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Engineering Note E-328

Project Whirlwind
Servomechanisms Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts

SUBJECT: PULSE TRANSFORMERS AND INTERSTAGE COUPLING IN WHIRLWIND I

To: Systems Group, Storage Tube Group

From: C. A. Rowland

Date: January 31, 1950

Abstract: Pulse transformers are useful for coupling between pulse circuits of a system because they permit a saving in the number and size of the tubes required.

A one-to-one inverter transformer is useful for coupling between adjacent stages, and a step-down step-up arrangement is useful for coupling remote stages. Crystal diodes are useful in coupling circuits for damping, isolating, and clamping purposes; the application of crystal diodes is particularly helpful in point-to-multipoint and multipoint-to-multipoint coupling. Unless fractional-microsecond pulses (order 0.1μsec) are at a very low impedance level, these pulses will normally feed loads that are predominately capacitive. When relatively large amplitudes and small delays take precedence over pulse shape, it is best to replace the load resistor of the transformer with an inductance; the inductance is normally necessary to produce overshoot on the pulse and thereby permit the use of a crystal diode to damp out oscillations. Such circuits have handled 0.1 μsec pulses at repetition frequencies as high as 3 megacycles without appreciable variation in pulse amplitude as a function of repetition frequency.

There is a good possibility that the present Whirlwind transformers designed for 0.1 μsec pulses could be improved upon; this is particularly true when the transformers drive on RLC load instead of a predominately resistive load. It is believed that non-metallic magnetic materials (ferrites) might prove to be better than metallic materials for cores of transformers designed for 0.1 μsec. pulses.

A. Introduction

Information in Whirlwind I is transmitted in the form of unilateral pulses. The polarity of a pulse is reversed every time it passes

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through a vacuum-tube amplifier. If capacitive coupling is used between stages, every other stage must be normally on. The use of normally-on stages is undesirable for two reasons: (1) since pulses are present less than half the time, the power consumption is greater than with normally-off stages, (2) small noise pulses and pulse overshoot are amplified. The use of inverter pulse transformers with the proper turns ratio for interstage coupling permits all pulse amplifiers to be cut off during the absence of pulses. This method of coupling is used extensively in WWI allowing the use of smaller tube types and providing noise reduction throughout the system.

B. The Transformer Vs the Cathode Follower

When a buffer amplifier is required to drive a low-impedance source, there may be a question of using a cathode follower instead of a conventional amplifier and a step-down transformer. The gain of a cathode follower having a load resistor R is:

$$\frac{\mu R}{r_p + (\mu+1)R} .$$

The gain of an amplifier using a pulse transformer with a turns ratio of N:1 is

$$\frac{N\mu R}{r_p + N^2R} .$$

The gain of the amplifier exceeds the gain of the cathode follower if $N\left[r_p + (\mu+1)R\right] > r_p + N^2R$, or the gain of an amplifier exceeds the gain of a cathode follower if $N < (\mu+1)$. A cathode follower has a lower input capacitance and a lower output impedance than an amplifier so that pulses with faster rise times may be handled; however, in most cases the desired rise times and greater amplitudes can be attained with buffer amplifiers and pulse transformers.

Interstage coupling can be classed into four groups (1) point-to-point coupling, (2) multipoint-to-point coupling, (3) point-to-multipoint coupling, (4) multipoint-to-multipoint coupling. The coupling of short pulses (1 μsec or less) is accomplished in the computer by using pulse transformers of the required ratios and by the use of crystal diodes for mixing and isolation purposes.

Five transformers have been designed for use in Whirlwind circuits. The design specifications for these transformers are included in the standards books for Project Whirlwind. Pulse transformers with turns ratios of 1:1, 3:1, and 5:1 have been designed for 0.1 μsec half-sine wave pulses. A pulse transformer with a turns ratio of 5:1 has been designed for a trapezoidal pulse with a rise time of 0.1 microsecond and a duration of 1/2 microsecond. A three-winding pulse transformer has been designed for blocking oscillators. Report R-122 contains valuable information on the theory and design of low-power pulse transformers. A large portion of Volume 5 of the Radiation Lab. Series is devoted to the theory and design of pulse transformers.

C. Point-to-Point Coupling

Point-to-point coupling may be from a pulse amplifier to an adjacent stage or from a pulse amplifier to a remote stage. A one-to-one inverter is used to couple adjacent stages, and a step-down step-up arrangement is used to couple remote stages.

1. One-to-One Inverter

The 6-193-6 (Whirlwind Spec.) transformer was designed for 0.1-microsecond pulses and has a turns ratio of 1:1. This transformer is used to reverse the polarity of pulses that are coupled from a gate tube to a buffer amplifier or from one buffer amplifier to another in the manner indicated in Figure 1. The 6-193-6 transformer was originally designed to work into a resistive load of 1000 ohms; a 1000-ohm load gives the best transient response for this pulse transformer when it is driven from a current source. Because of the stray capacitances in the circuit it is impossible to present a resistive load to the pulse transformer without sacrificing a large portion of the pulse amplitude. The circuit in Figure 1 is the most satisfactory arrangement for coupling between two pulse amplifiers, assuming the pulse amplifiers are normally cut off. The transformer works into a parallel R-L-C combination that behaves something like an R-L-C peaker that is underdamped for the first half-cycle of oscillation and critically damped for the second half-cycle. The leakage inductance of the transformer and the capacitances of the transformer and the circuit combine to produce ringing on the trailing edge of the pulse. If the value of the tail-reversing inductance L is too large the ringing will not swing below the voltage axis and it can not be damped out by the resistance R. If the value of L is too small, the duration and amplitude of the pulse are decreased. A suitable value for L can be determined rapidly by experimental methods. The value of the inductance L depends on the transformer, the pulse duration and the stray capacitances of the circuit; a small value of L is required for large shunt capacitance. The shunt capacitance C_s and C_p usually total between 30 to 40 μμf in Whirlwind circuits; if the total shunt capacitance exclusive of the transformer capacitance is between 30 to 40 μμf and the pulse duration is near 0.1-microseconds a 50-microhenry inductance is satisfactory for use with the 6-193-6 transformer. The value of R is important if the circuit is to handle pulses at a high repetition rate. The value of R should be chosen to give critical damping. When R is too small the circuit is overdamped, and when R is too large the circuit is underdamped. For most Whirlwind circuits in which a one-to-one transformer is used, a resistance of 470-ohms is suitable for R. (The forward resistance of the germanium crystal diodes is about 100-ohms.) The circuit of Figure 1 will work for 0.1-microseconds pulses at a repetition rate of well over 2 megacycles without appreciable prf sensitivity.

Since most of the Whirlwind circuits that require a one-to-one inverter have nearly the same shunt capacitance, it seems that it ought to be possible to design a transformer with a lower magnetizing inductance so that a tail-reversing inductance is unnecessary. If the number of turns on the transformer are reduced, the magnetizing inductance, leakage inductance, and transformer capacitance are reduced. Pulse transformers with fewer turns were tried in an attempt to eliminate the necessity for the tail-reversing inductance. However, the results were unsatisfactory; it seems that if the number of turns on the transformer was reduced so that no tail-reversing inductance was required the pulse amplitude was less than with the 6-193-6 transformer and a tail-reversing inductance. The reason for this is not understood. One explanation could be the non-linearity of the magnetizing inductance of a transformer wound on a laminated cone. The effective permeability of an iron core varies with induction and time. The permeability of a core increases as the $\sqrt{\text{time}}$ for short pulses because the initial eddy currents in the core are large and tend to prevent the magnetizing flux from being uniformly distributed in the core.

2. Step-Down Step-Up

In some cases one pulse amplifier is required to drive another amplifier at a remote point. A low-impedance line is usually necessary in connecting remote points to prevent excessive distortion, attenuation, and delay of the pulses. A step-down transformer may be used to drive the low-impedance line; if the amplitude of the pulse on the line is not large enough to drive the second stage, a step-up transformer may be useful at the receiving end. This method of interstage coupling is similar to using a 1:1 transformer between stages that arennot remotely connected; a tail-reversing inductance and a damping diode are usually required. The 6-193-7 transformer is designed for 0.1-microsecond pulses and has a turns ratio of 3:1, this transformer is useful for step-down step-up purposes if the impedance of the transmission line is around 100-ohms. Again, when pulses with fast rise times (0.05-microsecond) are used it is practically impossible to terminate the 90-ohm line or the transformers with resistive loads without sacrificing considerable amplitude because of the input capacitance of the succeeding stage. As in the case of the 1:1 inverter it is usually best to leave the transformer as well as the transmission line unterminated. The step-down step-up arrangement shown in Figure 2 is useful for coupling 0.1-microsecond pulses between two stages (7AK7, 7AD7, 6Y6 etc.) connected by a length of RG 62U transmission line. (The characteristic impedance of RG 62U line is 93 ohms. The delay of RG 62U is approximately 1-microsecond per 1000 feet.) The sizes of the tail-reversing inductance and the damping resistor are about the same as for the 1:1 transformer; they can be determined best and most rapidly by experimental methods. Since the line is unterminated, reflections do occur; however, if the delay of the transmission line is less than a quarter of the delay of the pulse these reflections are damped out (because of losses in the transformer) before the overshoot of the pulse is completed and do not cause any difficulty. If the input capacitance to the succeeding stage is small a transformer with a high turns ratio might be useful at the receiving end; however, in most cases in Whirlwind, an increase in the turns ratio of the second transformer increases the rise and fall time of the circuit so that there is little or no gain in the pulse amplitude.

3. Effect of Transformers on Pulse Shape

Many of the circuits in the Whirlwind computer are designed for 0.1-microsecond half-sine-wave pulses. If the pulse duration is too long, the circuits do not have sufficient time to recover for high speed operation; if the pulse duration is too short, unnecessarily large tubes are required to deliver the required pulse amplitudes. The shape, amplitude, and delay of pulses is affected by the pulse transformer and their associated circuits. Usually a pulse amplifier is biased a few volts beyond cutoff to prevent small noise signals from being amplified; since the amplifier is biased beyond cutoff the effective duration of the input pulse is decreased. If the pulse duration is to remain unchanged the plate circuitry must act to broaden the pulse: the leakage inductance of the transformer, the shunt capacitances in the plate circuit, and the tail reversing inductance affect the shape and amplitudes of the pulses out of a pulse amplifier. Because most of the stages are biased beyond cutoff and because the circuitry affects the shape of the pulses, output pulse shape becomes reasonably independent of the input pulse shape after passing through four or five similar pulse amplifiers. The analysis in Engineering Note E-138 indicates some of the effects of pulse transformers on the shape and amplitude of the pulses. In order to make any reasonably simple analysis of these pulses circuits a number of assumptions have to be made; the analysis in E-138 does not account for non-linearities in the control grid to plate transfer characteristics, the magnetizing inductance of the transformer, or the input impedance to the second tube. The analysis was primarily for a 1:1 inverter used in the manner indicated in Figure 1; however, the behavior for step-down step-up arrangements is nearly the same. The equivalent circuit of the plate circuit was simplified as shown in Figure 3.

L_1 - leakage inductance of transformer

C_1 - output capacitance of first stage

C_2 - input capacitance of second stage plus shunt capacitance of the pulse transformer

L_2 - tail reversing inductance in parallel with magnetizing inductance of pulse transformer

If L_2 is neglected and an impulse of current is supplied across C_1 the expression for e_2 is:

$$e_2 = \frac{1}{C_1 + C_2} (1 - \cos \alpha t)$$

where $$= \frac{C_1 + C_2}{L_1 C_1 C_2}$$

It is argued that the effective duration of the input pulse is always appreicably less that the duration of the output pulse so that the idea of an impulse is usable. The expression indicates that L_1 does not influence the amplitude of the pulse but that it does influence the frequency of oscillation in the output. It also indicates that the oscillations will not swing below the voltage axis if L_2 is infinite. If the effect of L_2 is considered in the circuit of Figure 3 for an impulse of current, the expression for e_2 becomes more complex and is rather meaningless in algebraic form. However, the addition of L_1 results in the two superimposed oscillations of different frequencies so that

$$e_2 = A(\cos \omega t - \cos \beta t),$$

where A, ω and β are constants determined by the circuit parameters. From E-138 and experimental evidence it is known that the pulse duration can be lengthened by increasing either the leakage inductance of the transformer, or the shunt capacitance across the transformer, or both; in any case, an increase in pulse duration by the circuitry results in a more triangular pulse shape and/or a decrease in pulse amplitude and an increase in delay time through the circuit. The analysis in E-138 indicates that the leakage inductance of the pulse transformer affects the pulse amplitude much less than the shunt capacitance. The leakage inductance of the transformer is increased and the interwinding capacitance decreased if the spacing between the windings is increased; when the shunt capacitance is decreased the amplitude of the ringing increases and a larger tail reversing inductance may be used. Thus the pulse duration can be increased somewhat without a serious loss in amplitude; however, the pulse shape becomes more triangular and the delay is increased. The 6-193-6 and 6-193-7 transformers in Whirlwind circuits usually result in a decrease in pulse width from the standard 0.1-microsecond to a 0.07 to 0.08-microsecond. It is questionable whether the transformer should be designed to provide greater pulse widths; the amplitude of the pulse at its final destination is usually the deciding factor that must be considered, assuming the time delay is not too great.

The point-to-point coupling in Whirlwind circuits is primarily a matter of attaining moderate Q's and high L-C ratios. Normally higher Q's for transformer can be attained by using cores of magnetic materials; however, as the pulse duration is decreased the effective premeability of a core must be sacrificed in order to keep the eddy circuit losses at the same order of magnitude as the copper losses (ideally core losses should equal copper losses for highest Q's). In general, pulse transformers have been designed to drive resistive loads; in these cases, eddy-current losses were not so important as long as they were small in comparison to the power dissipated in the load resistor. The leakage inductance and shunt capacitance of a transformer increase with the number of turns; in order to attain a minimum transformer capacitance and leakage inductance a high permeability core is desired to reduce the number of turns required for a desired magnetizing inductance. Experiments with the airecore pulse transformers in Whirlwind circuits has shown that these transformers are comparable in performance to the 6-193-6 and 6-193-7 transformers. Although a greater number of turns are required for the air-core transformers so that the leakage inductance and interwinding capacitance are increased, the performance of air-cored transformers is nearly as good as the ones with Hipersil cores because (1) the leakage inductance does not seriously affect the pulse amplitudes unless the grid of the succeeding stages is driven positive (2) the shunt capacitance of air-cored transformer is not necessarily as great as the ones with Hipersil cores (3) the core losses with Hipersil cores are not negligible. The effective shunt capacitance of transformers with Hipersil cores is affected by the winding-to-core capacitance and the core-to-ground capacitance as well as the interwinding capacitance. If air-cored transformers work nearly as well as those with Hipersil cores it may be possible to design transformers with powdered iron cores that work just as well, if not better. Non-metallic magnetic materials (Ferroxcubes, Ferramics) have been developed that have effective resistivities as good as powdered iron cores and greater effective permeabilities than powdered iron cores; these materials are being produced in small quantities by North American Phillips Co. and General Ceramics & Steatite Co. The new magnetic materials may make possible better transformer designs for short pulses and relatively large capacitive loads.

C. Multipoint-to-Point Coupling

Multipoint-to-point coupling is similar to point-to-point coupling; however, crystal diodes are useful to mix the signals from the various sources at the receiving point. The circuit of Figure 4 shows how several signals may be mixed at a common point. The mixing diodes prevent a signal on one line from feeding back on to adjacent lines, and also, these diodes prevent the amplitude of the pulse on one line from being affected by the loading effort of the adjacent lines and the magnetizing inductances of the adjacent transformers.

D. Point-to-Multipoint Coupling

Point-to-multipoint coupling is accomplished by driving a low-impedance line with a buffer amplifier and tapping the line at the desired receiving points as is indicated in Figure 5. The input impedance of the receiving points should be high compared to the characteristic impedance of the line so that the pulse amplitude at each receiving point is nearly the same. Generally speaking, step-up transformers cannot be used at the receiving points because the increased load on the transmission line results in excessive attenuation.

Since the clamping circuits at the receiving points will clamp to any pulse overshoots, it is important that the overshoot of the pulse should be small. The magnetizing inductance should be large to reduce the overshoot; however, the leakage inductance and capacitances should be small to prevent excessive attenuation and distortion of the pulse. The turns ratio of the pulse transformer should be chosen so that the amplitude of the pulse on the line is a maximum; if the pulse amplifier has linear characteristics, the voltage gain is a maximum if $N^2 Z_o = r_p$.

where N = turns ratio of transformer

Z_o = line impedance

r_p = plate resistance of tube

An increase in turns ratio increases the resistive load that appears in the plate circuit while decreasing the effect of capacitance on the line side of the transformer. If the turns ratio is too large the R-C time constant is increased to the point where the rise time of the circuit is excessive and possibly there is a loss in pulse amplitude; if the turns ratio is too small the low impedance in the plate circuit results in a loss of pulse amplitude. A turns ratio of 3:1 is about optimum for a transformer driving a 90-ohm load with 0.1-microsecond pulses from tubes having an output capacitance of 10-15 micromicrofarad; the 6-193-7 transformer was designed for 0.1-microsecond pulses and has a turns ratio of 3:1. Since the pulse amplifier driving the lines is usually biased below cutoff, the plate circuit must broaden the pulse if the pulse duration is to remain close to the standard width; the best method of increasing the pulse width without seriously affecting the pulse amplitude is to increase the turns ratio of the transformer.

For some cases in point-to-multipoint coupling an amplifier is required to drive a low impedance line in two directions; this is desirable on long lines feeding several points, in order to prevent excessive attenuation on the line. If a 90-ohm line is driven at its midpoint a 5:1 transformer is more desirable than a 3:1 transformer. The 6-193-8 transformer has a turns ratio of 5:1 and is designed for 0.1 microsecond pulses. The higher turns ratio helps to compensate for the decrease in pulse width resulting from the amplifier being biased below cut off. An increase in the rise time of the output pulse makes termination problems on the line simpler.

The 6-193-10 transformer is designed for trapedzoidal pulses with a rise time of 0.1-microsecond and a duration of 0.5-microsecond; this transformer has a 5:1 turns ratio and is designed to drive impedance of from 50 to 90 ohms. The magnetizing inductance of this transformer must be large enough to preserve the flat portion of the pulse and to prevent excessive overshoot; the leakage inductance and shunt capacitance of the transformer must be small enough to preserve the 0.1-microsecond rise time of the pulse.

If the overshoot of pulses passing through a transformer is small the recovery time is necessarily large because a transformer cannot pass a d-c component; this means that the voltage baseline will gradually shift an amount equal to the d-c component of a chain of pulses at a high repetition rate so that the effective amplitude of the pulse is reduced. Since computer circuits must handle pulses over a wide range of repetition frequencies, any form of prf sensitivity is undesirable. There are two possible methods of reducing prf sensitivity resulting from the averaging effect of the transformer: (1) the magnetizing inductance may be increased so that there is no appreciable shift in the base line for the longest chain of pulses at the highest repetition frequency to be used. This method of reducing prf sensitivity will work well if the chains of pulses are not too long, and if there is sufficient recovery time between the chains of pulses. (2) A diode may be used in the manner indicated in Figure 6. The action of the diode in this circuit is analagous to the action of the diode in a clamping circuit for capacitively coupling unilateral pulses; the capacitor in a clamping circuit discharges slowly during a pulse and recharges rapidly after the pulse has ended.

In the circuit of Figure 6 current builds up comparitively slow in the transformer winding while plate current flows but decays rapidly after plate current ceases and the pulse overshoots. In other words the time constant is L/R: R is equal to the load plus the forward resistance of the diode during the pulse and to the back resistance plus the load during the pulse overshoot. The overshoot of the transformer is large with the diode but since the back resistance of the diode is large compared to the line impedance this overshoot does not appear on the line. The 6-193-7 transformer used in the manner indicated by Figure 6 can handle 0.1-microsecond pulses at a repetition rate as high as 3-megacycles without appreciable prf sensitivity. The principal disadvantage of the circuit of Figure 6 is the loss in amplitude across the forward resistance of the diode. The D359 diode has an exceptionally low forward resistance (about 30-ohm) and a high current carrying capacity (500 ma peak). If a transformer is used to drive a 90-ohm line and the forward resistance of the diode is 30-ohms there is a 25% loss in amplitude. If pulse amplitude is of prime importance, the voltage drop across the diode may not be tolerable; however, if a chain of high prf pulses are desired with very little prf sensitivity (in test equipment for example) the circuit of Figure 6 is very useful.

E. Multipoint-to-Multipoint Coupling

Multipoint-to-multipoint coupling is illustrated by Figure 7; multipoint-to-multipoint coupling is simlar to point-to-multipoint coupling except that the driving amplifiers have to be isolated from the line to prevent excessive attenuation. Each line driver must be capable of driving a line in two directions. The line drivers are isolated from the line when not in use by crystal diodes used in the manner indicated by Figure 5. The receiving amplifiers are coupled to the line in the manner indicated by Figure 4.

F. Conclusion

If a coupling transformer is designed to drive a load that behaves nearly like a pure resistance, the design procedures in report R-122 are directly applicable. The core material of the transformer is, of course, a very important factor to consider in design. A core material should be chosen that has the highest effective incremental permeability for the pulses the transformer is required to pass. It is costly to wind transformers on stacked cores and continuously-wound cores; for this reason Mu metal and Permalloys may not be chosen as core materials even though these materials may have a somewhat higher effective permeability than materials that are manufactured into two-pien cores. In any case, better pulse transformers can be designed for resistive loads if core materials with higher effective incremental permeabilities become available.

The design of transformers to drive capacitive loads is not readily apparent from report R-122, although the general concepts do apply. Actually, not too much thought has been given to the design of pulse transformers for capacitive loads. If the transformer driving a capacitive load is required to pass a trapezoidal pulse with fidelty, the transformer circuit will have to have a low Q, and the design of the transformer will be very similar to the design of transformers for resistive loads. Section 3.43 of R-122 discusses a wide-band transformer circuit that is useful for capacitive loads. In the point-to-point coupling for Whirlwind circuits pulse amplitude, pulse delay, and recovery time take precedence over pulse shape; these coupling circuits are essentially peaking circuits so that high Q's and high L/C ratios are desired.

With improved magnetic materials for high frequencies, it seems likely that better transformers can be designed for coupling circuits that are essentially peaking circuits.

Signed: CA Rowland
C. A. Rowland

Approved: NH Taylor
N. H. Taylor

CAR:sst

Drawings: A-35261
A-35262
A-35263
A-35264

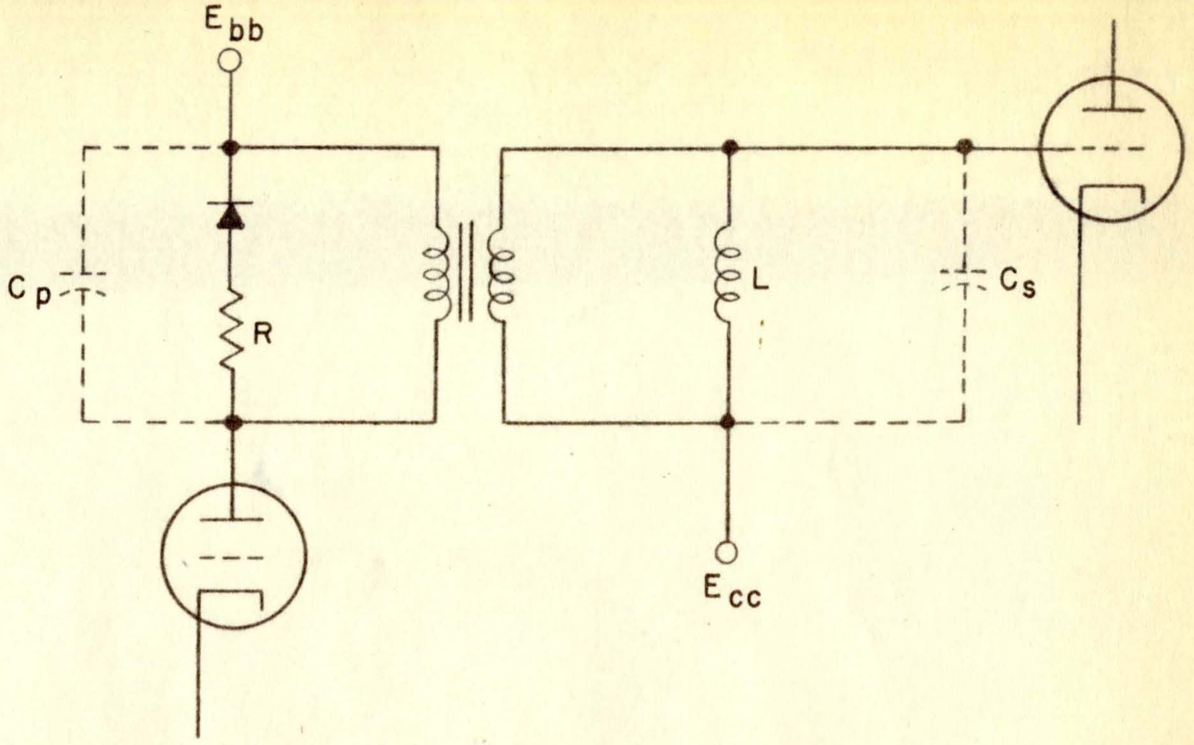

FIG. 1

COUPLING ARRANGEMENT BETWEEN ADJACENT STAGES.

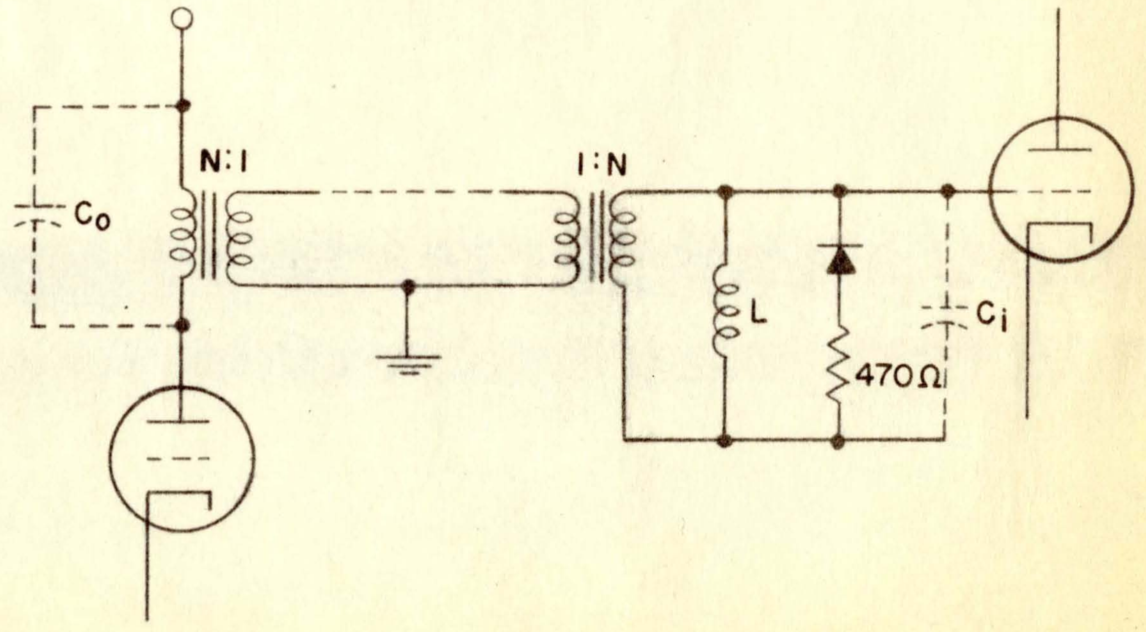

FIG. 2

COUPLING BETWEEN REMOTE STAGES

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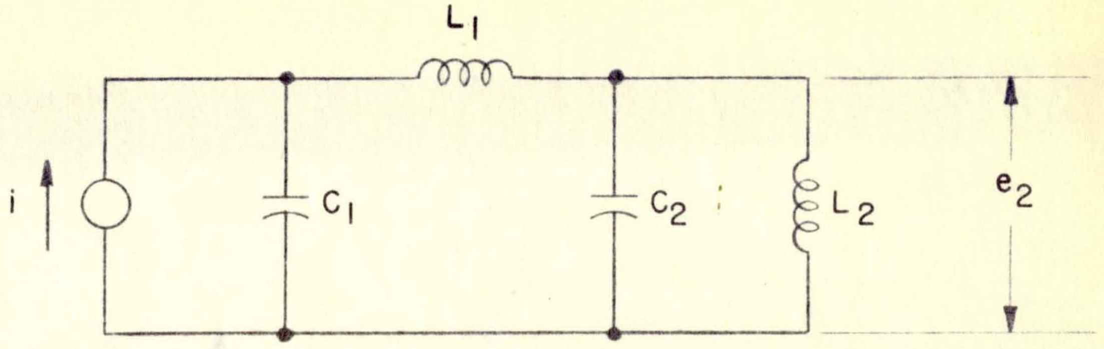

FIG. 3

SIMPLIFIED EQUIVALENT CIRCUIT FOR TRANSFORMER COUPLING

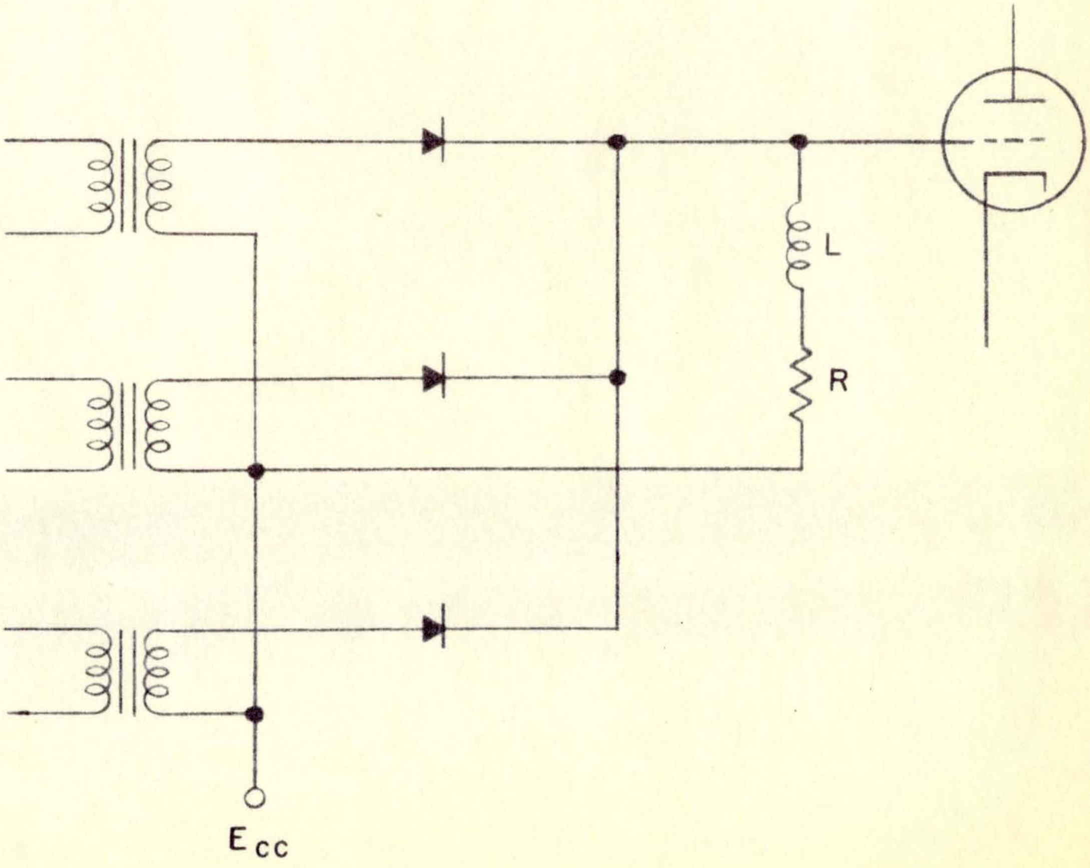

FIG. 4

MULTIPOINT TO POINT COUPLING

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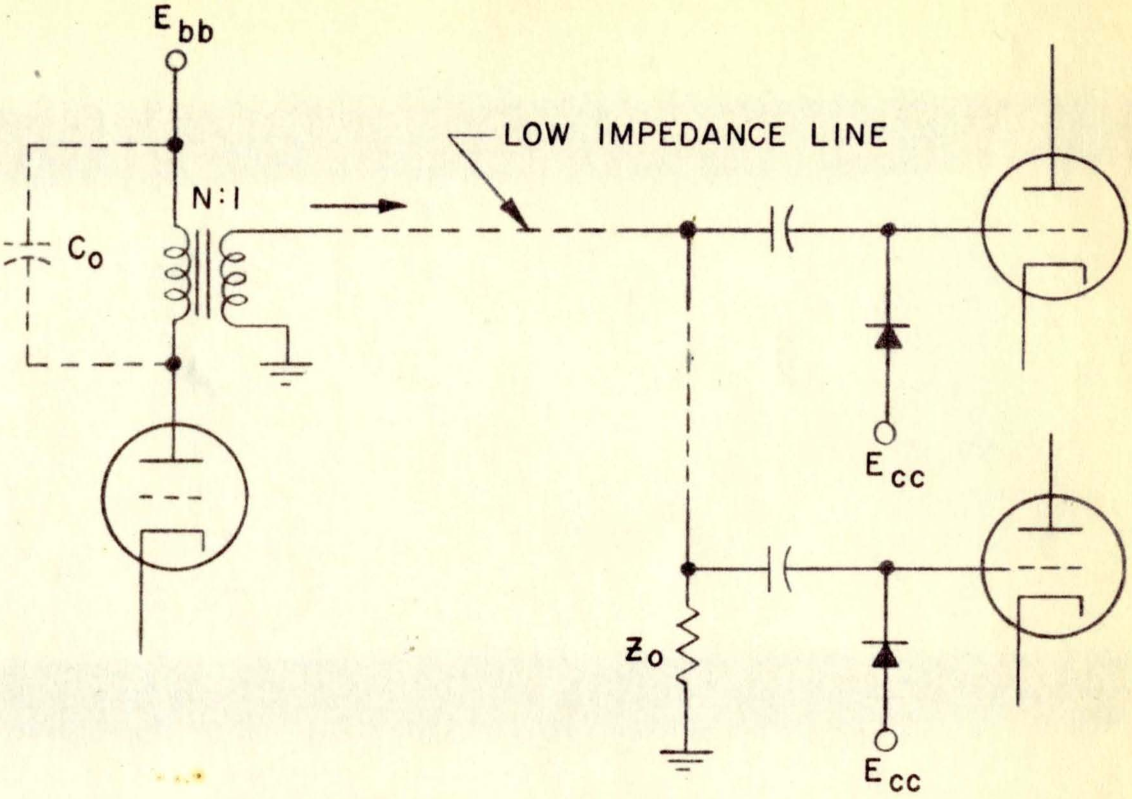

FIG. 5

POINT TO MULTIPOINT COUPLING

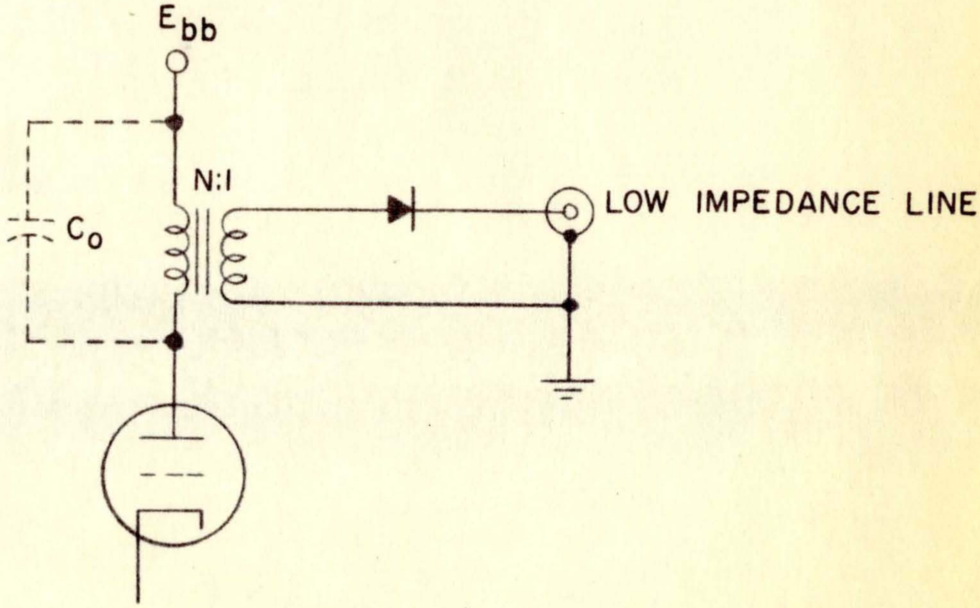

FIG. 6

THE USE OF AN ISOLATING DIODE FOR TRANSFORMER COUPLING

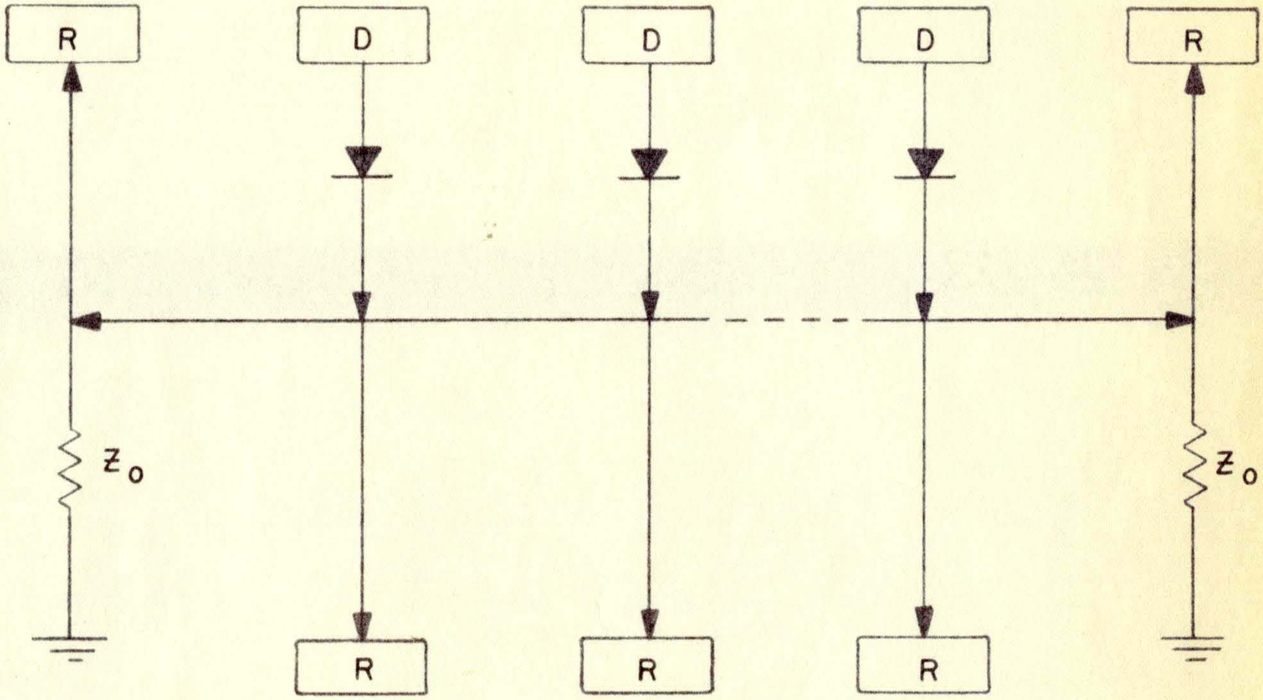

FIG. 7

MULTIPOINT TO MULTIPOINT COUPLING