JOURNAL OF

The British Institution of Radio Engineers

(FOUNDED IN 1925—INCORPORATED IN 1932)

" To promote the general advancement of and to facilitate the exchange of information and ideas on Radio Science. "

Vol. IX (New Series) No. 8 AUGUST 1949

NOTICE OF THE TWENTY-FOURTH ANNUAL GENERAL MEETING

NOTICE IS HEREBY GIVEN that the TWENTY-FOURTH ANNUAL GENERAL MEETING (the Sixteenth since the Incorporation) of the Institution will be held on THURSDAY, SEPTEMBER 22nd, 1949, at 6.30 p.m., at the London School of Hygiene and Tropical Medicine, Keppel Street (Gower Street), London, W.C.1.

AGENDA

1. **To confirm the Minutes of the Annual General Meeting held on October 21st, 1948.** (Reported on pages 261-263 of Volume VIII (New Series) of the Journal dated November-December, 1948.)

2. **To receive the Annual Report of the General Council.** (Presented on pages 241-251 of the July, 1949, Journal.)

3. **To elect the President.**

   The Council unanimously recommends that Mr. Leslie H. Bedford, O.B.E., M.A.(Cantab.), B.Sc., be re-elected President of the Institution for a further year.

4. **To elect the Vice-Presidents.**

   Air Vice-Marshal R. S. Aitken, C.B., C.B.E., M.C., A.F.C., retires and Council unanimously recommends the re-election of Mr. Paul Adorian and Mr. William E. Miller, M.A.(Cantab.).

5. **To elect the Ordinary Members of the General Council.**

   The retiring members of the General Council are :—

   E. A. Cattanes.
   L. Grinstead.
   H. Moss, Ph.D.
   Sir Louis Sterling, D.Lit.
   G. A. Taylor.
   J. L. Thompson.

   In accordance with Article 29, the six vacancies thus arising must be filled by five from the class of Member and one from the class of Honorary Member. The Council nominates :—

   Sir Louis Sterling, D.Lit. (Hon. Member).
   N. C. Cordingly, O.B.E.
   G. L. Hamburger, Dipl.Ing.
   Group Captain S. Lugg, C.B.E.
   E. T. A. Rapson, M.Sc.
   J. L. Thompson.

6. **To elect the Honorary Treasurer.**

   The Council unanimously recommends the re-election of Mr. S. R. Chapman, M.Sc. (Member).

7. **To receive the Auditors' Report, Accounts and Balance Sheets for the year ended March 31st, 1949.**

   The Accounts for the General and Special Funds were given on pages 252-4 of the July, 1949, Journal.

8. **To receive the Annual Report of the Trustees and the Accounts and Balance Sheet of the Benevolent Fund for the year ended March 31st, 1949.**

   The Accounts for the Benevolent Fund were given on pages 255-6 of the July, 1949, Journal.

9. **To appoint Auditors.**

   Council recommends the re-appointment of Messrs. Gladstone, Titley and Co., 74 Victoria Street, S.W.1.

10. **To appoint Solicitors.**

    Council recommends the re-appointment of Messrs. Braund & Hill, 6 Grays Inn Square, W.C.1.

11. **Awards of Premiums and Examination Prizes.**

12. **An Address by C. O. Stanley, C.B.E.**

(Members unable to attend the Annual General Meeting are urged to appoint a proxy.)

ELECTRONICS IN HEAVY ENGINEERING*

by

W. Wilson, D.Sc., B.Eng.† (*Member*)

A paper read before the West Midlands Section on March 23rd, 1949, the South Midlands Section on March 24th, 1949, *and before the London Section on May* 19*th,* 1949.

SUMMARY

For years after the thermionic valve had been brought to a high state of perfection, and had been the means of achieving literally amazing results in very low-current circuits, neither its designers nor power engineers realized that it was capable of rendering the same services in heavy-current engineering. That realization has now come, and the paper describes the role that electronics has played and can in future play in industry.

After considering the fitness of the glass valve to form part of an industrial equipment, the principal functions which valves have performed in radio practice are considered in relation to their application in industry. First the mercury arc rectifier is compared with the mercury-filled rectifying valve, and the new forms are described which have resulted from a combination of the two, with their respective uses in power engineering. Then the enlargement of the oscillator and amplifier stages is similarly treated. Industrial oscillators and H.F. generators, with their applications, are dealt with.

Apparatus based upon electronic amplification are next considered. After a short section on industrial A.C. and D.C. amplifying circuits, including magnetic amplifiers, schemes governed by the photo-cell and by vibration and other pickups are described, including very heavy applications, one installed as far back as 1931. The theory of closed-cycle control follows, with methods of stabilization by mechanical and electrical feedback, the use of amplified field-current control and rotary amplifiers leading to the design of servo-mechanisms.

Electronic motor control is treated analytically, by listing first the defects of standard contactor gear, and then giving the type of motor required and its characteristics, the general principle of control, the component parts of a control circuit to give effect to these principles, and the building up of a complete scheme.

Applications of the cathode ray oscillograph in heavy testing rendered possible by amplification include winding comparators, permeability measurement, fault detection and location for electrical machines and batteries, and the use of radiolocation schemes in industry.

Finally, a short section is devoted to electronic instruments used in industry (apart from those already mentioned), including metal detection.

Introduction

The years immediately following the 1914-18 war were marked by the extraordinarily rapid development and application of the thermionic valve for radio communication. New types were produced in quick succession, giving continually improving characteristics, until a standard of performance was reached that went far beyond the expectations of the most sanguine pioneer. In talking pictures and in television, the photo-cell joined forces with the valve and enjoyed an equally successful career. But these accomplishments were restricted for years to very low-power circuits, in which the current was measurable in micro- and milli-amperes, and were apparently of no interest to power engineers.

Parallel with this development, but proceeding at a somewhat slower pace, the mercury arc rectifier was being brought to a high pitch of efficiency and general performance. Suddenly, and quite late in the day, its designers became aware of its similarity in all but size to the vapour-filled diode "rectifier" valve. They thereupon proceeded to adopt radio practice by adding a grid to the large rectifier, converting

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U.D.C. No. 621.38.

† Head of Development Laboratories—G. E. C. Witton.

it into an outsize gas-filled triode, capable of reproducing the performance of the existing small "thyratron" on a scale about 100,000 times larger. There was obviously no reason why a similar large-scale development should not be effected in the case of any other stage of the radio receiver, and the amplifier and oscillator circuits quickly experienced the same enlargement. Especially rapid progress was made during the war years 1939 to 1945, with the result that electronics has been widely applied in power engineering under the drive of war-time necessity, and its capabilities in this field are expanding at a rate comparable with the development of radio after the first world war.

This expansion has especially included the cathode ray tube, which by about 1933 had begun to establish itself in engineering test rooms, and had soon afterwards been brought to a high level of efficiency by the requirements of television. An ideal indicator was thus provided for tests and quantitative determinations of every kind, including those concerned with the highest powers and the heaviest equipment.

As can be readily imagined, most interesting and valuable possibilities have been opened up by combinations of these components. At the present moment, the electrical public have become very conscious of electronics as a means of solving many problems, and information as to its past and future applications is frequently asked for. The author proposes to meet these enquiries by recounting briefly what has been done in the past, and describing analytically its present possibilities.

1. Durability of Electronic Gear

It is perhaps natural that heavy current engineers should at the outset be apprehensive as to the reliability and robustness of glass tubes ; and it is frequently necessary to reassure them on this point. Actually, the great majority of glass valves will do duty for from 10,000 to 20,000 hours.

As regards resistance to shock and other rough treatment, the experience of the fighting services is a sufficiently convincing tribute. Bomber and fighter planes possess about 200 valves each ; while a modern warship depends for its navigation and fire control upon a very large number of them, as well as several hundred cathode ray tubes.[1] The greatest possible durability is needed for every part of this equipment ; and it is significant that the glass tubes are among the most reliable links in the whole chain ; so much so that the once familiar metal-tube valve is now rarely seen.

The number of glass valves in use will probably be reduced in the near future by two recent developments, viz. (*a*) the metal rectifier, especially when used as part of a magnetic amplifier, and (*b*) the germanium diode and triode, which are just (January 1949) coming into use. Both of these types are characterized by a practically unlimited life.

As regards the electronic gear generally, it possesses the great advantage of having no continuously moving parts ; while the ease with which a section can be withdrawn from the assembly and a replacement substituted, all in a matter of seconds, has reduced the problem of maintenance below that normally associated with electrical apparatus.

2. Rectification

2.1. *Mercury Arc Rectifier*

The mercury arc rectifier[2] affords a good example of the range of sizes and performance possessed by electronic apparatus ; and as the arc rectifier with grid control is practically interchangeable with the large gas-filled triode for many heavy power applications, its features and capabilities may with advantage be compared with those of the valve. It originated as an arc lamp which was enclosed in a vacuum, when it was observed that operation would only occur when the mercury pool used as one electrode was connected to form the cathode.

The original glass bulb form proved inadequate for currents exceeding about 500 A, i.e., 250 kW at 500 V ; and larger sizes, up to about 5,000 A, were made with cylindrical steel tanks, water jacketed and continuously evacuated. Twelve years ago the aircooled pumpless steel tank rectifier was developed in Birmingham, and units up to 1,250 A have been manufactured. These three types are illustrated in Fig. 1. As regards voltage, their main field of application is for power supply purposes at less than 1,000 V ; though they are used for traction at 3 kV, and for supplying the high tension for oscillator circuits, such as radio

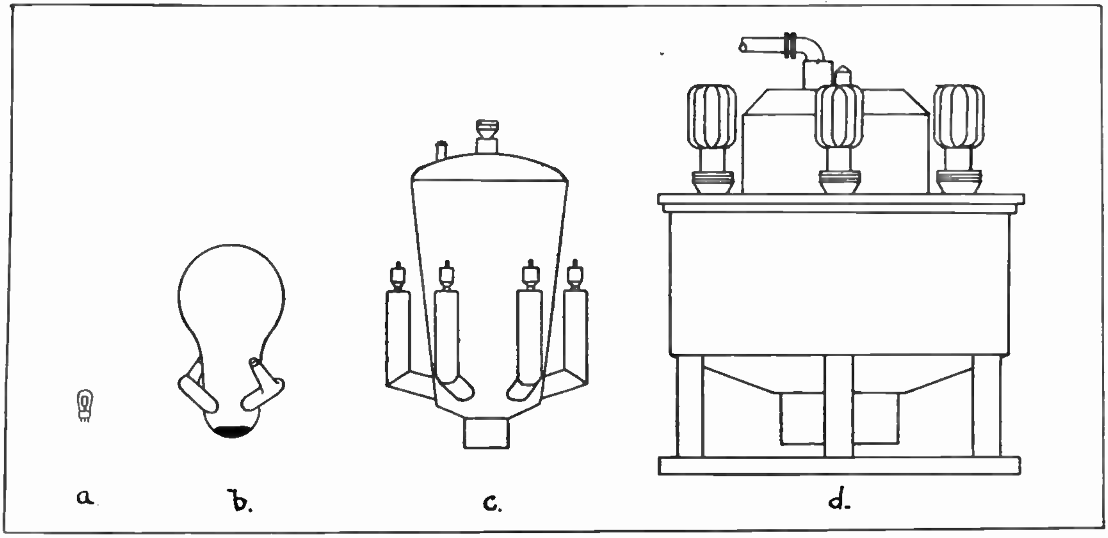


Fig. 1.—Four mercury filled rectifiers: (a) Diode valve; (b) Glass mercury-arc rectifier (3 phase); (c) Sealed-off arc rectifier (6 phase); (d) A continuously evacuated arc rectifier (6 phase). The respective current ratings are 0·3, 250, 1,000 *and* 4,000 *A.*

transmitters and cyclotrons, at voltages up to 20 kV.

In contrast to this development, the small gas-filled diodes were arrived at by injecting a small quantity of inert gas or liquid mercury into the vacuum of a standard diode. A rectifying effect was, however, already present, the effect of the filling being to reduce the voltage drop and to render the tube much more conductive.

The essential difference between the two types of rectifier is in the form of the cathode. The hot cathode of the valve enables the current flow to be initiated at will, but has a limited life. The pool cathode of the arc rectifier is, however, indestructible and hence especially suitable for industrial and heavy current purposes ; but it cannot initiate the electron flow, a special " igniter " electrode being necessary. In the ignitron type, the third electrode in each single-phase cylinder starts the arc when a current of 10 A at 150 V is supplied to it.

2.2. *Grid and Igniter Control*

In electronic control installations, the effect of the grids in the various tubes must be borne in mind. In a hard tube the grid modulates the anode current, but in a gas-filled triode it is simply a trigger device, causing the valve to conduct to its full extent and then being powerless to stop it. Hence, as far as switching on is concerned, the grid of the latter performs a similar function to the closing coil of a contactor; and the same is the case with the igniter electrode of an ignitron.

When used on D.C., the gas-triode can produce a square-fronted current, persisting until it is interrupted by external means. On A.C., the grid causes the current to start at a definite point in the cycle, and to continue the wave until the next zero point is reached, whereupon the discharge ceases until it is again initiated in the same manner. Thus, with the aid of an auxiliary valve or other device for applying the triggering impulse at the desired point in each half-cycle, the duration of each current pulse can be regulated, and with it the r.m.s. value of the current. The same capabilities have been afforded the mercury arc rectifier by the addition of the grid.

The ignitron, with its single-phase construction and three electrodes, looks perhaps more like an outsize radio valve than any other mercury arc rectifier. Like the others of its class, it has the advantages over the contactor of instantaneous operation and therefore precise timing, and large current capacity. Two typical examples of its use are the supply of power for automatic welding, and the control of regenerative braking in traction systems fed by rectifiers. In the former case, currents of up to some thousands of amperes are passed for a carefully measured short period such as a few cycles (1/50 second), for effecting a sequence of spot or projection welds ; and the success of the weld is dependent upon accuracy of timing to within a small fraction of a second.[3, 5]

In the second application, the return of power to the line by a tram or train is facilitated, which is especially economical for braking when descending hills. This is an inherent feature when the supply comes from motor-generators or converters, which feed back the excess power automatically ; but it is not practicable when a bank of standard rectifiers is substituted. Some means is then necessary to prevent dangerous over-voltages if there happens to be no other car drawing current from the section at the moment of braking. The usual method consists of switching a bank of resistors across the substation busbars immediately the voltage begins to rise above normal ; but as the rise is very rapid, contactor gear cannot act quickly enough to prevent a serious peak. By the use of an ignitron triggered by a thyratron functioning as a voltage relay, the delay can be reduced to a few milli-seconds. The scheme is indicated in Fig. 2, where V_1 is the thyratron triggering the ignitron V_2. The grid of the former is connected to a portion of the line voltage drawn off by the potentiometer XY ; but a fixed voltage drop across the resistance r, due to the current from a full-wave rectifier, is connected in opposition, the two voltages being so proportioned that V_1 just does not fire at normal line voltage. Immediately the voltage begins to rise, V_1 conducts and causes V_2 to connect resistance R across the line, where it provides dynamic braking. A follow-up contactor (shown dotted) then closes and short-circuits both V_1 and V_2.

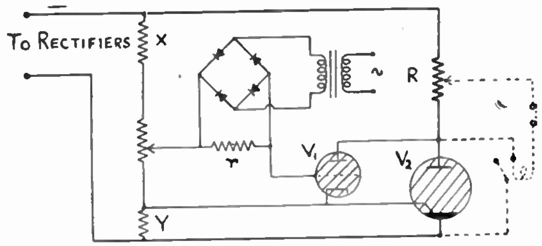


Fig. 2.—Ignitron (V_2) used for dynamic braking.

2.3. *Inverters*

The possession of a grid, in conjunction with a suitable transformer, also enables both valve and rectifier to reverse their functions, i.e., to convert D.C. to A.C. at a frequency set by a pilot wave applied to the grid. There are a number of circuits for the purpose, involving either two gas-filled triodes, which conduct alternately, or a single triode.[4] For isolated equipments, the pilot wave would be supplied by a tuned circuit, acting in conjunction with a feedback from the output, as illustrated in Fig. 3 ; but the need does not arise in the case of an installation feeding into an existing supply main. Inverters may be designed in the form of gas triodes or grid-rectifiers, and thus may be given outputs having a very wide range as regards power and frequency ; in addition to more usual ratings, they may be made for heavy current, and for frequencies up to about 2,000 c/s.

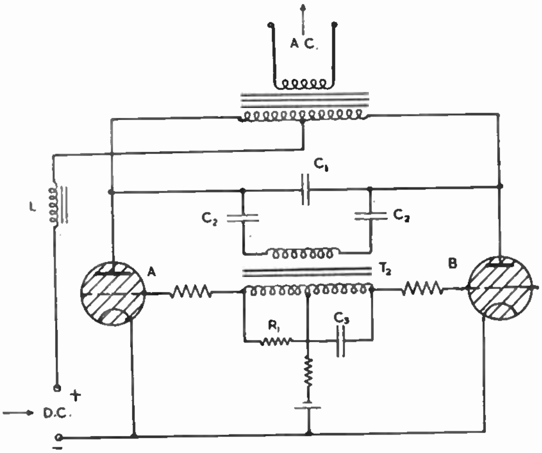


Fig. 3.—Inverter circuits showing tuned pilot circuit $T_2C_3R_1$, feedback condenser and transformer C_1 and T_2, and phase correcting condenser C_2.

Inverters have, however, not yet been used much for really large-scale power purposes, owing to a peculiarity which calls for further development. This is a leading phase angle in the A.C. wave, which at present requires the provision of wattless current from an external source, such as a synchronous condenser.

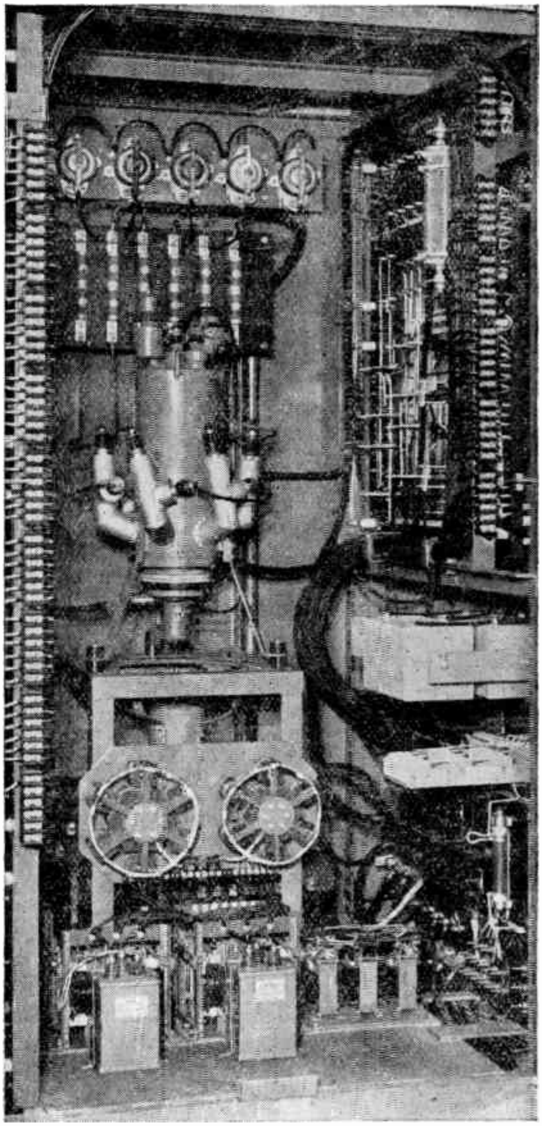


Fig. 4.—Small 6-phase grid rectifier in control cubicle for planing machine.

An interesting example of a grid-rectifier which includes the functions of both rectifier and inverter is shown in Fig. 4. This is part of a control scheme for a 50-h.p. planing machine, for which the grid rectifier takes the place of the usual Ward-Leonard motor-generator set, taking power at 50 c/s A.C., and delivering it in the form of D.C. to the driving motor at just the right voltage for every part of the working cycle. Since the requirements include braking by returning power to the mains, inversion is an important part of the scheme. Among the advantages which the grid-rectifier has over the motor generator for such purposes are the virtual absence of stand-by losses, the much greater efficiency, and the absence of wear and tear.

Mercury arc inverters can function as high frequency generators up to 2 kc/s, and are so used for supplying induction furnaces and for other H.F. heating applications.

3. Oscillation

The detector or oscillator stage of a radio set has formed the basis for two classes of apparatus used in heavy industry ; small oscillators employed chiefly in connection with testing, and large H.F. generators furnishing power for dielectric or induction heating, with outputs such as 1, 2, 5, 25, 100 or 1,000 kW or more.

3.1. *Oscillators*

Standard size oscillators, as used in radio and telecommunication work, are employed for a number of purposes in power engineering. As would be expected, they form an important part of the testing plant in an establishment where electronic apparatus, especially amplifiers, are employed. They are also used for tuning anti-interference wave-traps, which in the case of trolley-buses or trams may reach large proportions ; and for testing filter-circuits generally. High frequency bridges, for recording pressures and other quantities, especially on oscillograph films, need them as an H.F. source.

Other uses include noise measurement, the checking of high speeds beyond the range of stroboscopic methods, and the tracing of timing waves on oscillograph records. The detection and location of faults in armatures are preferably effected with current having a frequency of 20 to 40 kc/s.[6] Duddell oscillograph elements are tested for natural frequency in comparison with an oscillator ; and it also forms a convenient source of ultrasonic noise.

Suitable oscillators for this kind of work are beat-frequency sets with a range of 0 to 12 kc/s, and " straight " sets with a range of 12 to 100 kc/s.[7]

3.2. *H.F. Generators*

However large an H.F. valve-type generator is, it always bears a close resemblance to the detector stage of a radio set, from which it has been derived; mains and filament transformers, variable condenser, air-core tuning coils, chokes and transformers, and valves all forming overgrown versions of the radio gear. Such large oscillators are designed for capacities up to about 2,000 kW, and mostly employ the well-known Colpitts, Hartley and coupled-grid circuits. They are practically always used for high frequency heating. In view of the very practical papers that have already been published by the Institution on this subject, by L. Grinstead[8] and B. Keitley,[9] only a brief reference is necessary.

Harm has been done to the cause of H.F. heating by its employment for work that does not make adequate use of its peculiar advantages. The most valuable of these are:—

(1) The heat is developed in the work itself, no transmitting agent being necessary. Hence a very great saving of time may be brought about.[10]

(2) In the case of non-conductors (or dielectrics), heating is nearly uniform throughout the mass of material, and thus the risk of overheating the exterior or other part becomes negligible.

(3) In the case of conductors the heat can be localized to just those parts where heat treatment is required, such as a ·03-in depth of skin, a journal, a knife-edge, etc.

(4) The amount of heat developed, and hence the temperature, can be regulated to an exact figure by control of the voltage and the timing.

At the present time the apparatus is relatively expensive, and uneconomical results will be given unless at least one of the above advantages is important. For example, more than one of them favour its use in a mass-production line. Other suitable applications are the drying of foundry cores, the gluing of furniture, the cementing of laminated wood, the heat treatment of metal parts such as the teeth of gear-wheels and the surfaces of journals.

Two typical examples in practical use may be briefly described, one of the induction heating of metals, and one of dielectric heating. The first is the brazing of tungsten carbide tips on to the cutters for machine tools, an operation requiring from 1 to 5 kW of H.F. power, according to the size of the cutter. A frequency of about 5 Mc/s is used, the heater coil being a copper tube of about $\frac{3}{16}$-in outside diameter, continuously cooled by water circulation. A single turn is sufficient and the heating time is from 20 to 40 seconds.

Dielectric heating may be exemplified by the gluing of plywood, which is to-day carried out by means of a thermo-setting cement, such as phenol- or urea-formaldehyde. The stack of laminations, which in a typical case consists of sheets measuring 54 ins by 48 ins, each varnished with the cement, is squeezed in a press at a pressure of about 10 tons per sq. ft between metal platens that form the earthed electrodes and are heated by steam or resistance coils to prevent the loss of heat through conduction. In the middle of the stack, which has a height of 12½ ins, is inserted the high-voltage electrode or platen, so that the two halves of the stack are in parallel. An H.F. generator of about 25 kW output is used, working at 10 Mc/s, and completely polymerizing the urea-formaldehyde cement in about 30 minutes, an operation requiring a temperature of 95° C.

In both the above examples the advantages of H.F. heating are fully exploited; especially as regards high rate of working and safeguarding the material from excessive heating or burning.

4. Amplification

It may be claimed with justice that the amplifying faculty of the thermionic valve has rendered the most valuable service of all. The ability to reproduce a very small fluctuating voltage on a scale many times larger, but exactly copying the variation of the original, had already been of the greatest value in many well-known light-current applications. For power engineering, however, it is the key to the whole situation, since it definitely renders possible the precise control of heavy-current machinery by the regulation of an extremely small current or voltage.

Hence it is natural that the first entry of thermionic methods into industrial engineering, a year or two prior to 1930 in this country, should have been effected by means of amplifiers, which enabled various operations to be carried out or controlled by the photo-cell. At first the development was chiefly concerned with auxiliary operations such as counting and monitoring; but the complete success of the early equipments soon led to the control by this means of apparatus and machines requiring a large horse-power. Other pick-up devices than the photo-cell were then pressed into service, and provided controls depending on such factors as noise and vibration. Finally, the performance of electrically driven machinery is being made more precise and versatile by exciting or regulating the generators or motors from a light-current source through the medium of amplification.

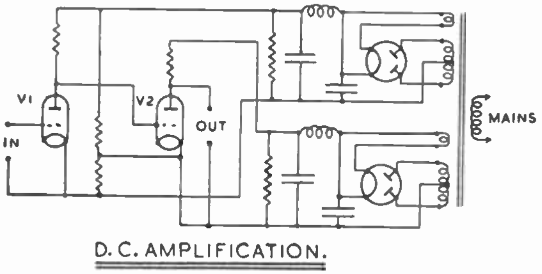


Fig. 5.—D.C. amplifier with independent H.T. supplies.

The chief applications of amplifiers in industry can therefore be tabulated as follows :—

(1) Control of operations and processes by means of photo-cells.
(2) Control by means of other pick-ups, e.g., sound or vibration.
(3) Control by amplified excitation of generators and motors.
(4) As an important accessory in " straight " motor control.
(5) As an almost essential component in testing equipments, especially those based on the cathode ray tube.

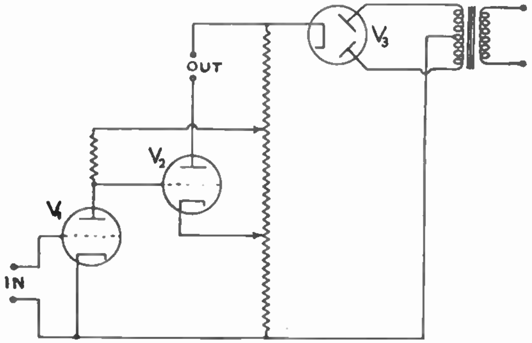


Fig. 6.—A direct coupled D.C. amplifier with potentiometer voltage connections.

After a brief discussion upon the theory and practice of industrial amplification, a description will be given of the above applications in turn.

4.1. *A.C. and D.C. Valve Amplifiers*

The principles of valve amplification for heavy engineering are in general the same as for radio, the chief difference being that whereas the current concerned in the latter is practically always alternating, D.C. is more frequently encountered in the former.[11] When a single stage of D.C. amplification is sufficient, no difficulty arises ; but when there are more than one, the inter-stage coupling needs consideration. Two typical examples used in heavy-current engineering are shown in Figs. 5 and 6. The former employs separate power supplies to the two stages for keeping the anode/grid voltages at their correct value, while the latter embodies a potentiometer, the smoothing and cathode-heating circuits being omitted for the sake of simplicity. This type would be suitable for operating, for example, the control winding of a saturable reactor.

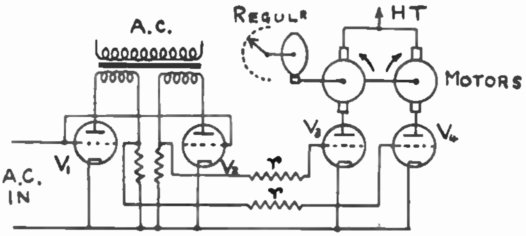


Fig. 7.—Phase conscious amplifier.

A.C. amplifiers are usually resistance-capacity coupled as in radio practice ; but phase-conscious amplifiers, in which both grids and anodes are energized by A.C., deserve a brief mention. These are useful when two alternative operations have to be effected in response to two corresponding signals. In the diagram forming Fig. 7, the input signals come from opposite sides of a wind velocity relay, and the outputs go to two motors which turn the regulator of a Ward-Leonard set in opposite directions, through reduction gearing, and thus maintain a constant large-scale wind supply. The final valves V_3, V_4 are biased to cut-off by the resistance arrangement indicated at r, r.

4.2. *Magnetic Amplifiers*

There are two alternatives to the valve in amplifying practice, both of which should be considered, as although they are not themselves electronic, they are used with electronic components, often together with valves in the amplifier itself. One of these is the rotary amplifier, described later under Section 4 (5); and the other is the magnetic amplifier, consisting essentially of a saturable choke and a " dry " metal rectifier.[12] A typical form, having two stages, is shown in Fig. 8. It is not a new device, an example having been described by the author 17 years ago in connection with D.C. protective gear; but its advantages are being specially recognized at the present time as a valuable component in electronic equipments.[13]

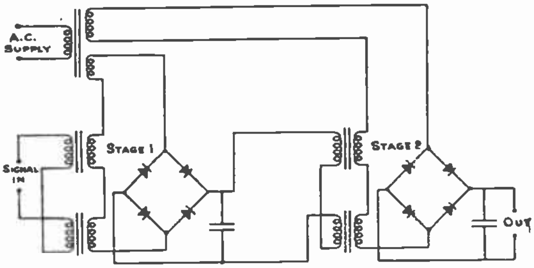


Fig. 8.—Electromagnetic amplifier.

A saturable reactor consists of an iron-cored choke coil so designed that the core is nearly saturated by the usual A.C. winding. There is also, however, a D.C. winding on the core, through which the signal input is passed, increasing the degree of saturation and thus reducing the inductance, so that it passes a greatly increased current. This A.C. output is usually converted to D.C. by a full-wave metal rectifier; and there may be a further full-wave rectifier in series with the first for providing a negative feedback to a special coil on the reactor core.

One obvious advantage of magnetic amplification is its freedom from deterioration, since there is no part that cannot be so designed as to be practically everlasting. Magnetic amplifiers can therefore be contained in a sealed case, a practice employed in connection with certain automatic regulators of the ordinary electromagnetic pattern. They are also more likely to secure the approval of engineers who are prejudiced against the glass valve; while in addition they are undoubtedly more suitable for a few really difficult locations.

It must not, however, be assumed that the magnetic amplifier is necessarily in competition with the valve type, as their functions are to a considerable extent complementary. It requires a current input, the valve type requires a voltage; its input impedance is low, that of the other is very high; it gives a large power amplification, which may amount to 10^6 for a single stage, as compared with a voltage amplification for the valve type. There is no necessity to make all the stages of the one type; in some cases it may be worth while to use a magnetic final stage following, say, two preliminary valve stages, in order to secure a large power output without requiring an unusual valve or an excessive supply of H.T.

In the figure, the input signal goes to two saturating coils in series opposition. Two identical chokes are used in this way in order to prevent any induced A.C. voltage from getting through to the D.C. side. It will be seen that the A.C. voltages are equal and opposite in the two chokes, and hence cancel out. The only part of the circuit which requires special care is the A.C. winding of each stage, which must be so proportioned that the core is brought nearly to the saturation point.

Instead of two similar chokes being used in opposition in each stage, they are often combined to form a single 3- or 4-limb unit. This type is shown later in Fig. 17, accompanied by a description of typical applications in the realm of motor control. Test curves are also given illustrating the performance, and showing the amplification to be nearly linear.

The low impedance input has extended the advantages of amplification to a number of pickup devices, such as photovoltaic (barrier-layer) cells, thermocouples, and resistance strain-gauges, which on account of their low impedance are not suitable for valve amplification. Further, the input goes to a winding on an iron core, and it is therefore practicable to have several quite distinct inputs, the amplifier responding to their algebraic sum. Under certain conditions the absence of a delay during " warming-up " is an additional advantage.

There is a slight time-lag, due to the presence of the iron circuits, that forms a disadvantage for some applications. It is inversely proportional to the frequency, and can hence, if necessary, be minimized by raising the latter; and it increases with the gain. It can also be increased by the presence of a shunt circuit. For the great majority of requirements, however, the delay is not at all a serious matter.

Two points should be borne in mind: first, although valve amplifiers are free from time-lag, they are customarily associated with components, such as transformers and condensers, that are not; and secondly, the equipments to be controlled possess a time-lag in nearly every case, especially those covered by this paper. For these reasons the effect of the amplifier delay is usually negligible.

It is not an easy matter to define the length of the time-lag, although various attempts have been made to do so. But it can be said that under the least favourable conditions at 50 c/s it may amount to a second or somewhat more; but for motor and generator control purposes it is comparable with that of the equipment to be controlled.

4.3. *Photo-cell Control*

There are three types of photo-cell[14, 15, 16] employed extensively in practice, of which the photo-voltaic, or barrier-layer type, is not well adapted for use with a valve amplifier because of its low internal resistance, usually ranging from 300 to 2,000 ohms. As was stated in the last section, however, the magnetic amplifier has altered the position, and this combination of cell and amplifier has already been used for the simpler applications, such as counting at rates up to about 100 per minute.

The photo-conductive, or selenium, cell has been used for the automatic switching of street lamps in accordance with the brightness of the existing daylight, and for similar purposes; but it is not generally regarded as so suitable for present purposes as the photo-electric type, which, being an electron tube, combines well with the amplifying valves.

In most of its applications, the photo-cell takes the place of a human observer, either for the purpose of detecting a condition and initiating the appropriate response, or for measuring any quantity that can be converted into a variation of light intensity. In both cases, not only are the services of the attendant dispensed with, but also his work is usually performed with greater reliability and precision.

One of the earliest applications was for counting, an equipment having been installed to check the output of a Birmingham rubber tyre factory in about 1928. The interception of a light beam by each of the wrapped tyres forming the finished product from the mill, causes a relay to operate a step-by-step recorder. Protection against a lengthy shut-down owing to tearing of the paper is a valuable addition to printing presses and paper calenders, Rupture occurs first at an edge, and is so serious a mishap in a paper works that there would be a separate provision for each margin. In the case of printing, one edge or both would be checked, and a device is frequently incorporated to adjust the lateral position of the paper if it wanders to one side or the other. This provision is especially valuable in three- or four-colour printing to secure the exact superposition of the successive impressions.

Further applications are self-opening mechanisms for doors, meter-reading gear, danger signals at low bridges or passages to prevent too high a vehicle from trying to pass, self-filling hoppers, floor-levelling gear for lifts, postal sorting apparatus and burglar alarms, an invisible infra-red beam being employed in the last case.

Special reference may be made to three very "heavy" applications, which were installed 18, 12 and 4 years ago respectively. The first controls the discharge of the still-glowing product as it comes off a large steel tube rolling mill. Here the photo-cell equipment replaced a man and, in addition, performs more precisely the accurate timing required. No projector lamp is needed, as the glowing tube itself actuates the cell. Photo-cell equipment is also responsible for the automatic operation of the longest and heaviest swing bridge in Europe, that across the Forth at Kincardine, 364 ft in length and 1,600 tons in weight, which is controlled by a single switch.

Finally, a recent naval application should be worth describing. Its initial purpose was to warn the engineers of a warship that tell-tale smoke was about to emerge from the funnel, and reveal her position to possible raiders; but the scheme was found to provide also a sensitive metering service, enabling the furnace air-supply to be regulated at the optimum value. In the first ship fitted, an aircraft carrier, there were four separate equipments fitted to the uptakes at the base of the funnel, but the latest battleship, *H.M.S. Vanguard*, has as many as eight. Each outfit consists of a projector lamp, mirrors and photo-cell-amplifier unit, causing the light beam to pass through the smoke-duct four times in the case of the carrier and three times in that of the battleship, before coming to rest on the sensitive cathode. Evolution of smoke decreases the current emitted by the photo-cell, enabling the relative amount to be shown by three lamps resembling colour signals. Of these, amber indicates that there is a very slight issue of smoke; and the engineers found that by so adjusting the blower that the green lamp shows nearly all the time, with only an occasional short flick of the amber, the most efficient mixture of air and fuel is maintained. It should be remembered that excess air wastes heat very seriously, besides lowering the furnace temperature; steady conditions conducing not only to fuel economy, but to increased life for the boilers. All three elements can be seen in Fig. 9, which was taken looking vertically down the base of the funnel. The enclosure on the left contains the projector lamp, that in the middle one of the three mirrors, and that on the right the photo-cell and amplifier.

4.4. *Vibration and other Pickups*

A photo-cell is in reality a pickup operated by light. Similar devices responding to other conditions or parameters, such as vibration, noise or pressure, can be made the subject of amplification. Of these, the recording of vibration in a dynamic balancer will be described as a typical example. There are several reasons why a moving part, such as a motor armature, should be balanced while rotating, the chief being that there may be two equal and opposite unbalances at different positions along its length, which would cancel out on a static test, but produce a double vibration upon rotation. By means of the electronic apparatus, not only is the balancing effected dynamically, but it is done in only a fraction of the usual time.

The rotor under test is rotated in bearings that are free to vibrate only in a direction at right angles to the axis; and their movement is registered by a pickup connected to each, resembling a moving coil microphone in principle and a small loudspeaker unit in appearance. Two A.C. voltages are thus produced, representing in magnitude and phase-angle the amount and angular position of the vibrations at the two bearings respectively. From these indications, the unbalances at the two balancing planes are read off by means of a valve voltmeter through the medium of a mixing circuit and amplifier.[17]

The method consists of cancelling the effect of the unbalance at each end in turn, by opposing to the voltage at that end a proportion of the voltage at the other. Potentiometers across the pickup terminals enable the value of the voltage to be adjusted, while so-called " phasing " circuits, consisting of a resistance and an inductance, vary the phase-angles as required. There are two duplicate sets of potentiometers, one of which is adjusted to render the voltmeter insensitive to the unbalance at one balancing plane, and vice versa, thus enabling the weight that is to be added or subtracted to be separately determined for each point; while its position is found by causing the difference voltage to operate a stroboscopic lamp, whereby a mark on the rotor appears stationary in space. The apparent position is recorded by adjusting an angular pointer, which when the rotor is brought to rest, indicates the place where weight has to be added or removed.

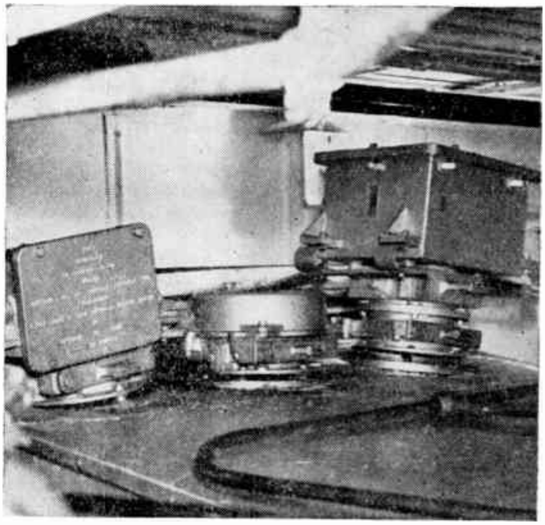


Fig. 9.—Photo-cell smoke measuring equipment on H.M.C.S. " Warrior." The cell and amplifier are in the enclosure on the right.

When the small rotors for which the scheme was originally devised were being balanced, the operation consumed only about one-fifth of the time required by the usual method. As a result of this successful performance, demands were made for similar machines to balance all sizes of rotor up to those of large turbo-alternators. All requirements were successfully fulfilled by a modified scheme due to Mr. L. G. Ward, and it will be of interest to describe this scheme in some detail.

In the first place, a somewhat more accurate method of assessing the angular position of the unbalance was desired for the very large machines. It was found that the stroboscopic method just described gave results correct to within ±5°, which is adequate for the small rotors but not for large ones. A very small alternator of the magslip type is therefore coupled to the rotor shaft, with its stator adjustable as regards angular position. Its output is taken to one pair of plates of a small cathode ray oscilloscope, the other pair being energized by the output from the mixing circuit ; and the position of the stator is varied until the Lissajous figure on the screen is a straight line, indicating that the two waves are in synchronism. This method is correct to within ±1°.

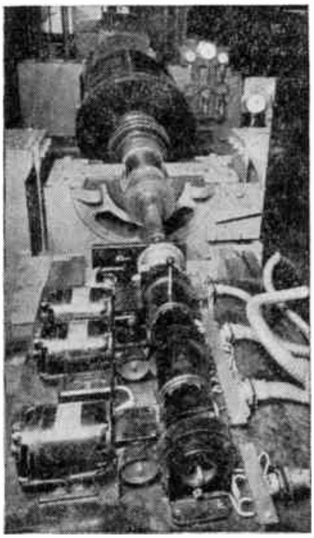


Fig. 10. — Dynamic balancer for rotors up to 40 tons showing the calibrating generators in front, spring suspended bearings and 10 - ton rotor between them.

The most important change is, however, in the method of calibration. For the small machines, which are usually being turned out by mass production, it is an easy matter to secure a perfectly balanced rotor, e.g., by trial and error, and to find the value of the meter readings by attaching a known unbalance to it. As turbo and other large rotors are produced at much less frequent intervals, and are of more diverse design, another method had to be found. The principle was adopted of running up the rotor under test and cancelling the out-of-balance indications from the pickups by means of two more small alternators, identical with the first and connected up through potentiometers. Then, although the rotor is not itself balanced, the recording circuit is, and a known weight can be added at a suitable position and its effect upon the meters accurately measured. In this way the apparatus is calibrated without being affected by any existing unbalance. About 50 minutes are required for the process, but the calibration then holds good for any other rotors of the same type. The actual balancing takes only another 20 minutes.

The photograph forming Fig. 10 illustrates the salient details. Each bearing is suspended by two flat steel springs about 21-in long and 11-in × ½-in in cross-section. The three alternators, with their shafts in line, are seen in the foreground ; while the rotor under treatment weighed 10 tons, which was actually only one-quarter of the maximum capacity of the apparatus. Measurements are made by a valve voltmeter, and results correct to about a quarter of an ounce at the rotor radius are obtained.

4.5. *Rotary Amplifiers*

For extremely heavy amplification, in which the output is measured in hundreds of kilowatts, use is made of rotary machines, consisting of D.C. generators (dynamos), in which the current supplied to the field forms the input and that delivered from the armature forms the output. In a typical case, the generator is driven by a motor at constant speed, and an amplification of 100 times is obtainable. As with electronic amplification, two or more stages can be used in succession. For example, it is quite common for a smaller machine, viz. an " exciter," to be mounted on the same shaft as the main generator, with its output taken to the field coils of the latter, and its own field coils forming the input circuit, giving an overall amplification of 100 × 100, or 10,000. Further, the addition of a third machine, an " auxiliary exciter," is also common practice, affording a total amplification of 10^6 and there may be even more stages.

Such an arrangement is called a " Cascade exciter," and is illustrated in Fig. 11. Its great advantage is that it brings the heaviest operations under the direct voltage control of a very small power source such as a thermionic valve. In the figure, an electronic amplifier is shown supplying the input current on the extreme right, while the final output goes to the big load-motor above. Two driving motors are shown, but all the three amplifying machines might just as well be operated by a single motor or prime mover.

The two first stages may be compressed into a single machine, as in the case of the Metadyne and Amplidyne.[18] In these, the brushes forming the usual output terminals are short-circuited together. An extremely small voltage applied to the field then produces a heavy armature current, which induces a strong magnetic flux at right-angles to that from the normal field. This is caused to function as the field flux for the second stage, inducing a still greater voltage in the second set of brushes, located at 90 electrical degrees to the first set and forming the output terminals. The advantages of the two-in-one type of machine are compactness, lightness and quick response through low mechanical and electro-magnetic inertia.

4.6. *Open and Closed Cycle Regulators*

It will be seen that by virtue of the various types of amplifier, a small current or voltage from an electronic source is enabled to modulate a very large amount of power and thus build up a sensitive and automatic high power regulator. To do so, it must be preceded by a device to convert the quantity or parameter which is to be regulated (e.g. speed or pressure) into a voltage or current, forming the input to the amplifier.

Now the usual purpose of a regulator is to keep some quantity at a constant and predetermined value. For example, constant speed is the aim of most engine governors; and precise speed adjustment is also the goal of many electronic regulators. Either the speed is required to be maintained at the same value to within 1 per cent or less, or the speed of one machine is to be correlated with that of another which is taking part in the same operation. Other requirements that may have to be met are constant voltage, current, power, frequency, acceleration, temperature, pressure, tension, position, liquid level or pH value, to name only the most common.

In the case of speed regulation, the usual device is a tachometer generator, which generates a voltage in direct proportion to the speed. Acceleration control is not quite so obvious; but it is frequently needed, in order to carry out an operation in the shortest possible time consistent with the safety of the motor and its load. A common method is to connect the D.C. voltage, varying as the speed, to the primary of a transformer, the secondary of which will then develop a voltage proportional to the rate of change of the primary voltage, i.e., to the acceleration. For temperature, the pickup would be a thermocouple; for pressure, probably a piezo-crystal; and so on.

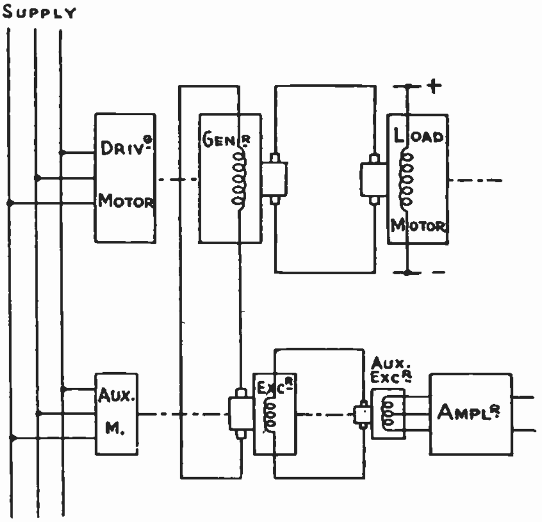


Fig. 11.—*Cascade exciter.*

There are two general schemes whereby this modulating signal can be applied. In the first, or open-cycle type of scheme, the pickup is simply connected to the amplifier, and the latter to the motor, as indicated in Fig. 12a; where *a* represents the amplifier, *i* the input device, and *o* the output or load. The disadvantage of this scheme is that the control may be interfered with by various conditions affecting some link or other of the chain, such as variations of temperature in the windings, or of friction in the bearings, any of which will cause errors in performance.

Hence the second, or "closed cycle" type of scheme is much more common. In this, a signal is sent back from the output side representing the actual performance, which is balanced against the input signal, and it is the difference between these, or the " error," that is amplified and passed on to the field of the exciter. The second " block " diagram forming Fig. 12b represents the change, a signal proportional to the output being brought back and compared with the input, and the difference or error, e, fed into the amplifier.

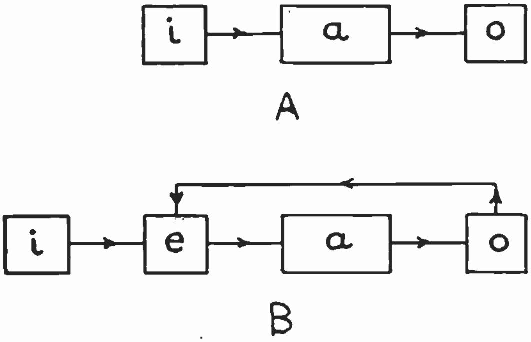


Fig. 12.—(A) Open cycle scheme. (B) Closed cycle scheme.

Error control has been used for many years in connection with governors and similar regulators, but its great advantages have only been recognized to the full since electrical amplification has been used as the servo means. Closed cycle working is particularly suited to electronic methods, and control practice during the past decade has shown a strong movement in its favour. It is particularly desirable in connection with electronic control because it not only improves the output performance, in that it can maintain an accuracy to within 1 per cent of normal without requiring delicate adjustment or components, but it also safeguards the control apparatus. A peculiarity of valves, including power valves such as gas triodes, is that although they are mechanically robust, they are subject to serious damage if a current beyond their rating is passed through them, even for a moment, in the shape of a loss of emission from the cathode. Closed cycle working provides an effective check against this occurrence.

Unfortunately, the use of amplification in a closed cycle is seldom possible without introducing a time-lag between cause and effect (due, for example, to the self-induction of a field coil), which gives rise to hunting. The reason for the instability is that the correcting means is caused to persist a little too long, and the error is hence over-corrected. A reversal of the correcting means follows, which again overshoots; and unless some positive method is employed for cancelling the tendency to swing, it will continue indefinitely.

4.7. *Stabilization*

Common remedies for hunting are damping the movement of the governor by introducing friction, and breaking up the governing means into a series of impulses; both of which are liable to reduce the sensitivity. The most effective cure however is by means of " feedback," that is, the return of power or movement from the output to the input side.[20, 7] In its mechanical form, this method is to be seen in the governor of nearly every steam or water turbine, the principle of which is that when the change of speed occurs (owing, for example, to a sudden change of load), the servo-cylinder rapidly begins to move the throttle; but at the same time it moves a lever which begins to oppose the effect of the governor-balls. In consequence, the latter effect gets less and less as the normal position is approached, and a balance is reached without hunting. Electrical feedback is, of course, applied much more simply, a fact which partly accounts for the great success of electronic servo-mechanisms. Radio engineers will be well acquainted with the methods of producing feedback, and with its use in stabilizing H.T. supplies and other circuits. It will therefore be sufficient to refer to the example of its use in Fig. 14 and to literature on the subject already published in the Journals of this and other Institutions.[20, 21, 22, 28]

4.8. *Typical Servo-schemes*

Two practical examples will be given of schemes based on electrical amplification, which is all-electronic in the first case, and partly rotary in the second.

4.8.1. *Electronic Regulators*

The first scheme, shown in Fig. 13, was got out some years ago and has been in successful operation since then as a sensitive speed regulator in a number of cases, and a voltage regulator in others. It incorporates two stages of D.C. amplification, of which the last consists of two tetrodes in parallel. When used as a voltage regulator, the "error," or difference between the output voltage and a fixed "pattern" voltage, is connected across the input terminals on the left. When used as a speed regulator, the voltage from a tachometer generator is similarly connected. The method whereby the two stages are coupled should be observed; the H.T. voltage applied to the coupling resistance of the first valve being the cathode voltage for the second stage, so that the stage voltages are virtually in cascade.

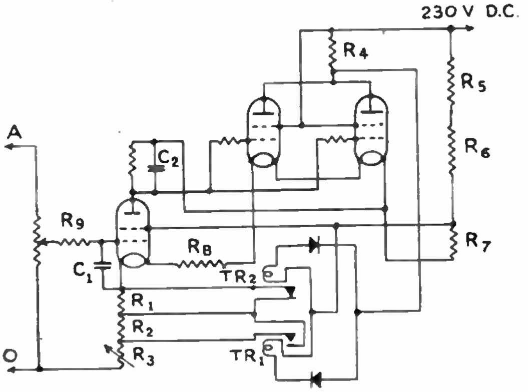


Fig. 13.—Electronic speed or voltage regulator.

The output from the last stage goes to two "telephone" type relays connected in parallel, but each controlled by a metal rectifier which ensures that one closes when the applied voltage (or speed) is too high and the other when it is too low. These relays initiate the means for correcting the error, not shown in the diagram. They also open the auxiliary contacts shown, which form the anti-hunting device. Each break cuts a small resistance R_1 or R_2 into the filament circuit of the first valve, which has the effect of varying the voltage at the input terminals AE in the opposite direction to the change being made by the relay. Unless the error is a large one, therefore, the relay immediately drops out; but if the correction made is insufficient, it closes again, starting a series of impulses which carry out the regulation without causing overshooting.

4.8.2. *Ward-Leonard Servo-mechanism*

It is appropriate to complete this section with a description of a Ward-Leonard equipment, with closed circuit for speed regulation, using amplified excitation with tachometer generator for error-control, and prevention of hunting by negative feedback from the final voltage. This is shown in Fig. 14, the driving motor and auxiliary exciter (if any) being omitted. Two connections leading from output to input will be seen. Of these the lower is the tachometer voltage, which is connected in opposition to a voltage at AE representing the "pattern" speed in order to give the "error"; while the upper is the negative feedback from the generator voltage for anti-hunting (stabilizing) purposes. The resistance-capacity differentiating combination near the right-hand end should be noted. Its purpose is to provide a steep rise of voltage upon the occurrence of a change of speed, following this by a decay to zero at a rate appropriate to the requirements of stability.

Through the stimulus provided by the ever increasing demands in connection with gun-laying, great advances were made in the mathematical design and in the potentialities of servo-mechanisms during the late war; and in particular the use of amplifiers for motor regulation extended and is still extending widely.[23]

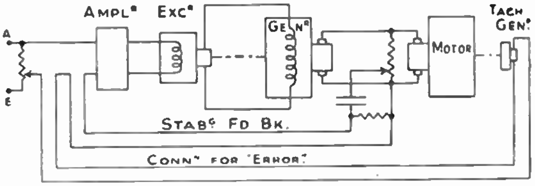


Fig. 14.—Ward-Leonard scheme with feedback.

5. Motor Control

5.1. *Requirements of Control Gear*

The most rapid progress in the application of the electric motor occurred one or two decades after the motor itself was fully developed, and was due to the evolution of automatic control gear, based upon the contactor and its associated relays. Through their good offices, not only has the motor been enabled to handle heavy and highly exacting loads without risk of damage, but also the successful operation of the electrical equipment has been made independent of the skill of the operator. Effective protection is provided for the motor against damage through overload or over-acceleration, while the duty accomplished is maintained at the maximum value compatible with safety. All this has been accomplished by means of practically indestructible apparatus which can be relied upon to operate for long periods without attention.^{27} In order that electronic gear can compete with the older type of control apparatus, it must obviously possess at any rate the majority of the above capabilities and advantages, and must also have sufficient advantages of its own to turn the scale in its favour.

To begin with, the basic advantage is very similar in both. In the contactor, the control operations are carried out upon the light exciting current instead of that in the heavy load circuit; while in the case of the valve, variation of the signal voltage applied to the grid is able to control the current in the anode circuit. But the introduction of electronic methods has brought an elegance and precision that has endowed the control gear with new capabilities, and is securing for it an ever widening application.

5.2. *Defects of Contactor Gear*

It will be of advantage to list the chief drawbacks of contactor gear, to assist in determining the conditions for which electronic methods are more likely to excel.

(*a*) Arcing at contacts.
(*b*) Wear of contacts.
(*c*) Power loss in controlling and regulating resistances.
(*d*) Lack of precision in speed regulation.
(*e*) Limited range of speed regulation.
(*f*) Need for maintenance, especially of contact surfaces.
(*g*) Control methods are often relatively clumsy.

Continual development has minimized these defects, and none of them can be considered vital. Care should therefore be taken to adopt electronic gear only when at least one of them is of unusual importance.

5.3. *Defects of Electronic Apparatus*

On the other side of the ledger must be entered the defects of electronic gear; though it should be borne in mind that they are partly due to its recent development, and especially to the small scale on which this type of apparatus has until recently been constructed.

(1) High first cost, and cost of replacements.
(2) Limited capacity of output valves at present available.
(3) Robustness at present less than that of contactors, especially as regards effect of over-currents.

These drawbacks are much what would be expected of a new type of apparatus, and they will undoubtedly be materially reduced in the next few years.

5.4. *Motors Employed*

The comparison that has been given between valve and contactor gear has indicated that electronic control is at an advantage, chiefly when precise and economical speed variation is desired. Now D.C. motors are much more flexible than A.C. machines, which in their usual non-commutator forms are in general only suited for constant speed. The power supply, however, is nearly always A.C., not only because it is easier to distribute than D.C. but also because it suits the capabilities of the valves, which possess inherent rectifying properties. It is, moreover, necessary for the various transformers that should form part of the circuit. A typical installation, then, is the rather strange combination of a D.C. motor supplied from an A.C. source.

5.5. *Control Methods*

Control requirements can be broadly stated as the variation of the voltage applied to the armature and/or the field; the speed being increased by raising the former or reducing the latter. With contactor or hand-operated gear, voltage variation is effected by cutting resistance into or out of circuit, the power absorbed in heating the resistance being wasted. With valves, however, the reduction of current or voltage can be carried out more simply and with negligible loss by delaying the " trigger " impulse to the grids until after the beginning of each wave, as indicated in Fig. 15. By so doing, the r.m.s. value of the wave is effectively lowered.

Two methods for continuously controlling the " firing " point are indicated in the figure. The requirement is to raise its voltage to the necessary low critical value, viz., to make it just more positive than the cathode; and this can be done by applying an unrectified A.C.

having the desired phase angle. A simple means for varying the latter appropriately is thus the chief need, and there are two main alternatives, indicated in Figs. 15a and 15b and c respectively. Both show the rectified A.C. applied to the anode in full lines and the voltage applied to the grid in dotted lines. For the sake of simplicity, only parts of the latter A.C. waves are put in, but they will be recognized as two A.C. voltages, one of which is reversed (or retarded by a half-cycle) as compared with the other. Since the valves in question are gas filled, they will conduct immediately after the grid voltage crosses the zero line, and the voltage applied to the motor will hence rise to its full value at that point in the cycle. In the figures, the motor voltage is represented by the shaded parts of the waves.

The difference between the two schemes lies in the method for varying the position where the grid voltage wave crosses the zero line. In Fig. 15a the phase angle of the wave is varied, and the crossing point thus made to occur at any position in the whole 180°. In Figs. 15b and c, however, the grid wave always lags about 90° after the anode voltage but, by adding or subtracting a D.C. voltage, it may be moved up or down, and the point of crossing again varied over the full range.

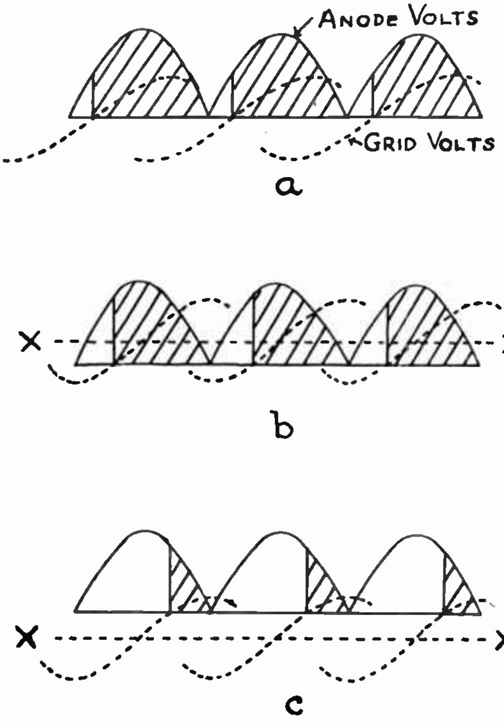


Fig. 15.—Variation of "firing point" of thyration: (a) by altering phase angle of grid voltage; (b) and (c) by bias control grid of voltage. XX is neutral axis.

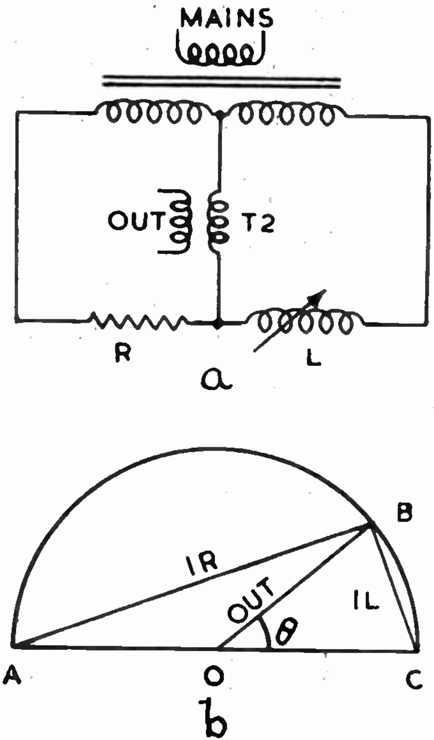


Fig. 16.—Phase shifting bridge: (a) Arrangement of bridge; (b) Vector diagram.

5.6. *Circuit Components*

A complete control scheme consists of a combination of circuits and devices for carrying out the various control functions. These will be described in detail as a prelude to the building up of a typical control diagram.

5.6.1. *Phase-shifting Bridge*

Both the methods that have just been given for varying the voltage applied to the armature or field of a motor depend upon the adjustment of the phase angle. If this were done by the addition of inductance or capacity, the amounts that would have to be cut into a straight circuit in order to produce the variation required would be very large. Wide range can, however, be secured with small values of either inductance or capacity by the use of the phase-shifting bridge shown in Fig. 16. The two upper arms are the two halves of a centre-tapped transformer secondary; while the lower arms consist respectively of a resistance and an inductance or capacity, one or both of which may be made adjustable. Then the voltage across the bridge can be swung through a very wide angle by quite a minor alteration of either; and it is in this position that the winding, usually the primary of a small transformer, is connected in which the controlled phase angle is required.

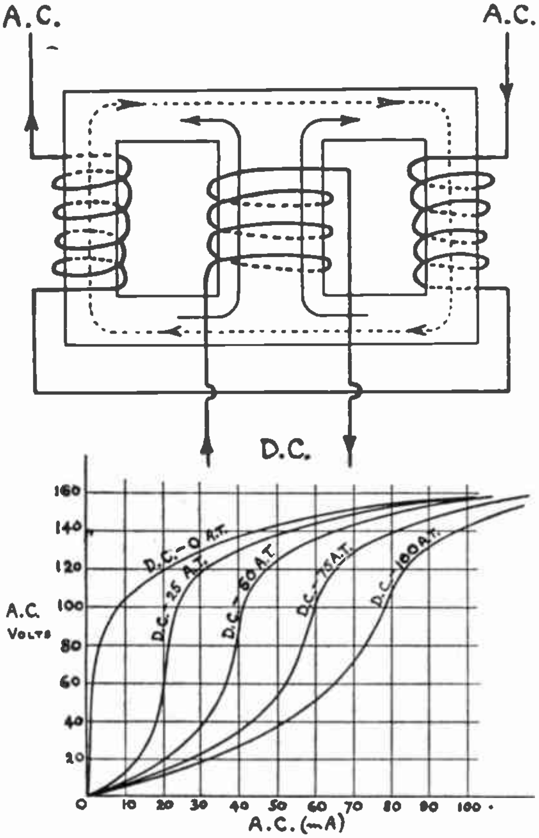


Fig. 17.—Saturable choke and characteristics.

Numerical values can be obtained by means of the vector diagram in Fig. 16, which also illustrates the principle. The voltages in the two halves of the supply transformer are represented by AO and OC, and the voltage drops across the resistance and the inductance by AB and BC respectively. Then BO represents the voltage in the bridge winding in both direction and magnitude. For present purposes, the variable inductance would usually consist of a choke with a movable iron core, or a saturable choke; or a variable condenser could be used.

The resistance R required to produce a given phase angle θ, using a capacity of *a* microfarads, is given by

$$AB = BC \cot \theta/2$$

$$\text{i.e., } R = (\cot \theta/2)/(2\pi f C)$$

$$= (\cot \theta/2)/(2\pi f \times a \times 10^{-6})$$

If, instead of a capacity, it is desired to use an inductance of L henries, then

$$R = 2\pi f L. \cot \theta/2.$$

5.6.2. *D.C. Transformer*

The chief deficiency of D.C. as compared with A.C. is the inability to transform the voltage or current without the use of rotary apparatus. This gap has been largely filled by the saturable reactor, when, as in the present case, a supply of A.C. is also available. Its principle has already been described in connection with electro-magnetic amplifiers, using the single-window type of core which generally needs to be used in duplicate.

A type very frequently employed in control circuits is shown in Fig. 17, together with a diagram giving its characteristic operation. Here the duplicate windings that were previously accommodated upon separate cores are now wound on separate limbs of the same core. The arrows show the directions of the A.C. and D.C. fluxes, and it is readily seen how the D.C. flow increases the degree of saturation in the outer limbs, reducing the inductance of the A.C. winding. The passage of a very low wattage current through the D.C. coil thus causes the A.C. to rise considerably; and by suitable design the relationship between the increases of the two currents can be made almost linear. The diagram also shows that the two A.C. coils produce equal and opposite effects upon the D.C. coil in the middle.

The five characteristic curves in the lower diagram connect applied r.m.s. voltage with resultant r.m.s. current at different values of D.C. excitation. That taken at zero D.C. is of the familiar B/H shape; and the others show the effect on this of equal increments of D.C. At 80 V A.C., for example, the corresponding current values are 3, 22, 39, 57 and 73 mA, which have a nearly uniform spacing.

Used by itself, the device forms a very convenient variable inductance, since the D.C. can readily be adjusted by means of a small rheostat or other means. If the D.C. input be regarded as the primary current (or voltage) and the A.C. output as the corresponding secondary, a transformer is obtained turning a D.C. into a much larger A.C. The addition of a rectifier to the A.C. side converts it to a D.C. transformer. Its use as a valveless amplifier has already been described.

5.6.3. *Voltage-Regulating Transformer*

The variation of the A.C. voltage applied to a circuit can be carried out by a straight transformer having the usual two coils. If one of these has its primary connected in series with that of the main transformer, a variable resistance connected across its secondary will vary the voltage absorbed by the primary, and so vary the voltage applied to the main transformer primary terminals.

An example is shown in Fig. 18, in which the voltage applied to the main transformer T_1, and thus to the motor armature M, is varied by absorbing a regulated part of the total voltage V in the series-connected transformer T_2. Instead of varying the resistance in the secondary of T_2, the firing point of the gas-filled triode V_3 is varied, as described earlier, by means of the phase-shifting bridge on the right, supplied by the transformer T_3. The variable inductance L would usually take the form of a saturable choke, controlled by a D.C. signal from an amplifier.

5.6.4. *Reference Voltage*

Voltage control schemes, especially those of the closed-cycle type, usually require a standard or " reference " voltage in order to establish a balance between the correct value and that of the output. There are four alternative methods of making this provision in common use, all of which give a constancy falling within ±1 to ±¼ per cent.

(1) A dry (or other suitable) battery. Dry batteries give a surprisingly constant voltage for a period of about a year when made with reasonable care. Their chief drawback is the need for periodic renewal.

(2) A lamp bridge. By connecting four incandescent lamps in Wheatstone's Bridge manner, two with carbon and two with metal filaments, and energizing them at opposite corners from the supply mains, the voltage across the " bridge " will be constant to within about the above limits. Again the drawback is the need for replacing the lamps ; but their life can be greatly extended by running them at a somewhat reduced voltage.

(3) A constant voltage transformer. There are several designs of transformer, having special arrangements of secondary winding and core, which counteract the effect of voltage fluctuations in the primary circuit. In general, there is an additional limb of the core, interrupted by an air-gap, partially shunting the flux between primary and secondary ; and in addition the secondary is tuned by a shunt condenser to resonate at the circuit frequency. This device is not suitable when appreciable variations of frequency can occur.

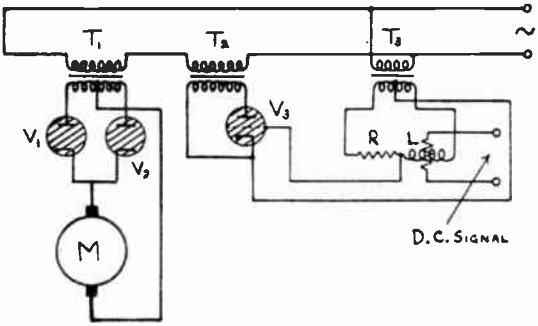


Fig. 18.—Series regulating transformer.

(4) A neon or other discharge tube The principle is that when the discharge is driven by a voltage well in excess of that needed to strike it, the remainder being absorbed in a series resistance, the voltage across the discharge is constant. Frequently there are two or more gaps in series, giving that number of reference voltages. Early forms varied appreciably with temperature, but improvements in design have largely overcome this defect.

In the diagrams that follow, a battery will often be used for the reference voltage, as affording the most convenient symbol, but it must be understood that other alternatives may be substituted

5.6.5. *Speed Regulation*

The regulation of the speed is obviously of the greatest importance and its easy and precise accomplishment is one of the chief advantages of electronic control. It may be carried out by varying the volts applied to the field or to the armature, or both. Field regulation possesses well-marked disadvantages and is only used, in combination with armature regulation, to secure a specially wide speed range, such as 200 : 1 ; as much as 50 : 1 being obtainable by armature control alone. With contactor control, resistance is cut into the armature circuit to lower the speed, a practice which is wasteful of power and causes the speed to vary with load. Both defects are obviated with electronic operation, and since control of the field, if used, is effected in much the same way as the armature, further reference to it is unnecessary.

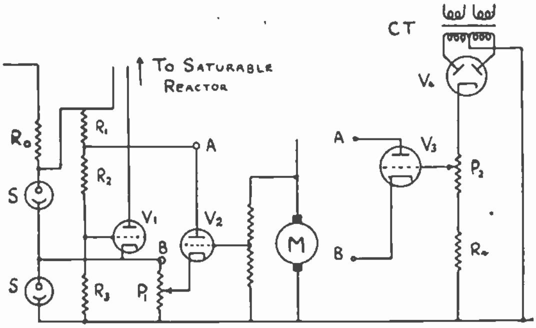


Fig. 19.—Speed regulator and current limiter.

It has been shown above that the r.m.s. voltage applied to the armature can be varied from zero to maximum by varying the current in the D.C. winding of a saturable reactor in one arm of the phase-shifting bridge. If this current is supplied by a valve energized from a constant-voltage source and adjusted to give maximum current at full voltage, its value can be reduced by passing current from another source through a resistance in series with the grid lead, and thus reducing the grid voltage. A number of functions can be carried out by so doing, of which the most important are : (1) maintaining a constant speed in spite of variations in load and line voltage, (2) adjusting the speed to any desired value, and (3) limiting the current to a predetermined safe value.

A typical scheme is shown in Fig. 19. Here the voltage supply for the valves is held constant by the stabilizing tubes SS on the left, in series with the resistance R_0. A potentiometer R_1 R_2 R_3 across these tubes enables the correct grid, anode and cathode voltage to be tapped off for valves V_1 and V_2, of which the first provides current for the saturable reactor and the second passes current through resistance R_1, developing a voltage drop and so reducing the grid voltage of V_1. The potentiometer P_1, shown connected to the cathode of V_2, varies its H.T. and grid voltages and hence forms a speed regulator. Finally, the voltage applied to the grid of V_2 is tapped off a resistance connected across the motor armature M, and is hence a constant fraction of the armature voltage. Since the latter is proportional to the motor speed, the reduction of the current supplied by V_1 is proportional to the speed and governing is directly effected.

5.6.6. *Current Limit*

The purpose of fuses and circuit-breakers is to prevent damage if the motor draws a dangerous over-current from the supply, owing to mechanical overload, insulation breakdown or other cause ; and they operate by opening the circuit and thus shutting down the motor. A better method of dealing with these events is to keep the current from exceeding a safe value without interrupting the supply. This is carried out by valve V_3, shown separately at the right of Fig. 19. Its anode and cathode are connected to the circuit on the left at A and B respectively, and its grid voltage is the voltage drop across a resistance R_4 due to a current proportional to the combined anode currents of the main thyratrons. These currents pass through the primaries of the current transformer CT, and the secondary current is rectified by a double-diode V_4 ; though metal rectifiers could be used instead. The resistance R_4 is so proportioned that V_3 does not pass current until the safe value of armature current has been exceeded ; the value of the current limit being adjusted by the potentiometer P_2.

5.6.7. *Typical Control Schemes*

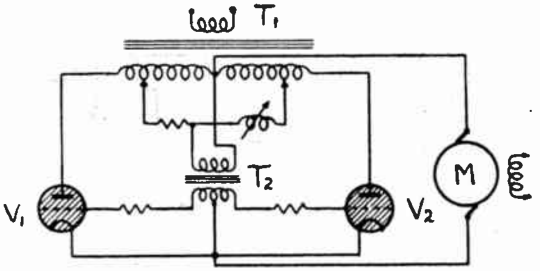
Following the description of the components of a control diagram, the building-up of complete schemes will now be exemplified. First, the application of the impedance bridge is shown for both methods of regulation. As before, it will be assumed that only the armature circuit is under treatment, i.e., the speed is controlled up to, but not beyond, the normal rated value for the motor ; but it should be understood that the field current can be regulated in a closely similar manner if desired.

The variable phase-angle method of control has already been exemplified in Fig. 18, in connection with the voltage-regulating series transformer ; and it is now shown directly applied to the control of a motor armature in the upper diagram of Fig. 20. The supply transformer T_1 is at the top, and a phase-shifting bridge is connected to suitable tappings brought out from its secondary winding. A variable inductance enables the phase angle of the voltage applied to the bridge transformer T_2 to be adjusted through the required 180° ; and the two portions of its centre-tapped secondary are taken to the grid of the gas-filled triodes V_1 and V_2. These supply the triggering impulses alternately, 180° apart in phase, as required by the dotted waves in Fig. 15.

The application of this scheme to an actual industrial function, involving a simple closed cycle system with mechanical reset arrangement, is not difficult. Suppose that the motor is operating a set of pumps, the object of which is to preserve a constant level in a flume or reservoir. Then the variable inductance could take the form of an iron-core choke, with the movable plunger connected by a suitable lever or other gear to a float indicating the water-level. A falling float would advance the " firing " point and increase the pumping speed, and vice versa. In the same way, any other operation, the extent of which can be represented by a mechanical movement, such as a tension or pressure, can be controlled in the same way ; while, by substituting a saturable reactor, operations can be similarly controlled which can be represented by a current or voltage.

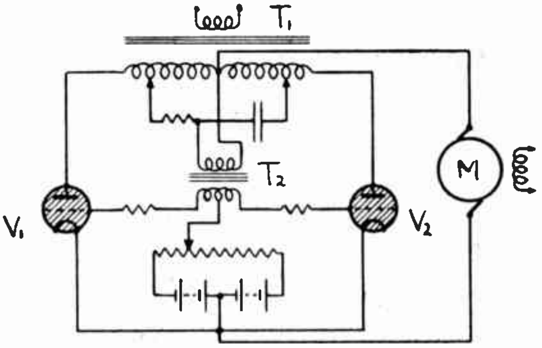
The lower diagram in Fig. 20 illustrates the application of the bias-voltage method ; represented by the two lower waves in Fig. 15. Here the phase-shifting bridge has fixed values of resistance and capacity, proportioned to give a lagging phase-angle of 90°. The adjustable portion of the circuit consists of the voltage source connected between the valve cathodes and the centre tapping of the grid transformer T_2, represented as a centre-tapped battery shunted by a potentiometer resistance. Each half must give a voltage at least equal to the amplitude of the A.C. applied to the anodes, sufficient, that is, to displace the axis of the grid voltage to the extent shown in Fig. 15.

Like the previous scheme, this one can also be readily adapted to form a closed cycle. If the voltage represented by the battery in Fig. 20b, instead of being adjustable over a wide range were fixed at a definite value, and a second voltage, dependent in some way upon the performance of the motor, inserted in series with and in opposition to the former, then the output from the valves would be controlled by the " error," or difference between these two voltages. For example, if the requirement were to preserve constant speed, the " reset " voltage could be supplied by a tachometer generator



A

— PHASE SHIFTING CONTROL —



B

— VARIABLE BIAS CONTROL —

Fig. 20.—Motor control schemes using two methods of adjusting the " firing point."

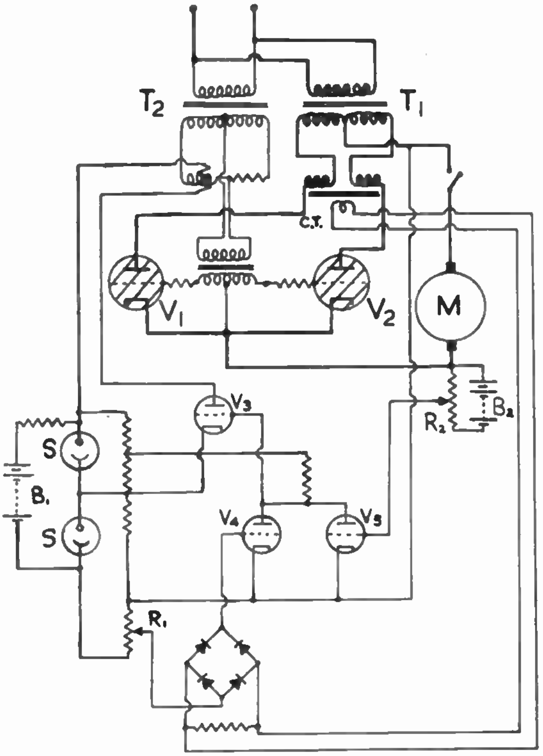


Fig. 21.—Complete control scheme for motor.

on the motor shaft ; or a connection could be taken from the armature terminals and smoothed by means of a series choke followed by a condenser across the leads. The original voltage would then be a " reference " or " pattern " voltage.

Finally, a complete control scheme is shown by means of the diagram in Fig. 21 and the actual apparatus in Fig. 22. Of these, the diagram will be recognized as an assemblage of parts that have already been dealt with in detail, but showing some variety as regards choice of methods. For example, two transformers are used for providing the power, of which T_1 on the right supplies the motor armature and T_2 on the left energizes the phase-shifting bridge. The upper half of the figure is in fact very like the phase-shifting control diagram in Fig. 20.

The lower part of the diagram consists of the valve gear for varying the saturating current of the phase-shifting bridge. On the left is the constant voltage supply for the control valves, which actually consisted of two neon stabilizers, SS, fed by metal rectifiers (here indicated by the battery B_1). The saturating current is supplied by the anode of the final amplifying valve V_3, its grid voltage coming from two first amplifying valves in parallel. Of these, V_4 controls the current limit, having its grid energized by a voltage proportional to the total armature current through the medium of a current transformer CT and a full-wave metal rectifier ; while V_5 controls the speed, being actuated by the difference between the armature voltage and a constant " pattern " voltage, indicated by the battery B_2, but again consisting of a metal-rectifier-fed neon stabilizer. Of the two regulating rheostats, R_1 sets the current-limit and R_2 the speed.

Speed reversal requires the addition of means to interchange the connections to the armature or alternatively the field. When carried out by contactors, four breaks are required in the connections ; and, on account of the high inductance of the field, this is usually arranged to take place in the armature circuit. The contactor method is usually adopted in schemes that are in other respects electronic.

There is, however, a simpler alternative available, especially for series motors of up to

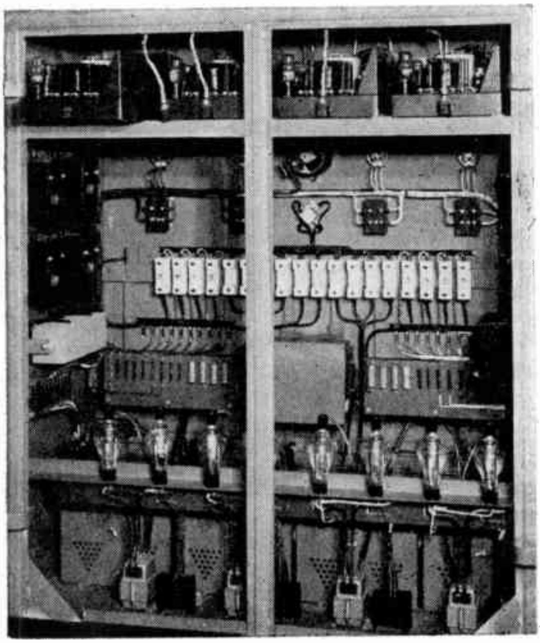


Fig. 22.—Electronic control equipment for four motors, showing left-hand amplifier partly withdrawn.

about 5 h.p., consisting in the fitting of duplicate fields, for forward and reverse running respectively. These are connected together at the motor, as shown in Fig. 23, and the arrangement is hence usually termed the " split field." Only two main connections have to be made and broken and, as the current is relatively small, there is no difficulty in doing it electronically.

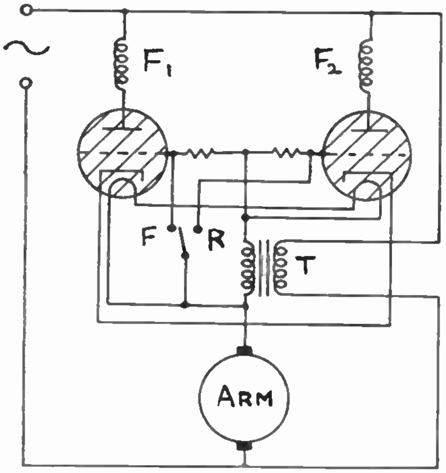


Fig. 23.—Split field motor control.

The scheme shown in the figure is one described by W. H. Elliot at the National Electronic Conference in Chicago in October, 1946 (see *Proc.*, p. 228) for enabling a sensitive relay, indicated by the changeover switch F.R., to control a small universal motor ; the purpose being to adjust the platens of an H.F. heater, in order to maintain the load constant. It will be observed that the cathode-heater transformer T also energises the grids at a voltage in opposition to that of the anodes, so that neither valve conducts when the relay is open. Closing either of the pairs of contacts brings the corresponding grid to the cathode potential, and hence causes the motor to rotate in the appropriate direction.

Since the change-over relay carries only a very small current, it may be a sensitive device responding to any desired parameter, such as temperature, position, P.H. value, or pressure. Speed control of the armature may be added if desired by the methods already described.

6. Cathode Ray Applications

There is little need to stress the manifold services of the cathode ray oscillograph for measuring rapidly varying, and even fixed quantities of literally every kind. In the author's experience it made its first appearance in heavy engineering works shortly before 1930, initially for indicating the waves of mercury arc rectifiers, and measuring the output of a surge generator. Its use has spread into nearly every manufacturing department, including routine test rooms recording the performance of motors and generators, short-circuit testing stations, transformer test rooms and steelworks. The author has, however, dealt at some length with this general subject in a previous lecture[24] to this Institution, and also elsewhere ;[25] and will here describe certain recent testing apparatus in which the cathode oscilloscope is an integral part, and which are instrumental in reducing manufacturing costs to an important extent.

6.1. *Winding Comparator*

The checking of windings for errors, especially in connection with mass production, is readily effected by comparing their response to an A.C. wave with that of a correct winding by means of the oscilloscope. In addition to simple coils, the stators of fractional H.P. and larger motors, and similar windings, can be tested to advantage in this manner. No time base is needed, as the cathode ray tube is used differentially, the energized coils being connected to the X and Y plates respectively, as shown in Fig. 24.

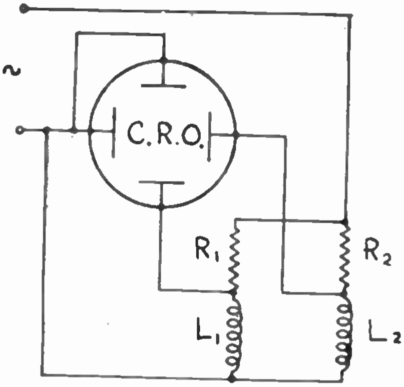


Fig. 24.—Winding comparator.

If the test winding is exactly like that used as a standard, a straight diagonal line is shown on the screen, which will be at 45° to the horizontal if the horizontal and vertical gains are made equal. If the voltage across one winding is a fixed ratio of that across the other, a straight line will still be traced, but at an angle greater or less than 45°. The line will be curved if the voltages differ

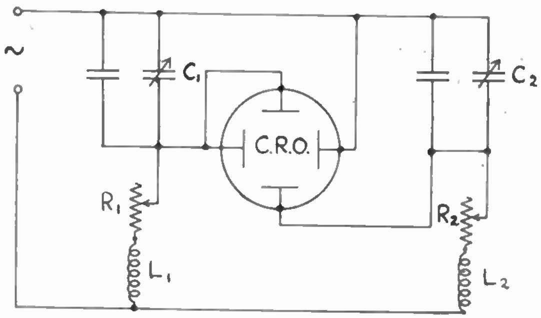


Fig. 25.—Winding bridge.

non-linearly; and, if they differ in phase, the figure on the screen will be looped or oval. Hence not only is a winding error detected, but some indication is given as to its nature.

The apparatus may be used at mains frequency, but greater sensitivity is given by using higher frequencies, which can conveniently be obtained from an aircraft type R alternator, giving up to 3 kc/s. There is no difficulty in detecting short-circuits, open-circuits, variations in resistance and variation in the positioning of the winding relatively to the iron, for which ordinary low frequencies are adequate. But a single short-circuited turn round a tooth in a winding having 286 turns per phase distributed over 15 slots per pole has required about 1,600 c/s; and a high resistance short-circuit round one tooth about 3 kc/s.

6.2. *Winding Bridge*

Greater sensitivity together with more definite discrimination between different types of fault are given by the slightly more complicated scheme shown in Fig 25. Two variable capacities C_1 and C_2 have been added, forming two arms of the bridge, while the coils, L_1 and L_2, each in series with a variable resistance R_1 and R_2, form the other two arms. The vertical plates are connected across the bridge, and the horizontal plates across C_1.

The bridge is first balanced with two sound windings in place, giving a horizontal straight line on the screen. One of the sound units is then replaced by the test windings, and the condition judged by the shape of the figure. A frequency of 50 c/s is quite satisfactory for most purposes.

One short-circuited turn out of 250 produces a circular figure, and one extra turn gives a definite tilt to the line and a slight opening up. Other kinds of fault show distinctive figures that are identifiable after a little practice.

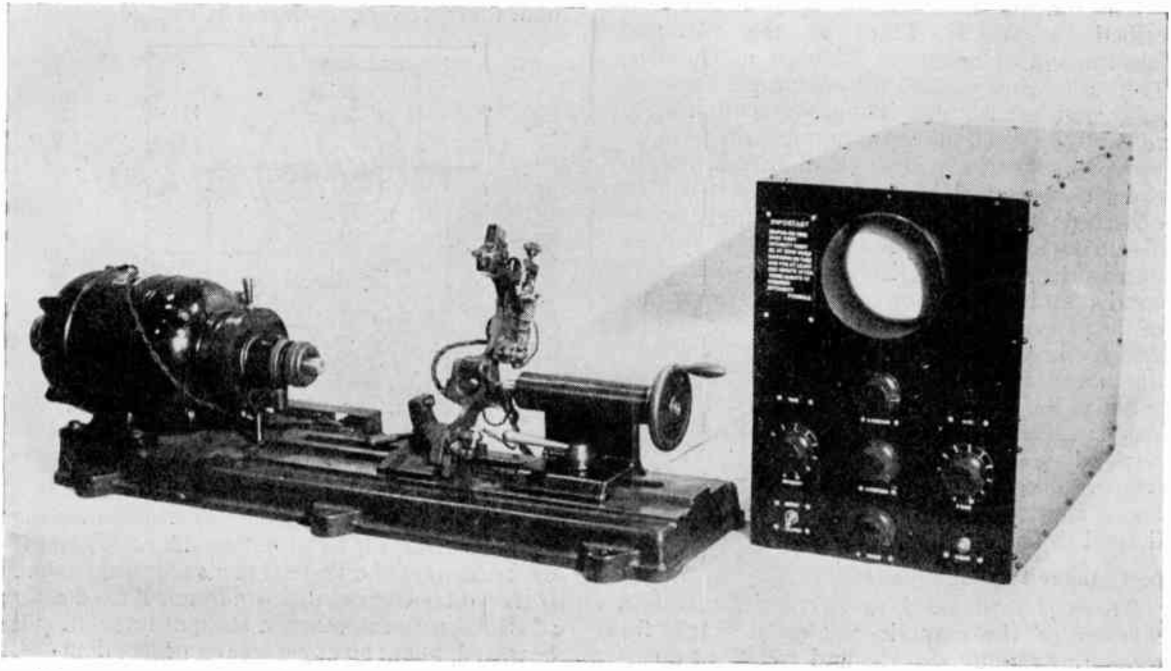


Fig. 26.—Armature fault locator.

6.3. *Armature fault locator*

The detection and location of faults in motor armatures is ordinarily a task consuming about 30 minutes, which is reduced to one-fifth or one-sixth the time when carried out with the apparatus shown in Fig. 26. It comprises a bed, and means for rotating the armature at something approaching its normal speed. Two pairs of brushes attached to the bed are lowered on to the commutator, of which one pair are 180 electrical degrees apart and act as feeding points, while the others are arranged to bear upon adjacent, or next-to-adjacent, sectors. These brushes are connected to the vertical deflectors of the oscillograph. There is also another pair of brushes that are short-circuited together once per revolution by a contact on the shaft, and trigger the time base. These last can be rotated bodily round the shaft so as to occupy any desired position.

When all the windings are sound, a series of parallel and equal ordinates are shown upon the oscillograph screen; but, if any of the sections is faulty, its ordinate is of a different height from the others. A dead short-circuited coil will have no voltage across it, and its ordinate will therefore have zero height as on the right of Fig. 27a; while an earthed connection in a winding will be shown by a gradual reduction in the height of the neighbouring ordinates down to the axis. An open-circuited section would have all the voltage drop applied to its ends, and this is indicated by a sudden high peak. A pointer is provided which indicates the faulty coil. The test voltage is preferably alternating with a frequency of about 30 kc/s, since this is able to break down incipient faults.

6.4. *Rotor Fault Locator*

A development of the foregoing scheme, by L. G. Ward, renders possible the finding and recognition of faults in squirrel-cage rotors, as well as other rotors and stators. Such a plant presents a rather more difficult problem than the D.C. armature, in that contact cannot be made with the winding conductors. Instead, an electro-magnet excited from a D.C. source is so arranged that its flux becomes interlinked with the individual windings as they pass in succession before its poles. For example, the poles may be brought very close to adjacent teeth of the core, or, in the case of a consequent-pole stator, one wound pole and the adjacent consequent pole would be nearly bridged by the magnet. Then a momentary voltage and circulating current would be generated in each winding, which would produce a proportionate secondary or "reflected" voltage in the magnet coils. The Y plates of the oscillograph are connected across the latter.

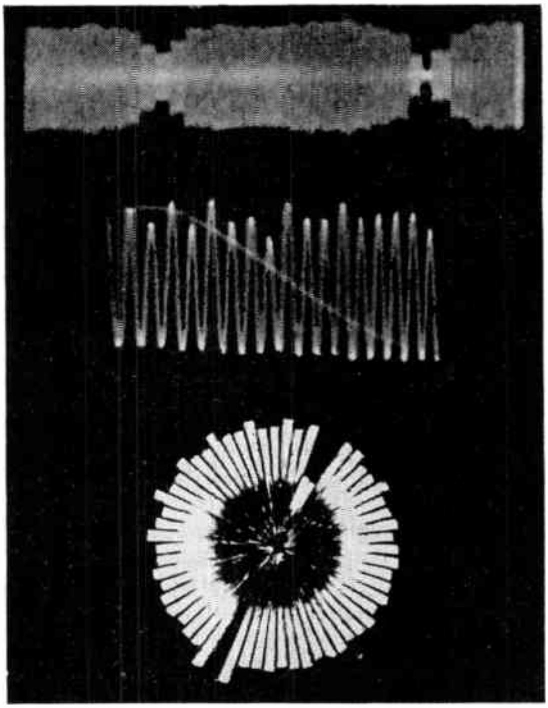


Fig. 27.—Oscillograms from three types of machine: (a) Armature fault locator figure showing a short circuit on the right and a partial short on the left; (b) Record from squirrel cage rotor showing uneven conductivity of bars; (c) P.P.I. record from D.C. motor showing short circuit on one coil.

It is evident that the current induced in the sections of the winding will be directly affected by their impedance, which, in turn, is affected by any fault they may possess, and the result will be a sequence of vertical peaks exemplified by those in Fig. 27b. Among the faults that are definitely revealed are broken joints, high resistance joints such as those due to bad soldering, and also all the possible faults in the wound rotor or stator, including earthed winding, short-circuited turns, magnetically-bridged coils and broken shading rings. In the case illustrated in the figure, asymmetry due to bad soldering is evident in the left half of the record.

6.5. *P.P.I. Fault Finder*

The plan position type of display, produced by a long-persistence tube with a revolving field circular time-base, has formed the basis of a fault-locating apparatus, and has introduced several simplifications. Instead of the mechanically rotating coils used for the standard P.P.I. oscilloscope, a magslip stator is fitted round the neck of the tube, and connected to the stator terminals of a complete magslip coupled to the armature shaft, as shown in Fig. 28. Since the rotor of the latter is excited from the pick-up brushes, the scheme records the voltages induced in successive armature conductors, and thus forms a kind of circular map of the winding, showing up faulty sections as with the rectangular figures already described. The connection to the modulator from the H.F. supply is for the purpose of blacking out all but the crests of the waves. One advantage of this method is that the armature need not be motor driven, and hence an elaborate bed with bearings is not required. Instead, the armature shaft is simply placed in V-rests and turned or oscillated by hand, when the figure indicating the condition of the windings appears on the screen. An abnormal radius can be further examined by rocking the armature about the point in question. A typical record showing a short-circuited coil is given in Fig. 27*c*.

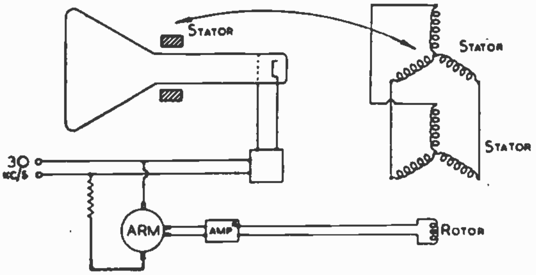


Fig. 28.—P.P.I. fault detector and locator.

6.6. *Battery Tester*

Dry batteries for radio sets and similar purposes are tested for weak cells by an analogous method. A set of about 30 to 60 spring contacts is lowered by a pedal, making connection between the central terminal of each cell and the segments of a commutator. A revolving contact then enables the voltage of each cell to deflect the cathode ray beam in turn, giving an almost instantaneous graph of all the cell voltages. In this way a complete battery can be tested in a few seconds. Either of the two previous methods can be adopted.

6.7. *Range/Amplitude Flaw Detector*

The original range-amplitude type of scheme for radiolocation has been adapted for detecting and locating cavities or cracks in solid masses, and is especially useful for the testing of steel forgings, such as those intended for high-speed turbo-alternator rotors. A very convenient and compact test equipment was put on the market by Messrs. Hughes at the end of the war, using a frequency of 2½ Mc/s, which is converted from an electrical to an ultrasonic wave by a quartz crystal in the transmitter, and back again by an exactly similar device in the receiver. Both of the latter are disc-shaped capsules about 1½ in in diameter, which are applied to the surface of the mass, one to send a series of " sound " pulses into it, and the other to receive the echoes from the further boundary, and also from a flaw if one is present.

The instrument has proved capable of detecting a cavity no bigger than a pin's head, in a forging 25 ft long by 3½ ft in diameter. In fact, its great sensitivity is not an unmixed blessing, since the operator must be able to distinguish which of its determinations should be disregarded. Location of the flaws is effected in two ways ; first by scaling off the distance between the peaks representing the initial pulse and the echo, and secondly by taking cross-bearings from two different directions. The size of the defect can be approximately found from the width between the direction lines on either side which just return an echo. Any homogeneous solid or liquid material can be tested in this way, including sea water (for sounding, and locating wrecks and shoals of fish), all forged metals, and nearly all castings ; but cast iron is not of sufficiently uniform texture owing to the presence of free carbon.

6.8. *Recurrent Surge Generators*

For several purposes in heavy industry it is important to find the effects of a surge in a circuit ; for example, the voltage distribution in the winding of a transformer or alternator, or the shape of the restriking voltage transient at the contacts of an oil circuit-breaker. These effects are the same for small surges as for large, except as regards amplitude, and are very conveniently recorded by means of the recurrent surge oscillograph for the former and the restriking voltage indicator for the latter type of test. As has already been stated, the " firing " of a thyratron gives a square-fronted current, which closely resembled a 1/50 surge due for example, to lightning, and is used in these instruments as a small-scale surge. By causing it to occur 50 or 1,000 times per second, the resultant phenomenon is recorded as a standing wave, which can be easily scrutinized and photographed.[26]

7. Other Electronic Instruments

In addition to the apparatus described in section 6, viz., those based on the cathode ray tube, numerous other valve applications are replacing electro-magnetic devices on account of their superior performance. A few typical examples will be accorded a brief description.

7.1. *Metal Detectors*

There are numerous reasons for detecting and locating large and small pieces of metal, but until 1939 the means for doing so was crude and insensitive. Urgent need during the war led to the development of the mine detector ; and an adaptation of this military apparatus is serving many useful purposes to-day.

The usual pattern comprises two similar coils, which would form an air-core transformer if they were not slid apart from exact superposition to the position of zero induction, i.e., that in which the voltage induced in the left-hand portion of the secondary coil by the right-hand portion of the primary is just able to cancel that due to normal induction. If, then, an oscillator is connected to the primary and an amplifier and telephone to the secondary as in Fig. 29, no sound will be heard in the latter. But if a piece of metal is brought near the coils, it will disturb the flux passing through them, and an audible note will be produced. Regeneration, brought about by a connection from the output to the input, is used to increase the sensitivity.

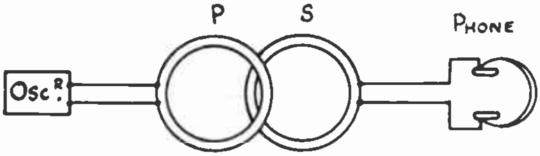


Fig. 29.—Metal detector.

Among the uses for this device are the testing of sick cattle for swallowed metal, and of felled tree-trunks for embedded metal parts such as gate hinges, line insulator supports and fencing wire, before they are taken to the saw-mill ; location of manhole covers and buried pipes in streets and fields ; and examination of luggage and even animals and men for contraband. It is also the principal component in conveyor-belt apparatus for detecting stray metal in cloth, in rags intended for paper-making, in plastic materials before moulding, in food and in other materials.

7.2. *Battery Cell Tester*

Before dry cells are made up into batteries, the voltage of each is checked. There are several obvious disadvantages in doing this with a voltmeter by hand, including grave risk of inaccuracy through the tester not allowing sufficient time for the pointer to come to rest. Machines are therefore in use whereby the cells, previously loaded into a chute, are connected in rapid succession to the grid of a valve, which makes the necessary determination instantaneously and accurately, diverting the faulty cells into a separate container. This is rendered possible by the negligible intake of power and the absence of inertia on the part of the valve.

7.3. *Shunt Voltage Regulator*

Regulation of voltage from a generator or other supply calls for sensitivity, instant response and independence of temperature and other variables, all of which are requirements giving electronic operation a manifest advantage. Regulators may be of the shunt or series type, the former of which modifies the field current of the generator, while the latter absorbs the surplus voltage by means of a device in series with the load.

Existing shunt regulators vary the resistance in the field circuit either by occasionally moving or by continuously vibrating contacts. In both cases, reliability is essential, and should be afforded with a minimum of maintenance. A circuit which forms the electronic analogue of the vibrating contact type is shown in Fig. 30. The field rheostat FR is seen in the lower part of the diagram, shunted by the plate circuit of a thyratron, which is caused to " go out " 50 times per second by the injection of an A.C. wave from a " mains " transformer. Its grid is connected across a bridge, two arms of which are the constant voltages given by the stabilizer tubes SS in the left-hand upper part of the figure, while the other two are the resistor R and the plate circuit of the triode T. A voltage proportional to that given by the generator is applied to the grid of T, any voltage fluctuations therefore altering the valve resistance and consequently the proportion of each cycle during which the thyratron conducts. Since the rheostat is short-circuited during the conducting periods, stable and instantaneous regulation is effected.

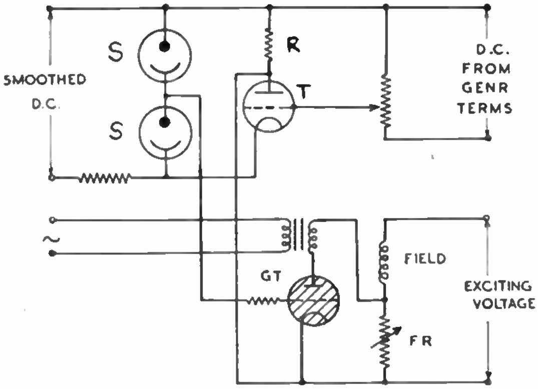


Fig. 30.—*Shunt voltage regulator.*

7.4. *Series Voltage Regulators*

In situations where the generator speed varies over wide limits, such as when driven by the main engines of an aircraft, or where the generator is inaccessible, the series type of regulator is at an advantage. For mobile conditions such as in the air and on board ship, the immunity of electronic gear to vibration and tilting gives it a decided advantage over older mechanisms possessing moving parts.

The voltage-regulating transformer described in section 5 (6.3.) and illustrated in Fig. 18, is an example of a series regulator, although it is there applied to the variation of motor speed. It would, however, be applicable, practically as it stands, for service as a voltage regulator.

7.5. *Humidity Detector*

The detection or measurement of humidity, and the automatic carrying out of necessary counter-action, are readily effected by the agency of a single valve, used as an amplifier for actuating a resistance bridge. An interesting application is to the closed-cycle cooling system used for the large motors and generators in electrically propelled ships. The cooling medium is dry air, which is itself cooled, after passing through the machine, by means of pipes through which sea water is circulated. In the event of a leakage occurring in these pipes, damp would be injected into the windings, which would ultimately lead to a breakdown, and frequent inspection was necessary to avoid this trouble.

The scheme is shown in Fig. 31, and was first used in the quadruple-screw *Monarch of Bermuda* in 1943. Here, D is a " grid " of cotton cord impregnated with a deliquescent but stable salt and wound round an insulating support. It is normally an insulator, but the appearance of the slightest amount of humidity lowers its resistance considerably and increases the grid voltage. The resultant anode current produces a voltage drop in R_4, which unbalances the bridge and causes an operating current to flow through the telephone-type relay Y. This relay can then light a signal lamp, sound a hooter, cut off the water circulation, or perform any other desired function.

Since, moreover, the effect of the dampness is quantitative, such a scheme can operate a meter or indicator, providing an accurate measure of the degree of humidity.

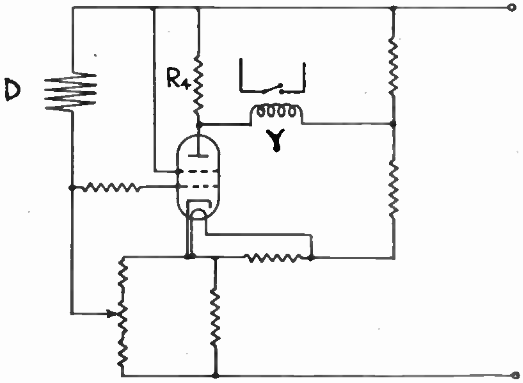


Fig. 31.—*Humidity detector.*

8. Conclusion

It will therefore be seen that electronic methods and devices are already well established in heavy engineering practice, and are playing a major part in a very wide variety of applications in this country as well as abroad. A scrutiny of the position with regard to any type of work to which electronic gear has been applied indicates that in practically every case further development is possible or is actually in hand. The immediate future will therefore see a considerable extension in its use and capabilities.

9. Acknowledgments

The author would like to thank a number of of his colleagues, including Messrs. S. Dale and G. E. Davis, for suggestions in connection with the text, and Mr. J. E. Burton for drawing many of the figures; also the General Electric Co., Ltd., for permission to publish the paper.

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A DESIGN FOR DOUBLE-TUNED TRANSFORMERS†

by

J. B. Rudd, B.Sc.*

A paper delivered before the Australian I.R.E. Radio Engineering Convention on November 4th, 1948

SUMMARY

The term " transformer " is used in the broad sense to include networks consisting of a pair of L-C circuits with either inductive or capacitive coupling. This paper describes a method of designing such transformers to provide uniform transmission of power over a frequency range ; the resulting insertion-loss curve is approximately symmetrical when plotted on a linear frequency scale.

The frequency variable used in the design equations allows a common representation of both inductively- and capacitively-coupled forms. The extent of the uniform transmission band and the transformation ratios possible with various types of coupling are discussed. Charts are presented which simplify the process of design.

1.0. Introduction

The term " transformer " is used in the broad sense to include networks which consist of two parallel-tuned L-C circuits with either inductive or capacitive coupling between them. It is assumed that these networks are inserted between a generator and a load resistance. Initially, the generator and the load resistances are assumed to be equal ; later, the design is extended to include impedance-transforming networks between unequal terminations.

So many papers have been written on this subject that the justification for a further one might well be questioned. However, the majority of the papers are concerned with transformers in which the assumption is made that the pass band is a small percentage of the mid-band frequency. There are a number of papers in which the parallel-tuned transformer is examined by regarding it as a three-element Zobel-type filter.[1,3] These methods are not entirely successful because simple filter theory assumes image impedance terminations, and it is only by the application of extensive corrections that the true insertion loss and phase shift of single sections, with fixed resistance terminations, can be obtained by this approach.

Recently, a design method for a wide-band transformer, consisting of a pair of parallel-tuned circuits with mutual inductance coupling, has been published.[4] This design is the result of a mathematical experiment based upon two simple assumptions, (*a*) that both primary and secondary L-C circuits are individually tuned to the same frequency and (*b*) that the maximum possible power is transferred from the generator to the load circuit at the " tune " frequency. The experiment is most successful ; there is a second frequency at which the maximum possible power is transferred and the loss between this frequency and the " tune " frequency is very small (0·005 db for a coupling coefficient of $k = 0{\cdot}5$). Furthermore, the insertion loss and transmission-delay characteristics are approximately symmetrical when plotted on a linear frequency scale.

The present paper details the results of a somewhat similar mathematical experiment which leads to the design of an inductively-coupled circuit which has the same characteristics as the transformer described by Rideout. The same mathematics yields, as a by-product, the circuit design for a capacitively-coupled network with somewhat similar characteristics. The circuits initially considered consist of symmetrical Π networks in which each shunt arm is formed by a parallel-tuned L-C circuit, while the coupling is provided by either an inductance or a capacitance in the series arm. The only assumption made is that, at a reference frequency, $\omega_0/2\pi$, the reactances of the shunt arms (i.e., the reactance of the parallel L-C combinations) and the reactance of the series arm have the same magnitude as the generator and load resistances ; under this condition, the networks transfer the maximum possible power from the generator to the load. For these networks, it is found that

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there is a second frequency at which the transfer of the maximum possible power takes place, and further examination shows that the network with inductive coupling is identical with Rideout's design.

The transformer parameters are given in terms of the reference frequency, $\omega_0/2\pi$, and the coupling coefficient, k. This frequency, $\omega_0/2\pi$, is *not* the one chosen by Rideout, and the expressions for insertion loss, insertion phase shift, time delay, and input impedance are given in a different form. The frequency of reference used in this paper appears to be more suitable, because all the expressions are obtained in a simpler form, adapted to easy computation.

By the choice of a frequency variable, β, it has been possible to represent both inductively- and capacitively-coupled networks by a common Π circuit. For inductive coupling $\beta = \omega/\omega_0$, and for capacitive coupling $\beta = -\omega_0/\omega$. This frequency variable has been extensively used for the common representation of low- and high-pass filters.

The paper commences with definitions of insertion loss and insertion phase shifts and, after a short discussion of symmetrical Π circuits, proceeds to a study of inductively- and capacitively-coupled networks with equal terminations. Design charts are developed which allow the selection of the correct value of the coupling coefficient for any bandwidth. The paper concludes with a discussion of impedance-transforming circuits.

2.0. Definition of Insertion Loss and Phase Shift

In Fig. 1 (*a*) a generator of e.m.f. E, and resistance R, is shown directly connected to a load circuit consisting of an equal resistance, R. In Fig. 1 (*b*), a four-terminal network (e.g., a tuned transformer) is shown inserted between the generator and the load circuit. For the circuit of Fig. 1 (*a*), the load and source resistances are matched, and the maximum possible power is drawn from the generator and dissipated in the load. If the current in the load is I_1, then

$$I_1 = E/2R \qquad (1)$$

For the circuit of Fig. 1 (*b*), the current in the load resistance, R, is

$$I_2 = E/Z_t, \qquad (2)$$

where Z_t is the transfer impedance connecting the generator e.m.f., E, and the load current I_2.

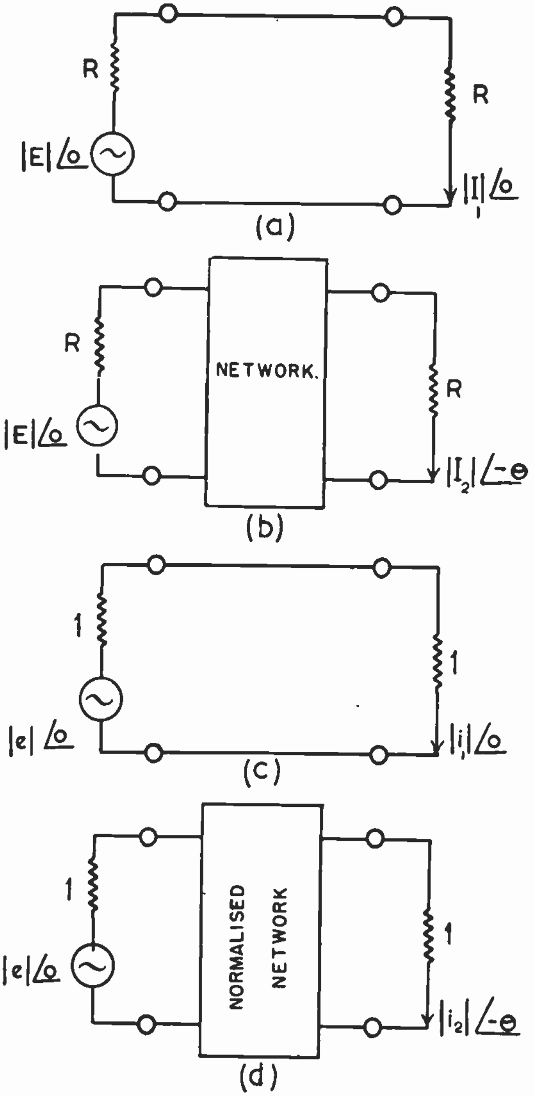


Fig. 1.—Circuits used in defining insertion loss and insertion phase shift.

(It is to be noted that Z_t is not defined as a property of the inserted network alone, but as a characteristic of the network plus its terminations.)

From equations (1) and (2),

$$I_1/I_2 = Z_t/2R, \quad = |Z_t|/2R \angle \theta, \qquad (3)$$

where $|Z_t|$ is the magnitude of the transfer impedance and θ its angle. Equation (3) provides a basis for defining the insertion loss, L, and the insertion phase shift, B, in the form

$$\begin{aligned} L &= 10 \log_{10} |I_1/I_2|^2, \\ &= 10 \log_{10} \left[|Z_t|^2/4R^2\right] \text{ decibels} \qquad (4) \end{aligned}$$

and $B = \theta$ radians. (5)

In the consideration of networks terminated at each end in a resistance R, it has been found convenient to express all reactances, impedances, voltages and currents in a normalized form. Thus the reactance jX would be represented by jx, where $x = X/R$; the impedance, Z_t, by z_t, where $z_t = Z_t/R$; the e.m.f., E, by e, where $|e| = |E|/R^{\frac{1}{2}}$, and the current, I, by i, where $i = |I|R^{\frac{1}{2}}$. On this basis, the circuits of Figs. 1 (*a*) and 1 (*b*) may be redrawn as in Figs. 1 (*c*) and 1 (*d*) with terminating resistances of unity instead of R. Equations (1) to (5) may now be rewritten in the form

$$i_1 = e/2 \qquad (1a)$$

$$i_2 = e/z_t, \qquad (2a)$$

$$i_1/i_2 = |z_t|/2\angle\theta, \qquad (3a)$$

$$L = 10 \log_{10} \left[|z_t|^2/4\right] \text{ decibels,} \qquad (4a)$$

and $B = \theta$ radians. (5*a*)

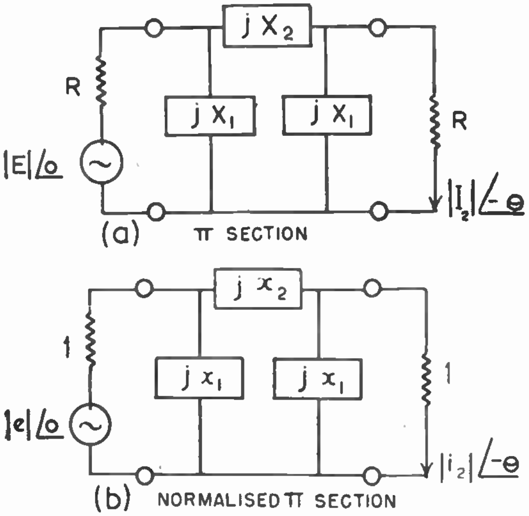


Fig. 2.—Circuits showing a symmetrical Π *section and its normalized form.*

The process of normalizing a network greatly simplifies the mathematical equations met with in solving the network. Briefly, the process of normalizing a network, whose terminal resistances are each equal to R, is carried out by dividing all reactance values by R.

3.0. Transfer Impedance of Symmetrical Pi Network

In Fig. 2(*a*) a Π circuit of reactances jX_1, jX_2, jX_1, is shown inserted between a source resistance R and a load resistance R. In Fig. 2 (*b*) the circuit of 2(*a*) is shown in a normalized form. The relationships between the two circuits are:

$$\left.\begin{aligned} x_1 &= X_1/R, \\ x_2 &= X_2/R, \\ |e| &= |E|/R^{\frac{1}{2}}, \\ |i_2| &= |I_2|R^{\frac{1}{2}}, \\ \text{and } z_t &= Z_t/R. \end{aligned}\right\} \qquad (6)$$

It can be shown[2] that the transfer impedance of the Π circuit of Fig. 2 is given by

$$\begin{aligned} z_t &= e/i_2, \\ &= 2a - j\left[(a+1)/x_1 - x_2\right], \qquad (7) \end{aligned}$$

where $a = x_2/x_1 + 1$.

The insertion loss of the Π network is

$$\begin{aligned} L &= 10 \log_{10} |z_t|^2/4, \\ &= 10 \log_{10} \left\{1 + \tfrac{1}{4}[(a+1)/x_1 + x_2]^2\right\} \\ &\qquad \text{decibels,} \qquad (8) \end{aligned}$$

and the insertion phase shift is

$$B = \tan^{-1} - \frac{[(a+1)/x_1 - x_2]}{2a} \text{ radians} \qquad (9)$$

From equation (8) it can be shown that the insertion loss is zero when

$$\left.\begin{aligned} x_1 &= -1, \\ x_2 &= +1, \end{aligned}\right\} \qquad (10a)$$

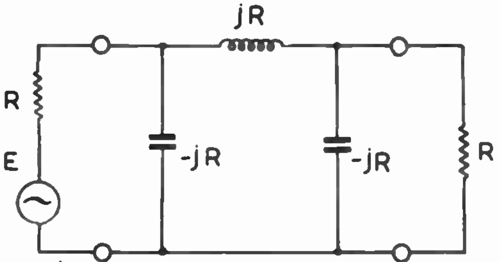
and, also, when

$$\left.\begin{aligned} x_1 &= +1, \\ x_2 &= -1. \end{aligned}\right\} \qquad (10b)$$

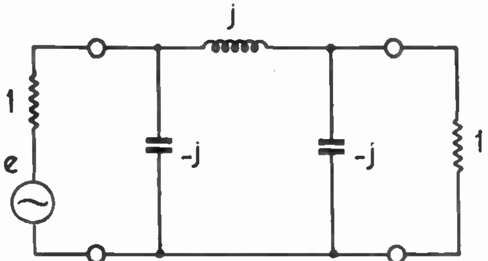
The circuits which satisfy the conditions of equations (10*a*) and (10*b*) are shown in Fig. 3. It will be seen that, in both cases, the magnitudes of the reactances of the arms of the Π network are equal to the terminating resistances. The circuits of Figs. 3 (*a*) and 3 (*c*) are such that the maximum possible power is drawn from the generator and transferred to the load; in other words, the networks have no insertion loss at the frequency concerned.

4.0. Coupled Circuits with Equal Terminations

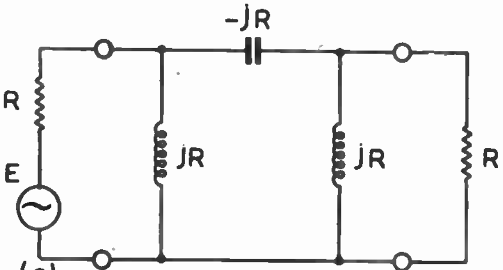
Figure 4 (*a*) represents a double-tuned transformer with inductive coupling obtained by the presence of a series inductor whose reactance, at



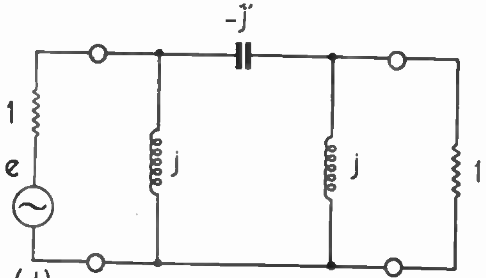
(a) ACTUAL CIRCUIT $X_1 = -R$ $X_2 = +R$



(b) NORMALISED CIRCUIT $x_1 = -1$ $x_2 = +1$



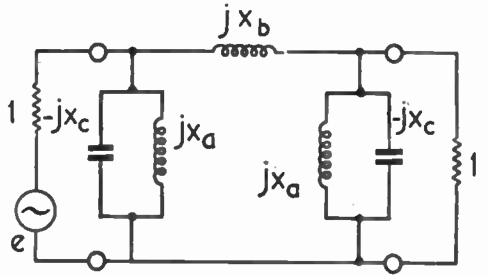
(c) ACTUAL CIRCUIT $X_1 = R$ $X_2 = -R$



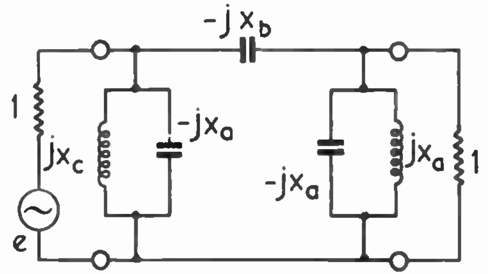
(d) NORMALISED CIRCUIT $x_1 = +1$ $x_2 = -1$

Fig. 3.—Π *networks having zero insertion loss.*

a reference frequency $\omega_0/2\pi$, has a magnitude equal to x_b times the value of the terminating resistance. The tuned circuits are such that the reactances of the capacitive and inductive branches, at the frequency $\omega_0/2\pi$, are x_c and x_a times the terminating resistance respectively. Similarly, Fig. 4 (*b*) represents a double-tuned transformer with capacitance coupling obtained by reason of a series capacitor whose reactance is x_b times the terminating resistance at the reference frequency $\omega_0/2\pi$. The tuned circuits are such that, in this case, the inductive branch has a magnitude x_c times the terminatng resistance, while the capacitative branch has a magnitude x_a times the same resistance; the order is the reverse of that in Fig. 4 (*a*).



(a) INDUCTIVE COUPLING



(b) CAPACITIVE COUPLING.

Fig. 4.—*Normalized circuits with* (*a*) *inductive coupling and* (*b*) *capacitive coupling. The reactance values correspond to a frequency* $\omega_0/2\pi$.

For both circuits, the coefficient of coupling is the same, given by

$$k = x_a/(x_a + x_b). \tag{11}$$

For the circuit of Fig. 4 (*a*), the reactance of the combined shunt arm, at the frequency $\omega_0/2\pi$, is

$$-j\, x_a x_c/(x_a - x_c),$$

while, for the circuit of Fig. 4 (*b*), the combined shunt arm has a reactance

$$+j\, x_a x_c/(x_a - x_c),$$

at the same reference frequency. Thus, the reactances of the shunt arms of Figs. 4 (*a*) and 4 (*b*) are equal in magnitude but opposite in sign. Likewise, the series arms of Figs. 4 (*a*) and 4 (*b*) have reactances of equal magnitude, but opposite sign. If, now,

$$x_b = 1, \qquad (12)$$

$$\text{and } x_a x_c/(x_a - x_c) = 1, \qquad (13)$$

the circuits of Figs. 4 (*a*) and 4 (*b*) become identical with those of Figs. 3 (*b*) and 3 (*d*), respectively. It has been shown in the previous section that, under these conditions, the networks have zero insertion loss. Thus, at the frequency $\omega_0/2\pi$, the relationships between the network reactances and the terminal resistances are such that the maximum possible power is transferred by the networks from the generator to the load circuit.

Combining equations (11), (12) and (13), the reactance values of the circuit elements, at the reference frequency $\omega_0/2\pi$, in terms of the coupling coefficient k, are

$$\left.\begin{aligned} x_a &= k/(1-k), \\ x_b &= 1, \\ x_c &= k. \end{aligned}\right\} \qquad (14)$$

The similarity of the circuits of Figs. 4 (*a*) and 4 (*b*) suggests that it is possible, by suitable choice of a frequency variable, to represent both types of circuit by a single circuit. For the inductively-coupled circuit of Fig. 4 (*a*), let

$$\omega/\omega_0 = \beta \text{ (inductively coupled)} \qquad (15)$$

and, for the capacitively-coupled circuit of Fig. 4 (*b*), let

$$\omega_0/\omega = -\beta \text{ (capacitively coupled)} \qquad (16)$$

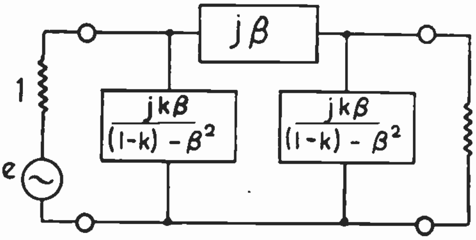


Fig. 5.—Normalized Π *circuit for the common representation of double tuned transformers. The reactance values correspond to a frequency of* $\omega_0/2\pi$. *For inductive coupling,* $\beta = \omega/\omega_0$, *for capacitive coupling,* $\beta = -\omega_0/\omega$.

It can now be shown that at the general frequency $\omega/2\pi$ each of the two circuits can be represented by the single Π-section network of Fig. 5, in which the series arm has a reactance of

$$jx_2 = \beta, \qquad \text{(series arm)} \quad (17)$$

and each shunt arm has a reactance of

$$jx_1 = j\frac{k\beta}{(1-k)-\beta^2} \text{ (shunt arms)} \quad (18)$$

Substitution of $\beta = 1$ in Fig. 5 will give the circuit of Fig. 4 (*a*) at the frequency $\omega_0/2\pi$, and a value $\beta = -1$ will give the circuit of Fig. 4 (*b*) at the same frequency.

The reactance values, given in equations (17) and (18), when substituted in equations (8) and (9), yield expressions for the insertion loss and insertion phase shift :

$$L = 10 \log_{10}\left\{1 + \frac{1}{4}\left[\frac{(\beta^2 - 1)(\beta^2 - \overline{1 - k^2})}{k^2\beta}\right]^2\right\} \text{ decibels,} \quad (19)$$

$$B = \tan^{-1}\frac{\beta^4 - (2 + k^2)\beta^2 + (1 - k^2)}{2k\beta(\beta^2 - 1)} \text{ radians.} \quad (20)$$

4.1. *Insertion Loss*

Examination of equation (19) shows that the insertion loss is zero at a pair of frequencies corresponding to $\beta = \pm\sqrt{1 - k^2}$ and $\beta = \pm 1$, where the $+$ sign applies to the inductively-coupled circuit and the $-$ sign to the capacitively-coupled circuit. One of the frequencies for zero insertion loss is the reference frequency $\omega_0/2\pi$, the second, $\omega_1/2\pi$ say, is lower than the reference frequency in the inductively-coupled case, and higher in the capacitively-coupled case. Thus, for inductive coupling,

$$\omega_1/\omega_0 = \sqrt{1 - k^2}, \qquad (21)$$

and for capacitive coupling,

$$\omega_0/\omega_1 = \sqrt{1 - k^2}. \qquad (22)$$

The insertion loss is small for all frequencies within the range between ω_0 and ω_1. A maximum of loss occurs at a frequency corresponding to

$$\beta = \pm\sqrt{\frac{2 - k^2 + \sqrt{k^4 - 16k^2 + 16}}{6}}, \qquad (23)$$

where the positive value corresponds to inductive coupling and the negative value to capacitive coupling. For inductive coupling, with small values of k, the frequency, at which maximum loss occurs, is the arithmetic mean of $\omega_1/2\pi$ and

$\omega_0/2\pi$. As k is increased the frequency for maximum loss deviates from the arithmetic mean, and is 1 per cent higher when $k = 0{\cdot}95$, and 5 per cent when $k = 0{\cdot}99$. In the case of capacitive coupling, the frequency at which the maximum loss occurs is approximately the harmonic mean of the frequencies $\omega_0/2\pi$ and $\omega_1/2\pi$, this is to be expected since the frequency scale for capacitive coupling is the inverse of that for inductive coupling.

Rideout[4] presents a formula for the maximum loss in the frequency band between $\omega_0/2\pi$ and $\omega_1/2\pi$. This formula,

$$L = \frac{0{\cdot}136\,k^4}{2 - k^2}\ \text{decibels} \qquad (24)$$

applies to both capacitively- and inductively-coupled circuits. Equation (24) applies strictly only when k is small, since it is based upon the assumption that the maximum loss occurs when $\beta^2 = \sqrt{1 - k^2}$. The error is, however, quite small even for $k = 0{\cdot}95$; for this value of k, exact calculation gives $L = 0{\cdot}11$ db, whereas equation (24) gives the value $L = 0{\cdot}10$ db.

Considering the frequency ranges outside the boundaries imposed by the frequencies $\omega_1/2\pi$ and $\omega_0/2\pi$, it can be shown from equation (19) that

$$L = 10 \log_{10} [1 + \tfrac{1}{4}(1 - k)]\text{db}, \qquad (25)$$

when $\beta = \pm\sqrt{1 - k}$,

and $$L = 10 \log_{10} [1 + \tfrac{1}{4}(1 + k)]\ \text{db}, \qquad (26)$$

when $\beta = \pm\sqrt{1 + k}$.

For small values of k, the losses expressed in equations (25) and (26) are each approximately 1 db. In passing, it is noted that the shunt arms of Figs. 4 (*a*) and 4 (*b*) are anti-resonant for the condition of equation (25).

The response curve for a network with a coefficient of coupling $k = 0{\cdot}707$ is shown in Fig. 6. In the inductively-coupled case, the pass band is approximately symmetrical with frequency. For capacitive coupling, the scale of ω_0/ω is an *inverse* frequency scale, and the actual curve of insertion loss against frequency, in this particular example, departs markedly from symmetry. When the value of the coefficient of coupling is smaller, both the inductively-coupled and the capacitively-coupled forms will have response curves that tend to follow arithmetic symmetry.

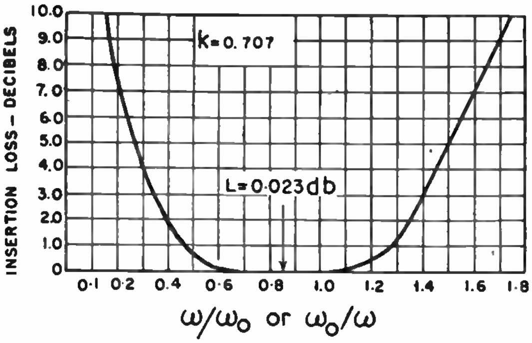


Fig. 6.—*Insertion-loss characteristic of a transformer with a coupling coefficient of* $k = 0{\cdot}707$. *The mid-band loss is* 0·023 *db.*

From equation (19), the insertion loss may be expressed as

$$L = 10 \log_{10} (1 + r^2/4)\ \text{db}, \qquad (27)$$

$$\text{where } \pm r = \frac{(\beta^2 - 1)(\beta^2 - \overline{1 - k^2})}{k^2\beta} \qquad (28)$$

In equation (27), if $\pm r$ takes on the successive values of 0, 1, 2 and 6, the corresponding insertion losses will be 0, 1, 3 and 10 db. Equation (28) is a quartic in β and its solution is difficult. An alternative graphical method may be employed to find the values of β for a given loss. This is done by rearranging equation (28) in the form

$$k^2 = \frac{(1 - \beta^2)^2}{(1 - \beta^2) \pm r\beta}, \qquad (29)$$

and plotting a graph of k against β for various values of r. This has been done in Fig. 7 for values of $\pm r$ equal to 0, 1, 2 and 6, corresponding to losses of 0, 1, 3 and 10 db.

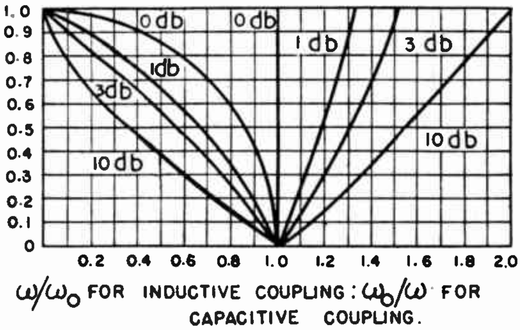


Fig. 7.—*Chart showing the relationship between band width and coupling coefficient*

As an example of the use of this chart, consider a transformer with inductive coupling designed to have zero insertion loss at 1,000 kc/s and with a coupling coefficient of 0·8. By drawing a horizontal line at $k = 0{\cdot}8$ it is possible to read off the frequencies at which the insertion loss will be 0, 1, 3 and 10 db. These frequencies are shown in Table 1.

TABLE 1. Inductive Coupling $k = 0{\cdot}8$. $\omega_0/2\pi = 1{,}000$ kc/s

Insertion Loss (db)	Lower Frequency (kc/s)	Upper Frequency (kc/s)
0	600	1,000
1	335	1,280
3	225	1,440
10	90	1,830

The information contained in Fig. 7 is expressed in an alternative fashion in Fig. 8. In this figure k has been plotted against the ratio of the upper and lower frequencies at which the losses are equal; four curves are drawn, corresponding to losses of 0, 1, 3 and 10 db. This chart provides a ready method of selecting the value of k for any given frequency band. For example, if the frequency ratio between the band extremities is to be 7/1, with a loss not exceeding 1 db, $k = 0{\cdot}9$; if the allowable loss is 3 db the value of k may be reduced to 0·815.

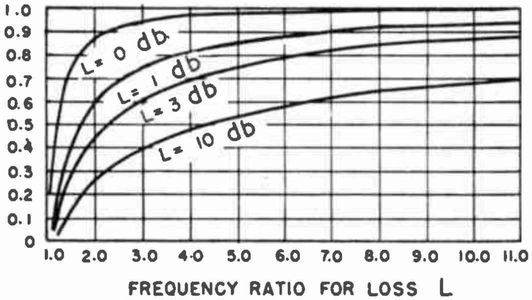


Fig. 8.—Chart showing the relationship between bandwidth and coupling coefficient

4.2. *Time Delay*

The insertion phase shift B given in equation (20), is usually of less importance than the slope, $dB/d\omega$. The time delay, or transmission delay, of networks such as those under discussion is given by

$$T = dB/d\omega \text{ seconds} \tag{30}$$

In many applications, such as the use of band-pass filters for frequency modulated signals, it is important that the time delay, T, be constant for all the component frequencies of the transmitted signal. An example of the use of a delay line in an exciter unit for a frequency modulated transmitter has recently been published.[5]

From equations (19) and (20) it can be shown that

$$\frac{dB}{d\beta} = \frac{1}{2k^3 l}\left[\beta^4 - \beta^2(1-k^2) - 1 + \beta^{-2}(1-k^2) + 4k^2\right] \tag{31}$$

where l = insertion loss power ratio,
$= \text{antilog } L/10.$ (32)

Equation (31) may be rearranged and put in the form

$$\frac{dB}{d\beta} = 2k\left\{\frac{(\beta^2+1)(\beta^2-1)(\beta^2-\overline{1-k^2})+4k^2\beta^2}{(\beta^2-1)^2(\beta^2-\overline{1-k^2})^2+4k^4\beta^2}\right\} \tag{33}$$

This equation does not involve the loss ratio l, but expresses $dB/d\beta$ in terms of β directly. A useful alternative to equation (31) is

$$\frac{dB}{d\beta} = \frac{2}{kl}\left\{1 \pm \tfrac{1}{2}|\beta + 1/\beta|\sqrt{l-1}\right\}, \tag{34}$$

where the — sign applies to the frequency band between $\omega_1/2\pi$ and $\omega_0/2\pi$, and the + sign for frequencies outside these two limits. When k is small, $|\beta + 1/\beta|$ is approximately equal to 2 for all frequencies of interest, and equation (34) then expresses $dB/d\beta$ in terms of l directly.

From equations (33) or (34) it can be shown that

$$\frac{dB}{d\beta} = \frac{2}{k}, \quad \text{when } \beta^2 = 1, \tag{35a}$$

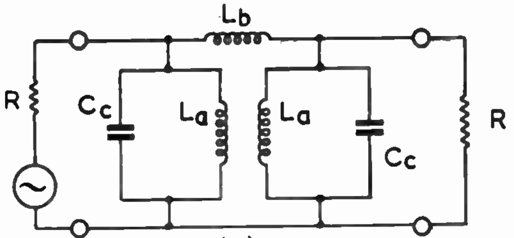
$$\frac{dB}{d\beta} = \frac{2}{k}, \quad \text{when } \beta^2 = 1 - k^2, \tag{35b}$$

$$\frac{dB}{d\beta} = \frac{2}{k}\left\{\frac{6-k}{5-k}\right\}, \quad \text{when } \beta^2 = 1 - k, \tag{35c}$$

$$\frac{dB}{d\beta} = \frac{2}{k}\left\{\frac{6+k}{5+k}\right\}, \quad \text{when } \beta^2 = 1 + k, \tag{35d}$$

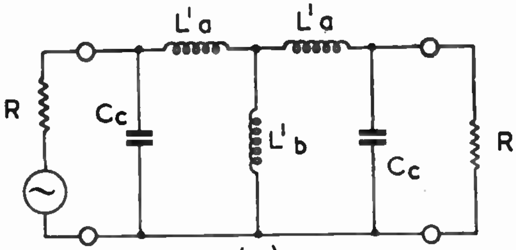
$$\frac{B}{\beta} = \frac{2}{k}\left\{\frac{1 - 5k^2/8}{1 - k^2/2}\right\}, \text{ when } \beta^2 = \sqrt{1 - k^2}. \tag{35e}$$

quation (35*e*), which expresses the slope at the eometric mean frequency, is approximate only.



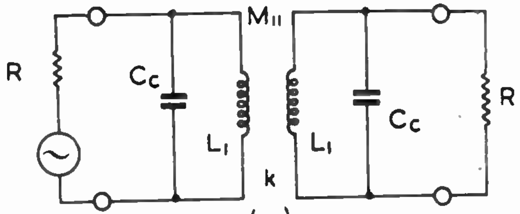
(a)

$\omega_0 L_a/R = k/(1 - k)$
$\omega_0 L_b/R = 1$
$1/\omega_0 C_c)/R = k$
$k = L_a/(L_a + L_b)$



(b)

$\omega_0 L^1{}_a/R = k/(1 + k)$
$\omega_0 L^1{}_b/R = k^2/(1 - k^2)$
$1/\omega_0 C_c)/R = k$
$k = L^1{}_b/(L^1{}_a + L^1{}_b)$



(c)

$\omega_0 L_1/R = k/(1 - k^2)$
$(1/\omega_0 C_c)/R = k$
$\omega_0 M_{11}/R = k^2/(1 - k^2)$
$k = M_{11}/L_1$

Fig. 9.—Practical circuits with inductive coupling. All circuits have zero insertion loss at $\omega_0/2\pi$ *and* $\omega_1/2\pi$ *where* $\omega_1 = \omega_0\sqrt{1-k^2}$. *Note that for (c),* $L_1 C_c \omega_1^2 = 1$.

From equations (35*a*), (35*b*) and (35*e*) it can be shown that $dB/d\beta$ is constant within 5 per cent. for values of k up to 0·2.

For inductive coupling, $\beta = \omega/\omega_0$, and

$$T = dB/d\omega$$
$$= \frac{1}{\omega_0}\cdot\frac{dB}{d\beta} \text{ seconds.} \tag{36}$$

Thus, to obtain the delay time in seconds, equations (35) must be multiplied by the constant $1/\omega_0$.

For capacitive coupling, $\beta = -\omega_0/\omega$, and

$$T = dB/d\omega,$$
$$= (\omega_0/\omega)^2\left\{\frac{1}{\omega_0}\cdot\frac{dB}{d\beta}\right\} \text{ seconds.} \tag{37}$$

In this case the time delay does not tend to remain constant within the frequency range from $\omega_0/2\pi$ to $\omega_1/2\pi$; rather, it varies inversely as the square of the frequency. For many purposes the capacitively-coupled circuit will be unsuitable because of this varying time delay.

4.3. *Input Impedance*

The input impedance of the circuit of Fig. 2 is given by

$$Z_{in}/R = z_{in} = \frac{a + jx_2}{a - j(a + 1)/x_1}, \tag{38}$$

Substitution of the values for x_1 and x_2 from equations (17) and (18) into equation (38) gives an expression for the input impedance of Fig. 5. This is

$$Z_{in}/R$$
$$= \frac{(\beta^2 - 1) - jk\beta}{(\beta^2 - 1) + j(\beta^2 - 1 + k)(\beta^2 - 1 - k)k\beta}, \tag{39}$$

from which it can be shown that

$$Z_{in}/R = 1, \quad \text{when } \beta = \pm 1, \tag{40a}$$

$$Z_{in}/R = 1, \quad \text{when } \beta = \pm\sqrt{1 - k^2}, \tag{40b}$$

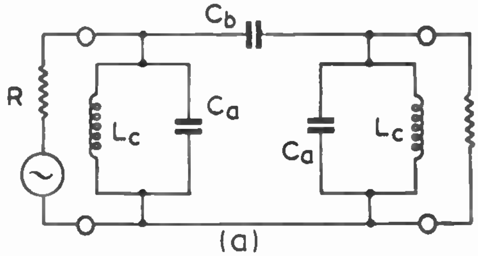
$$Z_{in}/R = 1 \pm j\sqrt{1 - k}, \quad \text{when } \beta = \pm\sqrt{1 - k}, \tag{40c}$$

$$Z_{in}/R = 1 \pm j\sqrt{1 + k}, \quad \text{when } \beta = \pm\sqrt{1 + k}, \tag{40d}$$

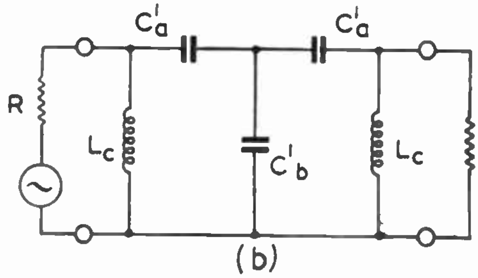
$$Z_{in}/R = \frac{1 \pm j\,\dfrac{k.\sqrt[4]{1-k^2}}{1-\sqrt{1-k^2}.}}{1 \pm j\,\dfrac{2.\sqrt[4]{1-k^2}}{k}} \qquad (40e)$$

$$\text{when } \beta = \pm\sqrt[4]{1-k^2}$$

where the + sign applies to the inductively-coupled case and the — sign to the capacitively-coupled case.



$(1/\omega_0 C_a)/R = k(1 - k)$
$(1/\omega_0 C_b)/R = 1$
$\omega_0 L_c/R = k$
$k = C_b/(C_a + C_b)$



$(1/\omega_0 C^1{}_a)/R = k/(1 + k)$
$(1/\omega_0 C^1{}_b)/R = k^2/(1 - k^2)$
$\omega_0 L_c/R = k$
$k = C^1{}_a/(C^1{}_a + C_b{}^1)$

Fig. 10.—Practical circuits with capacitive coupling. BOTH circuits have zero insertion loss at $\omega_0/2\pi$ and $\omega_1/2\pi$, where $\omega_0 = \omega_1\sqrt{1-k^2}$.

5.0. Practical Circuits

For inductive coupling, three forms of practical circuit are possible; these are illustrated in Fig. 9. Fig. 9 (*a*) shows the II circuit considered in this paper; Fig. 9 (*b*) is an equivalent obtained by replacing the II of inductors by an equivalent T. Figure 9 (*c*) is the equivalent two-winding transformer with pure mutual inductance coupling. For this last circuit, $L_1 C_c \omega_1^2 = 1$. When k is small, the design equations take on the well-known form

$$1/Q = \omega_0 L_1/R = (1/\omega_0 C_c)/R = k \quad (41)$$

With capacitive coupling, only two circuits are possible; these are illustrated in Fig. 10. Fig. 10 (*b*) is obtained from 10 (*a*) by replacing the II of capacitors with an equivalent T.

6.0. Coupled Circuits with Unequal Terminations

In Fig. 11 are shown two transformers, (*a*) with equal terminations and (*b*) with unequal terminations. The primary sides of both circuits are the same and the same coefficient of coupling, k, is used. However, for Fig. 11 (*b*) the secondary inductance is n^2 times the primary inductance, the secondary capacitance $1/n^2$ times the primary capacitance, and the resistance termination n^2 times the generator resistance.

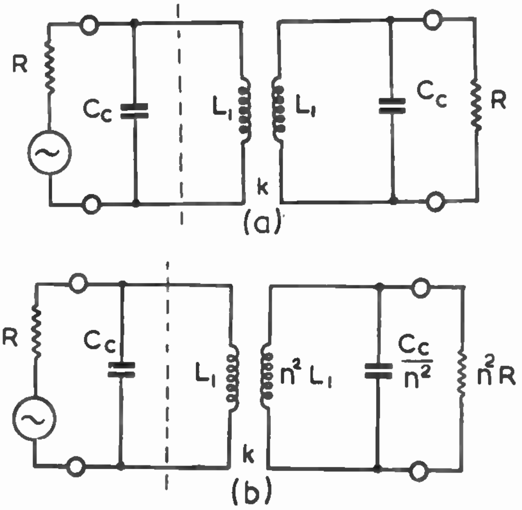


Fig. 11.—Transformers with (a) equal terminations and (b) unequal terminations.

For Fig. 11 (*a*), the impedance looking into the circuit to the right of the broken line is

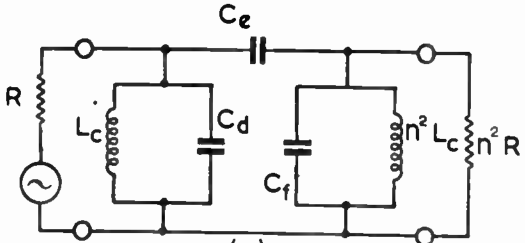
$$Z_a = j\omega L_1 + \frac{k^2\omega^2 L_1{}^2}{j\omega L_1 + \dfrac{R(-j/\omega C_c)}{R - j/\omega C_c}} \qquad (42)$$

For the circuit of Fig. 11 (*b*), the corresponding impedance is

$$Z_b = j\omega L_1 + \frac{k^2 n^2 \omega^2 L_1{}^2}{j\omega n^2 L_1 + \dfrac{n^2 R(-jn^2/\omega C_c)}{n^2 R - jn^2/\omega C_c}}$$

$$Z_b = j\omega L_1 + \frac{k^2\omega^2 L_1{}^2}{j\omega L_1 + \dfrac{R(-j/\omega C_c)}{R - j/\omega C_c}} \qquad (43)$$

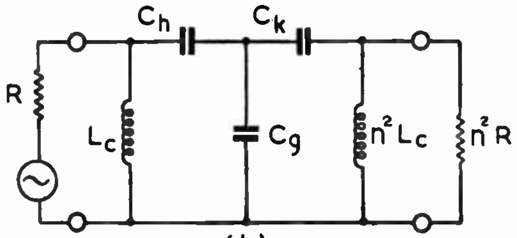
Comparisons of equations (42) and (43) shows that $Z_b = Z_a$, independent of the value of the impedance ratio n^2. This means that the secondary circuit of Fig. 11 (*b*) reacts on its primary circuit in exactly the same way as the secondary circuit of 11 (*a*) reacts on an identical primary circuit. Thus, the transformer shown in Fig. 11 (*b*) has the same transmission characteristics as that of Fig. 11 (*a*).



(a)

$(1/\omega_0 C_d)/R = nk(n - k)$
$(1/\omega_0 C_e)/R = n$
$(1/\omega_0 C_f)/R = n^2k/(1 - nk)$
$\omega_0 L_c/R = k$

$$k = \frac{C_e}{\sqrt{(C_d + C_e)(C_f + C_e)}}$$

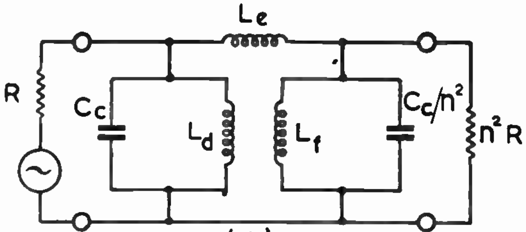


(b)

$(1/\omega_0 C_h)/R = k(1 - nk)/(1 - k^2)$
$(1/\omega_0 C_g)/R = nk^2/(1 - k^2)$
$(1/\omega_0 C_k)/R = nk(n - k)/(1 - k^2)$
$\omega_0 L_c/R = k$

$$k = \frac{\sqrt{C_h\, C_k}}{(C_h + C_g)(C_k + C_g)}$$

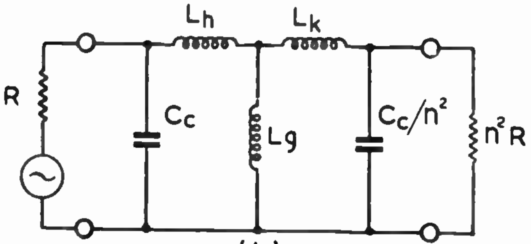
Fig. 12.—Practical circuits, with capacitive coupling, for unequal terminations. Both circuits have zero insertion loss, relative to an ideal network of impedance ratio n^2, at two frequencies $\omega_0/2\pi$ and $\omega_1/2\pi$, where $\omega_0 = \omega_1\sqrt{1 - k^2}$. Circuits (a) and (b) are physically possible when $nk < 1$.



(a)

$\omega_0 L_d/R = nk(n - k)$
$\omega_0 L_e/R = n$
$\omega_0 L_f/R = n^2k/(1 - nk)$
$(1/\omega_0 C_c)/R = k$

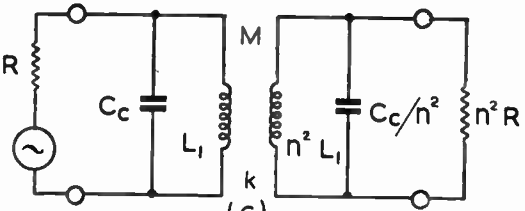
$$k = \sqrt{\frac{L_d L_f}{(L_d + L_e)(L_f + L_e)}}$$



(b)

$\omega_0 L_h/R = k(1 - nk)/(1 - k^2)$
$\omega_0 L_g/R = nk^2/(1 - k^2)$
$\omega_0 L_k/R = nk(n - k)/(1 - k^2)$
$(1/\omega_0 C_c)/R = k$

$$k = \frac{L_g}{\sqrt{L_h + L_g)(L_k + L_g)}}$$



(c)

$\omega_0 L_1/R = k/(1 - k^2)$
$(1/\omega_0 C_c)/R = k$
$\omega_0 M/R = nk^2/(1 - k^2)$
$k = M/nL_1$

Fig. 13.—Practical circuits, with inductive coupling, for unequal terminations. All circuits have zero insertion loss, relative to an ideal network of impedance ratio n^2 at two frequencies $\omega_0/2\pi$ and $\omega_1/2\pi$, where $\omega_1 = \omega_0\sqrt{1 - k^2}$. Note that for (c), $L_1 C_c \omega_1{}^2 = 1$. Circuits (a) and (b) are physically possible when $nk < 1$.

6.1. *Practical Circuits*

With unequal termination, three practical circuits may be used with inductive coupling. These are illustrated in Fig. 13, where the variations shown in (*a*) and (*b*) have been obtained from the two-winding transformer of (*c*) by using the II and T equivalent circuits.

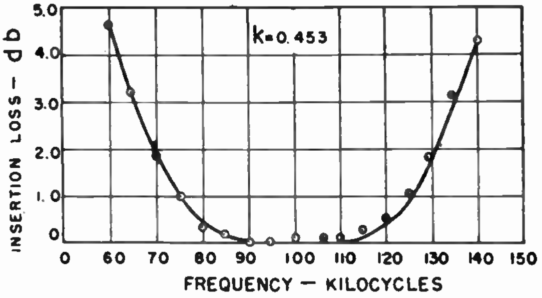


Fig. 14.—Insertion loss of an experimental transformer. The full line curve is calculated and the circled points are measured.

For unequal terminations, two forms of capacitively-coupled circuit may be used. These two circuits, shown in Figs. 12 (*a*) and 12 (*b*), have been obtained from their counterparts in Figs. 13 (*a*) and 13 (*b*) by the simple process of interchanging capacitance and inductance, while retaining the same magnitude of reactance of each corresponding arm at the common reference frequency, $\omega_0/2\pi$.

The circuits of Figs. 13 (*a*), 13 (*b*), 12 (*a*) and 12 (*b*) cease to possess true band-pass characteristics when $nk \geqslant 1$. When $nk = 1$, one reactance in each of the four circuits is either zero, or infinite ; when $nk \geqslant 1$, these reactances change in the wrong sense with frequency. Thus, these four circuits are limited to the case where

$$nk < 1. \qquad (44)$$

Figure 8 illustrates the fact that the frequency ratio of the band limits, for a given loss, increases with the value of the coupling coefficient. With this in mind, equation (44) indicates that the impedance ratio n^2 falls as the frequency ratio is increased. For the circuit of Fig. 13 (*c*), where the coupling is obtained by pure mutual induction, there is no limit to the impedance ratio.

7.0. Conclusion

The design methods discussed in this paper have been verified by the construction of a number of experimental transformers. Fig. 14 shows, in full line, the calculated insertion loss of a transformer with an inductive coupling coefficient of $k = 0{\cdot}453$; the circled points show the measured loss corrected for a mid-band insertion loss of 0·35 db due to dissipation effects on the components.

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THE CALCULATION OF THE ELECTRODE TEMPERATURES IN RADIO VALVES*

by

Dr. S. Wagener†

A commentary on the paper by I. A. Harris (Associate Member) published in the Nov.-Dec. 1948 issue of the Institution's Journal.

A method for calculating the electrode temperatures in radio valves has recently been given by Harris. He investigated the exchange of radiation between the electrodes of the valve by examining in detail the complicated paths followed by the radiation energy when radiated, reflected, absorbed and re-radiated by the different electrodes. By this method a general solution of the problem can only be given for a diode, while for valves with more than two electrodes, simplifying assumptions must be made because the radiation paths become too complex. It may therefore be of interest to note that a general solution of the problem applicable to valves with any number of electrodes has been given some time ago[1]; a short outline of the method of obtaining this general solution will be given here.

The main feature of this method is that the reflection paths of the radiation from the various electrodes are not examined in detail but are accounted for by introducing some additional unknowns in the equations to be formed.

Using the symbols introduced by Harris, and assuming n electrodes indicated by $k = 1, 2, 3 \ldots . n$, the energy radiated per second from the unit area of any of the electrodes will be denoted by σ_k. These σ_k are the real unknowns of the problem from which, once they are determined, the temperatures of the electrodes can easily be calculated. In order to account for the reflection from the various electrodes, the total energy reflected per second from the unit area of the kth electrode will be denoted by $\sigma_k^{(r)}$. The additional unknowns $\sigma_k^{(r)}$ can then be treated mathematically in exactly the same manner as the unknowns σ_k. A solution of the problem will be possible if a sufficient number of equations for all the unknowns σ_k and $\sigma_k^{(r)}$ together, can be formed.

The equations required can be found by considering the energy balance in the system of electrodes.

Considering the kth electrode again, the energy lost by this electrode per second will be $S_k \sigma_k$ where S_k denotes the surface area. On the other hand, the energy gained by this electrode per second is made up of three separate quantities. The first of these is the energy $S_k W_{0k}$ supplied to this electrode as electric power (heater power, anode dissipation). The second quantity is the total energy which is absorbed by the kth electrode from all the energies σ_i radiated from the other electrodes and perhaps from the kth electrode itself. Using Harris's symbols again, the coefficient of absorption will be denoted by A_k, while f_{ik} gives that fraction of the radiated energy σ_i which is received by unit area of the kth electrode (f_{ik} radiation factor). Then the second quantity is

$$S_k A_k \sum_{i=1}^{n} S_i f_{ik} \sigma_i$$

The third quantity is the total energy which is absorbed by the kth electrode from the energies $\sigma_i^{(r)}$ reflected from the other electrodes and perhaps from the kth electrode itself. In order to allow for this quantity, a factor r_{ik} must be introduced which denotes the fraction of the reflected energy $\sigma_i^{(r)}$ which is received by unit area of the kth electrode (r_{ik} = reflection factor). The third quantity is then

$$S_k A_k \sum_{i=1}^{n} S_i r_{ik} \sigma_i^{(r)}$$

If the three components of the energy gained by the kth electrode are added and equated to the energy lost, we obtain

$$\sigma_k = W_{0k} + A_k \sum_{i=1}^{n} S_i (f_{ik} \sigma_i + r_{ik} \sigma_i^{(r)}) \ldots (1)$$

$$k = 1 \ldots . n$$

This is a system of n linear equations which is

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† Electronics Division, P.O. Research Station, Dollis Hill.

not sufficient for determining the 2 n unknowns σ_k and $\sigma_k^{(r)}$. Another set of equations can, however, easily be formed by deriving a formula for the total energy $S_k\ \sigma_k^{(r)}$ which is reflected from the kth electrode. The value of this energy is obtained by multiplying the sum on the right hand side of equation (1) by the coefficient of reflection R_k instead of by the coefficient of absorption A_k. This gives

$$\sigma_k^{(r)} = R_k \sum_{i=1}^{n} S_i (f_{ik}\sigma_i + r_{ik}\,\sigma_i^{(r)})\,..(2)$$

The fundamental formulæ (1) and (2) altogether give a system of $2n$ equations which is sufficient for calculating the $2n$ unknowns, provided all the factors f_{ik} and r_{ik} are known.

The radiation factors f_{ik} can be calculated by using the laws of radiation, and some of the formulæ needed have been given by Harris. As for the reflection factors r_{ik}, it has been shown in the investigation quoted above that under certain conditions

$$r_{ik} = f_{ik}\ \ldots\ldots\ldots\ldots\ldots(3)$$

The conditions to be complied with will not be discussed here in detail ; it may be only noted that in the case of a valve with axial symmetry those conditions are satisfied if a distinction is made between the reflection from the inside and that from the outside of the electrodes. The energy reflected per unit area of the inside of the kth electrode may be denoted by $\sigma_k^{(ri)}$ and the respective energy reflected from the outside by $\sigma_k^{(ro)}$. If such a distinction is made for the reflected energies the same must, of course, be done for the reflection factors. Two types of reflection factors are therefore used, the first of these being the factors r_{ik}, referring to the reflection going from the inside of one electrode to the outside of another, or to the reflection going from the outside of one electrode to the inside of another. The second type of reflection factor, which will be denoted by r_{ik}^{*}, are those which refer to the exchange of reflected radiation between the inside of one electrode and the inside of another. If equation (3) is accounted for, the following system of linear equations is finally obtained for a valve with axial symmetry :

$$\varepsilon_k\sigma_k = W_{0k} + A_k\left\{\sum_{i=1}^{k-1} S_i f_{ik}(\sigma_i + \sigma_i^{(ro)}) + \sum_{i=k+1}^{n} S_i f_{ik}(\sigma_i + \sigma_i^{(ri)}) + \sum_{i=2}^{n} S_i f_{ik}^{*}(\sigma_i + \sigma_i^{(ri)})\right\}\ \ldots\ldots\ldots\ldots(4)$$

$$k = 1\ldots.n \qquad \varepsilon_1 = 1,\ \varepsilon_2 = \varepsilon_3 = \ldots = \varepsilon_n = 2$$

$$\sigma_k^{(ri)} = R_k\left\{\sum_{i=1}^{k-1} S_i f_{ik}(\sigma_i + \sigma_i^{(ro)}) + \sum_{i=2}^{n} S_i f_{ik}^{*}(\sigma_i + \sigma_i^{(ri)})\right\}\ \ldots\ldots\ldots\ldots(5)$$

$$k = 2\ldots.n$$

$$\sigma_k^{(ro)} = R_k \sum_{i=k+1}^{n} S_i f_{ik}(\sigma_i + \sigma_i^{(ri)})\ \ldots\ldots\ldots\ldots(6)$$

$$k = 1\ldots.(n-1)$$

The factors ε_k in equations (4) must be introduced in order to account for the fact that the cathode ($k = 1$) only radiates away from one side whilst the other electrodes ($k = 2 - n$) radiate away from both sides.

The formula (4), (5) and (6) form a system of $3n-2$ linear equations which is sufficient for calculating the $3n-2$ unknowns σ_k ($k = 1\ldots.n$), $\sigma_k^{(ri)}$ ($k = 2\ldots.n$) and $\sigma_k^{(ro)}$($k = 1\ldots.n-1$).

Solutions of this system for practical cases have been given in the investigations quoted above, where it has also been shown that a fairly good correspondence between calculated and measured values is obtained. The heat conduction in the electrodes can, if necessary, be accounted for by an additional term in equations (4).

References

1. Heinze, W. and S. Wagener. *Zeitschrift Fuer Technische Physik*, Vol. 18, p. 75, 1937.
   Wagener, S. *Zeitschrift Fuer Technische Physik*, Vol. 18, p. 270, 1937.

Mr. I. A. Harris (Associate Member) states:—

Dr. Wagener's approach is certainly more elegant and complete mathematically than the detailed approach which I adopted. Yet it is still felt that in solving the problem of the tetrode, for instance, the detailed method is more amenable to simplification, having the physical picture in view all the time, and the result saves much labour in computation. Also, the inaccuracy is little greater than that introduced by assuming an idealized structure (such as with axial symmetry) and carrying out a rigorous analysis.

NOTICES

Obituary

The Council regrets to record the assassination of Mr. Joseph Edward CHAPPELL, of Levenshulme, Manchester, at the age of 36 years.

Mr. Chappell was serving as a Commissioned Electrical Officer (R), Royal Navy, stationed at Singapore, as a Radio Maintenance Officer. During recent disturbances by bandits, he was killed.

Mr. Chappell was first elected an Associate of the Institution in March, 1943, and secured a transfer to Associate Membership in September, 1944.

Annual General Meeting

In accordance with Article 32, the General Council has nominated six members for the vacancies which now arise. The names are listed in the Agenda for the Annual General Meeting, which appears on page 277 of this issue.

" After the issue of the Council's lists and not later than twenty-one days after the date of such issue, any ten corporate members may nominate any other duly qualified person to fill any such vacancy by delivering such nomination in writing to the Secretary, together with the written consent of such person to accept office, if elected."

Secretary/Treasurer of North-Eastern Section

Consequent upon his transfer to Preston, Mr. Henry Armstrong (Associate Member) has had to resign his position as Treasurer of the North-Eastern Section.

Mr. Armstrong was one of the Founder Members of the North-Eastern Section and has been associated with the Committee ever since, either as Secretary or Treasurer. Mr. Armstrong has willingly devoted a great deal of his time to the duties involved in both these appointments, and the Council of the Institution wishes to place on record thanks and appreciation for his work on behalf of the North-Eastern Section.

" Ultrafax "

The following correction should be added to the paper on " Ultrafax," by D. S. Bond and V. J. Duke (No. 4, Vol. IX, April 1949).

The reference in line 6, column 1, on page 148, to the second anode current of a 5WP15, as " 1 to 30 mA " should have read " 1 to 30 uA."

Radiolympia, 1949

The Radio Industry Council (organizers o Radiolympia), has distributed some interestin literature as part of its publicity for the 16t National Radio Exhibition to be held in London from September 28th to October 8th, 1949.

A booklet, " British Radio for the World,' containing a foreword by Mr. John W. Ridgeway M.Brit.I.R.E. (Chairman, Radio Industry Council) and a brief article, " Electronics in Industry," b Mr. W. E. Miller, M.A.(Cantab)—a Vice President of the Institution, has been circulate abroad by The Radio Industry Council. Othe articles are written by Sir Edward Appleton an Dr. R. L. Smith-Rose.

Radiolympia, 1949, will be under the patronag of Her Majesty, Queen Mary.

Examination Prizes—1948

It is with pleasure that the Council announce the awards of prizes to the following candidate who sat the Graduateship Examination in May o November, 1948 :

PRESIDENT'S PRIZE : *awarded to the mos successful candidate who has passed the entir examination at one sitting.*

Mr. N. Morley (Associate Member), Kings Lynn

MOUNTBATTEN MEDAL : *awarded to th most successful candidate serving in H.M. Force at the time of the examination, who has passed th entire examination at one sitting.*

Mr. R. A. Bassett (Graduate), Ryde, I.O.W

S. R. WALKER PRIZE : *awarded to th candidate who takes second place in the order o merit and who has passed the entire examination a one sitting.*

Mr. R. A. Bassett (Graduate), Ryde, I.O.W.

AUDIO FREQUENCY ENGINEERIN PRIZE : *awarded to the most outstanding candidat who has passed part IV in Audio Frequenc Engineering.*

Mr. H. G. Anstey (Graduate), London, N.16

ELECTRONIC MEASUREMENTS PRIZE *awarded to the most outstanding candidate who ha passed part IV in Electronic Measurements.*

Mr. A. L. Whitwell (Graduate), Codsall, Staffs