March 25, 1930. H. WHITTLE 1,752,046

ELECTRIC COUPLING CIRCUITS

Filed April 6, 1927

Fig. 1

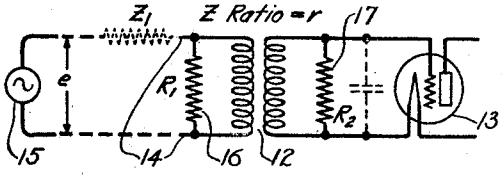


Fig. 2

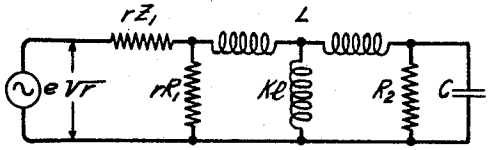


Fig. 3

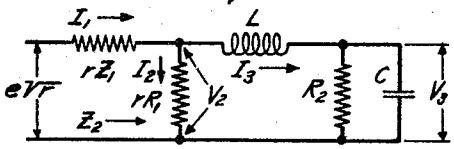


Fig. 4

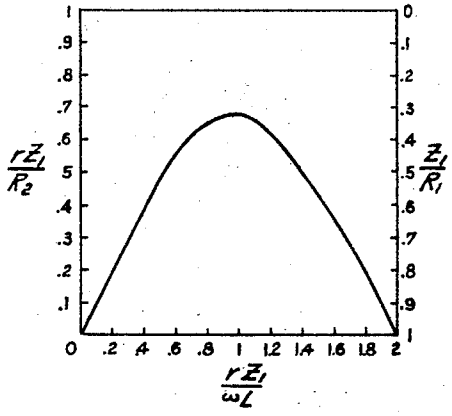


Fig. 6

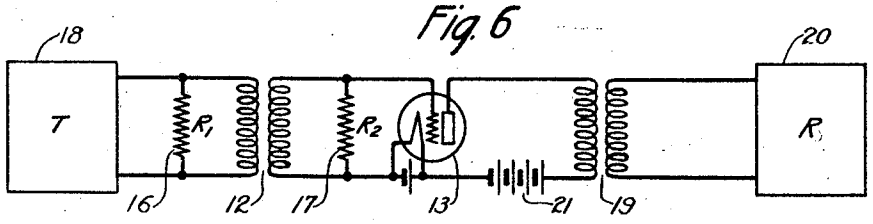
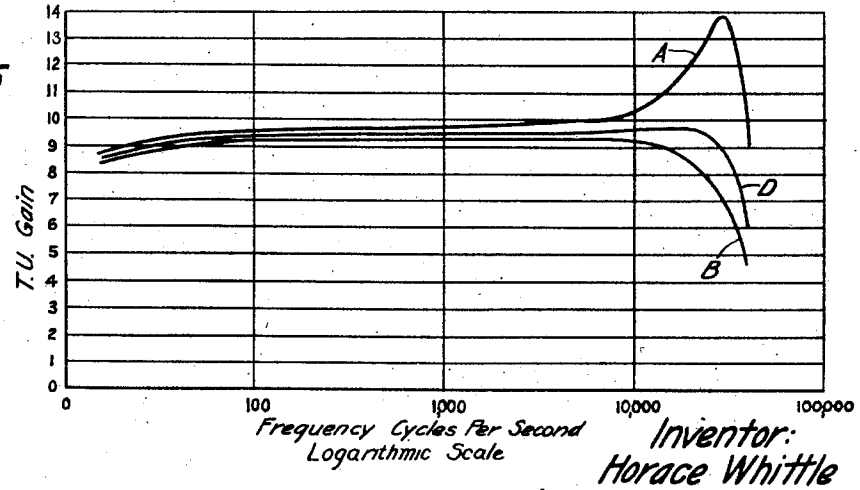


Fig. 5



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UNITED STATES PATENT OFFICE

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ELECTRIC COUPLING CIRCUITS

Application filed April 6, 1927. Serial No. 181,530.

This invention relates to transformer circuits and particularly to input transformer circuits for electric discharge devices required to transmit waves of a wide range of frequency.

Transformers are ordinarily employed in transmission systems for matching impedances between individual parts to obtain efficient and uniform transmission of the desired waves. With an electric discharge amplifier the output current is proportional to the input voltage, and uniform power throughout the frequency range will be delivered provided the input voltage is constant. The primary requirement for an input transformer, therefore, is that the ratio between the supply voltage and the input voltage be kept constant throughout the transmitted frequency range. Generally, it is required to match the impedances on the primary side of the transformer, but this is not the controlling factor. Heretofore, it has been found that the transmission is improved by resonating the leakage inductance of the transformer with the effective input capacities of the discharge device. Also, the requirement of impedance match is attained by the use of a resistance element, having a resistance approximately equal to the impedance of the input circuit, connected in shunt to the primary winding of the transformer. However, this arrangement gives a uniform transmission characteristic only for one particular transformer ratio, while other ratios give a non-uniform characteristic, so that it is not always possible to use the most advantageous transformer ratio. Similarly, a resistance in shunt to the secondary winding of the transformer tends to give a falling characteristic.

In a specific preferred embodiment this invention comprises an input transformer arrangement for an electric discharge amplifier, in which, the leakage reactance of the input transformer resonates with the combined distributed capacity of the secondary winding and the input capacity of the electric discharge amplifier at a frequency near the upper limiting frequency of a wide range of frequencies to be transmitted, and a resistance element is connected in shunt to each of the windings of the transformer. These elements are so proportioned with respect to one another and the transformer ratio that the impedance looking into the primary of the transformer with the resistance in shunt therewith is matched to the impedance of the transmitting circuit at frequencies in the lower portion of the range of frequencies to be transmitted. The resistances are further so proportioned with respect to the leakage reactance at the resonant frequency that the ratio between the input voltage and the secondary voltage of the transformer is the same at the resonant frequency as at the frequencies at which the primary impedances are matched. This arrangement has been found to maintain the voltage ratio substantially constant throughout the intermediate frequency range and is very flexible, making possible the choice of the preferable transformer ratio.

While this invention is particularly described as applied to an input transformer for an electric discharge amplifier it may be found useful for use with other circuits of capacity reactance. Although impedance matching is not the primary goal it has been found that the arrangement of this invention gives a substantial impedance match throughout the larger portion of the frequency range of the waves to be transmitted.

This invention will be better understood by reference to the following detailed description taken in connection with the accompanying drawing in which:

Fig. 1 represents in schematic form a repeater circuit in accordance with this invention comprising an input transformer serv-

ing as a coupling between a transmission line and a vacuum tube amplifier;

Fig. 2 shows an equivalent simplified circuit in which the transformer has been replaced by its equivalent unity ratio T network;

Fig. 3 is a modification of Fig. 2 and represents the net work at the high frequencies where the mutual impedance is so high as to be negligible;

Fig. 4 is a chart from which the proper values of the resistances connected in shunt to the windings of the transformer may be determined for any given condition;

Fig. 5 shows the characteristic curves representing the voltage amplification, or gain, of the transformer circuit working into the vacuum tube and covering a range of frequencies from 16 cycles to approximately 31,000 cycles, for three different conditions, namely, when a resistance is connected in shunt to the primary winding only, when the resistance is connected in shunt to the secondary winding only, and when two resistances are connected in shunt to the primary and secondary windings respectively; and

Fig. 6 represents a transmission system employing the amplifier circuit of Fig. 1 in connection with an output transformer.

The arrangements shown in the several figures of the drawing are particularly adaptable to signaling systems in which uniform transmission is required over a wide band of frequencies ranging, for example, from about 20 cycles to 31,000 cycles per second, and these arrangements will now be described in detail.

Referring to Fig. 1, there is shown an input transformer 12, employed for coupling an amplifying vacuum tube 13 to a line 14 which is connected at its opposite end to a source 15 of waves of a wide frequency range. Connected in shunt respectively to the primary and secondary windings of the transformer are resistance elements 16 and 17 which have values so proportioned with respect to each other and to the leakage reactance of the transformer as to substantially match the impedance of the transformer with the impedance of the line throughout a large portion of a wide band of frequencies ranging from about 20 cycles to approximately 31,000 cycles per second. The transformer is so designed that the leakage inductance resonates with the combined distributed capacity of the secondary winding and the input capacity of the amplifying vacuum tube at substantially the upper limiting frequency of the above mentioned band. This combined capacity is represented in the circuit of Fig. 1 by the dotted condenser across the input circuit of tube 13. The impedances of the primary circuit of the transformer are matched to the impedance of the line at the lower limiting frequency of the band. This arrangement gives a constant ratio between the input voltage and the secondary voltage of the transformer throughout the entire frequency band. While heretofore it has been possible to obtain uniform transmission for a fairly wide range of frequencies the choice of transformer ratios was generally very limited, with this invention the transformer ratio is only limited to those values which will keep the value of the ratio $\frac{r\mathbf{Z}_1}{\omega L}$ between 0 and 2, as will hereinafter be described, r being the impedance ratio of the transformer, $\mathbf{Z}_1$, the input impedance and ωL the leakage reactance at the resonant frequency.

In connection with the coupling circuit which has just been described, design formulæ were developed which show the relation between the shunting resistances and the leakage reactance at the resonant frequency, the transformer coil ratio, the transmitting end impedance, and the values of the shunt resistances 16 and 17 required to obtain a substantially flat transmission characteristic for the combination. For the purpose of analysis the essential parts of the circuit of Fig. 1 are shown in a simplified schematic form in Fig. 2 in which the transformer 12 is replaced by the well known equivalent T network of unity ratio. In this network the inductances of the arms are designated in terms of leakage inductance of which L indicates the total leakage in both primary and secondary windings of the transformer and kl indicates the mutual inductance. The resistance elements 16 and 17 are designated R_1 and R_2 respectively for the purpose of analysis and in assuming the transformer to be of unity ratio the electrical impedances on the primary side of the transformer are multipled by r which represents the impedance ratio of the transformer. In this way the transmitting or input impedance $\mathbf{Z}_1$ becomes $r\mathbf{Z}_1$, the resistance R_1 becomes rR_1 and the transmitting voltage e becomes $e\sqrt{r}$.

In this discussion the mutual inductance kl (of which k is the coupling factor of the transformer and l the high side inductance) may be disregarded at most of the frequencies under consideration since the value of kl is high as compared with L.

Neglecting the mutual inductance kl the schematic circuit shown in Fig. 3 is the equivalent of that shown in Fig. 2.

The following formulæ have been developed for the purpose of determining the values to be assigned to the resistances R_1 and R_2 in order that the transmission characteristic of the coupling circuit will be substantially flat over the entire range. In these formulæ C denotes the capacity between the input electrodes of the amplifying vacuum tube 13 plus the distributed capacity of the transformer, V_2 represents the

voltage drop across resistance 16, V_s the voltage applied to the grid of tube 13, Z_1 the impedance of the line 14, Z_2 the impedance looking into the transformer, and I_1, I_2 and I_3 the currents in the various portions of the circuit, as indicated in the drawing. Referring to Fig. 3:

(1) $I_3=V_3\left(\frac{1}{R_2}+j\omega C\right)$, ω being equal to 2π multiplied by the frequency.

(2) $V_2=V_3+j\omega L(I_3)=V_3+j\omega LV_3\left(\frac{1}{R_2}+j\omega C\right)$

(3) $I_2=\frac{V_2}{rR_1}$

(4) $I_1=I_2+I_3=V_3\left(\frac{1}{R_2}+j\omega C\right)+\frac{V_3+j\omega LV_3\left(\frac{1}{R_2}+j\omega C\right)}{rR_1}$

(5) $e\sqrt{r}=rZ_1I_1+V_2$

(6) $e\sqrt{r}=rZ_1V_3\left(\frac{1}{R_2}+j\omega C\right)+\frac{V_3Z_1}{R_1}\left[1+j\omega L\left(\frac{1}{R_2}+j\omega C\right)\right]+V_3\left[1+j\omega L\left(\frac{1}{R_2}+j\omega C\right)\right]$

(7) $\frac{e\sqrt{r}}{V_3}=rZ_1\left[\left(\frac{1}{R_2}+j\omega C\right)\right]+\left[\left(\frac{Z_1}{R_1}+1\right)\left(1+j\omega L\left(\frac{1}{R_2}+j\omega C\right)\right)\right]$

(8) $\frac{e\sqrt{r}}{V_3}=\frac{(rZ_1)}{R_2}+jrZ_1\omega C+j\left(\frac{Z_1}{R_1}+1\right)\frac{\omega L}{R_2}$

Formula (8) is obtained from Equation (7) by limiting ω to the resonant frequency, or $\omega^2LC=1$. Solving for the absolute value of $\frac{e\sqrt{r}}{V_3}$

(9) $\left[\frac{e\sqrt{r}}{V_3}\right]^2=\left(\frac{rZ_1}{R_2}\right)^2+r^2Z_1^2\omega^2C^2+\left(\frac{\omega L}{R_2}\right)^2\left(\frac{Z_1}{R_1}+1\right)^2+\frac{2rZ_1}{R_2}\left(\frac{Z_1}{R_1}+1\right)$

Now at low frequencies where ωL is small and $\frac{1}{\omega C}$ is large as compared to the value of R_2

(10) $Z_2=\frac{rR_1R_2}{R_2+rR_1}$ = two resistances in parallel.

Therefore by making $Z_2=rZ_1$ to properly match the impedances between the transmitting end and the receiving end.

(11) $rZ_1=\frac{rR_1R_2}{R_2+rR_1}$

(12) Then $\left(\frac{Z_1}{R_1}+1\right)=2-\frac{rZ_1}{R_2}$ which can be substituted in Equation (9).

(13) $\left[\frac{e\sqrt{r}}{V_3}\right]^2=r^2Z_1^2\omega^2C^2+\frac{4\omega^2L^2}{R_2^2}-\frac{4rZ_1\omega^2L^2}{R_2^3}+\frac{r^2Z_1^2\omega^2L^2}{R_2^4}+\frac{4rZ_1}{R_2}-\frac{r^2Z_1^2}{R_2^2}$

Equation (13) might be solved for R_2 directly but as R_2 appears in all powers up to R_2^4 the solution would be very complicated. It is therefore preferable to solve for rZ_1 in terms of R_2 giving an implicit solution.

Since at low frequencies $e\frac{\sqrt{r}}{V_3}=2$, as half the transmitting voltage is consumed in the

transmitting impedance when the impedances are matched, this ratio should also equal 2 at the resonant frequency in order to maintain the voltage ratio constant up to the resonant frequency after which the transmission falls rapidly corresponding to the cut-off of a filter.

Assuming $\frac{e\sqrt{r}}{V_2}=2$ and solving Equation (13) for $\frac{rZ_1}{R_2}$

$$(14)\quad \frac{rZ_1}{R_2}=\frac{-\left[4-\frac{4\omega^2L^2}{R_2^2}\right]\pm\sqrt{\left(4-\frac{4\omega^2L^2}{R_2^2}\right)^2-4\left[\omega^2C^2R_2^2+\frac{\omega^2L^2}{R_2^2}-1\right]\left[\frac{4\omega^2L^2}{R_2^2}-4\right]}}{2\left[\omega^2C^2R_2^2+\frac{\omega^2L^2}{R_2^2}-1\right]}$$

Multiplying through, simplifying and substituting ωL for $\frac{1}{\omega C}$

$$(15)\quad \frac{rZ_1}{R_2}=\left[\frac{2\left(\frac{\omega L}{R_2}\right)^2-2\pm2\sqrt{\left(\frac{R}{\omega L}\right)^2-1}}{\left(\frac{R_2}{\omega L}\right)^2+\left(\frac{\omega L}{R_2}\right)^2-1}\right]$$

By calculating $\frac{rZ_1}{R_2}$ with various values of $\frac{\omega L}{R_2}$ and then dividing,

$$\frac{\frac{rZ_1}{R_2}}{\frac{\omega L}{R_2}}=\frac{rZ_1}{\omega L}$$ the ratios for $\frac{rZ_1}{R_2}$ and $\frac{rZ_1}{\omega L}$ were obtained and the curve of Fig. 4 plotted therefrom.

From this curve R_2 can be determined when rZ_1 and ωL are known. R_2 is a minimum when $\omega L=rZ_1$ and is infinite when $rZ_1=0$ or ωL is infinite. To obtain $\frac{rZ_1}{\omega L}$ when $\frac{\omega L}{R_2}$ is zero, it is assumed that $\frac{\omega L}{R_2}$ is very small compared to 1, and substitute in Equation (15)

$$rZ_1=R_2\left[\frac{-2+2\sqrt{\left(\frac{r}{\omega L}\right)}}{\frac{R_2}{\omega L}}\right]$$

or $\frac{rZ_1}{R_2}=\frac{2\omega L}{R_2}$ when $\frac{R_2}{\omega L}$ is large compared to 1 or $\frac{rZ_1}{\omega L}=2$

Since the two resistances R_1 and R_2, which are effectively in parallel when viewed from the low side of the transformer, must equal rZ_1, then $\frac{Z_1}{R_1}$ must be a minimum when $rZ_1=\omega L$ as indicated in Fig. 4.

From the fact that,

$$rZ_1=\frac{rR_1R_2}{R_2+rR_1}$$

or

$$\frac{rZ_1}{rR_1}+\frac{rZ_1}{R_2}=1$$

or

$$\frac{rZ_1}{rR_1}=\frac{Z_1}{R_1}=1-\frac{Z_1}{R_2}$$

it follows that the ordinate distance between the curve and unity represents $\frac{Z_1}{R_1}$, so if it is assumed that

$$\frac{Z_1}{R_1}=1 \text{ when } \frac{rZ_1}{R_2}=0$$

and increasing values of $\frac{Z_1}{R_1}$ are plotted downward, the same curve can be used for obtaining R_1 as for obtaining R_2, $\frac{Z_1}{R_1}$ is then equal to unity at the ends of the curve and is minimum when $\omega L=rZ_1$ when it approximately equals a value of 0.3.

The use of this curve may be better understood by reference to the following design in which it is assumed that

$Z_1=600$ ohms, $r=44$ and $\frac{1}{\omega C}=\omega L=48{,}000$ ohms at 31,000 cycles

then $rZ_1=26{,}400$

and $\frac{rZ_1}{\omega L}=\frac{26{,}400}{48{,}000}=.55$

From the curve

$$\frac{rZ_1}{R_2}=.51$$

$$\frac{Z_1}{R_1}=.49$$

Then $R_2=\frac{26{,}400}{.51}=51{,}700$ ohms

and $R_1=\frac{600}{.49}=1{,}225$ ohms.

In designing a transformer according to this invention the transformer low side impedance can be assumed as a shunt impedance between two equal resistances equal to the transmitter impedance, which is assumed to be resistive, when considering the lowest frequency to be transmitted. This impedance can be made such a value that the transmission loss caused by it at the lowest frequency is less than a certain amount. The required ratio and the coupling factor of the design used are then determined in such a way that the leakage inductance considered from the

high side will resonate with the tube and transformer coil capacities at or above the upper limiting frequency. From the ratio of the transmitting impedance multiplied by the impedance ratio, to the high side leakage reactance at the resonant frequency, the abscissæ are obtained for the design chart shown in Fig. 4, the ordinates of the curve giving the relation of the shunting resistances R_1 or R_2 to the transmitting end impedance and coil impedance ratio. Other design charts of course can be derived if any relation between coil and line impedance is desired other than a substantial match but this is the most usual condition in telephone practice.

In Fig. 5 are shown transmission characteristic curves obtained by tests and representing in each case the relation between the voltage amplification or ratio of a particular transformer circuit and the frequency. In one case a pure resistance element is connected in shunt to the primary winding only; in another the resistance element is connected in shunt to the secondary winding only; and still, in another two resistance elements are connected in shunt to the primary and secondary windings respectively as shown in Fig. 1. In the first two cases, these resistances were given such values as to match the impedances at the primary side of the transformer to that of the line. For the case of the shunt across the primary winding, the characteristic indicated by A rises to a peak at the high frequencies while for the shunt across the secondary causes the characteristic indicated by B droops in the same range. The arrangement of this invention as indicated by curve D gives a substantially constant voltage ratio even at the high frequencies of a band ranging from about 20 cycles to approximtaely 31,000 cycles per second. This voltage is obtained for various coil ratios and it is to be noted that the gain in transmission units is constant within one T. U. for a range of frequencies from 20 cycles to 31,000 cycles.

In Fig. 6 is illustrated a transmission system required to transmit waves of frequencies from about 20 cycles to 31,000 cycles per second and which comprises a transmitting device 18, input transformer 12 and resistances 16 and 17 connected in shunt respectively to the primary and secondary windings thereof, a vacuum tube amplifier 13, output transformer 19, and receiver 20. The input transformer 12 and the output transformer 19 are preferably of different types. The input transformer may be of the shell type, for example, and may have a lower coil ratio than hereinbefore assumed in order to obtain a high primary impedance to improve the transmission at the lower frequencies, but with a higher primary impedance a considerable sacrifice is made in the step-up voltage of the transformer. A shell type transformer with pure resistances connected respectively across the primary and secondary windings thereof and proportioned in the manner as hereinbefore stated, may be adapted to connect a 600 ohm line to the input of a vacuum tube without producing serious distortion in the transmitted signals. The shell type core is preferably made up of E and I shaped laminations of a nickel-iron alloy having 78.5% nickel, generally known as 78.5% permalloy. The laminations are staggered in such a manner as to furnish a substantially closed magnetic circuit for the purpose of causing a high mutual inductance. Mounted upon the core are primary and secondary windings which are also interleaved for the purpose of cutting down the leakage between them. It was found necessary to employ this type of construction to obtain the low leakage inductance necessary in a transformer for transmitting such a wide band of frequencies.

The output transformer may be of the shell type but preferably should be of the toroidal type, the core being a solid ring of 78.5% permalloy and have mounted thereon primary and secondary windings interleaved, these features being provided for the same purpose as stated in connection with the input transformer. The shell type of output transformer is the same as the input transformer described above except that no resistive shunts are connected across the primary and secondary windings and the position of the transformer in the transmission circuit is reversed so that it acts as a step down transformer. The output transformer may have in addition a third winding (not shown) energized from battery 21 in series with a resistance (not shown) to produce sufficient flux to neutralize the effect of the flux set-up by the direct current in the primary winding.

The toroidal output transformers are capable of transmitting a band of frequencies which is still wider than the band transmitted by the input transformers described, the output transformer frequency band ranging approximately from 5 cycles to 35,000 cycles per second. The output transformers do not require resistances connected across the primary and secondary windings to reduce distortion at the frequency near the upper end of the band, inasmuch as there is no distortion at this point for the reason that the coupled circuits have impedances which are practically independent of frequency, the matching of impedances being obtained by the particular ratio used.

It is to be understood that the numerical values that have been given in the foregoing specification, for the frequency limits of the band or for other quantities, are not to be taken as limiting but are cited by way of examples.

What is claimed is:

1. A circuit for coupling a line to a secondary circuit having a capacity reactance to transmit a wide band of frequencies, comprising a transformer having primary and secondary windings and leakage inductance, said leakage inductance being of such a value as to resonate with said capacity reactance near the upper limit of said band, and resistances in shunt, respectively, to said primary and secondary windings, and proportioned with respect to each other so as to give said coupling circuit a substantially flat transmission characteristic over said band.

2. A circuit for coupling a line to the input of a secondary circuit having capacity reactance, to transmit a wide band of frequencies, comprising a transformer, having primary and secondary windings and leakage inductance, said leakage inductance being of such value as to resonate with said capacity reactance at a frequency near the upper limit of said band, and resistances in shunt, respectively, to said primary and secondary windings and proportioned with respect to each other and said leakage inductance so as to give said coupling circuit a substantially flat transmission characteristic over said band.

3. A circuit for coupling a line to a secondary circuit having a capacity reactance to transmit a wide band of frequencies, comprising a transformer having primary and secondary windings and leakage inductance, said leakage inductance being of such a value as to resonate with said capacity reactance near the upper limit of said band, and resistances in shunt, respectively, to said primary and secondary windings and proportioned with respect to each other and said leakage inductance so as to give said coupling circuit a substantially flat transmission characteristic over said band and to substantially match the impedance of said line to the impedance of the primary circuit of said transformer over the greater portion of said band.

4. A circuit for coupling a line to a secondary circuit having a capacity reactance to transmit a wide band of frequencies, and comprising a transformer having primary and secondary windings, said transformer having series inductive reactance and distributed shunt capacity, the total effective shunt capacity impedance including the shunt capacity reactance of said secondary circuit and the distributed capacity reactance of said transformer windings, and the total effective series inductive reactance being proportioned so as to be equal at the highest frequency of the band to be transmitted, and resistances respectively in shunt to said primary and secondary windings and so proportioned with respect to each other and said total effective series inductive reactance as to give a transmission characteristic having a maximum variation of one transmission unit over said band of frequencies.

5. In combination, a source of waves of a wide range of frequencies, a line receiving waves therefrom, an electric discharge device, an input transformer having primary and secondary windings for coupling said line to said device, the leakage inductance of said transformer being such as to resonate with the combined distributed capacity of said secondary winding and the input capacity of said device at a frequency near the upper limiting frequency of said range, and a resistance element in shunt to each of said windings, the resistances of said elements being so proportioned with respect to each other and the leakage reactance at the resonant frequency that the impedance into the primary winding and associated shunt resistance is substantially equal to the line impedance at frequencies in the lower portion of said range and that the ratio of the voltage of said source to the secondary voltage of said transformer is substantially constant throughout said range.

6. A combination according to the preceding claim in which the relation of the resistances of said elements is substantially represented by the equation:

$$\frac{Z_1}{R_1}=1-\frac{rZ_1}{R_2}$$

in which R_1 and R_2 are the resistances of the elements in shunt to the primary and secondary windings respectively, Z_1 is the impedance of the line, and r is the impedance ratio of the transformer.

7. In combination, a source of waves of a wide range of frequencies, a line receiving waves therefrom, an electric discharge device, an input transformer having primary and secondary windings for coupling said line to said device, the leakage inductance of said transformer being such as to resonate with the combined distributed capacity of said secondary winding and the input capacity of said device at a frequency near the upper limiting frequency of said range, and a resistance element in shunt to each of said windings, the relation of the resistance of said elements to each other and to the other elements of the circuit being substantially represented by the following equations:

$$\frac{Z_1}{R_1}=1-\frac{rZ_1}{R_2}$$

and

$$rZ_1=R_2\left[\frac{2\left(\frac{\omega L}{R_2}\right)^2-2\pm 2\sqrt{\left(\frac{R_2}{\omega L}\right)^2-1}}{\left(\frac{R_2}{\omega L}\right)^2+\left(\frac{\omega L}{R_2}\right)^2-1}\right]$$

in which R_1 and R_2 are the values of the resistances in shunt to the primary and secondary windings respectively, Z_1 is the impedance of the line, r is the impedance ratio

of the transformer, and ωL is the leakage reactance at the resonant frequency.

8. In combination, a line adapted for transmitting waves of a wide range of frequencies, an electric discharge device, an input transformer having primary and secondary windings for coupling said line to said device, the leakage inductance of said transformer being of such value as to resonate with the combined distributed capacity of the windings and the input capacity of said device at a frequency near the upper limiting frequency of said range, and a resistance element in shunt to each of said windings and of such relative value as to damp the resonance effect at said frequency, whereby the voltage amplification of said transformer is made substantially constant throughout said range.

In witness whereof, I hereunto subscribe my name this 5th day of April, A. D., 1927.

HORACE WHITTLE.