July 2, 1929. W. L. CASPER 1,718,946

TRANSMISSION CIRCUITS

Filed Sept. 25, 1924

Fig. 1

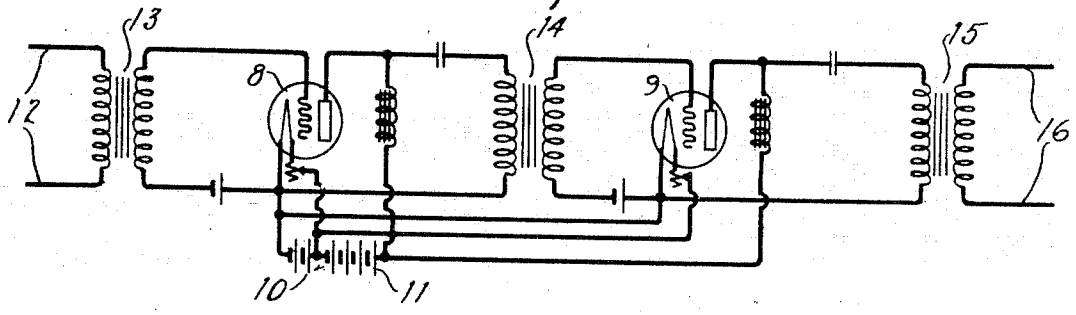


Fig. 2

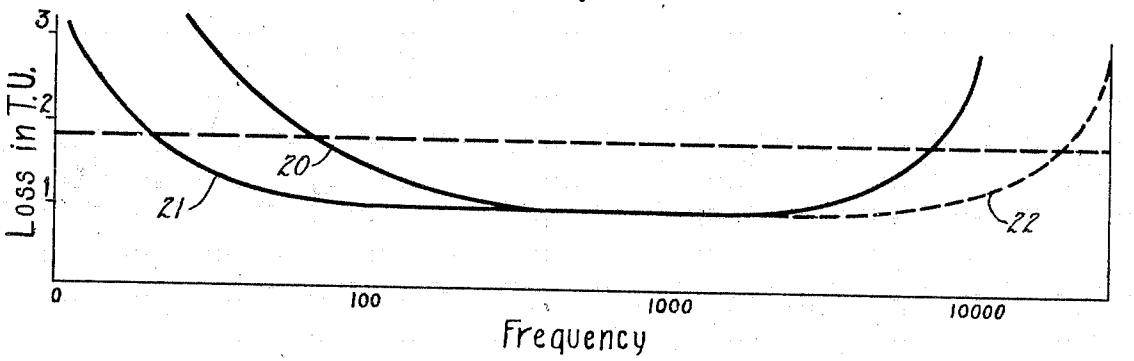
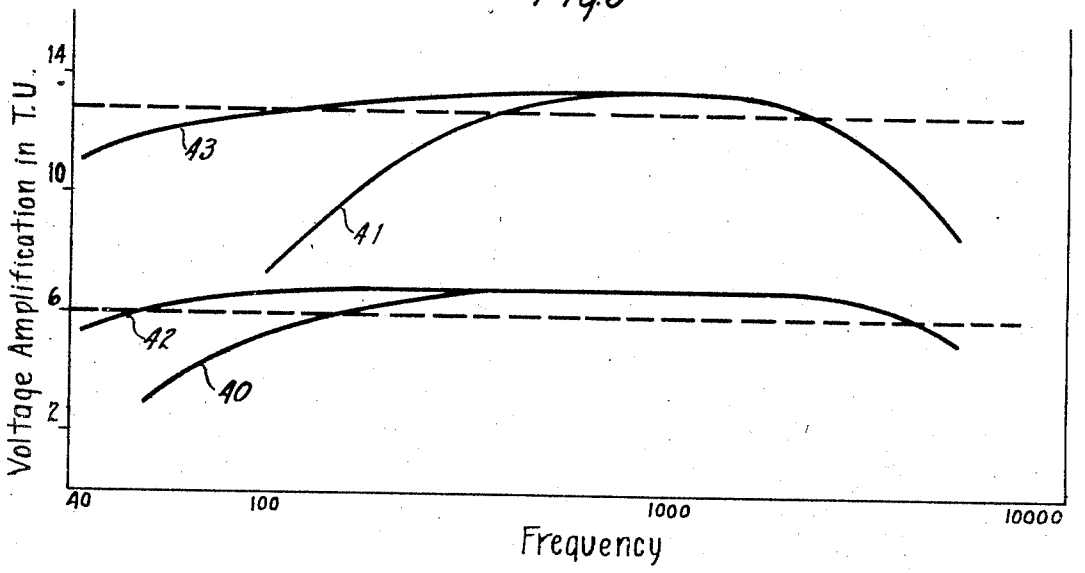


Fig. 3



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UNITED STATES PATENT OFFICE.

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TRANSMISSION CIRCUITS.

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This invention relates to electric circuits, and particularly to signaling circuits employing transformers.

In radio broadcasting, electrical phonographic recording and reprducing and similar operations, it is desirable to transmit a wide band of frequencies, and moreover it is, of course, frequently desirable to use transformers. If music or speech is to be recorded or reproduced with a high degree of naturalness, it is essential that the electrical system employed transmit a very wide band of frequencies without distortion. In the case of orchestral music, it is often especially desirable to reproduce the low frequency tones produced by such instruments as the pipe organ, the bass viol and the tuba.

One object of the invention is to increase the transmission efficiency of transformer circuits.

Another object of this invention is to widen the range of frequencies which can be efficiently transmitted by a transformer circuit.

A further object of the invention is to transmit the frequencies in the lower section of the audible range with the same efficiency as the frequencies in the middle and upper sections.

A further object of the invention is to transmit the frequencies in the upper section of the audible range with the same efficiency as the frequencies in the lower and middle sections.

Transformers heretofore made are not capable of transmitting a band of frequencies of such width that the ratio of the highest frequency to the lowest is greater than 250 to 1, if the degree of uniformity of transmission efficiency for a given transformer is such that the maximum variation in transmission loss with frequency in the band, introduced by the transformer is not in excess of one transmission unit. A transmission unit is defined so that the number of transmission units corresponding to a power ratio of P_1/P_2 is equal to 10 log $_{10}P_1/P_2$. In the specification and claims the ratio of the limiting frequencies of a band transmitted with the degree of uniformity defined above will be referred to as the band width ratio.

It has been found that, other things being equal, the transmission efficiency at the low frequencies can be increased by increasing the mutual inductance of the transformer.

In the case of a vacuum tube amplifier, to which the invention has particular application, there are two cases to consider, viz: 1, the case of the output transformer which couples circuits whose impedances are substantially resistances; and 2, the case of the input transformer which couples an incoming circuit of resistive impedance to the capacity-impedance represented by the grid-filament circuit of the vacuum tube.

In the first case above, the leakage impedance increases with frequency and determines the loss at the higher frequencies. The leakage is a function of the space relations of the windings of the transformer. In almost all practical cases it is not possible to get the close association of windings which would be necessary to make the leakage negligible on account of the increased electrostatic capacity and low dielectric strength that the close association produces. In any given case, therefore, it cannot be reduced beyond certain prescribed limits. The mutual impedance determines the loss at low frequencies since it is effectively a shunt inductance which offers smaller impedance as the frequencies are reduced. At the upper portion of the speech range the mutual impedance is in any practical case large enough not to have a determining effect on the loss. It follows, therefore, that if the mutual inductance can be increased in a transformer, the leakage remaining the same, the efficiency in the lower frequency region of the band is raised without affecting materially the efficiency at the upper frequencies and there is a gain in the band width efficiently transmitted since more of the lower frequencies are included in the range of substantially uniform transmission efficiency.

In the second case, that of the input transformer, the measure of efficiency at any frequency is the voltage amplification produced by the transformer at that frequency and applied to the grid-filament circuit, since the vacuum tube is a voltage-operated device. The losses at the various frequencies are determined by the circuit impedances at the different frequencies, and these impedances are determined by the circuit elements including the transformer. As in the previously discussed case, the losses at the upper frequencies are determined by factors other than the mutual impedance. The impedance of the tube circuit as seen from the primary of the transformer consists mainly of con-

ductance and capacity, the latter consisting of the tube capacity and the capacity of the transformer windings. By varying the relation of the leakage inductance of the transformer to these capacities, the higher frequency portion of the circuit characteristic can be controlled. At the lower frequencies, however, the loss is determined principally by the mutual impedance with relation to the resistive impedance of the input circuit. For a given input circuit, the losses at the lower frequencies can be decreased by increasing the mutual inductance, and the losses at the upper frequencies, since they depend mainly upon factors other than the mutual impedance, remain unaffected.

It is seen, therefore, that in either of the two cases above discussed, the efficiency of the transformer at the lower frequencies is raised and the band width increased if the mutual inductance is increased. It will be evident also that it is similarly possible to increase the efficiency of the transformer in the upper frequency region by reducing the leakage inductance without altering the mutual impedance. In the case of the input transformer, a reduction of the effective tube and transformer capacities may be necessary in addition to the reduction in leakage inductance. This reduction in capacity may be done by obtaining tubes of lower effective capacity reducing the transformer effective capacity or by neutralizing the effective capacity as by feed-back action. This reduction of leakage inductance may be done by the use of higher permeability core material and decreased number of turns in the windings. It is, therefore, evident that in either of the two types of circuits above described, the band width can be increased by extending the range of efficient transmission to include more of the lower frequencies or more of the higher frequencies, or some additional frequencies in both the lower and the higher regions, by controlling the mutual and leakage impedances in the manner above indicated. Both of the types of circuits mentioned above will now be discussed in greater detail.

Taking up first the case of the output transformer more in detail: such a case is typical of a transformer used to couple circuits of resistive impedances, that is, circuits in which the resistance component predominates over the reactance component. In any transmission circuit employing a transformer operating between two circuits whose impedances are of this type, the transmission loss introduced by the transformer increases with increase of the leakage impedance and decreases with increase of the mutual impedance, provided the effective capacity of the winding can be neglected. Both the leakage and mutual impedances are substantially pure inductive reactances so that at the upper frequencies the impedances are large and that portion of the loss which is variable with frequency is determined primarily by the leakage reactance, while at the lower frequencies both impedances are comparatively low and that portion of the loss which is variable with frequency is determined by the mutual impedance, the DC resistance of the windings producing a loss which is substantially independent of frequency. The width of the transmission band of the transformer circuit is, therefore, to a large extent, dependent upon the ratio of mutual to leakage inductance, and can be increased if that ratio can be increased.

The transformers used in signaling circuits such as telephone circuits or vacuum tube amplifiers are required to transmit only very small amounts of electrical energy. The force produced by this energy tending to magnetize the core of the transformer is so small that the core material operates approximately at the initial permeability. It has been found that with silicon steel, which is the core material formerly used having the highest initial permeability, it is impossible to build an efficient signaling transformer, which, when operating between resistance circuits, will efficiently transmit a band of frequencies having a band width ratio greater than 250. The best commercial signaling transformers heretofore in use transmit bands having band width ratios of from 160 to 200.

In accordance with a feature of this invention magnetic materials of greater initial permeability than that of silicon steel are employed in constructing transformer cores so that the ratio of mutual to leakage impedances may be increased with a consequent increase in band width ratio. One class of core materials of high initial permeability which has been found to be well suited to such use are the nickel-iron alloys containing from 30% to 90% nickel. By the use of these alloys it is possible to increase the ratio of mutual to leakage impedances 5 or 10 times over the best core material heretofore used. It has been found that these alloys when properly proportioned and properly heat treated develop high permeability particularly at low magnetizing forces. The characteristics and method of preparing these alloys are described in some detail in a paper by H. D. Arnold and G. W. Elmen entitled "Permalloy" and published in the May 1923, issue of the Journal of the Franklin Institute.

Taking up more in detail the case of the input transformer; in an input transformer the distributed capacity of the windings and inter-winding capacities are usually of a magnitude which is appreciable when compared with the tube capacity. These capacities may be combined for purposes of analysis into an effective capacity which may be considered to be connected across the secondary of the

transformer. This effective capacity, which will be called the winding capacity, and the capacity of the tube and the transformer inductance produce parallel resonance at a frequency in the transmitted frequency range, so that at this and the neighboring frequencies the effective amplification of the transformer approximates the transformer turns ratio or in other words the voltage impressed on the tube is practically equal to the voltage of the source multipled by the turns ratio of the transformer. By the capacity of the tube is meant the effective capacity between grid and filament with filament and plate batteries connected and the receiving circuit connected between plate and filament. At higher frequencies the mutual inductance of the transformer, the winding capacity and the tube capacity together have a capacity reactance and it has been found that a transformer which is designed to maintain its effective amplification at approximately the value of the turns ratio up to the highest possible frequency, so as to maintain uniform transmission efficiency of the circuit of the transformer and the amplifier up to the highest possible frequency, should have a leakage inductance which with the transformer and tube capacities forms a surge impedance equal to the impedance of the input circuit feeding the transformer when viewed through the transformer. Since the transformer leakage reactance can usually be adjusted to the desired value the upper frequency of the transmitted band is dependent chiefly upon these capacities and the transformer ratio. The winding capacity of the transformer can be reduced to a point where it is small compared to the tube capacity by reducing the space that it occupies, increasing its separation from surrounding metal, increasing the number of winding separators and by increasing the thickness of insulation between layers of the winding. The combined value of these capacities can therefore be determined principally by the tube design and only to a relatively small degree by the distribution of the transformer windings. For a given tube and a given winding ratio the upper frequency of the transmission band is therefore substantially fixed.

At the lower transmitted frequencies the mutual impedance of the transformer is of the same order of magnitude as the sum of the impedance of the input circuit feeding the transformer and the direct current resistance of the primary winding. The amplification at these lower frequencies is, therefore, dependent on the ratio of these two quantities of the same order of magnitude. Since the impedance of the input circuit is fixed and the DC resistance of the primary winding can readily be reduced to negligible value as compared to the circuit impedance, the amplification of the lower frequencies and consequently the lower end of the transmitted range is dependent primarily upon the value of the mutual inductance, which depends on the number of turns of the primary winding and the permeability of the core. Increasing the number of these turns and employing larger size wire in order to limit the direct current resistance and increasing the size of the coil to accommodate the increased winding, will increase the amplification at the low frequencies but this increase in size prevents the reduction of the winding capacity to a value which is of the same order of magnitude as or a lower order of magnitude than the tube capacity particularly if the increase in mutual inductance is to be obtained with no increase in leakage reactance, thus reducing the amplification at the higher frequencies and preventing an increase in and even causing a decrease in the width of the transmission band. In accordance with this invention core materials of greater initial permeability than those heretofore used are employed to increase the transmission band width.

Since the lowest frequency transmitted at a given loss is dependent upon the inductance of the primary winding, with a given winding space that frequency is dependent upon the coil ratio; for with all the winding space occupied there will be less room for the primary winding, the higher the coil ratio. It has been found that in a commercial transformer, with a silicon steel core, it is impossible, without reducing the limiting upper frequency transmitted below a value as determined from about twice the effective tube capacity, to make the lower transmitted frequency less than that represented by the following equation:

$$F=.0005\ Z\ (1+r)^2$$

where Z represents the impedance in ohms of the circuit from which the transformer is operating and r the turns ratio of the transformer, while by using high permeability materials such as permalloy, it is possible to build a transformer which transmits a frequency which is 1/5 or 1/10 of this frequency.

This invention will be more clearly understood by reference to the following description in connection with the drawing in which; Fig. 1 shows schematically a multistage amplifier circuit employing the invention; Figs. 2 and 3 show graphically the transmission efficiency of representative output and input transformer circuits, respectively.

Fig. 1 shows a two-stage amplifier comprising two vacuum tube amplifiers 8 and 9 connected in tandem. Direct current is supplied to the cathodes of these two tubes from the battery 10 and space current from bat-

tery 11. The amplifier is coupled to an incoming line 12 through an input transformer 13. The two vacuum tubes are coupled together by an inter-stage transformer 14 and the vacuum tube 9 is coupled to an outgoing line 16 by means of an output transformer 15. Transformers 13, 14 and 15 comprise primary and secondary windings wound on cores composed preferably of a nickle iron alloy so that they have high mutual inductances and transmit a wide band of frequencies.

The curves of Fig. 2 show the frequency loss characteristics of two transformers operating between resistances. This circuit condition is similar to that of the output transformer 15 when the amplifier is operating into the line or receiving device the impedance of which is practically independent of frequency. In the curves shown, the transformers were operating between resistances of 2,000 and 6,000 ohms. Curve 20 is for a transformer having a silicon steel core and curve 21 for a transformer having a core composed of nickel-iron alloy in which the nickel content is 78½%. The transformers are in other respects identical in construction. The dashed line represents a loss of one transmission unit more than the minimum loss. It will be noted that the two curves practically coincide at the middle and upper frequencies as at these frequencies the mutual impedances of the transformer is so high as to have practically no effect on the transmission characteristics, as was pointed out above. However, at the lower frequencies it will be noted that the nickel iron core transformer gives a much smaller loss than the silicon steel core transformer.

The transmission band could also be widened by increasing the efficiency of the transformer in the upper frequency region by using a high permeability core and at the same time proportionally decreasing the number of turns of the windings so as to keep the mutual inductance the same. This decrease in the number of turns would decrease the leakage reactance and consequently widen the band of efficient transmission by increasing the efficiency in the upper frequency regions. Such a transformer would have a characteristic curve of the type indicated by the dash curve 22 which coincides with the curve 20 in the lower and middle frequencies.

The curves of Fig. 3 show the voltage amplification in transmission units of various input transformers, curves 40 and 41 representing the amplification characteristics of silicon steel core transformers of ratios of 2.3:1 and 5:1 respectively, operating from an impedance of 20,000 ohms into a Western Electric Company 215-A vacuum tube. Curves 42 and 43 represent the amplification characteristics of two nickel iron core transformers, having cores composed of nickel iron alloy containing 78½% nickel, of the same respective ratios working between the same circuits. The dashed lines represent an amplification of one transmission unit lower than the maximum amplification. These curves show the very marked increase in efficiency obtained over the lower frequency portion of the band by using the high permeability core material. It will be noticed that characteristics of the silicon steel transformer and the permalloy core transformer practically coincide at the frequencies of the middle and upper range but that the lower frequency transmitted by the nickel iron core transformer is much lower than that transmitted by the silicon steel core transformer. If the improvement in efficiency at the lower frequencies had been obtained by using a larger transformer of silicon steel with a greater number of turns the efficiency at the upper frequencies would have been considerably reduced. In obtaining the data for the curves of both Figs. 2 and 3 the transformers used had butt-joined laminated cores which introduce small air-gaps into the magnetic circuits. Because of the high permeability of the nickel-iron alloys, these small air-gaps produce a much larger proportionate reduction in the inductance of nickel-iron core transformer than of the silicon steel core transformer. By using continuous laminations or lap joints it would, therefore, have been possible to increase the inductance of the nickel-iron core transformers to a much greater extent than that of the silicon steel core transformers. This would have given a considerably wider band for the nickel-iron core transformer but only a slightly increased band width for the silicon steel core transformer. These curves, therefore indicate considerably less than the maximum increase in band width which can be obtained by using materials of high initial permeability.

It is evident that while the specific examples of this invention herein discussed are audio frequency transformers the invention is not so limited but is equally applicable to transformers adapted for use in other frequency ranges, carrier or radio, for example. In general transformers for the higher ranges have windings of a reduced number of turns and the same type of characteristic curves apply to all cases. For other ranges the frequency scale would be multiplied by a given factor.

The invention claimed is:

1. A transformer for intercoupling a circuit of substantially resistance impedance and a circuit having appreciable capacity reactance, said transformer having a core composed of a magnetic material having a higher permeability than silicon steel at low magnetizing forces and primary and secondary windings arranged on said core so that the leakage reactance forms with the input impedance of said vacuum tube amplifier, a

surge impedance which when viewed through the transformer is practically equal to the impedance of said circuit of appreciable capacity, the mutual impedance of said transformer being so high that the lowest frequency transmitted by said transformer with 1 transmission unit distortion is at least as low as .0003 Z $(1+r)^2$ where Z is the impedance of the circuit section in ohms and r is the turns ratio of the transformer.

2. A transformer according to claim 1 having a core composed of a nickel-iron alloy having a nickel content between 35 and 90 percent of the whole.

3. A transformer acording to claim 1 having a core composed of a nickel-iron alloy in which the nickel component is of the order of 78% of the whole.

4. A transformer for intercoupling a circuit of substantially resistive impedance with a circuit having an impedance practically inversely proportional to frequency, said transformer having a core composed of a magnetic material having a higher initial permeability than silicon steel and primary and secondary windings arranged on said core, the leakage reactance of said transformer forming with the input impedance of said second mentioned circuit a surge impedance, which when viewed through the transformer is practically equal to the impedance of said second mentioned circuit, the mutual impedance of said transformer being so high that the lowest frequency transmitted by said transformer between said circuits with one transmission unit distortion is lower than .0004 Z $(1+r)^2$ where Z is the impedance in ohms of said first mentioned circuit and r is the turns ratio of said transformer.

5. A transformer having primary and secondary windings for inclusion in respective circuits, said transformer having a core composed of a magnetic material comprising nickel and iron proportioned and heat treated in a manner known in the art to possess high permeability at low magnetizing forces compared with silicon steel, said transformer having its mutual and leakage impedances proportioned relative to each other and to the other constants of said circuits to transmit between said circuits, with a maximum distortion not greater than 1 transmission unit, all components in a frequency band of which the ratio of the highest frequency to the lowest frequency is as great as of the order of 250 : 1, the lower limit of said band being as low as of the order of 15 cycles per second.

6. A transformer having primary and secondary windings for inclusion in respective circuits, said transformer having a core composed of a magnetic material comprising nickel and iron proportioned and heat treated in a manner known in the art to possess high permeability at low magnetizing forces compared with silicon steel, said transformer having its mutual and leakage impedances proportioned relative to each other and to the other constants of said circuits to transmit between said circuits, with a maximum distortion not greater than 1 transmission unit, all components in a frequency band of which the ratio of the highest frequency to the lowest frequency is as great as of the order of 250 : 1, the lower limit of said band being as low as of the order of 30 cycles per second.

7. A transformer according to claim 5 in which the nickel content is between 35% and 90% of the whole.

8. A transformer according to claim 5 in which the nickel content is of the order of 78% of the whole.

9. A transformer according to claim 6 in which the nickel content is between 35% and 90% of the whole.

10. A transformer according to claim 6 in which the nickel content is of the order of 78% of the whole.

11. A transformer for transmitting a wide range of frequencies substantially uniformly into a circuit having a portion whose impedance decreases with increasing frequency, said transformer having primary and secondary windings, and means comprising a core of an alloy of nickel and iron in which nickel predominates, said core having higher initial permeability than commercial silicon steel, said transformer having such a high ratio of mutual to leakage impedance that the circuit as a whole transmits a band of components in the speech and music range of a band width ratio as great as 300 : 1.

12. A transformer for transmitting currents of frequencies extending over a band the ratio of whose highest to lowest frequency is at least as great as 250 to 1 within one TU amplitude variation, the space dimensions and relations of the windings being made as in prior art practice to secure substantially the optimum leakage impedance as regards its effect upon determining the upper limiting frequency of the band, and means for extending the transmission band in the low frequency region without effecting materially the leakage impedance or the upper limiting frequency, said means comprising a core of space dimensions to accommodate the aforementioned space dimensions and relations of the windings, said core being composed of an alloy of nickel and iron in which nickel predominates, heat treated to possess an initial permeability which is high compared to that of silicon steel at low magnetizing forces.

In witness whereof, I hereunto subscribe my name this 24 day of September, A. D., 1924.

WILLIAM L. CASPER.