Aug. 7, 1928. 1,679,434

R. G. McCURDY

ELECTRIC WAVE FILTER FOR VARIABLE LOAD CIRCUITS

Filed April 21, 1926 2 Sheets-Sheet 1

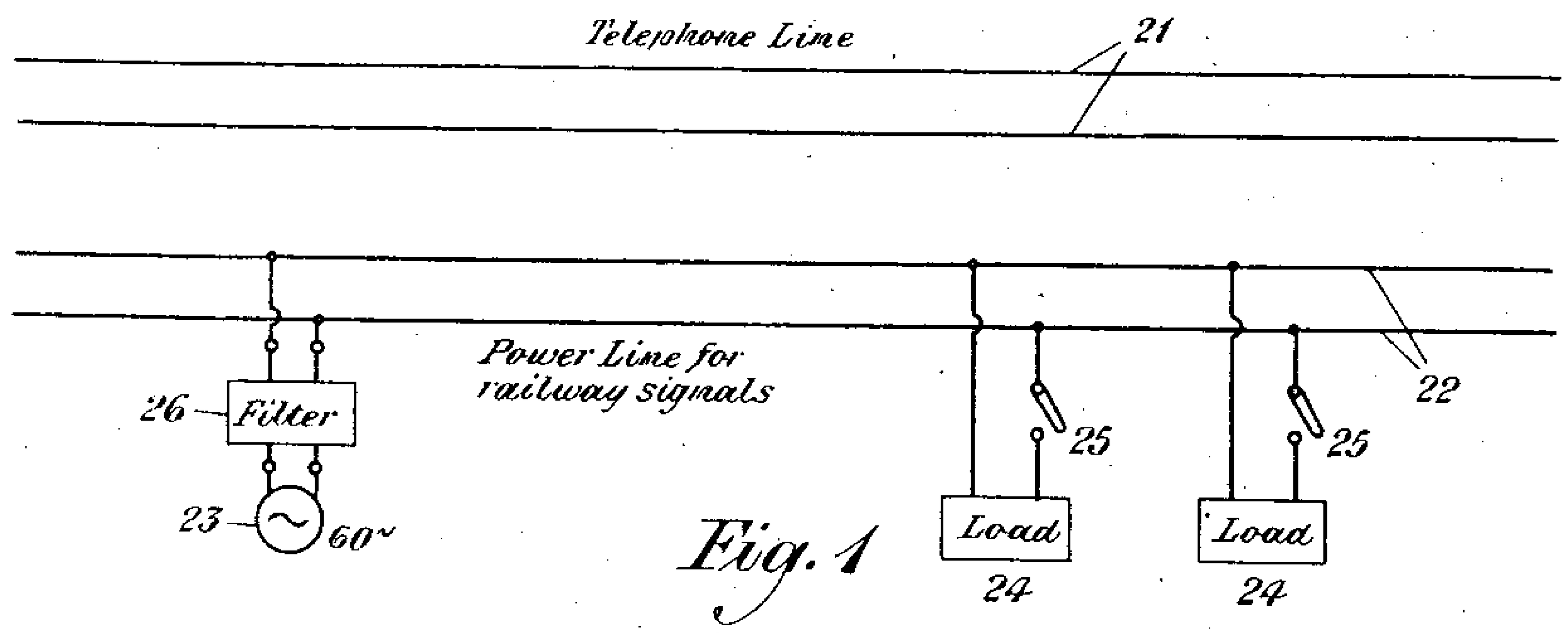

Fig. 1

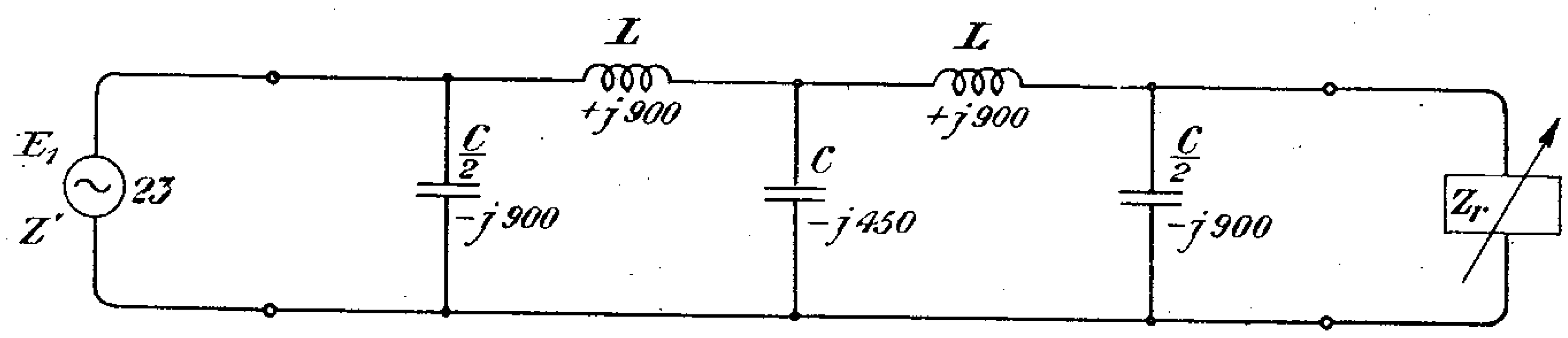

Fig. 2

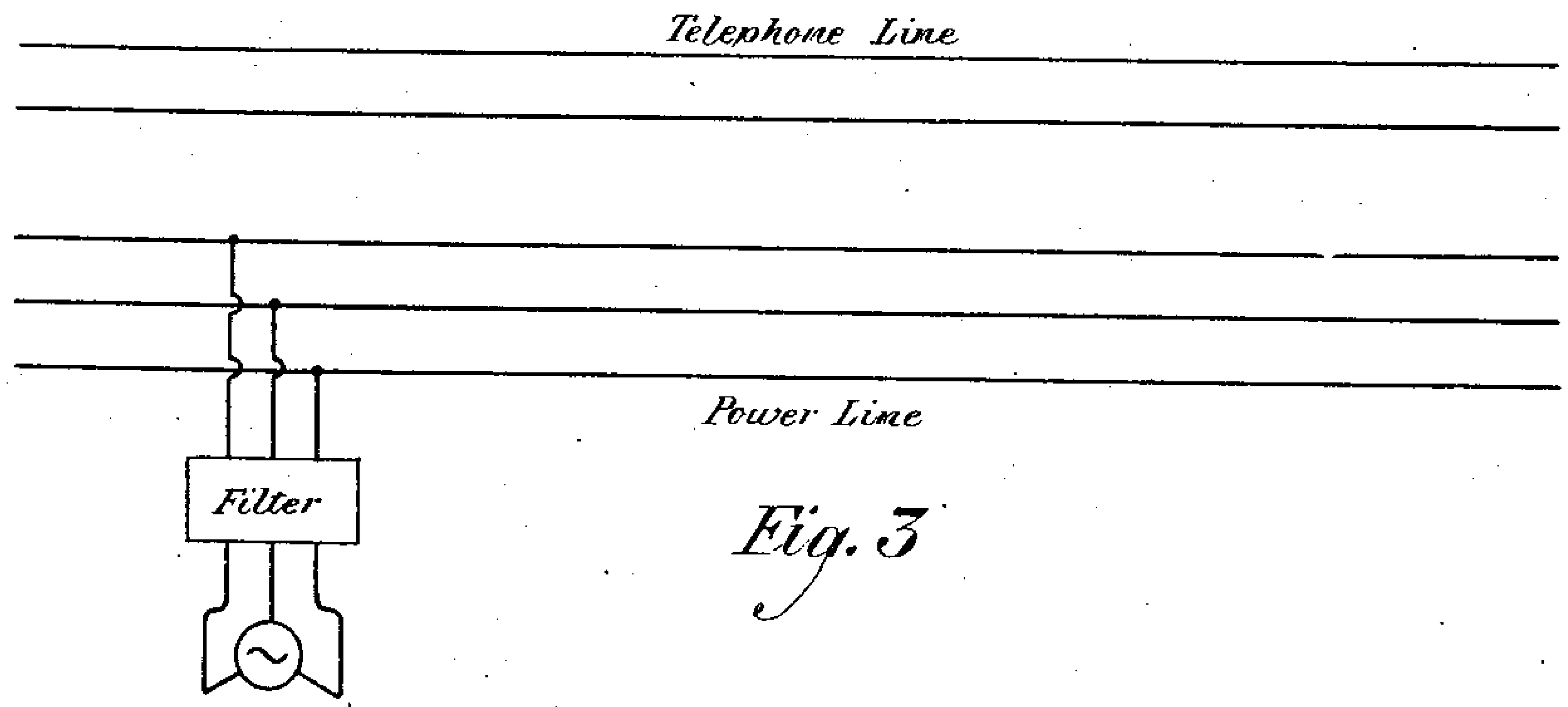

Fig. 3

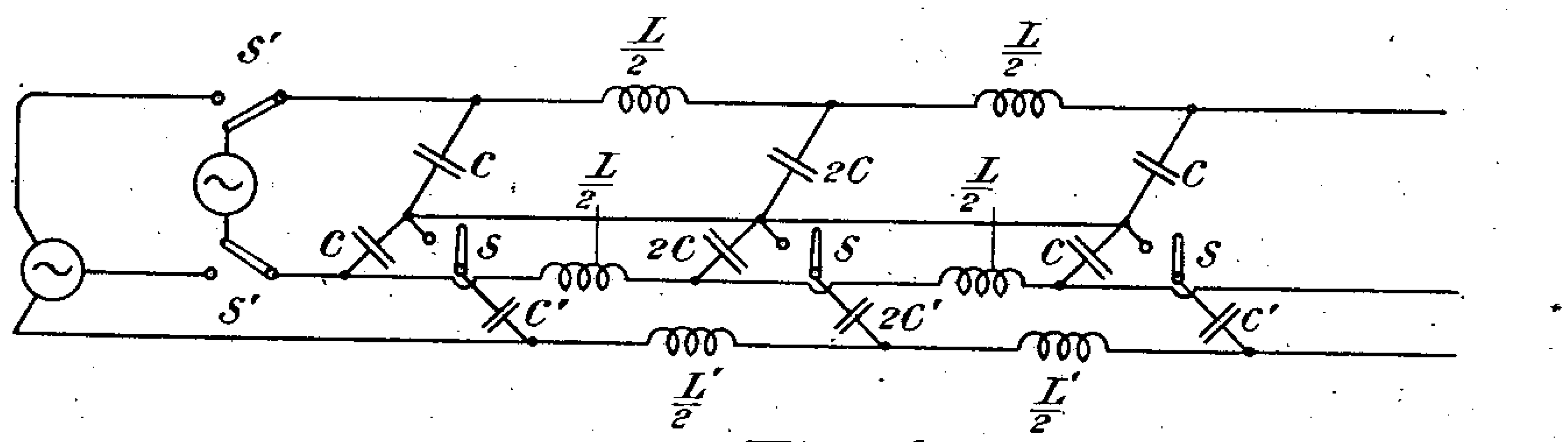

Fig. 4

INVENTOR
R. G. McCurdy
BY
J E Fole
ATTORNEY

Aug. 7, 1928.

R. G. McCURDY

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2 Sheets-Sheet 2

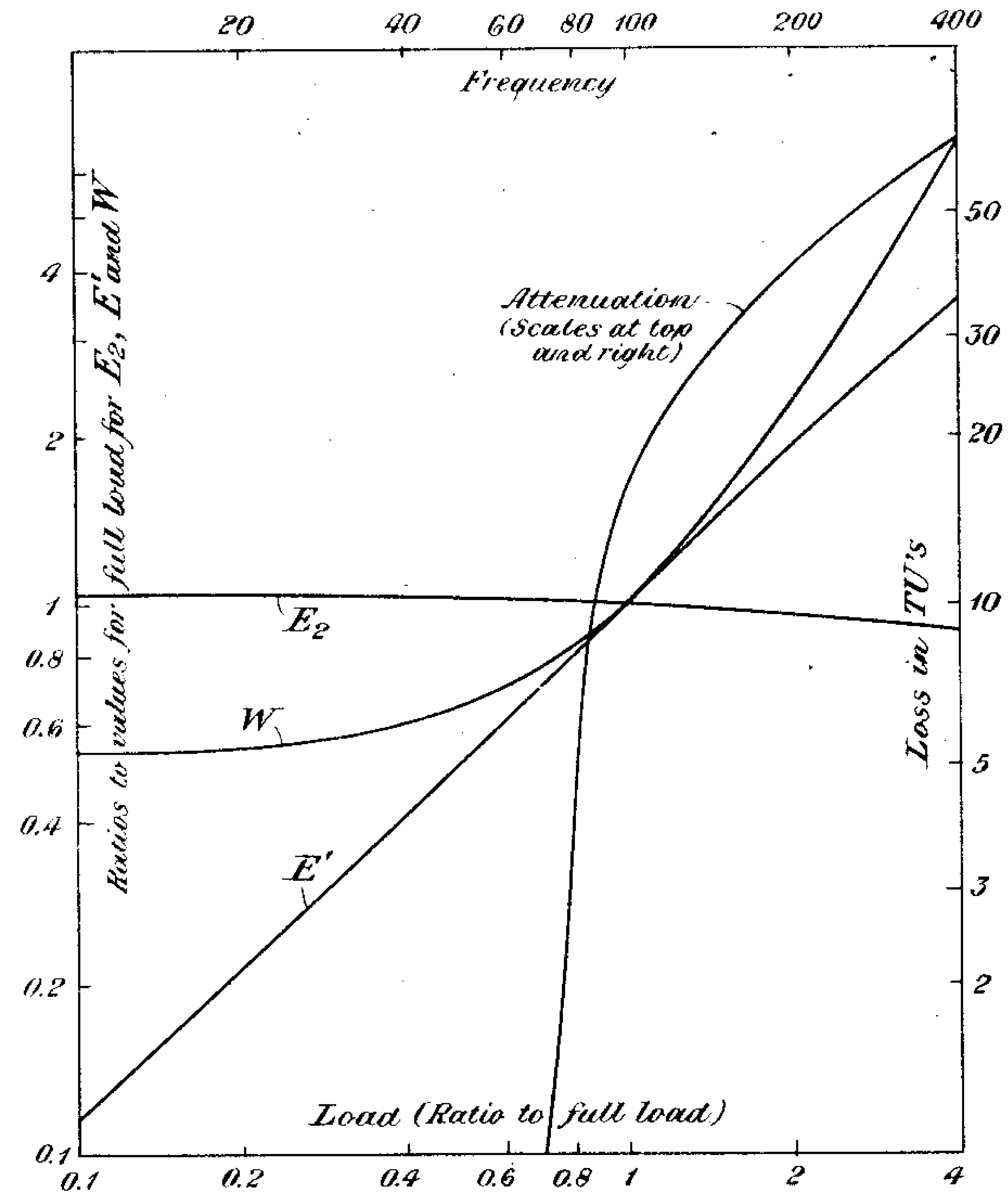

Fig. 5

INVENTOR
R. G. McCurdy

BY

ATTORNEY

Patented Aug. 7, 1928. **1,679,434**

UNITED STATES PATENT OFFICE.

RALPH G. McCURDY, OF ENGLEWOOD, NEW JERSEY, ASSIGNOR TO AMERICAN TELEPHONE AND TELEGRAPH COMPANY, A CORPORATION OF NEW YORK.

ELECTRIC WAVE FILTER FOR VARIABLE-LOAD CIRCUITS.

Application filed April 21, 1926. Serial No. 103,615.

An object of my invention is to provide a new and improved system for suppressing harmonics on a power circuit. Another object of my invention is to provide an electric wave filter to be interposed in a line without affecting the load impedance on the source for the current of frequency desired to be transmitted. Another object of my invention is to suppress harmonics on a power line that parallels a telephone line without altering the impedance which the power line presents to the source supplying it. These objects and various other objects of my invention will become apparent on consideration of a limited number of examples of practice according to the invention which I have chosen here to disclose to illustrate the nature and use of the invention. It will be understood that the present specification relates largely to these examples of the invention, and that the invention will be defined in the appended claims.

Referring to the drawings, Figure 1 is a diagram of a power line paralleling a telephone line, and equipped according to my invention; Fig. 2 is a detail diagram of the filter shown symbolically in Fig. 1; Fig. 3 is a diagram of a 3-phase system corresponding to the single-phase system shown in Fig. 1; Fig. 4 is a detail diagram of the filter for the 3-phase system shown symbolically in Fig. 3; and Fig. 5 is a curve diagram to show performance in a certain case.

As an example of practice under my invention I show in Fig. 1 a telephone line 21 extending several hundred miles, and in parallel therewith a power line 22 for the operation of railway signals along the right-of-way. The current for this line 22 is of 60 cycles from the generator 23, and in the particular example that I have in view, it is put on the line 22 at as high as 4,400 volts. The load on the line varies over a rather wide range from time to time, and this is indicated symbolically by the loads 24 with switches 25, by which they may be temporarily connected across the line 22. Under some conditions the power put on the line 22 from the generator 23 may be as high as 21.5 kilovolt-amperes.

Obviously, there will be a considerable tendency to induce currents in the telephone line 21. So far as currents of the fundamental frequency of 60 cycles per second are concerned, these are below the essential voice frequency range, and by well-known methods they can be eliminated or compensated or otherwise dealt with effectively in the telephone line 21. But it will ordinarily be the case that harmonics will be present, especially odd harmonics, in the output from the generator 23. These harmonics, being of higher frequency, will be comprised in the essential voice frequency range and will introduce complexities if they appear in the telephone line 21, and be difficult to eliminate or compensate or deal with effectively in that line.

Filters are ordinarily designed for stable impedance conditions in the load connected on their output sides. In an ordinary filter, if the impedance connected to the output should vary, the electromotive force across the output terminals would also vary even though it were kept constant on the input side of the filter. Hence the introduction of an ordinary filter, as at 26 in Fig. 1, is impracticable, for, as the load varies on the line 22, it would cause a variation of electromotive force on the line even though the generator 23 is of the usual constant voltage type. I have divised a filter that will suppress the harmonics but will transmit the fundamental, and such that the impedance looking into the filter across its input terminals is always substantially the same for the fundamental frequency as the impedance looking into the line from the filter output terminals, no matter how the load on the line may vary.

A particular filter that is adapted to be introduced at 25 is shown in Fig. 2. This is a low-pass filter, consisting of two "mid-shunt" sections. That is, there are two sections, each of π type, and each consisting of a series inductance L and two shunt capacities in the two legs each of value C/2. In Fig. 2 the two adjacent capacities, each of value C/2 in parallel, are united in the single capacity C.

It is a feature of design of the filter shown in Fig. 2 that its cut-off frequency is $\sqrt{2}f$ where f is the frequency that is to be passed; 60 cycles in this case. This cut-off frequency is related to the values L and C by the well-known equation for the low-pass filter,

$$\sqrt{2}f=\frac{1}{\pi\sqrt{LC}} \quad (1)$$

The foregoing equation imposes one condition of design on the coil L and the condenser C. Another condition lies in making them of such values that they will safely transmit currents as high as to give 21.5 kilowatts with unity power factor at 4,400 volts. As will be shown a little farther along in this specification, this leads to the assignment of impedance values at 60 cycles as follows: for each of the coils L, $+j$ 900 ohms; for the condenser C, $-j$ 450 ohms; and for each of the condensers C/2, $-j$ 900 ohms.

With these impedance values for the elements of the filter, and with an impedance of Z' connected to the filter input, and Z_r connected to the filter output, and with an electromotive force E_1 applied at the filter input, the complete data are furnished for solving the network of Fig. 2, and it will be found that the current I_2, through the terminal impedance Z_r, is given by the equation,

$$I_2 = -\frac{E_1}{Z'+Z_r} \quad (2)$$

The result given in Equation (2) may be obtained by formula 16 on page 284 of K. S. Johnson's "Transmission Circuits for Telephonic Communication", published by D. Van Nostrand, New York. Thus it will be seen that for current of 60 cycles the interposition of the filter in Fig. 2 is of no effect on the magnitude of the current through the load. No matter what the value of the load Z_r may be, the current will be the same as if it were connected directly to the source E_1 through the source impedance Z'.

Thus far the discussion has been based on the assumption that the coils and condensers of the filter are pure reactances. With reasonable care coils may be constructed to have a resistance value R, such that

$$\frac{2\pi f L}{R} = 57 \quad (3)$$

The diagram of Fig. 5 is obtained subject to Equation (3). This is a logarithmic diagram, and with the legends thereon expressed it shows that as the load varies from 0.1 of full load up to 1.1 times full load, the value of the voltage E_2 across the filter output terminals remains very nearly constant. All the curves of Fig. 5 are drawn for unity power factor. The diagram also shows the variation in the voltage E' across the condenser C, and the variation in the energy loss W in the coils of the system. Also superposed on Fig. 5 is a curve showing the attenuation through the filter for various frequencies. It will be seen that at 60 cycles the attenuation is negligible. At 70 cycles the loss is only about 0.1 T U (transmission unit). But at the frequency of the lowest odd harmonic, that is at 180 cycles, the attenuation is as high as 37 or 38 T U's.

The particular installation that I have in view as an example of practice under my invention is on a single-phase power line, for which it may be desirable later to add another conductor and make it 3-phase. Therefore, the installation is made as shown in Fig. 4, where each inductance L is represented by two coils each of value L/2, and the condenser C is represented by two condensers in series, each of value 2C, and each condenser C/2 of Fig. 2 is represented by two condensers in series in Fig. 4 each of value C.

If, at a later stage, the system is changed to 3-phase, it will then be necessary only to add the coils and condensers marked with primed letters, and to make the changes of connection that will be obtained by throwing the three switches S and the two switches S'.

For any periodic artificial line of n sections, starting at mid series or mid shunt, the following formulas hold:

$$\frac{E_1}{E_2} = \cosh n\Gamma + \frac{Z_0}{Z_r}\sinh n\Gamma \quad (4)$$

$$\frac{I_1}{I_2} = \cosh n\Gamma + \frac{Z_r}{Z_0}\sinh n\Gamma \quad (5)$$

$$Z_s = Z_0\frac{Z_r + Z_0\tanh n\Gamma}{Z_0 + Z_r\tanh n\Gamma} \quad (6)$$

where Γ is the propagation constant per section, Z_0 is the characteristic impedance, Z_s is the sending end impedance, Z_r is the load impedance (at the receiving end), E_1 and I_1 are voltage and current at the sending end, E_2 and I_2 are voltage and current at the receiving end, and $Z_r = E_2/I_2$.

For perfect regulation E_1/E_2 and I_1/I_2 must be independent of the load, that is, they must be independent of Z_r. Hence from Equation (4), it must be that

$$\sinh n\Gamma = 0 \quad (7)$$

assuming Z_0 and Z_r are finite and not zero, which is obviously a proper assumption. When Equation (7) obtains, it follows that $\cosh n\Gamma = \pm 1$ and $\tanh n\Gamma = 0$, and Equations (4), (5) and (6) reduce to $E_1/E_2 = I_1/I_2 = \pm 1$ and $Z_s/Z_r = 1$.

The solutions for Equation (7) are given by

$$n\Gamma = j k \pi \ (k = 0, 1, 2 \ldots) \quad (8)$$

Let the periodic artificial line be of "ladder-type" with series impedances z_1 and shunt impedances z_2. For such a line

$$\Gamma = \cosh^{-1}\left(1 + \frac{1}{2}\frac{z_1}{z_2}\right) \quad (9)$$

To arrive at the filter shown in Fig. 3

subject to the foregoing Equations (4) to (9), let the ladder-type artificial line be a low-pass filter with series inductances each of value L and shunt capacities each of value C. Then from Equation (9)

$$\cosh \Gamma = 1 - \frac{1}{2} 4\pi^2 f^2 LC \quad (10)$$

where f is the frequency. Let the critical or cut-off frequency of the filter be f_0, for which

$$f_0 = \frac{1}{\pi\sqrt{LC}} \quad (11)$$

Now consider the frequency f' such that $f' = f_0/\sqrt{2}$. Substituting this value in Equation (10), and by the aid of Equation (11), we get that $\cosh \Gamma = 0$ and $\Gamma = j\frac{\pi}{2}$. From this we see that an even number $2k$ of sections of the network considered will give the equation

$$2k\Gamma = jk\pi.$$

This satisfies Equation (8) above when n of that equation is an even number. Moreover, the characteristic impedance at $f' = f_0/\sqrt{2}$ is found to be (Equation (9) on page 125 of the said Johnson book)

$$Z_0 = \sqrt{\frac{2L}{C}} \quad (12)$$

which is finite and hence the conditions for unattenuated transmission at all loads are fulfilled.

In the design of the filter, the characteristic impedance is determined from the equation $E^2/Z_0 = P$ where P is the power. In the present case, letting P=21.5 kilowatts and E=4,400 volts, we get the value of Z_0 at 900 ohms. Substituting this in Equation (12), and assigning a chosen value for f_0 in Equation (11), namely $f_0 = 60\sqrt{2}$, it is seen that these two equations (11) and (12) serve to fix the values of L and C.

The condition of perfect regulation is obtained when the phase shift through the filter for the frequencies to be transmitted is 180°. This may be obtained by using a number N of sections, the requirement being that the phase shift through one section be $\frac{180°}{N}$. The number of sections must be increased when the cut-off frequency is increased, approaching infinity as the line approaches a smooth line. By properly choosing the number of sections, any desired cut-off frequency from the square root of two times the transmitted frequency may be approximated. In the foregoing specific example of my invention, it will be seen that I have chosen to make the filter of two sections and the cut-off frequency $\sqrt{2}$ times the fundamental frequency.

After the foregoing Equation (9) we assumed a low-pass filter; but we might, for example, assume a confluent band pass filter with mid-section terminations and we should find that if its critical or cut-off frequencies were chosen so that the frequency to be passed was a mean proportional between them, then it would transmit freely for all loads at the frequency to be passed. In this case, a reasonable assumption would be that the upper cut-off frequency is double the frequency to be passed; this would cut off the lowest odd harmonic by a safe margin. This assumption easily leads to the condition that each series coil shall have 8 times the inductance of each shunt coil.

I claim:

1. A wave filter to pass current of a certain frequency and to stop harmonics thereof, with substantially zero impedance change for current of said frequency through the filter notwithstanding changes of the output impedance, said filter being of low-pass ladder type, and consisting of two mid-shunt sections and having its cut off frequency at $\sqrt{2}$ times said certain frequency.

2. A network to be interposed between an alternating current source of constant voltage and a variable impedance load to pass current of fundamental frequency f and to stop harmonics thereof and to keep the network input impedance substantially the same as the load impedance, said network being of ladder type with three cross members of successive capacity values C/2, C and C/2, and two alternately disposed series members each of inductance value L, subject to the condition that $f = 1/\pi\sqrt{2LC}$.

3. A wave filter to pass current of a certain frequency and to stop harmonics thereof, with substantially zero impedance change for current of said frequency through the filter notwithstanding changes of the output impedance, said filter being of low-pass ladder type, and consisting of an even number of sections and having its cut off frequency at $\sqrt{2}$ times said certain frequency.

4. A wave filter to pass current of a certain frequency and to stop harmonics thereof, with substantially zero impedance change for current of said frequency through the filter notwithstanding changes of the output impedance, said filter being of ladder type with mid-section terminations and with a pass range of frequencies comprising said certain frequency and with the critical frequencies at the end of the pass range so related to the said certain frequency that said impedance relation is maintained.

5. In the transmission of alternating current of a certain frequency from a constant

voltage source the method of suppressing harmonics without introducing substantial variation of voltage on the load with variation of load impedance which consists in filtering the current with permissive transmission of frequencies up to $\sqrt{2}$ times the said certain frequency and cut-off of frequencies above that value, and with phase-relations throughout the filtering process to keep the input and output at the desired frequency in phase or in phase opposition.

In testimony whereof, I have signed my name to this specification this 20th day of April, 1926.

RALPH G. McCURDY.