

May 13, 1947.

S. DARLINGTON

2,420,302

IMPULSE GENERATOR

Filed Aug. 19, 1943

3 Sheets-Sheet 1

FIG. 1

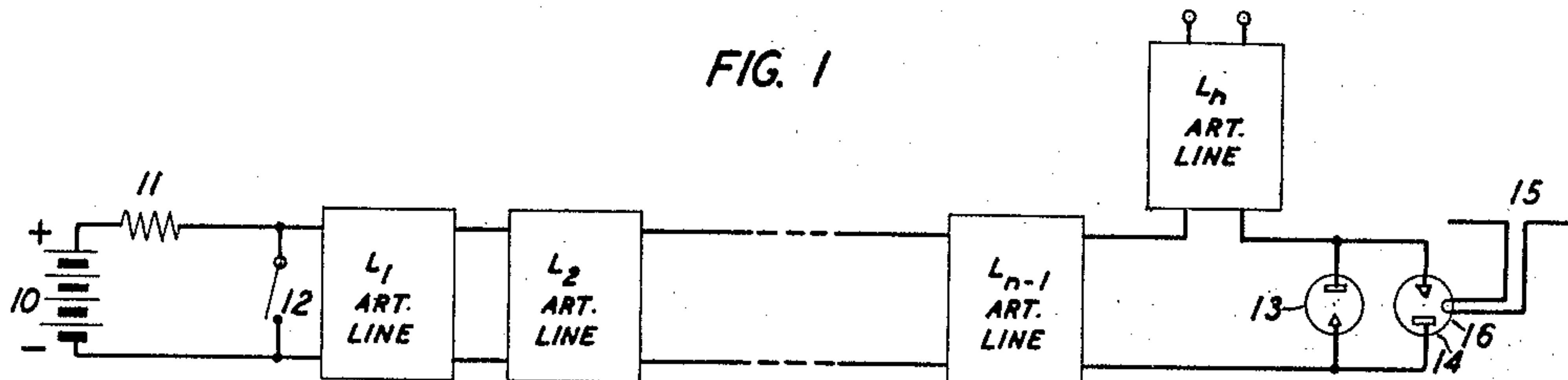


FIG. 3

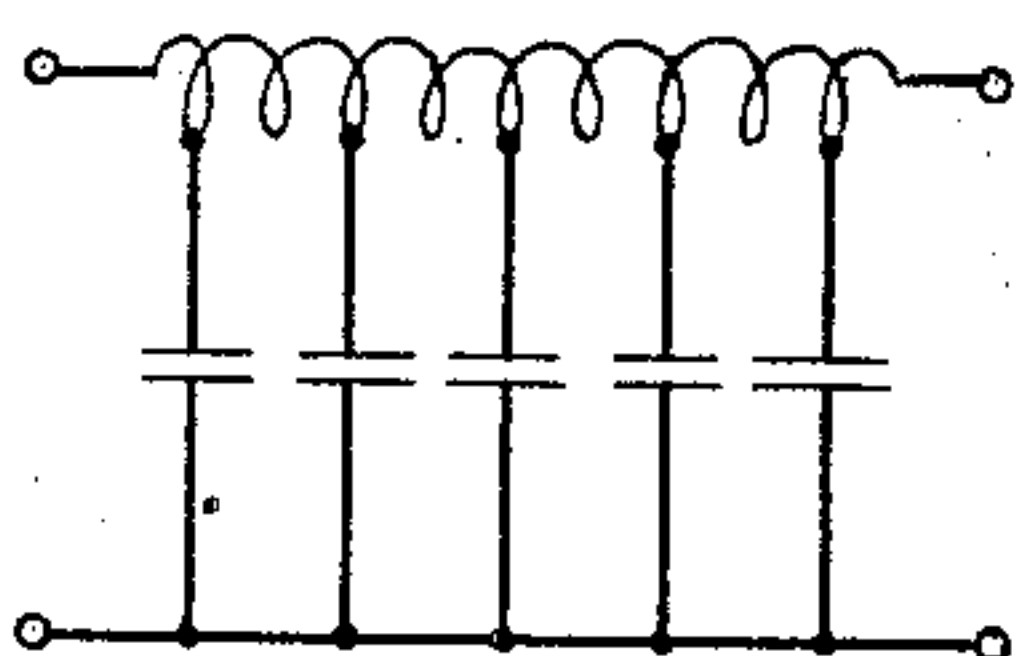


FIG. 2

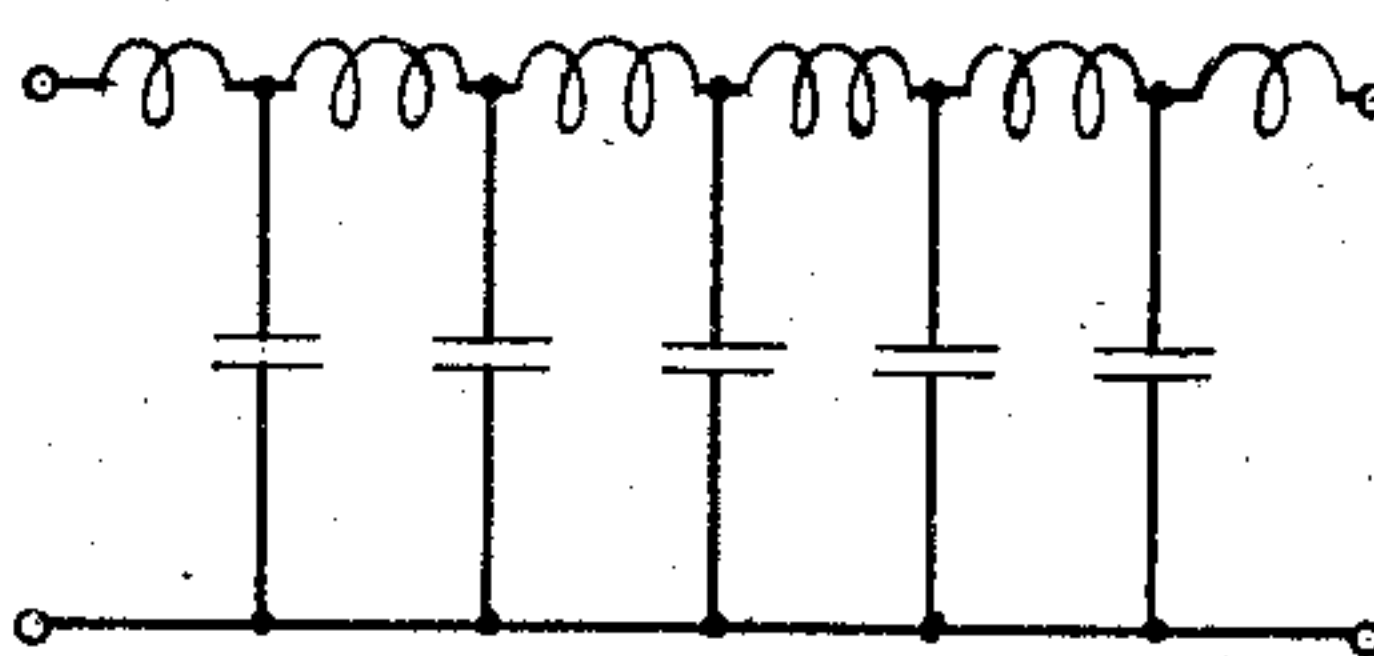


FIG. 4

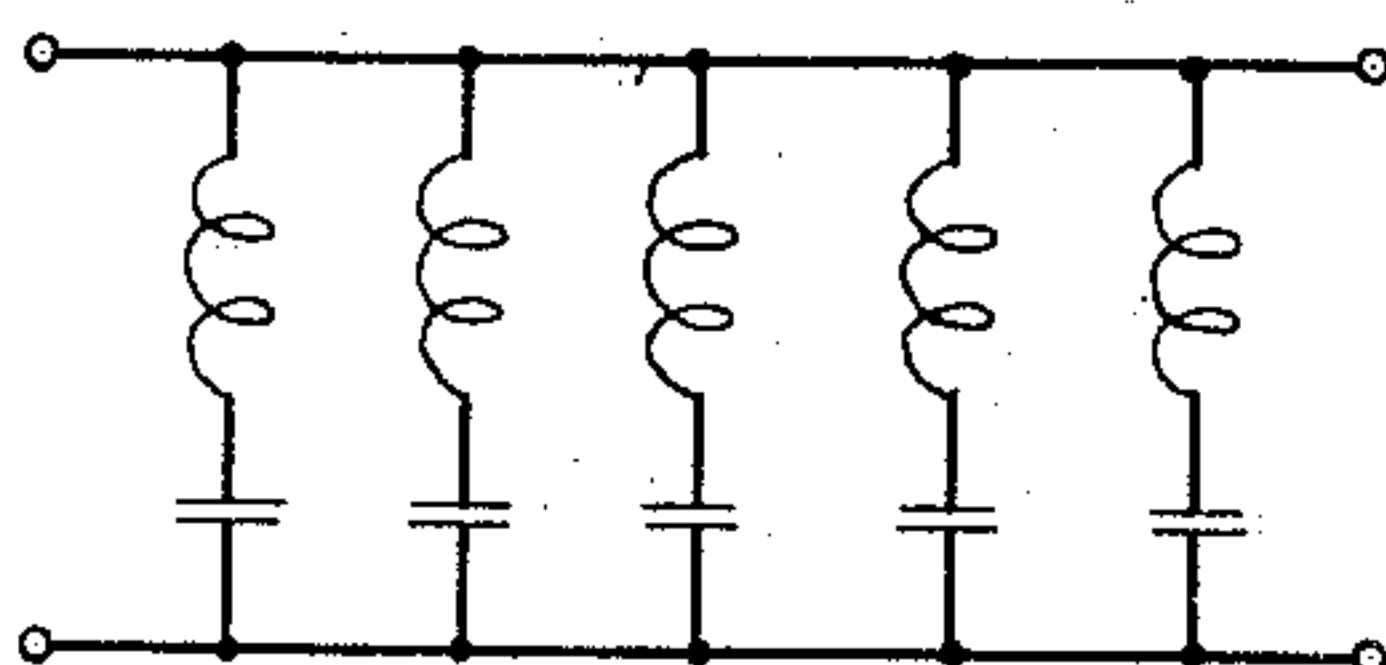


FIG. 5

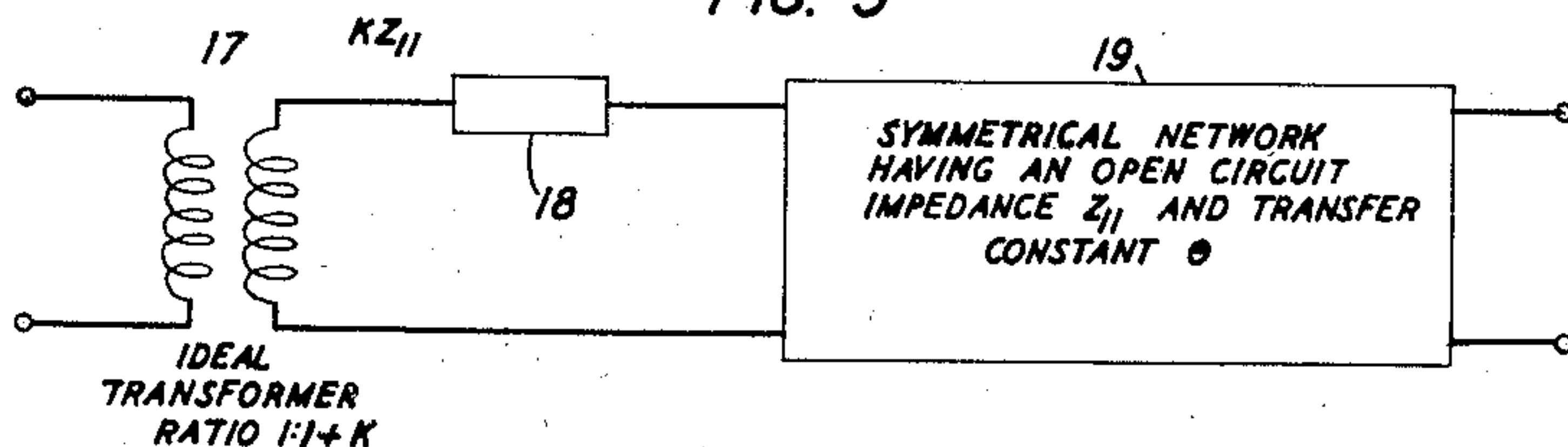
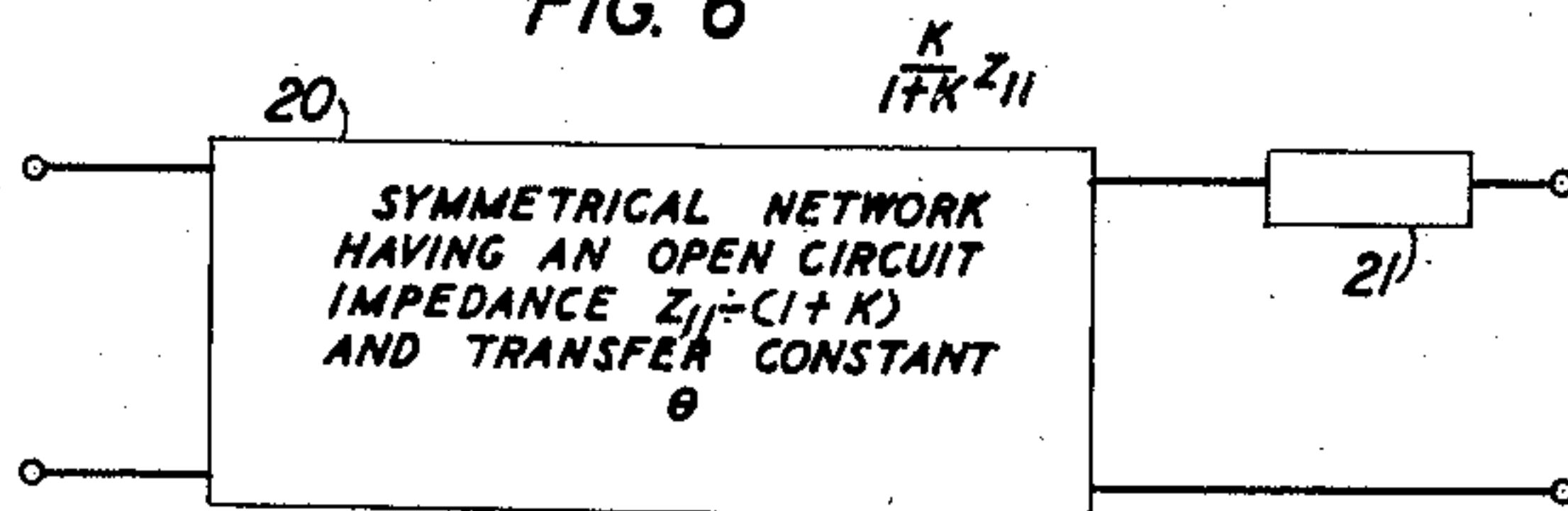


FIG. 6



INVENTOR
S. DARLINGTON
BY *G. H. Stevenson*
ATTORNEY

May 13, 1947.

S. DARLINGTON

2,420,302

IMPULSE GENERATOR

Filed Aug. 19, 1943

3 Sheets-Sheet 2

FIG. 7

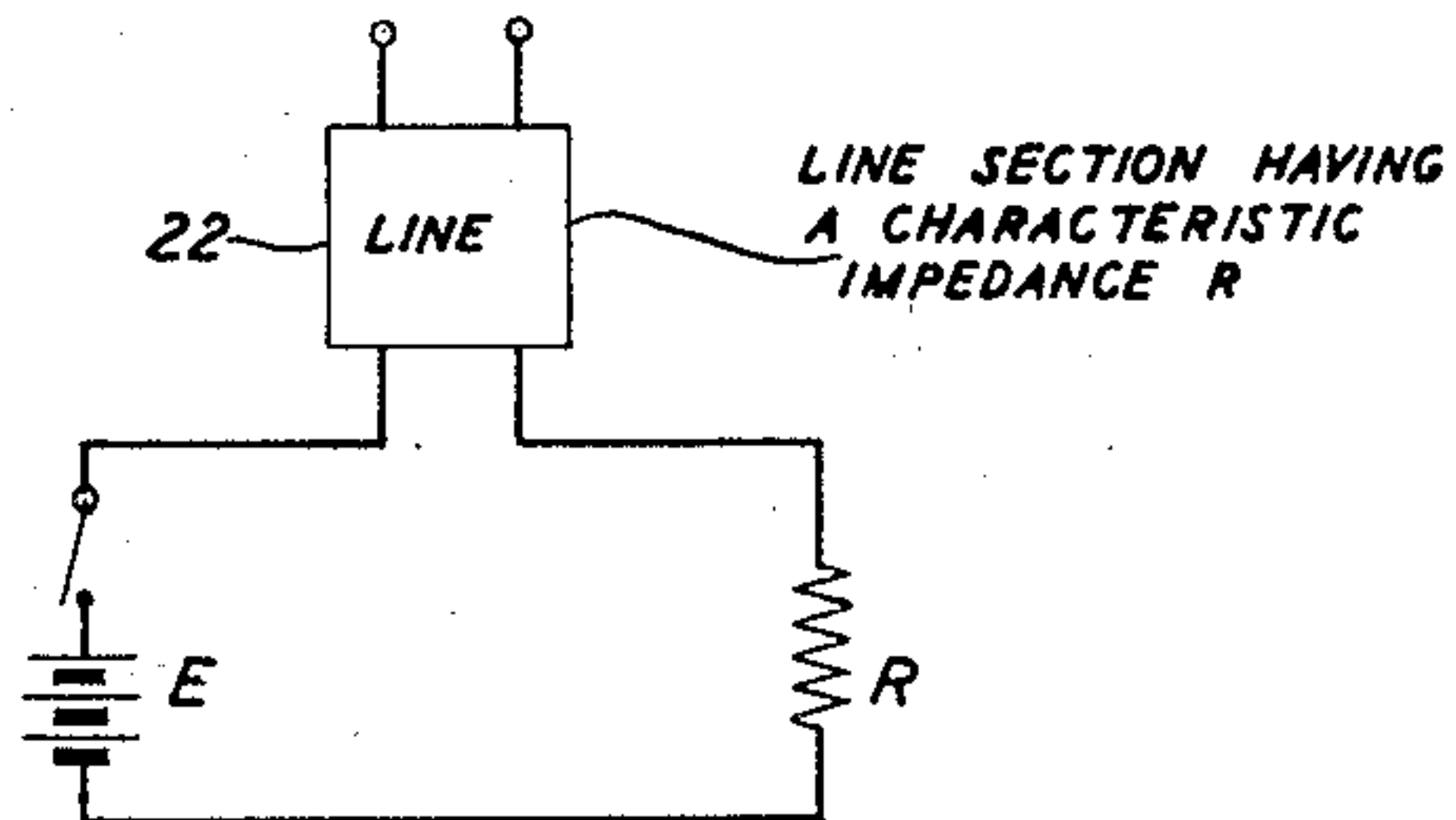


FIG. 8

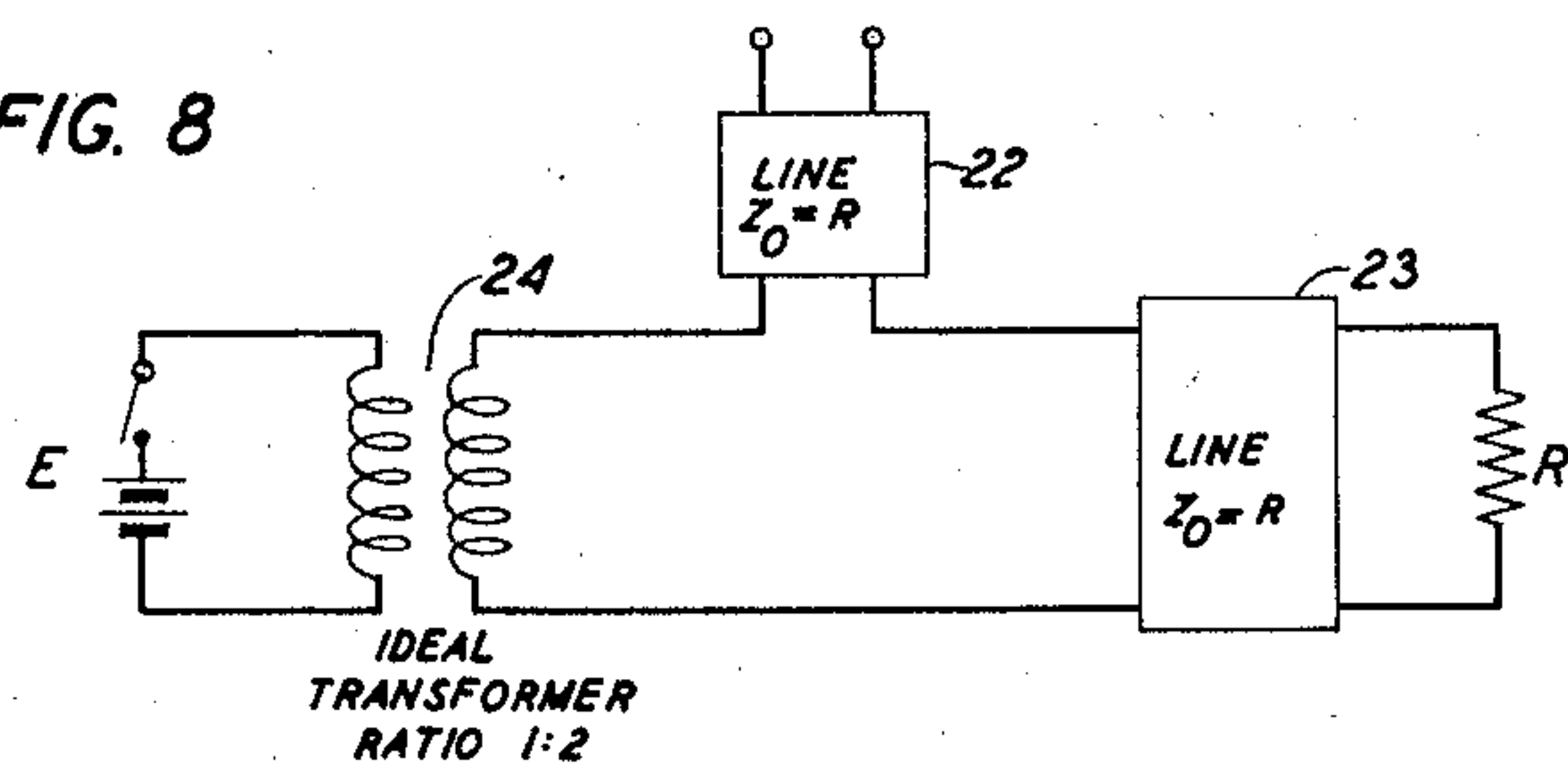


FIG. 9

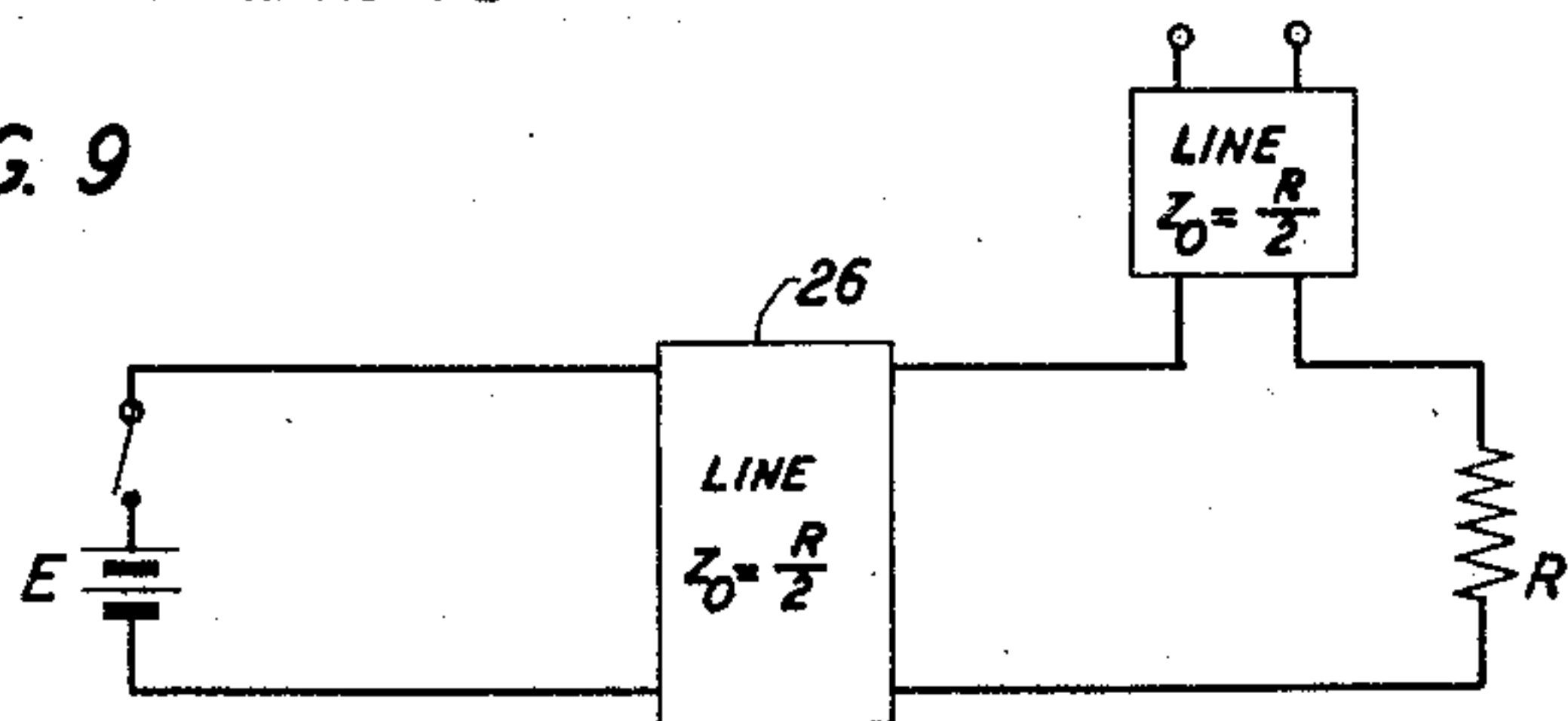


FIG. 10

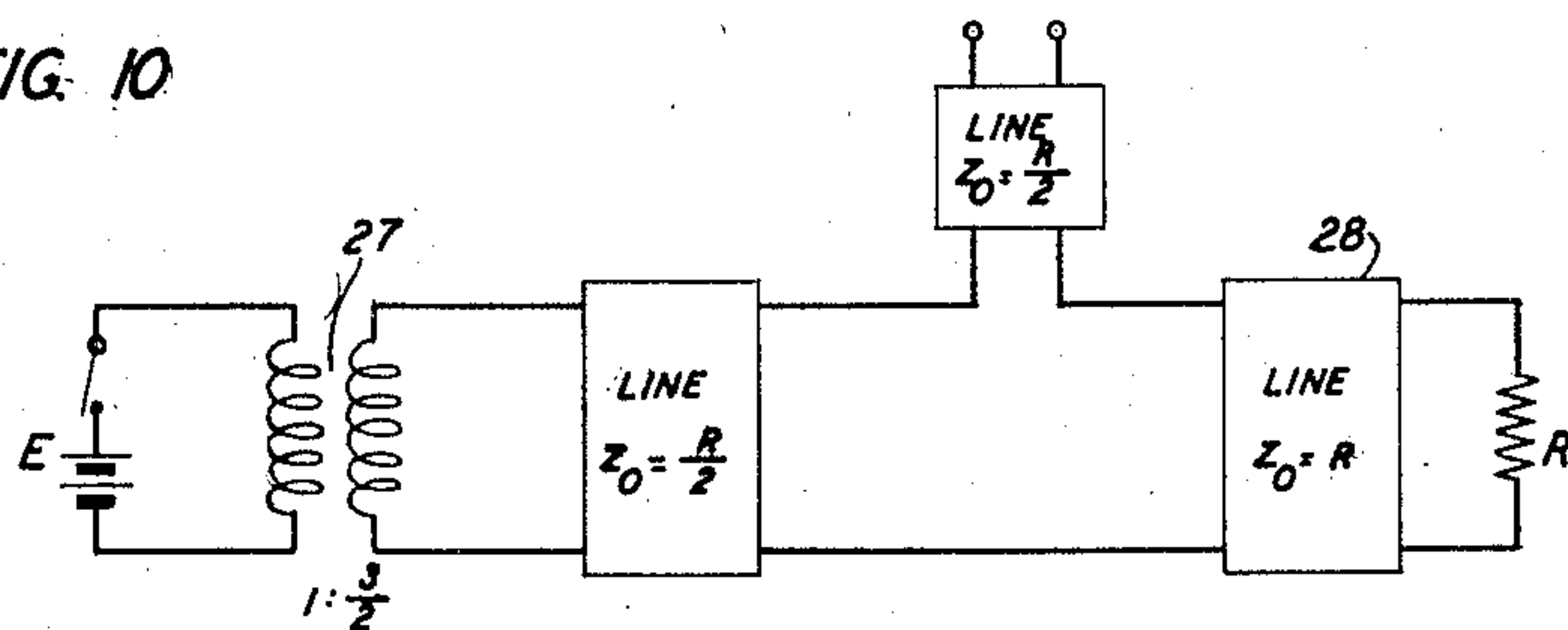
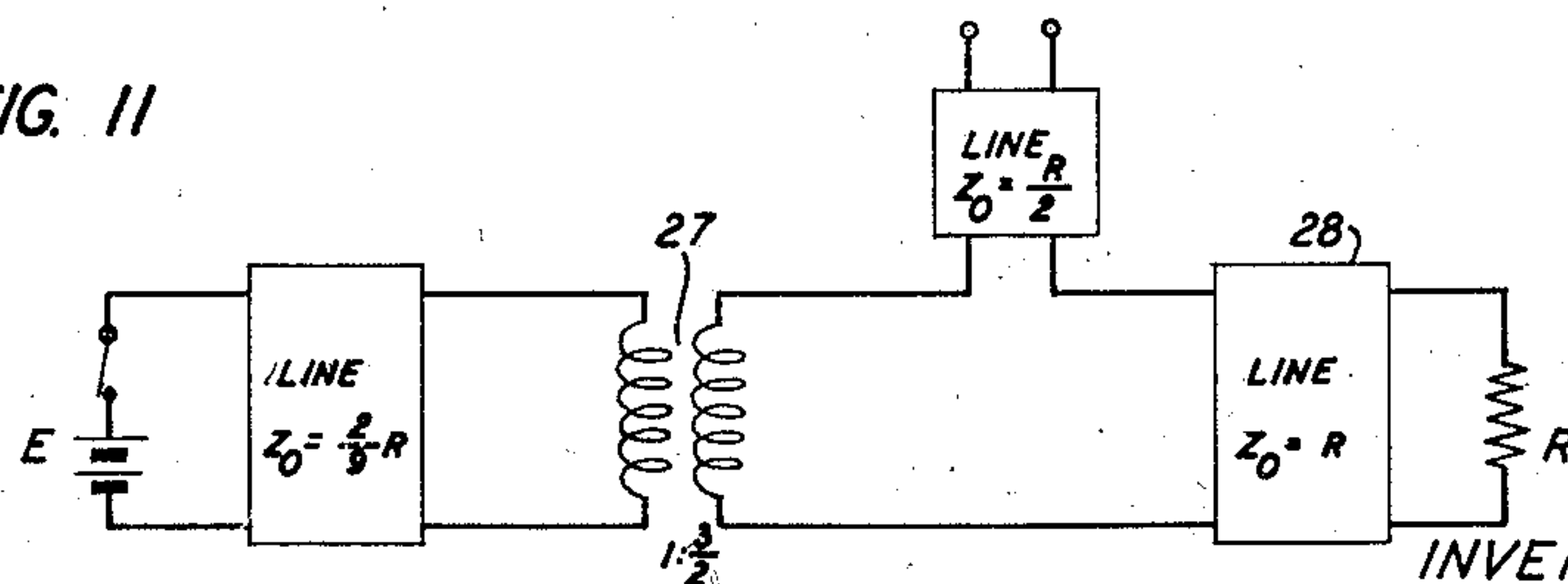


FIG. 11



INVENTOR
S. DARLINGTON
BY *G. H. Stevenson*
ATTORNEY

May 13, 1947.

S. DARLINGTON

2,420,302

IMPULSE GENERATOR

Filed Aug. 19, 1943

3 Sheets-Sheet 3

FIG. 12

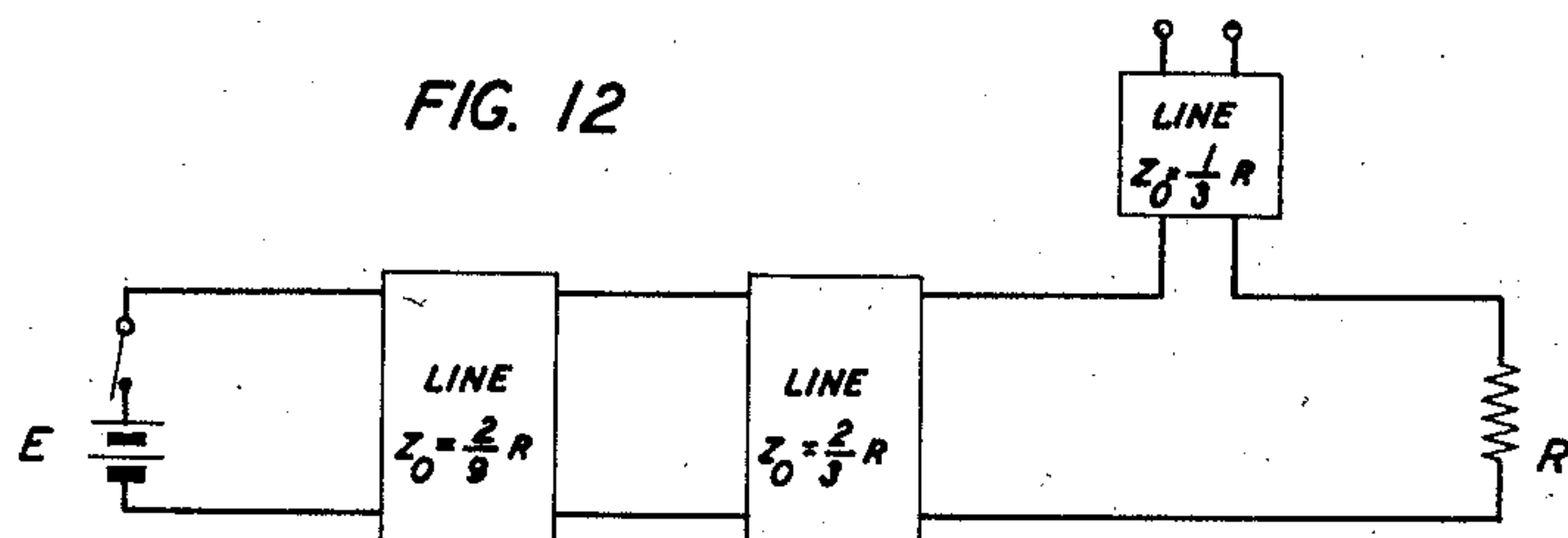


FIG. 13

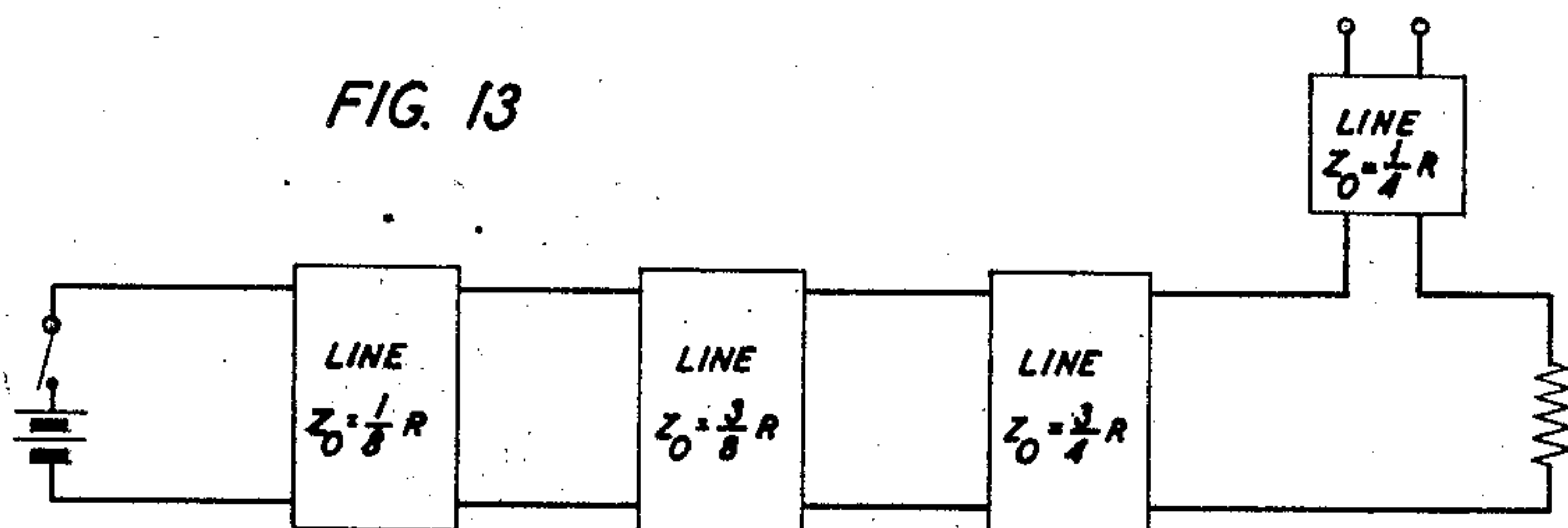
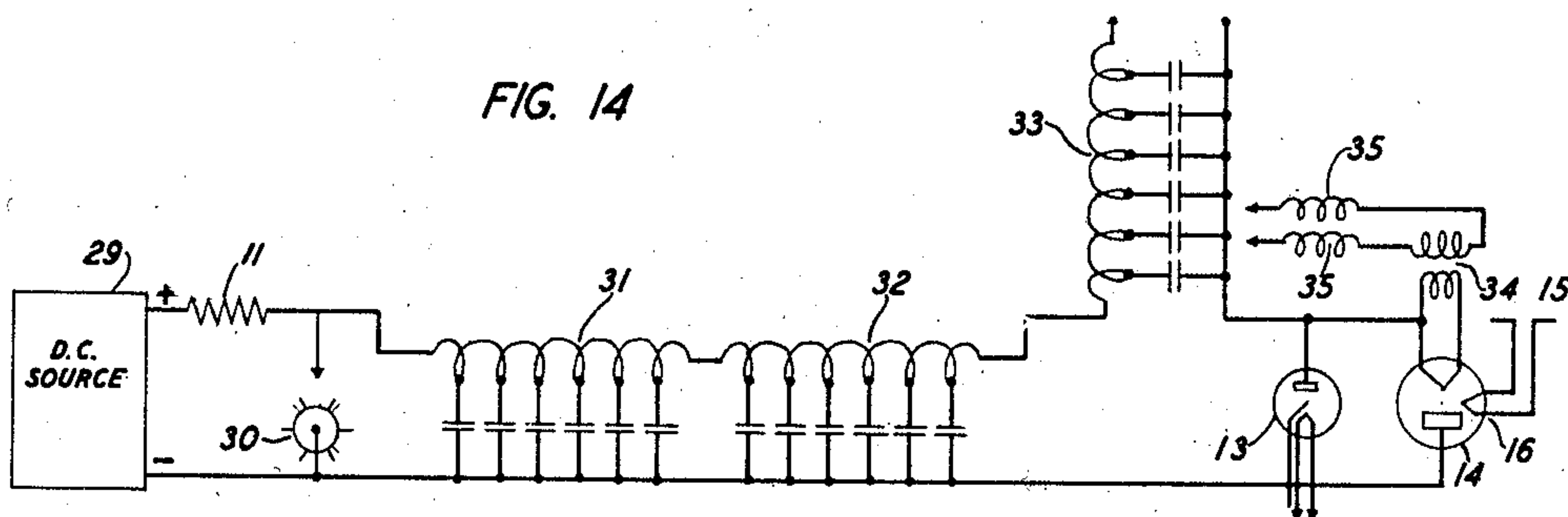


FIG. 14



INVENTOR
S. DARLINGTON
BY *G. H. Stevenson*
ATTORNEY

UNITED STATES PATENT OFFICE

2,420,302

IMPULSE GENERATOR

Sidney Darlington, New York, N. Y., assignor to
Bell Telephone Laboratories, Incorporated,
New York, N. Y., a corporation of New York

Application August 19, 1943, Serial No. 499,193

6 Claims. (Cl. 178—44)

1

This invention relates to impulse generating systems and more particularly to circuits for generating impulses of controlled wave form and duration. Its principal objects are to facilitate the voltage transformation of an impulse while at the same time maintaining its wave form; to provide for voltage multiplication without recourse to the use of electromagnetic transformers; and to increase the useful energy of generated impulses.

In impulse transmission systems such, for example, as radio echo systems, in which high frequency impulses of very great intensity and of short duration are radiated at regular intervals, it has been found desirable that the individual impulses should have a substantially rectangular wave form, that is, one characterized by uniform amplitude throughout the whole of the impulse duration and by sharp growth and decay at the beginning and at the end of the impulse, respectively. The radiated impulses are ordinarily produced by exciting an ultrahigh frequency vacuum tube oscillator with unidirectional voltage impulses of the desired shape and intensity, the radiated energy being derived almost wholly from that contained in the exciting pulse. Heretofore the generation of impulses of suitable shape and of sufficient intensity has presented a problem of considerable magnitude for the reasons that direct currents of the required voltage are not readily obtained and that electromagnetic transformers capable of providing the necessary voltage transformation without impairing the impulse wave form are costly and difficult to construct.

The present invention overcomes the above-mentioned difficulties by making use of wave reflection effects to bring about the desired voltage step-up. For this purpose, a generating impulse is caused to traverse a chain of artificial lines having different characteristic impedances which are graded in a particular manner as hereinafter described. The wave reflection effects occur at the junctions of the several lines and I have found that, by suitably proportioning the line characteristics, it is possible to effect any desired degree of voltage multiplication while maintaining a rectangular wave form.

The nature of the invention will be more fully understood from the detailed description which follows and by reference to the accompanying drawings of which:

Fig. 1 is a schematic representation of an impulse generating system in accordance with the invention;

2

Figs. 2, 3 and 4 represent configurations of artificial lines and impedance networks that may be used in the system of Fig. 1;

Figs. 5 and 6 illustrate a theorem upon which an explanation of the invention is based;

Fig. 7 represents schematically a known type of impulse generator which is a prototype of the systems of the invention;

Figs. 8 to 13, inclusive, illustrate the derivation of multiplying systems in accordance with the invention from the prototype circuit; and

Fig. 14 shows in more detail a voltage tripling system in accordance with the invention.

Referring to Fig. 1, 10 is a source of direct current, 11 a resistor, 12 a switch, elements L_1 to L_n , inclusive, are sections of artificial lines having negligible energy dissipation, 13 is a thermionic diode, 14 is a diode oscillator, for example, of the type shown in United States Patent 2,063,342, issued December 8, 1936, to A. L. Samuel, and 15 is a dipole antenna coupled to the oscillator by a small coupling loop 16 inserted in the oscillator field. The source 10 has its negative terminal grounded. Diodes 13 and 14 are poled in opposite directions, the former in conductive relation to the battery and the latter in opposition thereto. The cathode heating circuits for these vacuum tubes are omitted for the sake of simplicity. Lines L_1 to L_{n-1} are connected in cascade and the terminal line L_n is connected as a two-terminal impedance in series in the output circuit of the cascade system. Line L_n is open-circuited at its outer terminals. These lines may be portions of actual transmission lines, for example, coaxial conductor lines, but to save space it is generally advantageous to construct them as artificial lines, suitable configurations for which are shown in Figs. 2 and 3.

The lines conform to certain general requirements which may be stated as follows: Those designated L_1 to L_{n-1} are symmetrical, that is, they exhibit the same characteristics at each of their two pairs of terminals. They should be substantially dissipationless and should all have the same propagation constant. Their open-circuit impedances are similar in that they exhibit resonances and anti-resonances at the same frequencies, but the magnitudes of the impedances increase systematically from left to right in the drawing as hereinafter explained. The lines should also contain no conductive shunt branches so that in the open-circuit condition they are able to store electrical energy in the form of an electric charge. Line L_n should be similar to the others with respect to delay time and may also

be of similar configuration, but since it is used only as a two-terminal impedance, its desired impedance characteristic may be realized in various other well-known configurations.

For the generation of impulses of rectangular wave form, it is desirable that the artificial line sections have characteristics approximating those of actual dissipationless transmission lines. Their characteristic impedances should therefore be substantially pure resistances over a wide frequency range and their phase shift characteristics should be substantially linear in the same range. To produce impulses of a given desired duration the lines should have a delay time equal to half the length of the impulse.

Fig. 2 shows a low-pass filter configuration that may be used for the lines, the series inductances and the shunt capacities being proportioned to place the cut-off frequency well above the frequency range required to produce the desired pulse wave form. An alternative construction is shown in Fig. 3 in which the series inductances are provided by a single long solenoid and in which the shunt condensers are connected at equal intervals along the inductive winding. The mutual inductance between the successive sections in this construction tends to increase the linearity of the phase shift characteristic.

Fig. 4 shows a configuration that may be used for the terminating section L_n when the other lines are constructed according to Fig. 2 or 3. The design of this network may be related to that of the others by means of the theorem described by R. M. Foster in an article entitled "A reactance theorem," published in the Bell System Technical Journal, April 1924.

The range of frequencies over which the characteristics of the artificial lines should be uniform depends upon the pulse length and should be wide enough to include several harmonics of the fundamental frequency corresponding to a periodic time of two pulse lengths. Thus, in the case of a system intended for the generation of pulses of one microsecond duration, it is desirable that the artificial lines should have linear characteristics in the range of frequencies extended from zero to about four or five million cycles per second.

In the operation of the system, when switch 12 is opened, direct current passes along the lines to the terminal network L_n and builds up a charge in the capacities included in this network. During the charging part of the cycle the circuit is completed through diode 13 which is conductively poled with respect to the charging source voltage. The various transient currents that may arise during this interval are not of present concern since sufficient time may be allowed to permit the system to become fully charged to a steady voltage equal to that of the source 10. Resistance 11 in series with the direct current source limits the transients and serves to dissipate them quickly during the charging period. The high voltage impulses are produced upon the closing of switch 12 by the discharging of the lines through the switch contacts and through the oscillator diode 14. In so far as the effects produced are concerned, the closing of switch 12 may be regarded as equivalent to the sudden application of a steady voltage to the left-hand terminals of L_1 having the same magnitude as the source voltage but of opposite polarity. The transient phenomena during the discharge correspond to the transmission of this suddenly impressed reverse voltage, or negative step-voltage, through the system.

The wave front of the discharge, or of the hypothetical step-voltage, travels through the cascaded lines towards the output circuit and as it does so, is increased in voltage at each of the junction points because of the wave reflection effects arising there. Upon the arrival of the generating pulse at the output circuit, current begins to flow in the space path of the tube 14 and at the same time enters the line L_n . The current flow continues at a steady value until the wave entering L_n returns to the input terminals of that line after being reflected at the open circuit output terminals. When that takes place the current in the output circuit is neutralized by the reflected pulse and the current in the circuit drops to zero. The duration of the pulse is measured by the time taken for the generating pulse to travel through the line L_n and back again and is thus equal to twice the delay time of that line.

The complete cessation of the current at the end of the assigned pulse length requires that certain relationships of the parameters of the several line sections obtain. This has been mentioned before and will now be explained.

It will be evident that the wave front which travels directly through the lines upon the closure of switch 12 will be followed by a succession of wave fronts or step-voltages produced by the reflections at the different junction points in the system. For example, at the junction point of L_1 and L_2 a reflected wave will be transmitted back to the switch 12 and then after a second reflection will pass through the system and will arrive at the output circuit delayed by twice the delay time of line L_1 . Similar effects will be produced at each of the line junctions and these would ordinarily tend to produce an indefinitely long train of pulses in the output circuit. It is necessary that all of these later pulses should, in effect, neutralize each other so that the output current remains zero after the first pulse has passed. I have found that this result can be achieved by grading the line impulses and by making the lines all of the same delay time or the same electrical length.

The line impedances for the configuration shown have the following values: If the resistance of the load, that is, the space path of tube 14, be denoted by R , then the terminal line section L_n should have a resistive characteristic impedance of value

$$Z_n = \frac{R}{n}$$

and the other lines should have impedances of the values given by

$$Z_r = \frac{R(r+1)!}{n^2(r-1)!} = \frac{R(r+1)r}{n^2}$$

where Z_r denotes the impedance of the r th section and n denotes the total number of line sections including the terminal section L_n .

A demonstration of these relationships in terms of the successive wave reflections or transients is not simple, but the relationships may be arrived at from a consideration of the steady-state characteristics of the system. The development of the relationships on this basis makes use of certain steady state theorems on equivalent circuits and the application of these theorems to the impulse systems of the invention is justified by the well-known fact that circuits having the same steady-state characteristics at all frequencies also exhibit the same transient behaviors.

5

The equivalent circuit theorem upon which the demonstration is based is illustrated by Figs. 5 and 6. In Fig. 5 the circuit comprises an ideal transformer 17 having a transformation ratio of 1 to $1+k$, a series impedance 18 unrestricted in character and magnitude kZ_{11} and a symmetrical four-terminal network 19 having an open-circuit impedance Z_{11} and an image transfer constant θ . This network is equivalent in its behavior to that shown in Fig. 6 which comprises a four-terminal network 20 and a series impedance 21, the parameters of which are related to those of elements 18 and 19 of Fig. 5, as indicated in the drawing. In Fig. 6 the transposition of the series impedance to the other side of the four-terminal network and the change in the values of the network parameters has resulted in the elimination of the transformer. The equivalence of the two circuits may be demonstrated by developing and comparing the formulae for the open-circuit and short-circuit impedances at each of the two pairs of terminals of the two systems.

The application of the theorem illustrated by Figs. 5 and 6 to the development of the systems of the invention proceeds as follows: The circuit shown in Fig. 7 is a simple impulse generator of known type in which a single rectangular impulse is produced upon the closing of the battery switch. The line section 22 is a portion of an ideal dissipationless line having a delay time equal to one-half the desired pulse length and having a characteristic impedance equal to the resistance of the load R . The latter requirement is necessary for the generation of a single pulse, that is, for the suppression of additional transients following the first impulse. In this circuit the pulse voltage developed at the load terminals is equal to one-half the voltage of the direct current source. Starting with the circuit of Fig. 7, the modification shown in Fig. 8 is arrived at by the insertion of an ideal transformer 24 between the source and the line 22 and by the inclusion in front of the load of a line section 23 having the same electrical length as line 22. In this figure and in subsequent figures the designation Z_0 is used to indicate the characteristic impedance of the lines. If the characteristic impedance of the added line section be such as to match the load impedance, the only effect produced by its inclusion in the circuit will be to delay the appearance of the pulse at the load terminals by an amount equal to the delay of the line. The inclusion of the ideal transformer gives rise to the desired voltage step-up. The circuit arrangement in Fig. 8 now corresponds to that shown in Fig. 5 for the particular case where k is equal to unity. Accordingly, the transformation shown in Fig. 6 may be used and the circuit of Fig. 9 is arrived at directly. This circuit which produces a voltage multiplication of two comprises a terminal line section 25 having a characteristic impedance equal to half the load impedance and a four-terminal section 26 also having the same characteristic impedance.

By repeating the procedure outlined above as many times as desired, additional line sections of the proper impedances may be inserted and corresponding increases in the voltage magnification may be obtained. It is necessary, however, that all of the lines have the same electrical length or delay time in order that the shape and the singular character of the pulse be maintained. The successive steps in the development of the circuit of a voltage tripling system are shown in

6

Figs. 10, 11 and 12, respectively. The first step indicated by Fig. 10 consists in the introduction of an ideal transformer 27 adjacent the voltage source having a ratio of 1 to $3/2$ and the inclusion of a line section 28 adjacent the load and having the same impedance as the load. The circuit in Fig. 11 is derived from that in Fig. 10 by a simple shift of the location of the transformer and an appropriate change in the impedance of the first line section. Fig. 12 then follows from Fig. 11 by the application of the equivalent circuit theorem of Figs. 5 and 6. The final impedances of the various line sections are as indicated in the drawing.

Fig. 13 shows the final result obtained by further application of the principle to produce a voltage quadrupling system. Here, the lines have the impedances from left to right, $\frac{1}{8} R$, $\frac{3}{8} R$, $\frac{3}{4} R$ and $\frac{1}{4} R$. The derivation of this circuit from that of Fig. 12 involves the introduction of an ideal transformer having a step-up ratio of 1 to $4/3$.

The expressions for the impedance values given in equation 1 may be arrived at by inductive reasoning from a comparison of systems having progressively increasing numbers of line sections. The values given for systems having two, three, and four line sections, respectively, agree with the values determined from the equation and the values for systems of greater complexity are readily obtained. The voltage multiplication in any given system of the invention is equal to the number of line sections used as may be seen from a consideration of the successive voltage transformations introduced in the course of the development from the prototype circuit of Fig. 7. For example, the successive transformations introduced into the development of Fig. 13 are 2, $3/2$, and $4/3$, the continued product of which is 4. The theory of the invention has been developed in the foregoing on the assumption that the line sections are ideal dissipationless lines. When artificial lines or networks comprising lumped impedance elements are used, the performance of the system may differ somewhat by that produced by the use of ideal lines, but if the artificial lines are so constructed that they have linear phase shift characteristics over a sufficiently wide range, the difference in performance will not be serious and will appear primarily as a slight rounding of the corners of the rectangular pulse. As already stated, the range in which the network characteristics should be linear should include several harmonics of the fundamental frequency corresponding to a periodic time of twice the pulse length.

Fig. 14 shows an impulse system arranged to generate repeated impulses and to provide a voltage multiplication of three. The circuit is supplied with energy from a direct current source 29 which may, for example, be a rectifier taking alternating current from a power line or other primary source. The discharging switch 12 in Fig. 1 is replaced in this system by a rotary spark gap 30 driven by a motor, not shown. The number of points on the rotary portion of the gap and the speed of the driving motor may be chosen to provide various impulse rates up to about 2000 per second. The three artificial lines 31, 32 and 33 by which the voltage tripling action is obtained are of the type shown in Fig. 3. Resistance 11, charging diode 13, oscillator tube 14 and output circuits 15 and 16, correspond to the like numbered elements of Fig. 1. Cathode heating circuits are indicated for the vacuum tubes,

the cathode of tube 14, since it is at a high potential above ground, being supplied with heating current through an insulating transformer 34 in the primary leads of which high frequency chokes 35 are inserted.

The source 29 may be capable of supplying a direct current voltage of about 20,000 volts in which case an impulse voltage of 30,000 volts would be developed at the oscillator terminals. This compares with the voltage of 10,000 that would be produced in the prototype circuit of Fig. 7. The spark gap 30 breaks down and provides a discharge path of very low resistance each time one of the rotating points comes into juxtaposition with the fixed point. Since the pulse duration including the delay time introduced by the multiplying network is generally very short in comparison with the interval between successive impulses, the system can be fully discharged during the passage of the spark and can be charged again to a steady voltage in the subsequent open-circuit interval before the next spark.

What is claimed is:

1. In an impulse generating system comprising a pulse shaping network capable of storing electrical energy and proportioned to provide an impulse of uniform amplitude and preassigned duration, a load device, and means for discharging the energy stored in said network through said device, means for multiplying the voltage of the generated impulse comprising a plurality of wave transmission networks interposed in tandem between said discharging means and said storage network, said wave transmission networks having characteristic impedances which vary progressively from one to the next, the magnitudes of the impedances and the delay characteristics of the networks being so proportioned with respect to the impedance of the wave shaping network and the preassigned pulse duration as to substantially suppress transients following the initial discharge of said shaping network.

2. A system in accordance with claim 1 in which the wave transmitting networks are constituted by artificial lines having substantially linear phase shift characteristics and equal delay times, and in which the pulse shaping network has an impedance substantially equal to the open-circuit impedance of a uniform line having the same delay time.

3. In an impulse generating system for impulses of substantially rectangular wave form and preassigned duration comprising a pulse shaping network capable of storing energy in

the form of an electric charge, a load device and means for discharging energy stored in said network through said load device, means for multiplying the voltage of the generated impulse comprising a plurality of wave transmission networks interposed in tandem between said discharging means and said shaping network, said wave transmission networks having characteristic impedances the values of which increase progressively from one to the next in the direction from said discharging means, the impedances and the delay characteristics of the transmission networks being proportioned with respect to the impedance of the load device and preassigned impulse duration to substantially suppress transients following the discharge of said shaping network.

4. A system in accordance with claim 3 in which the pulse shaping and the wave transmission networks are constituted by artificial lines having delay times substantially equal to one-half the preassigned duration of the impulse.

5. A system in accordance with claim 3 in which the wave transmission networks are constituted by artificial lines having linear phase shift characteristics and delay times substantially equal to one-half the preassigned duration of the impulse and having characteristic impedances substantially of the magnitudes defined by

$$Z_r = \frac{R(r+1)!}{n^2(r-1)!}$$

wherein Z_r denotes the impedance of the r th network of the tandem chain counting from the discharging means, R is the impedance of the load device and n is the total number of networks including the pulse shaping network.

6. A system in accordance with claim 3 in which the pulse shaping and the wave transmission networks are constituted by artificial lines having delay times substantially equal to one-half the preassigned duration of the impulse, in which the wave transmission lines have characteristic impedances of the magnitudes defined by

$$Z_r = \frac{R(r+1)!}{n^2(r-1)!}$$

and in which the pulse shaping line has a characteristic impedance equal to R/n wherein Z_r denotes the impedance of the r th network of the tandem chain counting from the discharging means, R is the impedance of the load device and n is the total number of networks including the pulse shaping network.

SIDNEY DARLINGTON.