

Dec. 17, 1946.

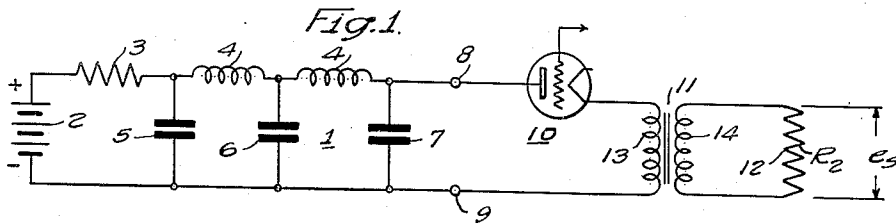
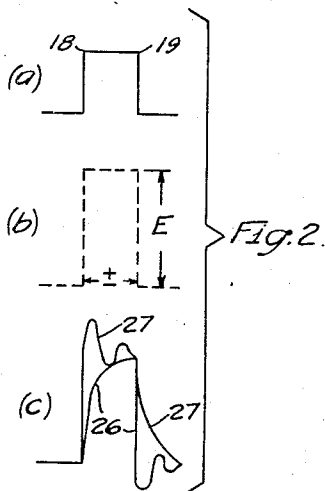
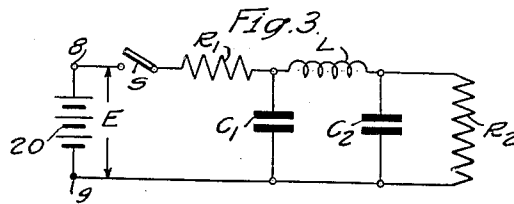
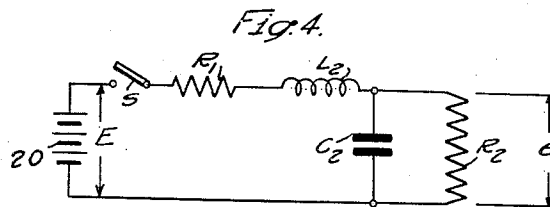
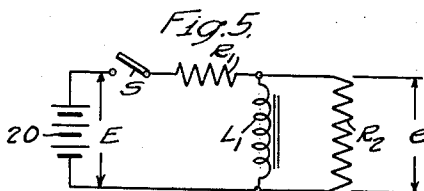
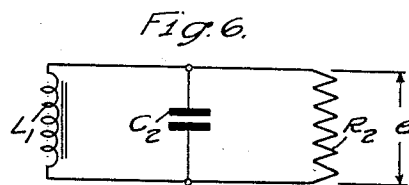
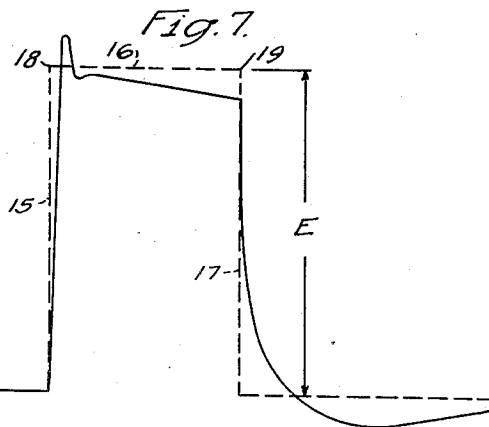
R. LEE

2,412,893

PULSE TRANSFORMER

Filed Oct. 21, 1943

3 Sheets-Sheet 1



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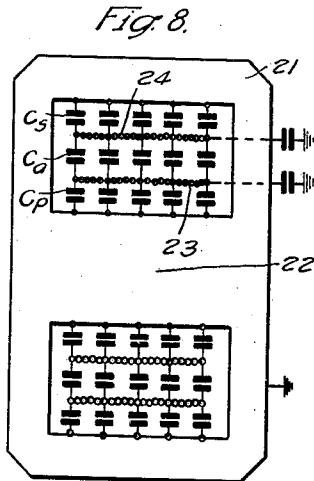
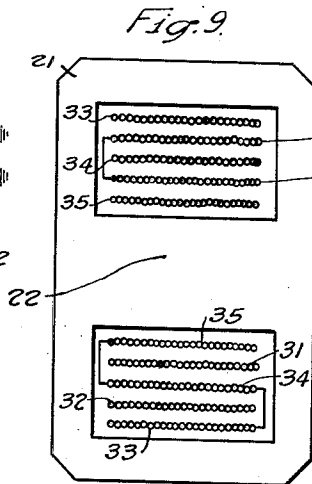
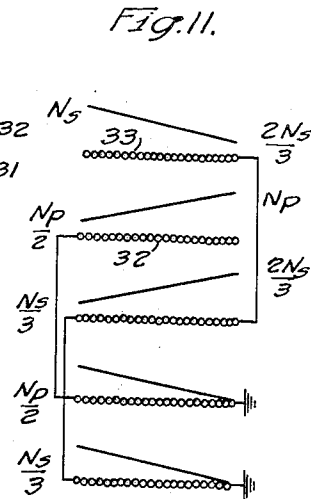
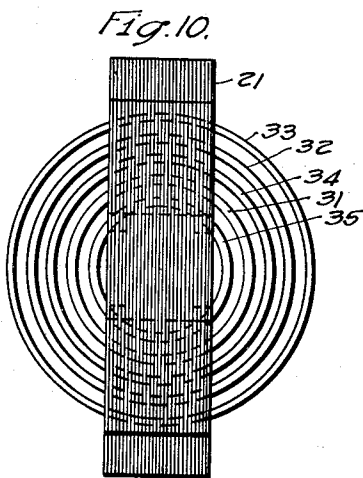
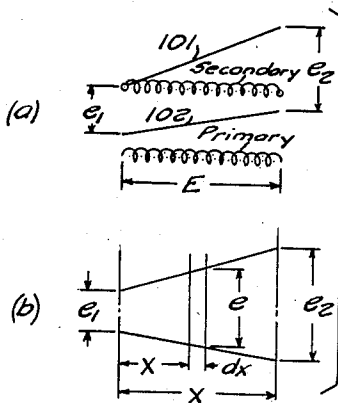
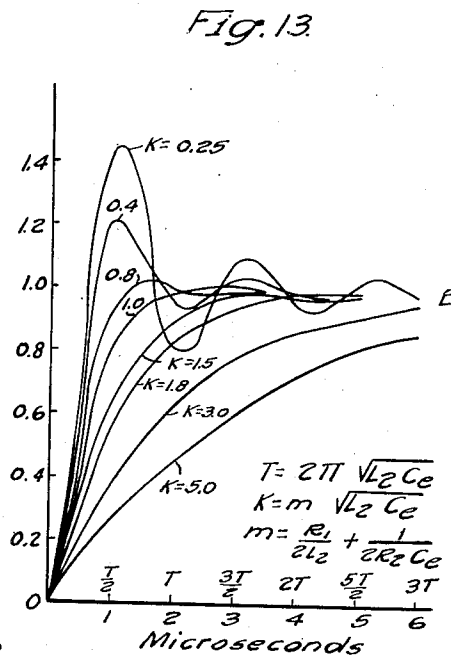
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PULSE TRANSFORMER

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3 Sheets-Sheet 2



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3 Sheets-Sheet 3

Fig. 15.

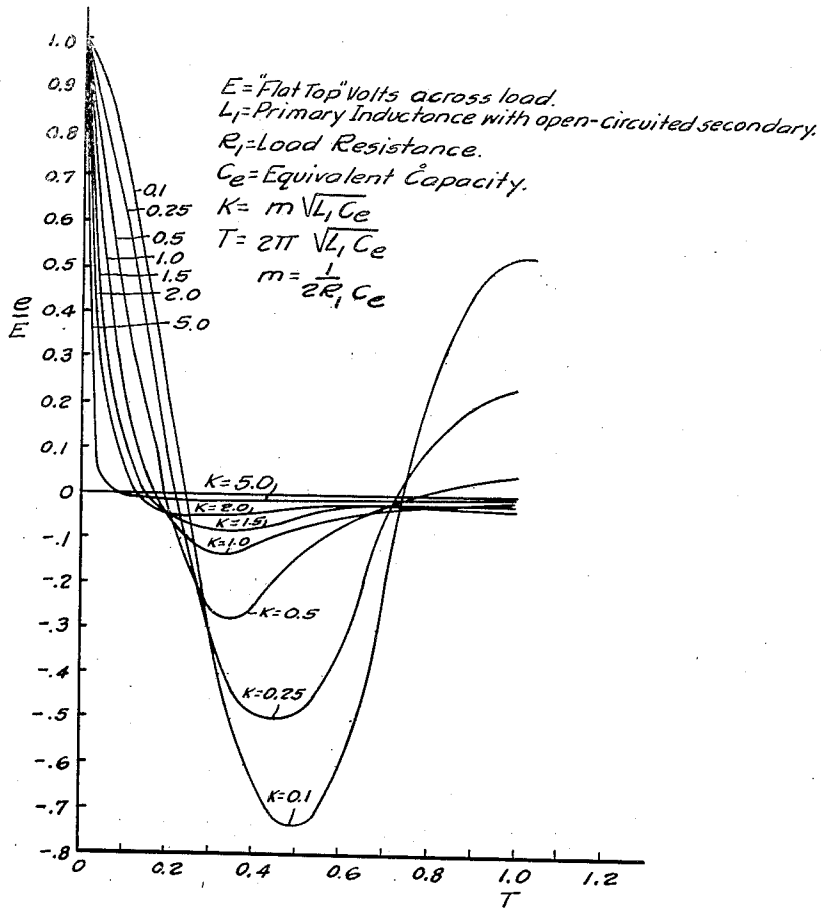
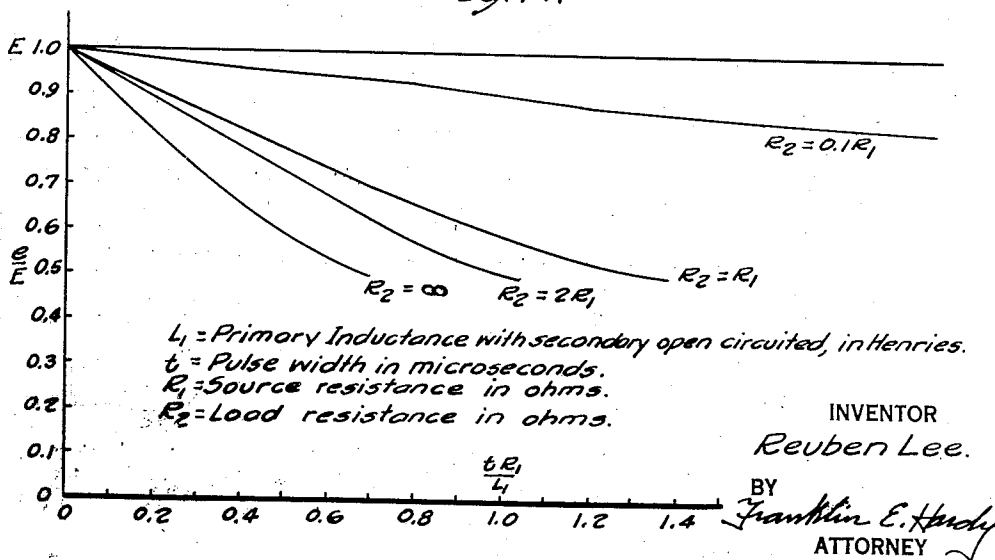


Fig. 14.



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2,412,893

PULSE TRANSFORMER

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Application October 21, 1943, Serial No. 507,120

4 Claims. (Cl. 178-44)

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My invention relates to pulse transformers, such as are used between a pulse generator and a load device to transform the voltage produced by the pulse generator to a higher or a lower output voltage than that of the pulse generator. The pulses produced by such generators are usually of short duration, that is, 1 to 15 microseconds, and may be rectangular in shape, or nearly so. It is desirable that the pulse wave shape applied to the load be as nearly as possible that of the generator supplying it. When a rectangular wave pulse is generated and a transformer is employed between the pulse generator and the load device supplied therefrom, there are certain distortions that may be introduced into the wave by the transformer such as a slanting of the vertical edges of the pulse wave or oscillations distorting the top of the pulse wave. Either form of distortion may render the pulse unsuitable for practical use.

It is an object of the invention to provide a pulse transformer in which the above-mentioned distortions of the wave form are minimized or substantially eliminated.

Other objects and advantages of the invention will be apparent from the following description of a preferred embodiment of the invention, reference being had to the accompanying drawings, in which:

Figure 1 is a diagrammatic view illustrating a pulse generator and transformer supplying a load;

Fig. 2 is a view illustrating forms of wave pulses;

Fig. 3 is a diagrammatic illustration of a circuit equivalent to the circuit of Fig. 2 relating circuit constants either to the primary or to the secondary circuit;

Figs. 4, 5, and 6 are equivalent circuits illustrating the circuit characteristics in parts which result in forming the front of the pulse, the top of the pulse, and the trailing edge of the pulse, respectively;

Fig. 7 illustrates the shape of a pulse wave delivered to a load from a pulse generator through a pulse transformer;

Fig. 8 is a view partly in section and partly shown diagrammatically illustrating the capacities between the several parts of the transformer structure;

Figs. 9 and 10 are side and end views, respectively, of a transformer core and coil assembly;

Figs. 11 and 12 are diagrammatic views illustrating voltage gradient along parts of the apparatus; and

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Figs. 13, 14 and 15 are views illustrating curves showing the relationship between certain electrical quantities corresponding to the equivalent circuits shown in Figs. 4, 5, and 6, respectively.

Referring to Fig. 1 of the drawings, a pulse generator 1 is illustrated comprising a source of electrical energy 2 connected to a circuit including the resistor 3 and inductances 4 and capacitors 5, 6, and 7 for delivering electric pulses through the terminals 8 and 9 of the pulse generator and a pulse transformer 11 to a load 12. The pulse transformer 11 comprises a primary winding 13 and a secondary winding 14 inductively related to each other. The tube 15 serves as a switch for controlling the circuit between the pulse generator 1 and the transformer 11 and is shown as a grid controlled electronic tube of well known character and is used in a well known manner to control the emission of electrical pulses from the pulse generator. The pulse generator 1 and the tube 10 for controlling it are conventional and are not a part of my invention but are illustrated for the purpose of showing the use of the pulse transformer 11 in the circuit in which it is employed.

Referring to Fig. 2 of the drawings, the full-line wave *a* is a rectangular wave pulse typical of that generated and supplied by the pulse generator 1 to the transformer 11 delivering the electric energy to the load. The dotted line wave *b* represents the wave form that it is desired to impress across the load and which is similar in form to the primary pulse *a* except differing in the voltage value thereof. The curves *c* show two forms of distortions that may be introduced into the transformer output wave by the transformer if its electrical characteristics are not properly designed. The curve 26 shows a slanting of the vertical edges of the pulse, and curve 27 shows oscillations distorting the top of the pulse. If the transformer windings have too much electrostatic capacity, the sides of the pulse will be sloped as in curve 26, and if the inductance of the windings is preponderant, oscillations may be developed as shown in curve 27 of Fig. 2.

Either form of wave distortion may render the pulse unsuitable for practical use. It has been commonly thought that a transformer capable of operation at frequencies several times that of

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pulse duration

55 would transform a pulse satisfactorily. This is

not, however, always true. It may be that such a transformer would have distortions of the character shown in curves *c* of Fig. 2.

In accordance with my invention, I have developed a transformer having characteristics necessary to minimize these irregularities and to prevent wave distortion in the pulse transformer.

With the open circuit inductance sufficiently high that it may be neglected, the transformer equivalent circuit which refers to either the primary or secondary side of the transformer can be represented in Fig. 3. This figure includes all elements of the circuit to the right of the terminals 8 and 9 in Fig. 1. If the transformer steps up the voltage, the primary capacitance C_1 can usually be neglected. If the transformer steps down the voltage, the secondary capacitance C_2 can usually be neglected. The transformer iron loss is combined with R_2 and in some cases may constitute the whole load.

In the circuit of Fig. 3 and in the following discussion, the following symbols are used:

L_1 =primary inductance with secondary open-circuit in henries

L_2 =primary inductance with secondary short-circuited, in henries

C_1 =primary capacitance in farads

C_2 =secondary capacitance $\times \left(\frac{N_s}{N_p}\right)^2$ in farads

N_p =primary turns

N_s =secondary turns

R_1 =resistance in source in ohms

R_2 =resistance in load $\times \left(\frac{N_p}{N_s}\right)^2$ in ohms

In all transformers, L_1 should be large enough so that a comparatively small fraction of the total pulse current is required to maintain a pulse voltage

$$e = L_1 \frac{di}{dt}$$

constant, or nearly so, throughout the pulse duration.

Step-up transformers should be designed so that

$$A = \frac{k}{\sqrt{L_2 C_2}} \frac{(R_1 + R_2)}{R_2}$$

where

$$A = \frac{2R_1}{L_2} + \frac{2}{R_2 C_2}$$

and $k=0.2$ to 5.0 .

If

$$\frac{R_2}{L_2} \gg \frac{1}{R_2 C_2}$$

and $R_2 \gg R_1$, this reduces to:

$$R_1 = 2k \sqrt{\frac{L_2}{C_2}}$$

Step-down transformers should be designed so that

$$A = \frac{k}{\sqrt{L_2 C_1}} \frac{R_1 + R_2}{R_1}$$

where

$$A = \frac{2R_1}{L_2} + \frac{2}{R_2 C_1}$$

and $k=0.2$ to 5.0 .

If $\frac{R_1}{L_2} \gg \frac{1}{R_2 C_1}$ } this reduces to: $R_2 = 2k \sqrt{\frac{L_2}{C_1}}$
and $R_1 \gg R_2$

1:1 ratio transformers should be designed so that

$$A = \frac{k}{\sqrt{L_2 (C_1 + C_2)}}$$

where

$$A = \frac{2(R_2 + R_1)}{R_1 R_2 (C_1 + C_2)} + \frac{2(R_1 C_1 + R_2 C_2)}{R_1 R_2 C_1 C_2}$$

If $R_1 \gg R_2$ and $C_1 = C_2$, this reduces to

$$R_2 = \frac{3}{4k} \sqrt{\frac{2L_2}{C_2}}$$

If $R_2 \gg R_1$ and $C_1 = C_2$, this reduces to

$$R_1 = \frac{3}{4k} \sqrt{\frac{2L_2}{C_1}}$$

$k=0.2$ to 5.0 in this also.

The criteria here given are for a rectangular or flat topped pulse impressed upon the transformer from some source. Such a pulse is shown in Fig. 7, and a generalized circuit for the amplifier is shown in Fig. 1. So far as the transformer action is concerned, the equivalent circuit for such an amplifier is given in Fig. 3. A voltage is impressed across the terminals 8 and 9 of the load circuit through the switch *S* to the circuit having the electrical characteristics shown. This is the circuit which applies to the front edge 15 of the pulse which is shown in Fig. 7 as rising abruptly from zero value to some steady value *E*. The dotted line in Fig. 7 shows the impressed or original pulse and the solid line the impulse wave delivered to the load. This change is such that the transformer open-circuit inductance can be considered as presenting practically infinite impedance to such a change, and is omitted in the circuit of Fig. 3. On the other hand, the transformer leakage inductance is of appreciable influence and is shown as inductance *L* in Fig. 3. The resistor R_1 of Fig. 3 represents the source impedance; the transformer winding resistances are generally negligible compared to the source impedance. The transformer winding capacitances are shown as C_1 and C_2 for the primary and secondary windings, respectively. The transformer load resistance, or the load resistance into which the amplifier works, is shown as R_2 . All these values are referred to one side or the other of the transformer; that is to say, the load resistance R_2 , the leakage inductance *L*, and secondary capacitance C_2 are multiplied or divided by a factor which is the square of the transformer turns-ratio N_p/N_s in order to treat these quantities as if they actually existed on the primary side. If it were more convenient to treat the transformer completely on the secondary side, then the quantities R_1 , C_1 and *L* would be multiplied by a reciprocal factor. Since there are two capacity terms C_1 and C_2 , it follows that for any considerable deviation of the transformer turns-ratio from unity, one or the other of these capacitances will become preponderant. Turns-ratio and therefore voltage-ratio affect these capacitances in such a way that for a step-up transformer, C_1 may be neglected and for a step-down transformer, C_2 may be neglected. The discussion here will be confined to the step-up case, although the step-down and the 1 to 1 ratio cases are not markedly different.

The step-up transformer is illustrated by Fig. 4. When the front of the wave, Fig. 2(a), is suddenly impressed on the transformer, it will be simulated by the closing of switch *S*. At this initial instance, the voltage *e* across R_2 is zero,

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and the current entering from the battery 29 is also zero. This furnishes us with two initial conditions to be used in the derivation of a formula which expresses the rate of rise of voltage e from its initial value of zero to its final steady value of E times the ratio R_2 divided by R_1 plus R_2 . It is apparent from this that the smaller R_1 is made, the more efficient will the amplifier be. The curves in Fig. 13 show the rate of rise of the transformed wave pulse for an amplifier where R_1 is negligibly small. However, if the value E for the top of the pulse is multiplied by the ratio

$$\frac{R_2}{R_1 + R_2}$$

the curves are reasonably accurate.

The scale of abscissae for these curves is not time but percentage of the time constant T of the transformer. The equation for this time constant is given on the curve, and is in turn a function of the leakage inductance and the capacitance C_2 . The rate of voltage rise is governed to a marked extent by another factor k which is the ratio of the decrement to the angular velocity for an oscillatory circuit, but retains the same form even when the circuit is not oscillatory. The relation of this factor k and the various constants of the transformer is given directly on the curve. Other things remaining equal, the greater the transformer leakage inductance and distributed capacity, the slower is the rate of rise, although the effect of the two resistances R_1 and R_2 is also of considerable importance as they affect the factor k . It will be noted that if a slight amount of oscillation can be tolerated, the wave rises up much faster than if no oscillations are present, and if the circuit is far removed from the oscillatory conditions, the rise is indeed very slow. On the other hand, if the circuit is damped very little, the oscillation may reach a maximum initial value of two times the steady state voltage E and often such marked peaks would be objectionable. The values for k given on the curve appear to be those which fall within the most practicable range.

Once the pulse top is reached, the value E is dependent upon the transformer open-circuit inductance for its maintenance at this value. If the pulse stayed on indefinitely at the value E , it would require an infinite inductance to maintain it so, and of course this is not practical. There is, therefore, always a drooping tendency to the top of such a pulse. The equivalent circuit during this time is shown in Fig. 5. Here the inductance L is the open circuit inductance of the transformer, and R_1 and R_2 remain the same as before. Since the rate of voltage change is relatively small during this period, the capacitances C_1 and C_2 disappear from the picture. Also, since the leakage inductance is usually small compared to the open-circuit inductance, it is neglected here. When the switch S is first closed, the voltage e across R_2 is assumed to be at the steady value E , which is strictly true only when R_1 is negligibly small. Therefore, the curves for the top of the wave, Fig. 14, need to be corrected the same as those for the front of the wave, in that e should be multiplied by the ratio R_2 divided by $R_1 + R_2$. Several curves are given, representing several types of pulse amplifiers ranging from a pentode where R_2 is $\frac{1}{10}$ of R_1 , where the source resistance is very high, to an amplifier whose load resistance is infinite or

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whose output power is zero. In the case of the latter curve, the value e need not be multiplied by any ratio of resistances; its final value is the same as that of the battery. All the curves are exponential, having a common point at 0, 1. Again the abscissae are not time, but are the product of time and ratio

$$\frac{R_1}{L}$$

the time in this case being the duration of the pulse between points 18 and 19 in Figs. 2(a) and 7. Obviously, the greater the inductance L , the less deviation from a flat top pulse there is in traversing this amount of time.

At time instant 19 in Fig. 7, we will assume that the switch S in Fig. 5 to be suddenly opened. The circuit now reverts to that of Fig. 6, in which L is in the open circuit inductance, but C_2 , the secondary capacitance, is again present to an appreciable extent. It will be assumed that the current through L has not increased to an appreciable amount, and therefore the flat top wave was practically unimpaired at instant 19; but if this is true, it is the same as saying that there is no initial current in the inductance L , so when switch S is open condenser C_2 supplies all the load current momentarily to R_2 . This is the basis upon which the curves in Fig. 15 are drawn. The abscissae of these curves are plotted again in percentage of the transformer time constant but the time constant is now determined by the open-circuit inductance L with capacity C_2 rather than by leakage inductance and capacity C_2 as was the case on the curves in Fig. 13. The constant k on these curves is again the product of decrement and $\sqrt{L C_2}$, but the decrement has a different meaning as indicated on the curve. Lest it be assumed that the time constant is so great in this case that it precludes satisfactory performance, attention is drawn to the fact that higher open-circuit inductance L_1 results in higher values of k , and the curves with higher values of k drop much more rapidly than do the smaller values, but only with reference to the time constant T . This does not mean that such a wave will drop more rapidly in time, but only with reference to the time constant which is determined by open-circuit inductance and capacitance. It does mean, however, that the slope of the trailing edge can be kept within tolerable limits, provided the capacitance of the transformer can be kept small enough. The accurate predetermination of this capacitance is therefore of first importance.

By means of the three sets of curves we can now construct the pulse shape delivered to load R_2 . Suppose a transformer with the following measured constants be required to deliver a flat top pulse of 15 microseconds duration,

L_2 leakage inductance (secondary short-circuited) -----	1.89×10^{-4} H
L_1 primary open-circuit inductance -----	0.1 H
Primary/secondary turns ratio N_p/N_s -----	1:3
R_1 source resistance -----	ohms-- 800
R_2 load resistance (primary equivalent) -----	ohms-- 5000
C_2 capacitance -----	mmfd-- 388

From the expressions given in Fig. 13, we find

$$m = 2.38 \times 10^6$$

$$T = 1.7 \text{ microsecond}$$

$$k = 0.65$$

The front of the wave will follow a curve between those marked $k=0.4$ and $k=0.8$ in Fig. 13.

The value E will be reached in 0.5T or 0.85 microsecond, and a peak of about 10% occurs in 1 microsecond.

The top of the wave will slope down to a value determined by the product

$$\frac{tR_1}{L} = 0.12$$

and by a curve between those for $R_2 = \infty$ and $R_2 = 2R_1$ in Fig. 14. The value is evidently 0.91E.

The trailing edge is given by the curves in Fig. 15. Here

$$\begin{aligned} m &= .258 \times 10^6 \\ T &= 39.1 \times 10^{-6} \\ k &= 1.6 \end{aligned}$$

so that the load voltage reaches zero in 0.115T or 4.5 microseconds. There is a slight negative loop of 7% at 0.3T or 11.7 microseconds beyond the pulse edge 17.

The pulse delivered to load R_2 as shown in Fig. 7 is a combination of these three curves.

The primary leakage inductance used is the inductance measured on the primary terminals of the transformer when the secondary terminals are connected together, and this is a measurable inductance.

The equivalent capacitance is not directly measurable but can be evaluated from measurable capacitance. A capacitance, across which a uniformly tapered voltage exists, may be given an effective value in terms of a fixed voltage E . Referring to the sketch shown in Fig. 12 in which the voltage gradients between the primary and secondary windings are shown by the sloping lines 101 and 102, the minimum voltage difference between the two windings is shown at one end as e_1 , and the maximum voltage difference being shown at the other end as e_2 with the gradients between the opposite ends of the windings progressing linearly between these two values. If the primary voltage is represented by E , it can be shown that the equivalent capacitance referred to the primary side of the transformer is

$$C_e = \frac{C_M}{3E^2} (e_1^2 + e_2^2 + e_1 e_2)$$

where C_M is the measured capacity between the two windings.

The capacitance between the primary winding and the core and between the secondary winding and the core should be included after evaluation of these quantities in terms of their respective voltage gradients.

If it were desired to refer this capacitance to the secondary winding, the secondary voltage should be used in place of the primary voltage E in the above formula.

Also there are normally differences in the number of coil turns in the primary and secondary. Call these Δn_1 and Δn_2 . Then the formula can be written

$$C_e = \frac{C_M}{3Np^2} (\Delta n_1^2 + \Delta n_2^2 + \Delta n_1 \Delta n_2)$$

where Np is the number of turns in the primary winding.

If the voltage between the left ends of the two windings is zero, the above formula is reduced to

$$C_e = \frac{C_M e_2^2}{3E^2} \text{ or } C_e = \frac{C_M \Delta n_2^2}{3Np^2}$$

The capacitances C_1 and C_2 must, as pointed out above, be evaluated in terms of voltage gradients in the windings. That is, the values C_1 and C_2 are not the ordinary measurable ca-

capacity between the primary winding and core, or between the secondary winding and core or between the primary and secondary windings, but usually exceed these values if the transformers are step-up transformers, and are less than these values if the transformers are step-down transformers. In any transformer, regardless of turns-ratio, these values must be taken in terms of voltage gradient.

For example, in the transformer whose cross-section is shown in Fig. 8, a core 21 is provided having a winding leg 22 about which the primary turns 23 and secondary turns 24 are each wound each in a single layer concentrically. It will be assumed that they are wound in the same rotational direction, and in the same traverse direction (right to left). It will further be assumed that the right ends of both windings are connected to ground (or core) through large capacitances, as shown dotted, so that the right ends are at substantially the same alternating-current potential. Capacitance C_1 is composed of many small incremental capacitances C_p and C_2 of many small incremental capacitances C_s each of which has a different voltage across it. Likewise, there exist many small incremental capacitances C_a between primary and secondary which have different potentials across them. If the transformer is step-up,

$$C_1 = \frac{1}{2} \Sigma C_p \text{ and } C_2 = \frac{1}{2} \left[\Sigma C_s + \left(\frac{N_s - N_p}{N_p} \right)^2 \Sigma C_a \right]$$

If the transformer is step down

$$C_1 = \frac{1}{2} \left[\Sigma C_p + \left(\frac{N_p - N_s}{N_p} \right)^2 \Sigma C_a \right]$$

and $C_2 = \frac{1}{2} [\Sigma C_s]$

If the ratio is 1:1, $C_1 = \frac{1}{2} [\Sigma C_p + \frac{1}{2} \Sigma C_a]$ and $C_2 = \frac{1}{2} [\Sigma C_s]$

For transformers with opposite angular rotations of primary and secondary windings, or with opposite traverse directions (but not both), the factors

$$\left(\frac{N_p - N_s}{N_p} \right)^2 \text{ and } \left(\frac{N_s - N_p}{N_p} \right)^2$$

in the foregoing equations become

$$\left(\frac{N_p + N_s}{N_p} \right)^2$$

there is no other change. For transformers with both angular rotations and traverse directions opposite there is no change at all in these equations. If there is a shield between primary and secondary, omit terms containing C_a in these equations, and make ΣC_s and ΣC_p include the capacity of secondary and primary to shield, respectively. Note that ΣC_s is the measurable capacity of the short-circuited secondary to ground (or core), and ΣC_p the measurable capacity of the short-circuited primary to ground (or core).

For more interleaving of primary and secondary windings, more elaborate evaluation of capacitance is necessary. This will be illustrated below by the description of an actual transformer.

As shown in Fig. 9, the primary is wound in two layers 31 and 32, interleaved between three secondary layers 33, 34 and 35. This interleaving is done to reduce leakage inductance. The transformer is used to couple an electronic tube to a pair of cathode-ray tube plates. The plates are an open circuit; hence R_2 would be infinite, but the transformer has sufficient iron and dielectric

loss to give R_2 a finite value. The measurable constants are:

$$\begin{aligned} N_p &= 112 \text{ turns (56 per layer)} \\ N_s &= 360 \text{ turns (120 per layer)} \\ R_1 &= 800 \text{ ohms} \\ R_2 &= 5000 \text{ ohms} \end{aligned}$$

The capacity from secondary to core is 100 mmfd. The capacitance (average) between primary and secondary layers is 46 mmfd. All windings are wound in the same direction of rotation, but the directions of traverse are:

Secondary			Primary	
1st section	2nd section	3rd section	1st section	2nd section
Left to rt.	Rt. to left	Left to rt.	Left to rt.	Rt. to left

Designate these winding sections, in the order above, as S_1 , S_2 , S_3 , P_1 , P_2 . The voltage gradients along these windings are as shown in Fig. 11, except that turns are used instead of volts. This is permissible since

$$\frac{ep}{es} = \frac{Np}{Ns}$$

In the space	Turn gradient is—
S_1 -core	0 to $\frac{Ns}{3}$
S_1 - P_1	0 to $\frac{Ns}{3} - \frac{Np}{2}$
P_1 - S_2	$\frac{Ns}{3} - \frac{Np}{2}$ to $\frac{2Ns}{3}$
S_2 - P_2	$\frac{Ns}{3} - \frac{Np}{2}$ to $\frac{2Ns}{3} - Np$
P_2 - S_3	$\frac{2Ns}{3} - Np$ to $Ns - \frac{Np}{2}$
S_3 -core	$\frac{2Ns}{3}$ to Ns

The transformer is so constructed that there is 10.3 mmfd. from S_3 to core. The secondary-to-core capacitance is mostly S_1 to core. The primary effective value of this capacitance is

$$\frac{\Sigma C_s}{3Np^2} \times \left(\frac{Ns}{3}\right)^2$$

Putting the numerical values Ns and Np in this expression from the above table we have

$$\frac{(100 - 10.3) \times (120)^2}{3 \times 112^2} = 38 \text{ mmfd.}$$

for the effective value when referred to the primary. For the inter-winding spaces we can use the equation

$$C_e = \frac{Ca}{3Np^2} (\Delta n_1^2 + \Delta n_2^2 + \Delta n_1 \Delta n_2)$$

Thus, we get for S_1 - P_1 , $\Delta n_1 = 0$

$$\Delta n_2 = \frac{Ns}{3} - \frac{Np}{2} = 120 - 56 = 64 \text{ turns}$$

$$C_e = \frac{46 \times (64)^2}{3 \times (112)^2} = 5.0 \text{ mmfd.}$$

for

$$P_1$$
- S_2 , $\Delta n_1 = 64$

$$\Delta n_2 = \frac{2Ns}{3} = 240$$

$$C_s = \frac{46}{3 \times (112)^2} [(64)^2 + 240^2 + 64 \times 240] = 84 \text{ mmfd.}$$

for

$$S_2$$
- P_2 , $\Delta n_1 = 64$

$$\Delta n_2 = \frac{2Ns}{3} - N = 240 - 112 = 128$$

$$C_e = \frac{46}{3 \times (112)^2} [(64)^2 + (128)^2 + 64 \times 128] = 35 \text{ mmfd.}$$

for

$$P_2$$
- S_3 , $\Delta n_1 = 128$

$$\Delta n_2 = Ns - \frac{Np}{2} = 360 - 56 = 304$$

$C_e =$

$$\frac{46}{3 \times (112)^2} [(128)^2 + (304)^2 + 128 \times 304] = 178 \text{ mmfd.}$$

for

$$S_3$$
-core $\Delta n_1 = \frac{2Ns}{3} = 240$

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$$\Delta n_2 = Ns = 360$$

$$C_e = \frac{10.3}{3 \times (112)^2} [(360)^2 + (240)^2 + 240 \times 360] = 75 \text{ mmfd.}$$

Thus, because of the high voltage across it, the small S_3 -core capacity becomes appreciable.

Since the secondary winding intervenes between any primary winding section and the core, $C_1 = 0$. C_2 is the sum of all the layers C_e 's plus C_e of S_1 -core. It has already been referred to the primary side in the above calculations, and hence the multiplier

$$\left(\frac{Ns}{Np}\right)^2$$

40 is unnecessary.

Hence, $C_2 = 75 + 38 + 5 + 84 + 35 + 178 = 415$ mmfd. Adding another 25 mmfd., for tube, load and incidental capacity, $C_2 = 440$ mmfd. If it had been referred to the whole secondary winding, this value would have been

$$440 \times \left(\frac{112^2}{360}\right) = 42 \text{ mmfd.}$$

The measured value of capacity from secondary to primary and core is 240 mmfd. Contrast this value with 42 mmfd., and the importance of the above calculations becomes apparent.

It will be apparent from the above description that modifications in the arrangement of the parts illustrated may be made within the spirit of my invention, and I do not wish to be limited otherwise than by the scope of the appended claims.

I claim as my invention:

1. In a system for transforming substantially rectangular voltage wave pulses with substantially no wave distortion, a transformer having primary and secondary windings connected respectively to a source of electric energy and to a load circuit in which the relation between R_1 (the resistance of the primary circuit in ohms), L_2 (the primary leakage inductance in henries) and C_e (the equivalent capacity of the transformer in terms of primary voltage in farads) are related by the following equation:

$$R_1 = 2k \sqrt{\frac{L_2}{C_e}}$$

where k is a value between 0.2 and 1.5.

2. In a system for transforming substantially

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rectangular voltage wave pulses with substantially no wave distortion, a transformer having primary and secondary windings connected respectively to a source of electric energy and to a load circuit in which the relation between R_2 (the resistance of the secondary circuit in ohms), L_s (the secondary leakage inductance in henries), and C_e (the capacity of the transformer in terms of secondary voltage in farads) are related by the following equation:

$$R_2 = 2k \sqrt{\frac{L_s}{C_e}}$$

where k is a value between 0.2 and 1.5.

3. In a system for transforming substantially rectangular voltage wave pulses with substantially no wave distortion, a transformer having inductively related primary and secondary windings connected respectively to a source of electric energy and to a load circuit and having a greater number of secondary winding turns than primary winding turns so that the secondary winding will deliver a greater voltage than that impressed on the primary winding and in which the relation between R_1 (the resistance of the primary circuit in ohms), L_2 (the primary inductance with the secondary short-circuited, in henries), and C_e (the equivalent secondary capacity of the transformer in terms of

$$\text{secondary voltage} \times \left(\frac{N_s}{N_p}\right)^2$$

in farads where N_p is the number of primary

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winding turns and N_s is the number of secondary winding turns) are related by the following equation:

$$R_1 = 2k \sqrt{\frac{L_2}{C_e}}$$

where k is a value between 0.2 and 1.5.

4. In a system for transforming substantially rectangular voltage wave pulses with substantially no wave distortion, a transformer having inductively related windings connected respectively to a source of electric energy and to a load circuit and having a fewer number of secondary winding turns than primary winding turns so that the secondary winding will deliver a lesser voltage than that impressed on the primary winding and in which the relation between R_2 (the resistance of the

$$\text{load circuit} \times \left(\frac{N_p}{N_s}\right)^2$$

in ohms), L_2 (the primary inductance with the secondary short circuited, in henries), and C_1 (the primary capacity in farads) are related by the following equation:

$$R_2 = 2k \sqrt{\frac{L_2}{C_1}}$$

where k is a value between 0.2 and 1.5.

REUBEN LEE.