

1

2,838,658

AUTOMATIC TUNING AND LOADING COUPLING NETWORK FOR A COMPLEX LOAD

Vernon H. Vogel, Phoenix, Ariz., and Francis J. Biltz, Glen Lake, Minn., assignors, by mesne assignments, to the United States of America as represented by the Secretary of the Air Force

Application February 23, 1954, Serial No. 412,133

6 Claims. (Cl. 250—17)

This invention relates to resonant circuits and more particularly to automatic tuning and loading coupling networks for complex loads.

It is an object of this invention to provide an automatic tuning and load coupling network for a complex load in which automatic control is achieved which is independent of the magnitude of power which is supplied to the load.

It is a further object of this invention to provide an automatic tuning and loading coupling network for a complex load in which the circuit for sensing the loading conditions is responsive to the resistive component of the load and will cause adjustment of the coupling network to maintain the resistive component of the load at a predetermined value, irrespective of the reactive component of the load.

The above objects, as well as other objects, features and advantages of this invention will be more fully understood in view of the following description when taken in conjunction with the drawings wherein:

Fig. 1 is a simplified schematic drawing of an automatic tuning and loading coupling network constructed in accordance with this invention.

Fig. 2 is a series of vector diagrams illustrating the phase relationship of voltages at various points in the apparatus of Fig. 1.

Fig. 3 is a family of curves illustrating the voltage E_0 of Fig. 1 as a function of reactance change from zero phase angle.

As shown in Fig. 1, a source of high frequency energy such as a transmitter 1 supplies its energy to a complex load such as an antenna 2 through a suitable transmission line such as a coaxial cable 3. There is provided between the transmission line 3 and the antenna 2 an adjustable L section coupling network 4 which may consist of a variable series capacitor 5 and a variable shunt inductance 6. A transformer 7 provides a potential e_{g1} and another potential e_{g2} which are both 90° out of phase with the current in the transmission line 3 and are 180° out of phase with each other. The transformer 7 is so constructed as to have a very low impedance compared to the load impedance and will therefore cause the least disturbance possible to the current in the transmission line 3 and, furthermore, the coupling between the primary winding and the secondary winding of transformer 7 is as tight as possible in order to obtain the largest possible values for the voltages e_{g1} and e_{g2} . In order to obtain the above phase relationship it is necessary that the loading on the secondary winding of transformer 7 be very small, that the resonant frequency of the secondary winding, due to its distributed capacity and the tube capacity, be kept well out of the operating range, and that the capacity coupling between the primary and secondary windings be kept to negligible proportions.

A tube 8 is provided having its grid 9 energized by the voltage e_{g2} and a tube 10 is provided having its grid 11 energized by the voltage e_{g1} . The anode 12 of tube 8 and the anode 13 of tube 10 are both energized by the line

2

voltage and are isolated D. C. wise from the line by means of capacitors 14 and 15.

Referring now to Fig. 2, there is illustrated three phase conditions, namely, when the line current I_1 is in phase with the line voltage E_1 when the line current I_1 leads the line voltage E_1 and when the line current I_1 lags the line voltage E_1 . As stated above, the same voltage is applied to the anodes of tubes 8 and 10 and equal but opposite voltages are applied to the grids of tubes 8 and 10, thus the average plate current of one tube compared to the average plate current of the other tube is dependent only upon the relative phase angles of the tube grid voltages to the plate voltages. When the line current I_1 and the line voltage E_1 are in phase, both grids are 90° out of phase with the plate voltage so that each tube conducts equally, hence there is no difference in average plate potential and, therefore, the differential voltage E_0 is zero. When the line current leads the line voltage it will be observed that the grid voltage on tube 10 is more nearly in phase with the plate voltage on that tube, thus lowering the average plate resistance of tube 10 during the positive half of the anode voltage cycle, while the grid voltage e_{g2} being more out of phase, increases the average plate resistance of tube 8. The D. C. circuits of tubes 8 and 10 are identical so that the D. C. voltages E_3 and E_4 are proportionate to average D. C. anode currents through tubes 10 and 8 respectively. The grids of tubes 8 and 10 are self biased by grid rectification, however, this grid current is low and, therefore, the loading of transformer 7 is small enough to prevent any appreciable phase shift from the theoretical 90° between the grid voltages and the line current. It will thus be apparent that the differential voltage E_0 is a function of the line voltage, the line current, the mutual impedance of the transformer 7 and the phase angle.

When the phase angle is not zero, the differential voltage E_0 will be dependent upon the line voltage, line current, and phase angle. A typical family of curves of error voltage output has a function of reactance change from zero phase angle is shown in Fig. 3. The line voltage was held constant for these curves.

The output voltage E_0 is zero and independent of the values of line voltage, line current and frequency so long as the phase angle is zero, however, the voltages E_3 and E_4 which make up the differential voltage E_0 are greatly dependent upon these factors, that is to say, there will be a common mode voltage about which the output voltage will fluctuate which will be dependent upon frequency and power level. To effectively utilize the above described circuit over a large power and frequency range without introducing serious error, a differential amplifier including tubes 16 and 17 is employed which, by virtue of a common cathode resistance circuit including resistor 18, will produce an output voltage in the differential amplifier which is much more sensitive to changes in difference between the voltages E_3 and E_4 than to changes in their common level.

The anodes of tubes 16 and 17 are connected through suitable coupling networks to the grids of tubes 19 and 20 respectively. Tubes 19 and 20 are normally biased to cut-off by a positive potential applied to their cathodes. Winding 21 of relay 22 is connected to the anodes of tubes 19 and 20 such that should a potential difference occur between those anodes, the relay 22 will be energized, closing its contacts 23 and thereby applying the 65 volt 400 cycle source to the winding 24 of motor M1. Winding 24 of motor M1 is series-resonated by capacitor 25 to produce the necessary 90° current phase relationship for the 2-phase motor. The other winding 26 of motor M1 is split. Tubes 19 and 20 are preferably of the thyatron type and firing of one of those thyatrons causes half-wave 400 cycle pulses to flow in half of the

3

split winding. Firing of the other thyatron causes the half-wave pulses to flow in the other direction in the other half of the split winding. The motor will therefore rotate in either direction, depending upon which half of the winding is excited. Because the half-wave pulses produce a relatively high direct current in the motor winding which reduces motor torque, a capacitor 27 is connected across the split winding which, by its "flywheel" effect, will cause a more nearly alternating current to be impressed upon the motor winding.

From the above description, it will be apparent that should the line current and line voltage be out of phase, the motor M1 will rotate in one direction or the other, dependent upon whether the line current leads or lags the line voltage. Rotation of motor M1 causes tuning of the capacitor 5 in the coupling network 4 and, therefore, the network will be automatically tuned such that the line current and line voltage will remain in phase.

The proper match of a complex load impedance to a line is achieved when (1) the line current and line voltage are in phase, i. e. the effective load is resistive and (2) the ratio of the line voltage to the line current equals the characteristic impedance; i. e. the effective load is equal in magnitude to the characteristic impedance of the line. Condition 1 is met by the apparatus above described. Condition 2 can be met by adjusting the tuning elements of the coupling network 4 to make the resistance component of the load equal to that of the line. In a practical automatic impedance matching device, tuning of an element to adjust to a proper resistance value also causes a change in the line voltage-line current phase relationship and, therefore, it is ordinarily necessary to carry on the operations of conditions 1 and 2 concurrently.

Referring now to Fig. 1, a transformer 28 has its primary in series with the transmission line and its secondary winding is heavily loaded with a noninductive resistor 29 causing it to perform as a current transformer. The transformer 28 is preferably so constructed as to produce a uniform voltage output over the operating frequency range while producing negligible phase shift between the primary current and secondary voltage. The A. C. voltage developed across resistor 29 is rectified by a suitable rectifier 30, obtaining a D. C. voltage E_b which appears at terminal 31 and is proportional to the line current. This relationship can be expressed mathematically as:

$$E_b = K_2 I_1$$

or

$$E_b = K_2 \frac{E_1}{\sqrt{R^2 + X^2}} \quad (1)$$

where K_2 is a constant determined by the circuit constants, I_1 is the peak value of line current, E_1 is the peak value of line voltage, R is the resistive component of the load on the transmission line and X is the reactive component of the load on the transmission line.

A triode rectifier 32 has its anode energized by the line voltage and its grid energized by the voltage across resistor 29 which is proportional to the line current. When the line voltage is in phase with the line current, the voltages at the anode and the grid of the triode are in phase; thus, in this case, the triode behaves much as if it were a diode, the tube conducting on the positive half-cycles of the line voltage (when both anode and grid are positive), and not conducting on the negative half-cycles (when plate and grid are both negative). The voltage across potentiometer 33 will be proportional to the line voltage, which is rectified by the triode 32; hence the D. C. voltage at terminal 34 will also be proportional to the line voltage. However, when a phase angle exists between the line voltage and line current, the grid of the triode rectifier 32 is negative for a portion of the positive half-cycle on the anode. The average anode-cathode current of tube 32 decreases and consequently the D. C. volt-

4

age at terminal 34 decreases and is proportional to the line voltage times the cosine of the phase angle between the line voltage and the line current. This relationship can be expressed mathematically as:

$$E_a = K_2 E_1 \cos \theta$$

or

$$E_a = K_2 E_1 \frac{R}{\sqrt{R^2 + X^2}} \quad (2)$$

where E_a is the output voltage at terminal 34, E_1 is the peak line voltage, K_2 is a constant determined by the circuit constants, θ is the phase angle between the line voltage and line current, R is the resistive component of the load on the transmission line and X is the reactive component of the load on the line.

From Equations 1 and 2 it will be apparent that the differential voltage between terminals 31 and 33 can be expressed mathematically as:

$$E_a - E_b = K_2 E_1 \frac{R}{\sqrt{R^2 + X^2}} - K_1 \frac{E_1}{\sqrt{R^2 + X^2}}$$

or

$$E_a - E_b = \frac{K_2 E_1 R - K_1 E_1}{\sqrt{R^2 + X^2}} \quad (3)$$

Before putting the equipment into automatic operation, the potentiometer 33 is adjusted to such a position that the differential voltage between terminals 31 and 34 is zero when a desired value of resistance termination for the transmission line 3 is obtained with the line current and voltage in phase. Under these conditions, the resistance component R of the load on the transmission line will be equal to the characteristic impedance R_0 of the transmission line, the reactive component of the load on the transmission line will be zero and the differential voltage between terminals 31 and 34 ($E_a - E_b$) will be zero. Substituting these values into Equation 3:

$$\frac{K_2 E_1 R_0 - K_1 E_1}{\sqrt{R_0^2 + 0^2}} = 0$$

or

$$K_2 R_0 = K_1$$

45 Substituting the value $K_2 R_0$ for K_1 in Equation 3:

$$E_a - E_b = \frac{K_2 E_1 R - K_2 R_0 E_1}{\sqrt{R^2 + X^2}}$$

or

$$E_a - E_b = \frac{K_2 E_1}{\sqrt{R^2 + X^2}} (R - R_0) \quad (4)$$

From Equation 4 it will be apparent that (A) the differential voltage ($E_a - E_b$) will always be zero provided that the resistance component R of the load is equal to the characteristic impedance R_0 of the line, irrespective of the reactive component of the load; (B) the differential voltage ($E_a - E_b$) will be positive if the resistive component R is greater than the characteristic impedance R_0 , irrespective of the reactive component of the load; and (C) the differential voltage ($E_a - E_b$) will be negative if the resistive component R is less than the characteristic impedance R_0 , irrespective of the reactive component of the load.

The differential voltage across terminals 31 and 33 is zero for the adjusted resistance condition, however, the D. C. common mode voltage to ground from each of those output terminals is dependent upon the power level of the energy in the transmission line 3.

To effectively utilize the circuit, a differential amplifier including tubes 35 and 36 is employed which, by virtue of a common cathode resistance circuit including resistor 37, will produce an output voltage in the differential amplifier which is more sensitive to changes in difference

voltage between terminals 31 and 34 than to changes in their common level.

The anodes of tubes 35 and 36 are connected through suitable coupling networks to the grids of tubes 37 and 38 respectively. Tubes 37 and 38 are normally biased to cut-off by a positive potential applied to their cathodes. Winding 39 of relay 40 is connected to the anodes of tubes 37 and 38 such that should a potential difference occur between those anodes, the relay 40 will be energized, closing its contacts 41 and thereby applying the 65 volt 400 cycle source to the winding 42 of motor M2. Winding 42 of motor M2 is series resonated by capacitor 43 to produce the necessary 90° current phase relationship for the 2-phase motor. The other winding 44 of motor M2 is split. Tubes 37 and 38 are preferably of the thyatron type and firing of one of those thyatrons causes half-wave 400 cycle pulses to flow in half of the split winding. Firing of the other thyatron causes the half-wave pulses to flow in the other direction in the other half of the split winding. The motor will therefore rotate in either direction dependent upon which half of the winding is excited. Because the half-wave pulses produce a relatively high direct current in the motor winding which reduces motor torque, a capacitor 45 is connected across the split winding which, by its "flywheel" effect, will cause a more nearly alternating current to be impressed upon the motor winding.

From the above description it will be apparent that should the resistive component of the load on the transmission line 3 be not equal to the characteristic impedance of the line, the motor M2 will rotate in one direction or the other, dependent upon whether the resistive component of the load is greater or less than the characteristic impedance of the line. Rotation of motor M2 causes adjustment of the inductor 6 of the coupling network 4 and therefore the network will be automatically adjusted such that the resistance component of the load will remain equal to the characteristic impedance of the line.

Although specific circuits and specific values for certain of the circuit elements have been illustrated and described, it will be understood that these are merely by way of example and many modifications, additions and omissions may be made without departing from the spirit and scope of this invention.

What is claimed is:

1. An automatic tuning and loading coupling network for coupling a source of high frequency energy to a complex load, said network comprising, a first adjustable reactor having means to connect it in series with said source and said load, a second adjustable reactor having means to connect it in shunt with said load; first means for producing a first error signal which is a function of the phase difference between the current and the voltage supplied to the input terminals of said coupling network, second means responsive to said first signal for adjusting the value of said series reactor to vary the tuning of said adjustable coupling network to a value such that said current and voltage supplied to said input terminals will remain substantially in phase with each other; third means for producing a second signal which is proportional to the magnitude of the voltage supplied to the input of said coupling network times the cosine of the angle between the voltage and the current supplied to said input, fourth means for producing a third signal which is proportional to the magnitude of the current supplied to said input of said coupling network, and fifth means responsive to the difference between said second and third signals for adjusting said shunt reactor to a value such that the difference between said second and third signals will be zero whereby the resistance reflected from said complex load to the input of said coupling network will be equal to a predetermined value.

2. Apparatus as in claim 1 wherein said third means comprises a transconductive device operated as a triode

rectifier, said transconductive device having its output terminal energized by the instantaneous voltage supplied to the input of said coupling network, and having its control terminal energized by a voltage which is proportional to the instantaneous current supplied to the input of said coupling network, said transconductive device having a load impedance across which will appear said second signal which is proportional to the magnitude of the voltage times the cosine of the angle between the voltage and the current supplied to the input terminals of said coupling network.

3. Apparatus as in claim 2 wherein said fourth means comprises a rectifier network connected in shunt with the control element of said transconductive device, said network including an impedance across which is developed a direct current voltage which is proportional to the magnitude of the current supplied to the input terminal of said coupling network, and wherein said fifth means comprises a differential amplifier having as one input said second signal produced by said third means and as the other input said third signal produced by said fourth means and having as its output a fourth signal which is proportional to the difference between said second and third signals; said fourth signal being connected to control means for adjusting the value of said shunt reactor to such a value that said signal will remain at zero value.

4. Coupling apparatus for automatically matching a transmission line and a complex load comprising, a source of high frequency energy, a transmission line having its input connected to said source, a first and second transformer each having its primary winding connected in series with one conductor of said transmission line, an L section adjustable coupling network having its input terminals connected to the output terminals of said transmission line, a complex load connected across the output terminals of said coupling network, said L section coupling network comprising an adjustable capacitor connected in series between said line and said load and an adjustable inductor connected in shunt across the output terminals of said coupling network; first means connected to the secondary of said first transformer for producing a first error signal which is a function of the phase difference between the current and the voltage in said transmission line, second means responsive to said first signal for adjusting the value of said capacitor to vary the tuning of said coupling network to a value such that the current and voltage in said transmission line will remain substantially in phase with each other; third means connected to the secondary of said second transformer for producing a second signal which is proportional to the magnitude of the voltage times the cosine of the angle between the voltage and the current in said transmission line, fourth means connected to the secondary of said second transformer for producing a third signal which is proportional to the magnitude of the current in said transmission line, and fifth means responsive to the difference between said second and third signals for adjusting said shunt inductor to a value such that the difference between said second and third signals will remain zero whereby the resistance reflected from said complex load to the input terminals of said coupling network will be equal to a predetermined value.

5. Apparatus as in claim 4 wherein said second transformer has a resistance connected across its secondary terminals and wherein said third means comprises a transconductive device operated as a triode rectifier, said transconductive device having its output terminal connected to that conductor of the transmission line which is in series with said transformer primary, and having its control terminal connected to one end of the resistor across the secondary of said transformer; the third terminal of said transconductive device having a common connection with the other end of said resistor and with the other conductor of said transmission line; and a variably tapped

7

impedance connected between the output terminal of said device and said common connection so that the direct current voltage between said tap and said common connection will be proportional to the magnitude of the voltage times the cosine of the angle between the voltage and the current in said transmission line.

6. Apparatus as in claim 5 wherein said fourth means comprises a rectifier network connected between the control element of said transconductive device and said common connection, said network including an impedance across which is developed a direct current voltage which is proportional to the magnitude of the alternating current in said transmission line, and wherein said fifth means comprises a differential amplifier having as one input said second signal produced by said third means and as the other input said third signal produced by said fourth means and having as its output a fourth signal which is proportional to the difference between said

8

second and said third signals; said fourth signal being applied to control means for adjusting the value of said shunt inductor to such a value that said fourth signal will remain at zero value whereby the resistance reflected from said complex load to the input of said coupling network will be equal to a value predetermined by the setting of the variably tapped impedance connected to the output terminal of said transconduction device.

References Cited in the file of this patent

UNITED STATES PATENTS

2,417,191	Fox	Mar. 11, 1947
2,449,174	O'Brien	Sept. 14, 1948
2,498,871	Beard et al.	Feb. 28, 1950
2,742,618	Weber	Apr. 17, 1956
2,745,067	True et al.	May 8, 1956