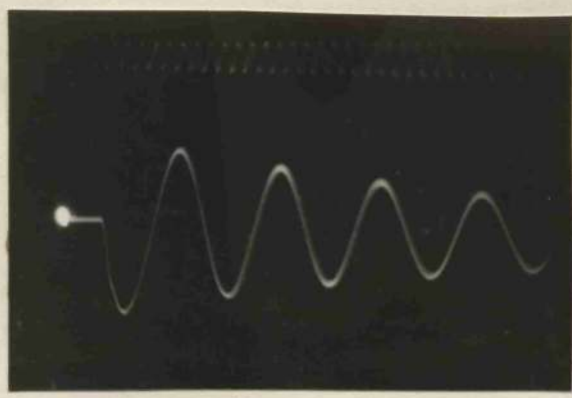
D2b



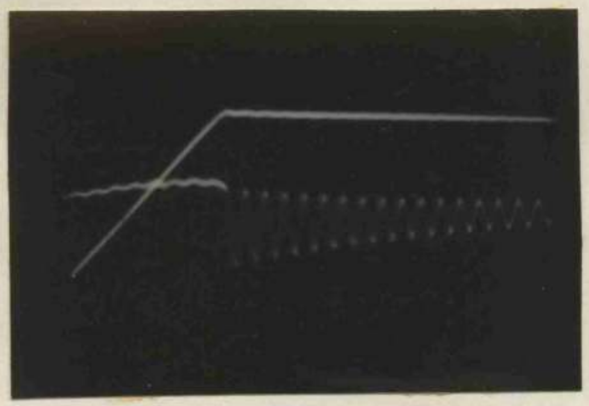
D3a



D3b

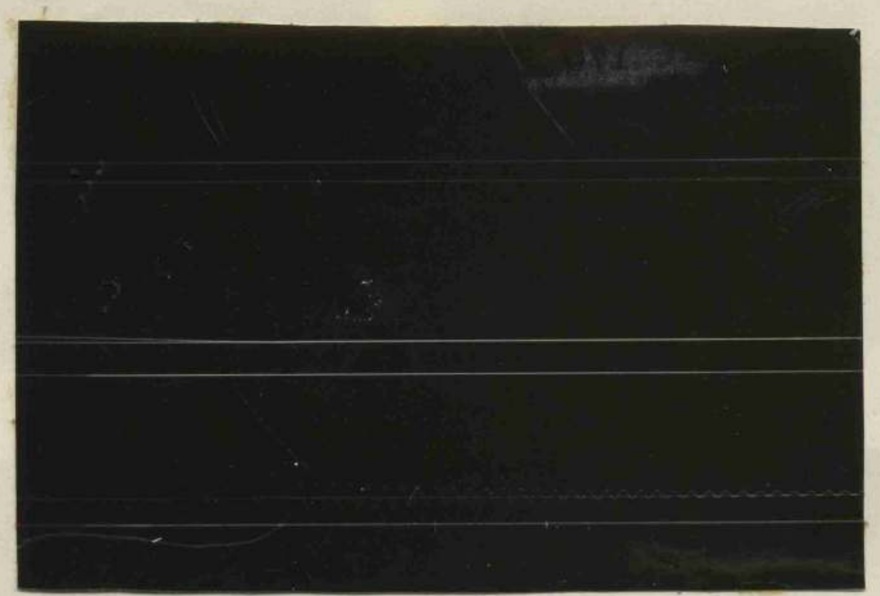


D4

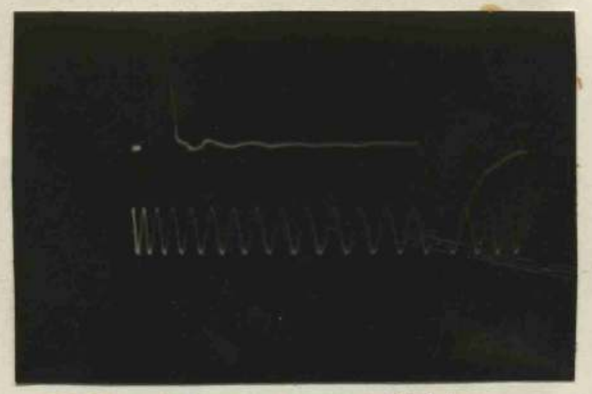


D5

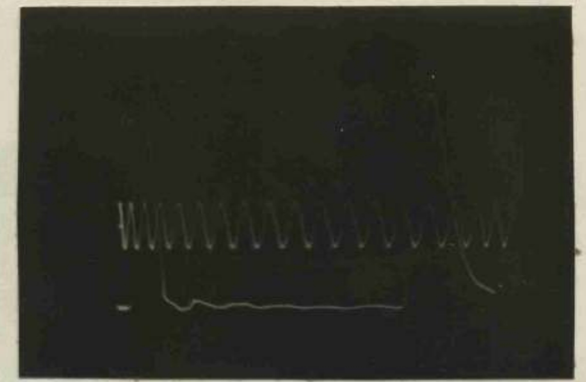
Oscillograms of Recovery Voltage — D1a and D1b for zero pause ($\theta = 0°$); D2a and D2b for θ small; D3a and D3b for θ large; D4 showing timing oscillation; D5 showing part of current wave.



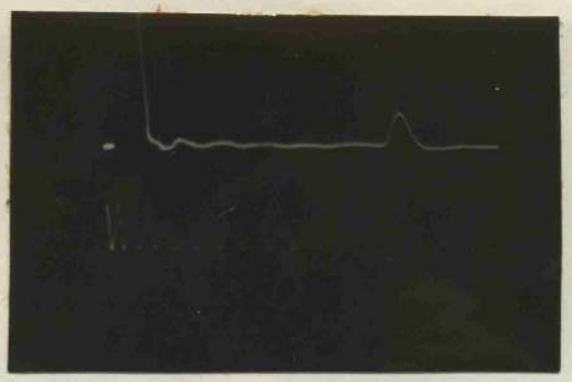
D.6. Recovery Voltage using high current test circuit.



D7. R.S.O. — Cable reflection for $Z_L = 0\Omega$.



D8. R.S.O. — Cable reflection for $Z_L = \infty$.



D9. R.S.O. — Cable reflection for $Z_L = Z_0$.

GENERAL CONCLUSIONS AND
STATEMENT OF ORIGINAL WORK

The common theme in the two parts of this thesis has been repetitive injection of voltages or currents to investigate properties of networks. The two equipments described in their respective parts differ widely in the injection generator circuits and in speeds of time-sweep required, and the applications are also peculiar to the equipments if viewed narrowly or superficially, but in fact have features in common (as has been shown by the ability to make certain comparisons of results) if treated systematically. The triggering and calibration oscillation circuits have much in common, but here also variety has been introduced by using a delay line in one case and a variable duration pulse generator in the other to produce a time shift from the initiation of the timebase to the commencement of the displayed phenomena; various also have been the methods of providing constant amplitude regeneration in the calibration oscillators. In fact, for repetitive transient application the fields of circuit techniques and of low- and high-speed oscillography have been fairly well exploited in an effort to provide direct improvement or increased versatility over existing designs. In the light of the experience gained by the design and use of the two equipments, the author feels that further developments are still possible especially with regard to making more portable equipments (if slightly less versatile), and to the extended use of the testing techniques by designers and maintenance engineers.

In as much as the particular combinations of well-known techniques are concerned, the equipments are unique, though following the trends of previous designers. The combination of pulses and calibration oscillations simultaneously to modulate a display, has not been described by previous designers of Recurrent-surge Oscillographs, nor has the use of the bootstrap circuit to provide a push-pull high-sweep-voltage timebase of reasonable linearity. The calibration oscillator circuit for the R.S.O. has been used by a colleague (Mr. I. Cochrane) but otherwise is little known. For the R.V.I., the technique of current chopping is entirely new, being an extension of the Half-Wave Injection Method used previously only by S.Y. King (Part 2, Reference 38).

In contrast to Germeshausen (Part 1, Reference 4, Section 8.11 et seq.) the author considers that, at least in the one case considered, the heater current and consequently the gas pressure have an effect on the firing delay of a hydrogen thyratron which may be quite noticeable within the specified heater supply tolerances; and also contrary to the general trend of opinion regarding the use of neutral-current tests on transformer windings to give a measure of indication of the position of a fault, the author has found, again in a particular case, that fault location might be practised especially where a standard previously prepared set of comparison oscillograms was available.

ACKNOWLEDGEMENTS

The author desires to express his sincere gratitude to Professor F.M. Bruce, M.Sc., Ph.D., M.I.E.E., A. Inst. P., of The Royal Technical College, Glasgow, for originally introducing the author to the subject of these researches, and for his continued interest and assistance during all stages of the work.

Appreciation is also due to those members of staff of the Department of Electrical Engineering in The Royal Technical College who have given advice on many matters, particularly Dr. E.S. Fairley and Mr. A.S. Husbands, and to those of the workshop staff who carried out the construction of experimental chassis and the final instruments. Mr. J. McGregor has undertaken much of the work of proving the capabilities of the R.V.I., and many of the comparative performance figures, and the author expresses his deep indebtedness for this invaluable assistance.

Without the scholarships awarded by the Governors of The Royal Technical College, and by The Carnegie Trust for the Universities of Scotland, the author would have been unable to commence and continue this work, and therefore a special appreciation is due to them for their financial aid.