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3,475,703

COARSE STEP-FINE TUNE AUTOMATICALLY TUNABLE ANTENNA

Filed Dec. 11, 1967

3 Sheets-Sheet 1

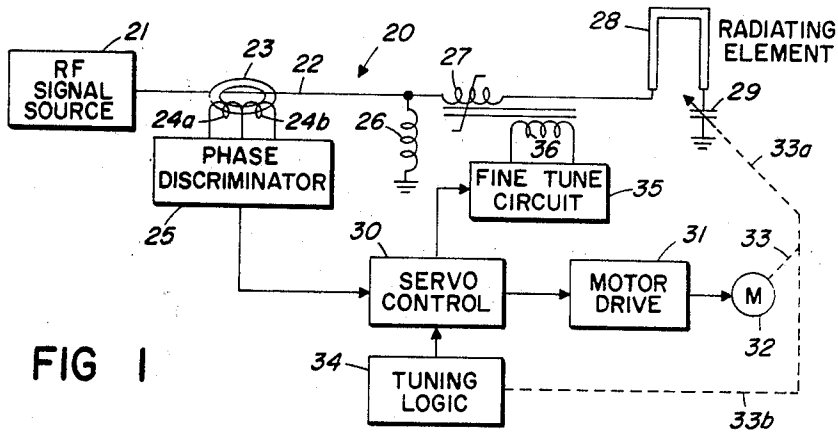


FIG 1

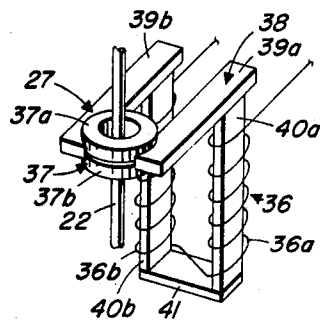


FIG 3

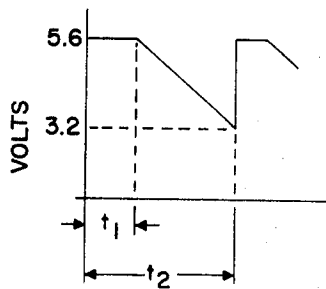


FIG 4

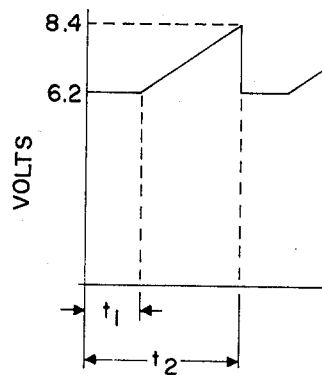


FIG 5

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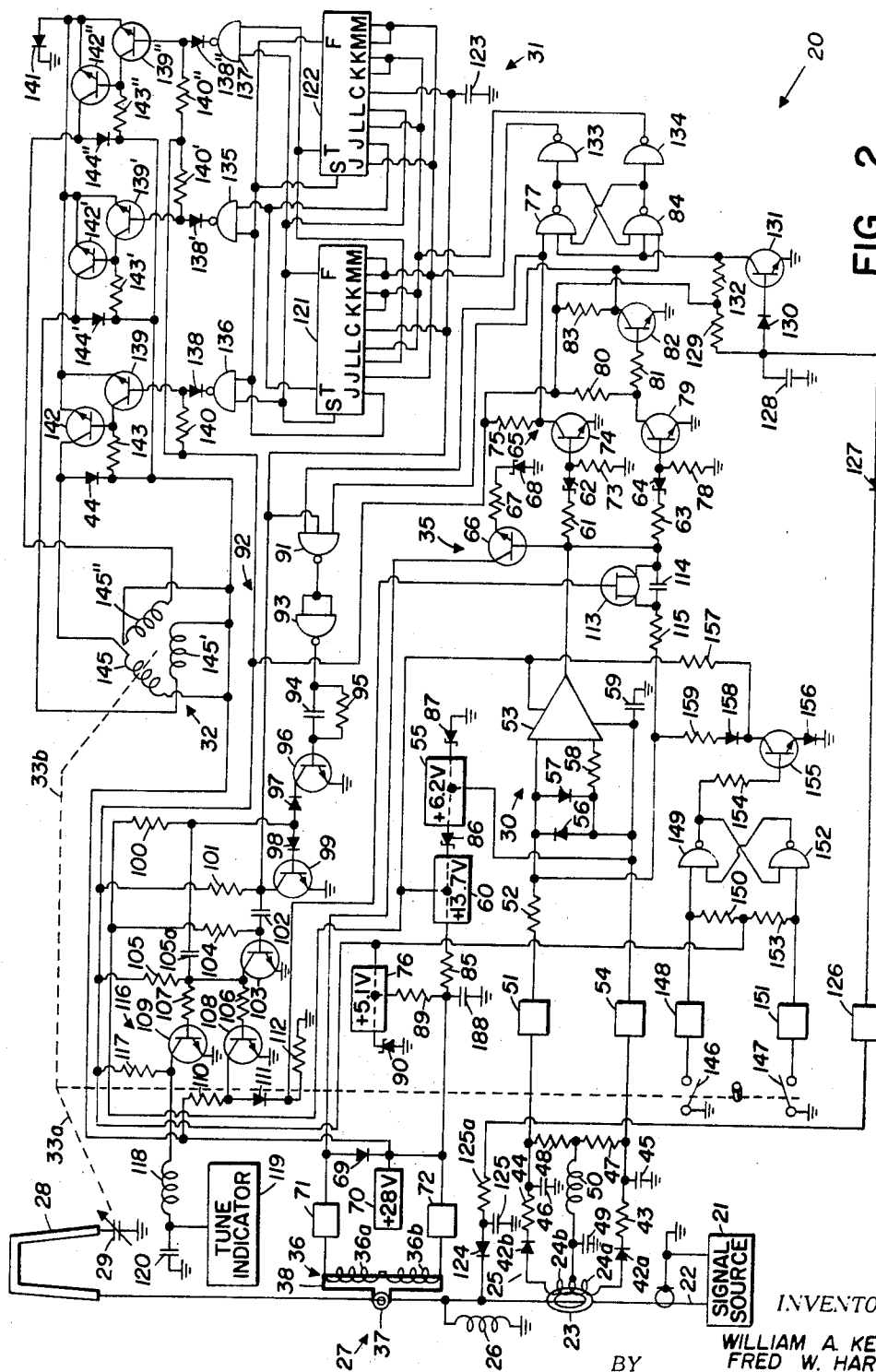
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3 Sheets-Sheet 2



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3 Sheets-Sheet 5

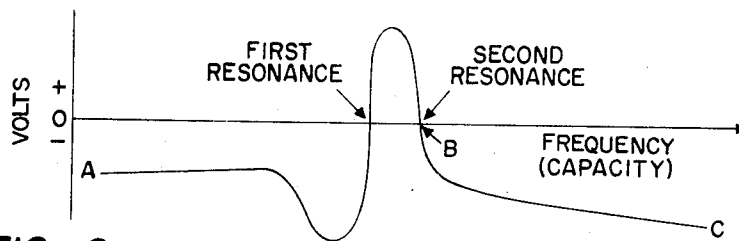


FIG 6

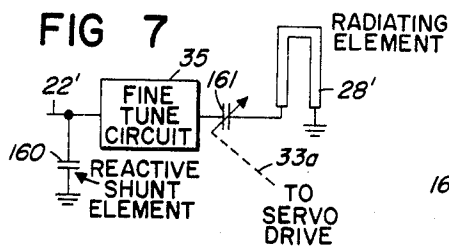


FIG 7

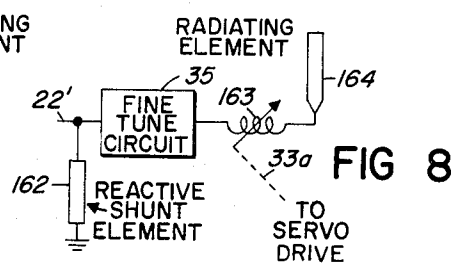


FIG 8

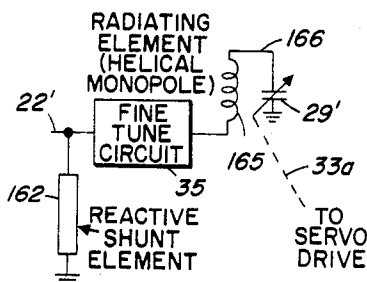


FIG 9

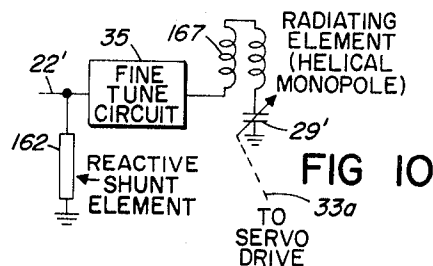


FIG 10

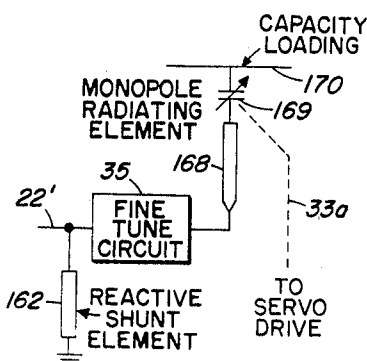


FIG 11

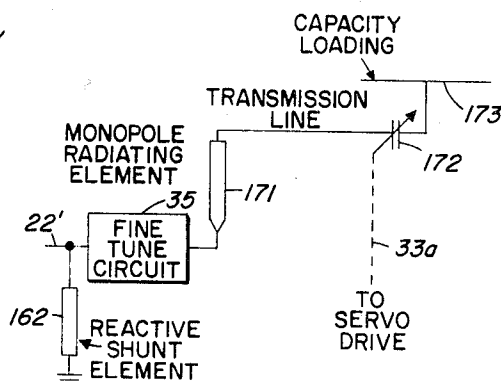


FIG 12

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COARSE STEP-FINE TUNE AUTOMATICALLY TUNABLE ANTENNA

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U.S. Cl. 333-17

16 Claims

ABSTRACT OF THE DISCLOSURE

A combination automatically tuned coupling network and radiating element with one element mechanically varied for a coarse tune mode and an electronically controlled fine tune system, and with automatic initiation of antenna tuning when the transmitter source is keyed if the antenna is not tuned on frequency and with the provision that the RF signal be over a predetermined power level. A fine tune circuit is used acting on servo control voltages in a servo motor control voltage control system for varying a small variable series inductance through signal controlled variance of permeability changes in a ferrite core structure around the antenna signal path.

This invention relates in general to transmitter to antenna automatically controlled impedance matching systems, and in particular, to a combination automatically tuned switching network and radiating element with only one element mechanically varied for a coarse tune mode and an electronically controlled fine tune system.

Impedance matching between interconnected signal conveying electronics circuits is important and, generally, must be subject to continual tuning control with any signal frequency change. In order that this may be accomplished efficiently the magnitude and phase relationship of one circuit must be converted to balance with the other circuit connected therewith. This is particularly important with an RF signal source to antenna matching network where it is important to have substantially no signal reflection or mismatch. With many matching systems it has been necessary to sense both VSWR (amplitude) and phase. The system herein presented, however, utilizes the relative phase of the input voltage and current for determining when a satisfactory match has been achieved. It is important that the signal transmitting system have minimal tune-time requirements and yet have the capability to assure servo stability for relatively sharp error signal functions such as would be required for high Q antennas.

It is, therefore a principal object of this invention to attain minimum tune-time and yet assure servo tuned stability in a coarse step-fine tune automatically impedance match tuned antenna.

Another object is to provide such an automatically impedance match tuned antenna with relative phase of the input voltage and current providing the tuning control and determining when a satisfactory match has been achieved.

A further object is to provide such an automatically tuned antenna with only one mechanically varied tuning element required.

Another object with such a tuning system for an antenna is to provide fine tuning with a small variable series inductance provided by the antenna lead being passed through a ferrite material acting as a small variable series inductance to the antenna as varied through signal controlled magnetic field input induced permeability changes in the ferrite material.

Still a further object is to provide with such an antenna automatic tuning system having a first resonance

and a second resonance with the development of unstable-opposite direction servo control signals about the second resonance a servo rotation logic control and resetting of the servo system to servo tune to the first resonance.

Features of this invention useful in accomplishing the above objects include, in a coarse step-fine tune automatically tunable antenna, automatic initiation of antenna tuning when the transmitter source is keyed if the antenna is not tuned on frequency and with the provision that the RF signal be over a predetermined power level. It includes a servo motor pulse driven in 15° steps mechanically linked through a gear reduction to an antenna series tuning capacitor to bring the antenna circuit to resonance at, or very near to, the frequency that is being transmitted. For fine tuning in the area of resonance a fine tune circuit is used utilizing servo control voltage signals for varying a small variable series inductance through signal controlled variance of permeability changes in a ferrite core structure around the antenna signal path. Further, the fine tune circuit is, generally, much faster acting than the servo drive system acting through the servo motor to position the antenna series tuning capacitor.

Specific embodiments representing what are regarded as the best modes of carrying out the invention are illustrated in the accompanying drawings.

In the drawings:

FIGURE 1 represents a combination block schematic coarse step-fine tune automatically tunable impedance matching network and antenna system;

FIGURE 2, a more detailed schematic of such an automatically tunable impedance matching network and antenna system;

FIGURE 3, a perspective view showing the antenna lead as passed through a ferrite material toroid structure acting as a series inductance to the antenna lead passed therethrough, and with the ferrite toroid structure also part of a magnetic circuit with wire coiling through which varying DC signals may be passed for varying the magnetic field impressed through the ferrite toroid structure and thereby induce permeability change in the ferrite material of the toroid structure and provide small variations in series inductance required for fine tuning of the antenna system;

FIGURE 4, a typical output voltage versus time function waveform from the operational amplifier when the servo system is still in rotation logic but still not so much so as to be in the free-running condition at maximum rate pulse output to the servo motor and with approximately a positive 100 millivolt input to the operational amplifier for a specific set of component values and voltages used in the tuning system of FIGURE 2;

FIGURE 5, a typical output voltage versus time function waveform from the operational amplifier with a minus 100 millivolt input to the operational amplifier an input such as with the component values and voltages for the circuit embodiment of FIGURE 2 such as to not allow free-running condition in that direction of rotation logic;

FIGURE 6, a voltage versus frequency phase discriminator output curve;

FIGURE 7, a partial showing of an automatically tunable impedance matching network and antenna system similar to the embodiment of FIGURES 1 and 2 with, however, the reactive shunt element being a capacitor instead of a coil, and with the mechanically varied tuning element positioned between the fine tuned circuit and the antenna radiating element;

FIGURE 8, another embodiment with the mechanically varied tuning element a mechanically adjustable coil located in the same location as the mechanically variable capacitor in the embodiment of FIGURE 7, and with the antenna radiating element a monopole;

FIGURE 9, another embodiment similar in many respects to the other embodiments with the radiating element being a helical monopole with a wire return lead connected to a mechanical variable capacitor having a ground connection;

FIGURE 10, a folded helical monopole with a mechanically variable capacitor connection similar to the embodiment of FIGURE 9;

FIGURE 11, a monopole series tuned with top loading antenna embodiment; and

FIGURE 12, a monopole series tuned through a transmission line with capacity top loading.

Referring to the drawings:

In the coarse step-fine tune automatically tunable impedance matching network and antenna system 20 of FIGURE 1, an RF signal source 21 is connected to an antenna lead 22. The lead 22 from the signal source 21 passes through a toroid 23, upon which phase detecting coils 24a and 24b of phase detector 25 are wound, to a common junction of a shunt inductance 26 connected to ground and a series inductance 27 and through the series inductance 27 to antenna radiating element 28. The other end of the folded monopole radiating element 28 is connected to and through mechanically adjustable tuning capacitor 29 to ground. The output of phase discriminator 25 is connected as an input to a servo control circuit 30 developing output signal control voltages applied to motor drive circuit 31 for developing drive voltage inputs for motor 32. The motor 32 output drive train 33 extends through branch 33a to adjust the variable capacitor 29, and through a branch 33b to tuning logic circuit 34 to provide an overriding control input to the servo control circuit 30. An additional output connection of servo control circuit 30 serves as an input to the fine tune circuit 35 that has a coil winding 36 output.

The coil windings 36 are wound on part of a magnetic circuit including a ferrite material toroid portion thereof that with the antenna lead passed therethrough forms a variable series inductance 27. This is with a ferrite material toroid structure 37 indicated in FIGURE 2 and shown in much greater detail in FIGURE 3 with the antenna lead 22 passed through the ferrite material toroid structure 37. Further, the ferrite toroid structure 37 is part of a magnetic circuit 38 including the wire coiling 36 through which varying DC signals are passed for varying the magnetic field impressed through the ferrite toroid structure to thereby induce permeability change in the ferrite material of the toroid structure 37 and provide small variations in series inductance required for fine tuning of the antenna system. With reference further to FIGURE 3, the magnetic circuit 38 associated with the variable series inductance 27 includes in the ferrite toroid structure 37 two toroid rings 37a and 37b. Two iron bars 39a and 39b are connected to opposite sides of the toroid structure 37, vertical iron bars 40a and 40b are connected to and extend vertically downward from the other ends of iron bars 39a and 39b, respectively, and a bottom iron bar 41 interconnects the bottom ends of the vertical bars 40a and 40b. The coil winding 36 is divided into a 36a section and a 36b section wound about, respectively, the vertical iron bars 40a and 40b. The windings of the two coil sections 36a and 36b on the vertical bars 40a and 40b are so connected as to be additive in their magnetic circuit magnetizing affect when a DC current is applied thereto.

Referring again to FIGURE 1 and particularly to FIGURE 2, the phase discriminator 25 develops a DC error signal proportional to the phase shift between the RF line voltage and RF line current. As shown in FIGURE 2, the phase discriminator 25 is shown to include two diodes 42a and 42b with the anodes thereof connected, respectively, to the outer ends of phase detecting coils 24a and 24b. The cathodes of diodes 42a and 42b are connected through resistors 43, 44, respectively, and on through capacitors 45 and 46, respectively, to ground. The common junction of resistor 43 and capacitor 45 and the

common junction of resistor 44 and capacitor 46 are interconnected serially through resistors 47 and 48. The common junction of phase detecting coils 24a and 24b is connected through capacitor 49 to ground and also through coil 50 to the common junction of resistors 47 and 48. The common junction of resistor 44, capacitor 46 and resistor 48 is connected as a phase detector output through an RF filter 51, of standard construction, to and through the resistor 52 as an input connection to a DC operational amplifier circuit 53. The common junction of resistor 43, capacitor 45 and resistor 47 is connected as a phase discriminator connection through an RF filter 54, of standard construction, to DC voltage supply 55. The operational amplifier circuit is such as to be a linear input voltage to output phase rate converter with the DC operational amplifier 53 a high gain differential DC amplifier. With an input applied amplifier 53 normally produces a voltage gain of approximately 1000 with output polarity the inverse of the input polarity.

Operation of this system is initiated with the application of transmitted RF power in excess of a predetermined power level, for example, 1 watt with a working embodiment such as shown in FIGURE 2. The system is so arranged that if the transmitted frequency is below the resonant frequency of the antenna system, the polarity of the signal developed by the phase discriminator 25 is such that the servo system drives the series variable capacitor 29 to increase the capacitance. When the transmitted frequency is above the resonant frequency of the antenna system, an oppositely polarized error signal is developed, at least through a range of operation, and the capacitor is adjusted to reduce the capacitance. Discussion of this operation will be amplified further later in the specification particularly in the context of the FIGURE 2 embodiment where a first and second resonance are developed in the antenna system leading to an area of ambiguity in operation that must be provided for. When a matched resonant state is achieved, the discriminator output is at zero and when the output of the discriminator is in the area of zero, adjustment of the series capacitor 29 ceases.

Two diodes 56 and 57 are connected in parallel between the common junction between resistor 52 and the operational amplifier 53 and voltage supply 55 in reverse orientation one with the cathode to the junction and the other anode to the junction. A resistor 58 is connected between voltage supply 55 and the operational amplifier 53. Voltage supply 55 is also connected through capacitor 59 to ground and as a voltage supply directly to the operational amplifier 53. An additional voltage supply 60 is also connected to the operational amplifier 53.

The output of the operational amplifier 53 is connected through resistor 61 to the cathode of 8.2 volt Zener diode 62, in the embodiment of FIGURE 2, and also through resistor 63 to the cathode of 3.9 volt Zener diode 64 of servo rotation logic circuitry 65. This is in order that with DC excursions above approximately 8.2 volts the servo drive system will be activated to decrease capacitance of variable capacitor 29, and with voltage excursions below approximately 3.9 volts the servo rotation logic circuit and drive system will be activated to increase the capacitance of capacitor 29. The output of operational amplifier 53 is also connected to the base of NPN transistor 66 of the fine tune circuit 35. The emitter of NPN transistor 66 is connected through resistor 67 to the cathode of a 3.3 volt Zener diode 68, the anode of which is connected to ground. The collector of NPN transistor 66 is connected to the anode of diode 69, the cathode of which is connected to positive voltage supply 70 and also through an RF filter 71, of standard construction, to the coil sections 36a and 36b of coil winding 36. The other end of the coil windings 36 is connected through an additional RF filter 72, of standard construction, to the positive voltage supply 70. With output from the operational amplifier 53 conduction through NPN transistor

66 changes thereby providing a change in current through the coil winding sections 36a and 36b. This produces a change in their magnetic field proportional to the operational amplifier input voltage. This change in the magnetic field generated by the coil sections 36a and 36b in the magnetic circuit associated therewith results in a corresponding change in permeability in the ferrite toroid core structure 37. With the antenna lead 22 passed through the ferrite toroid core structure 37 and with the permeability of the core being changed, the ferrite toroid core structure 37 acts as a small variable series inductance to the antenna. This range of variable series inductance adjustment is such as to fine tune the antenna through a small range spanning approximately the same as two of the capacitive value adjustment steps provided by step tuning of variable capacitor 29 as determined by drive steps of the servo drive motor 32 in the embodiment of FIGURES 1 and 2.

In the servo rotation logic circuit 65, the anode of Zener diode 62 is connected both through resistor 73 to ground and also to the base of NPN transistor 74. The emitter of NPN transistor 74 is connected to ground and the collector is connected through resistor 75 to positive voltage supply 76 and as a signal input to NAND gate 77. The anode of Zener diode 64 is connected both through resistor 78 to ground and to the base of NPN transistor 79. The emitter of NPN transistor 79 is connected to ground and the collector thereof is connected through resistor 80 to the positive voltage supply 76 and also through resistor 81 to the base of NPN transistor 82, the emitter of which is connected to ground. The collector of NPN transistor 82 is connected through resistor 83 to the positive voltage supply 76 and also as an input to NAND gate 84.

At this point it may be well to note that the voltage supplies 55, 60 and 76 are actually junction points of a voltage dividing network connected between the +28 volt supply 70 and ground in the embodiment of FIGURE 2. This is with the 28 voltage supply 70 connected through resistor 85 to the cathode of Zener diode 86, the anode of which is connected to the cathode of Zener diode 87 having in turn an anode connection to ground. This is with the common junction of the two Zener diodes 86 and 87 being the positive 6.2 volt supply 55 and the common junction of resistor 85 and the cathode of Zener diode 86 being the positive 13.7 volt supply 60. The positive 28 volt supply 70, in addition to also being connected through capacitor 88 to ground, is also connected serially through resistor 89 to the cathode of Zener diode 90, the anode of which is connected to ground. In this branch of the voltage divider network the common junction of resistor 89 and the cathode of Zener diode 90 is the positive 5.1 volt supply 76.

The collector outputs of NPN transistors 74 and 82 in addition to being connected, in the servo rotation logic circuit 65, as inputs to NAND gates 77 and 84, respectively, are connected as dual inputs to NAND gate 91 of sequential pulsing logic circuit 92. The output of NAND gate 91 is passed to dual inputs of a NAND gate 93 acting as a signal inverter. The output of NAND gate 93 is connected through capacitor 94 and resistor 95, connected in parallel, to the base of NPN transistor 96. The emitter of transistor 96 is connected to ground while the output collector is connected to the cathode of diode 97, the anode of which is connected to the anode of diode 98, the cathode of which is connected to the base of NPN transistor 99. The common junction of the anodes of diodes 97 and 98 is connected through resistor 100 to positive voltage supply 60. The emitter of transistor 99 is connected to ground and the collector output thereof is connected both through resistor 101 to positive voltage supply 76 and through capacitor 102 to the base of NPN transistor 103. The base of NPN transistor 103 is connected through resistor 104 to positive voltage supply 60, the emitter is connected to ground, and the collector output is connected through resistor 105 to positive voltage supply 76. The collector

output of transistor 103 is also connected through resistors 106 and 107 to the base of NPN transistors 108 and 109, respectively. The emitter of NPN transistor 108 is connected to ground, and the collector output of the transistor is connected through resistor 110 to positive voltage supply 70 and also to the anode of diode 111 and through the diode to and through resistor 112 to ground. Capacitor 105A interconnects transistor 103 and diodes 97 and 98.

Please note that NPN transistor 108 is part of a gating circuit with the output junction point between diode 111 and resistor 112 connected as a controlling input to field effect transistor 113 the two gated circuit electrodes of which are connected across capacitor 114 in a feedback circuit from the output of operational amplifier 53. This feedback circuit also includes resistor 115 connected between the parallel connected field effect transistor 113 and capacitor 114 and the junction of resistor 52 with the input of DC operational amplifier 53. Through means of a degenerative feedback loop including the capacitor 114 and resistor 115 in action with input resistor 52 the output of amplifier 53 is controlled to a linear rate of increase, because every change in output produces an opposing change in input. The high gain of amplifier 53 approximating a gain of 1000 and the control via capacitor 114, resistor 115 and resistor 52 produces a very sensitive amplifier capable of sensing very low-level input signals and presents a linear gain amplifier for smooth operation. The gating circuit and system is so arranged that when the output from the operational amplifier 53 falls below the threshold of Zener diode 64 or increases to above the threshold of Zener diode 62 servo rotation logic is turned on, engaging the sequential pulsing logic circuit 92 to thereby, in turn, generate a gating pulse via the gating circuit to field effect transistor 113. When field effect transistor 113 is gated on, it supplies a portion of the DC voltage output of the operational amplifier 53 as a DC voltage feedback to the input of the operational amplifier causing the output to be pulsed in the direction of the input reference voltage of plus 6.2 volts from voltage supply 55. With field effect transistor 113 gated on, the amplifier circuit 53 is limited to a gain of approximately 6 as determined by the ratio of resistor 115 to the value of resistor 52, 33K ohms to 5.6K ohms, in the embodiment of FIGURE 2 when normally the amplifier produces a voltage gain of approximately 1000, and with the output polarity the inverse of the input polarity. When a gating pulse is supplied the field effect transistor 113, it becomes a short circuit across the capacitor 114 and the output voltage level is shifted upward or downward as the case may be, toward the positive 6.2 volt reference level of voltage supply 55. The output is returned to a voltage level six times the input signal level and, if the output voltage is returned to between +3.9 and +8.2 volts, it turns off the rotation logic, disengages the sequential pulsing logic, and removes the gating pulse from the operational amplifier 53. When the operational amplifier 53 is returned between the thresholds of Zener diodes 62 and 64 by a gating pulse the pulse rate of the gating pulses and sequence timing pulses is determined by the time taken to again pass, respectively, the thresholds of Zener diodes 62 and 64. If, when the gating pulse is supplied, the output voltage of DC operational amplifier 53 remains below +3.9 volts or above +8.2 volts, that is, outside the threshold values of the Zener diodes 62 and 64 rather than between the threshold values of these Zener diodes, the rotation logic remains on and the sequential pulsing logic remains engaged. When this occurs, the sequential pulsing logic free runs providing gating pulses and sequence timing pulses at a maximum rate of approximately 500 cycles per second.

FIGURES 4 and 5 illustrate, respectively, the voltage versus time sawtooth waveforms as developed at the output of the DC operational amplifier 53 and the pulsing action generated thereby as the voltage is taken from between the thresholds of the Zener diodes 62 and 64 down

through, in FIGURE 4, to below the threshold of Zener diode 64 and upward through the threshold of Zener diode 62, in FIGURE 5, until pulse controlled back to between the thresholds of the Zener diodes 62 and 64. Conduction of Zener diodes 62 and 64 occurs, respectively, at t_2 . With values of input voltage resulting in DC operational amplifier 53 voltage output voltage being continually closer, from between the thresholds of Zener diodes 62 and 64, to the respective threshold t_2 becomes smaller and at $t_2=t_1$ the maximum pulse rate of approximately 500 c.p.s. is attained. This voltage function as illustrated in FIGURES 4 and 5 also appears at the base of NPN transistor 66 which controls the current in coil sections 36a and 36b thereby producing a magnetic field proportional to the operational amplifier 53 input voltage and thereby, a change in the permeability of the ferrite toroid core structure 37. Since the antenna current passing through antenna lead 22 passes through this ferrite toroid core structure, the change in the permeability of the ferrite of the toroid core structure results in a change of inductance to the antenna current. Although this is a small series inductance, it is sufficient to provide for tuning of the antenna in the region of first resonance illustrated in the voltage versus frequency phase discriminator output curve of FIGURE 6, and in fact, provides fine tuning substantially throughout the nearly vertical portion of the phase discriminator response curve in the area of first resonance shown in FIGURE 6.

It is of interest to note that NPN transistor 109 is part of a tuning indicator drive circuit 116 receiving a gating pulse input signal from the output collector of NPN transistor 103 of the sequential pulsing logic circuit 92. The emitter of NPN transistor 109 is connected to ground and the output collector thereof is connected both through resistor 117 to positive voltage supply 76 and also as an output through coil 118 to tuning indicator 119, and with the junction of coil 118 and tuning indicator 119 connected through capacitor 120 to ground.

Please note that the collector output of NPN transistor 99 of the sequential pulsing logic circuit 92 is an output of a free running multivibrator subcircuit in association with the end and including the NPN transistor 103 and is connected back as a feedback input connection to the NAND gate 91. This signal line connection from the collector output of NPN transistor 99 is also connected as a sequence timing pulse line signal input to the C terminals of ring counter device circuits 121 and 122 and also through capacitor 123 to ground in the servo motor sequencing logic portion of motor drive circuit 31.

The servo rotation logic circuit 65 is also provided with an RF on circuit including a connection from the RF antenna signal input line 22 to the cathode of diode 124, the anode of which is connected through capacitor 125 to ground and also through, serially resistor 125a and an RF filter 126, of standard construction, to the cathode of diode 127. The anode of diode 127 is connected in common through capacitor 128 to ground, through resistor 129 to positive voltage supply 76, and to the anode of diode 130. The cathode of diode 130 is connected to the base of NPN transistor 131 which has an emitter connected to ground. The output collector of the NPN transistor is connected through resistor 132 to voltage supply 76 and is also connected as an additional input to both NAND gates 77 and 84 of the servo rotation logic circuit 65. This RF on circuit is provided to inhibit the servo amplifier against tuning from erroneous signals and enables the servo rotation logic circuit when transmit power is supplied to the antenna above, for example, in the embodiment of FIGURE 2, a 1 watt RF input level which is a signal power level well above RF received signal power levels generally encountered when operating the antenna in the receive mode. The outputs of NAND gates 77 and 84 are both applied back as inputs one for the other and also, respectively, as dual inputs to additional NAND gates 133 and 134 acting as inverters. The signal inverted output

of NAND gate 133 is applied as an input signal to a J input connection and to M input connections of ring counter device circuit 121, and also as a J connector input to M input connections of ring counter device circuit 122. The inverted signal output of NAND gate 134 is applied as an L circuit connection input and to dual K input connections of ring counter device circuit 121, and also as an L connection input and dual K terminal inputs of the ring counter device 122 in the servo motor sequencing logic circuit portion of the motor drive circuit 31. The T circuit output connection of ring counter device circuit 121 is connected as an input to NAND gate 135 and also as a J input to ring counter device circuit 122. The F terminal output of ring counter device circuit 121 is connected as an input to NAND gate 136 and to NAND gate 137, and it is also connected back as an S terminal input to the ring counter device circuit 121 and also as an L terminal input to ring counter device circuit 122. The T output terminal of ring counter device circuit 122 is connected as an input to NAND gate 137 and also as an L terminal input to the ring counter device circuit 121. The F terminal output of ring counter device circuit 122 is connected as an input to NAND gate 135 and to NAND gate 136, and it is also connected back as an S terminal input to the ring counter device circuit 122 and also as a J input terminal connection to the ring counter device circuit 121.

The output of NAND gate 136 is connected to the cathode of diode 138, the anode of which is connected to the base of NPN transistor 139, and the junction of diode 138 and the base of NPN transistor 139 is connected through resistor 140 to positive voltage supply 76. The emitter of NPN transistor 139 is connected to the anode of diode 141 and through the diode to ground. The collector output of NPN transistor 139 is connected both to the base of NPN transistor 142 and also through resistor 143 to the positive voltage supply 70. The emitter of NPN transistor 142 is also connected to the anode of diode 141 and through the diode to ground while the collector output is connected both to the anode of diode 144 and through the diode to the positive voltage supply 70, and also through the coil winding 145 of servo motor 32 to positive voltage supply 70.

In a circuit connected to the output of NAND gate 135 and duplicating the circuit connected to the output of NAND gate 136 and extending through the motor coil 145 the duplicating components are given primed numbers as a matter of convenience. The output of NAND gate 135 is connected to the cathode of diode 138', the anode of which is connected to the base of NPN transistor 139', and the junction of diode 138' and the base of NPN transistor 139' is connected through resistor 140' to positive voltage supply 76. The emitter of NPN transistor 139' is connected to the anode of diode 141 and through the diode to ground. The collector output of NPN transistor 139' is connected both to the base of NPN transistor 142' and also through resistor 143' to the positive voltage supply 70. The emitter of NPN transistor 142' is connected to the anode of diode 141 and through the diode to ground while the collector output is connected both to the anode of the diode 144' and through the diode to the positive voltage supply 70, and also through the coil winding 145' of servo motor 32 to positive voltage supply 70.

In a circuit connected to the output of NAND gate 137 and duplicating the circuits connected respectively to the outputs of NAND gates 136 and 135 duplicating components are given double primed numbers as a matter of convenience. The output of NAND gate 137 is connected to the cathode of diode 138'', the anode of which is connected to the base of NPN transistor 139'', and the junction of diode 138'' and the base of NPN transistor 139'' is connected through resistor 140'' to positive voltage supply 76. The emitter of NPN transistor 139'' is connected to the anode of diode 141 and through the diode to ground. The collector output of NPN transistor 139'' is connected both to the base of NPN transistor 142'' and also through

resistor 143" to the positive voltage supply 70. The emitter of NPN transistor 142" is connected to the anode of diode 141 and through the diode to ground while the collector output is connected both to the anode of the diode 144" and through the diode to the positive voltage supply 70, and also to the coil winding 145" of the servo motor 32 to positive voltage supply 70. It is of interest to note that the emitters of the six NPN transistors 139, 142, 139', 142', 139", and 142" are all connected in common to the anode of diode 141 and through the diode to ground.

Coarse tuning is accomplished through driving the series tuning capacitor 29 with the positioning thereof determined by the motor 32 used in the embodiment of FIGURE 2 being a motor driven in 15° angular incremental pulse driven steps as determined by the servo rotation logic circuit 65 and the motor drive circuit 31. Note further that these 15° angular incremental servo motor 32 steps are reduced to much smaller increments through a 34:1 gear reduction in the drive 33 and drive arm 33a extending from the motor 32 to the series tuning capacitor 29. Hence, for the coarse tuning mode, the degree of resolution is determined by the increment the servo motor 32 may be positioned and the gearing ratio between the motor 32 and the series tuning capacitor 29. Further, in an embodiment in accord with FIGURE 2, the fine tuning mode provides for continuous tuning of the antenna 28 within the range of at least two coarse tuning steps. This is accomplished through mutual coupling, a small value of inductance at the antenna input as has been discussed hereinbefore, with the value of this inductance being controlled by biasing the magnetic field of a ferrite toroid core structure, and with this biasing being control determined by the voltage output of the DC operational amplifier 53 in the servo circuitry.

Please refer again to the voltage versus frequency phase discriminator output curve of FIGURE 6. It should be noted that with the tuning servo control system provided, as long as the antenna is so tuned set as to fall within the range from A to B on the curve as shown in FIGURE 6 that the servo system will automatically set the antenna to the position of first resonance substantially in the immediate region of the first resonance 0 volt setting shown. However, point B in the second resonance portion of the curve is an unstable point and the servo motor should the tuned adjusted position at any moment fall below point B on the curve in the area from B to C the servo system will be control driven in a setting direction towards the point C. This is an undesired operational condition provided for in the embodiment of FIGURE 2 by tuning logic circuitry. This homing logic circuitry supplies a homing signal to return the antenna series tuning capacitor 29 to minimum capacitance, in other words the point equivalent of point A on the curve of FIGURE 6, after it has reached a maximum capacitance corresponding substantially to point C in the curve of FIGURE 6.

The homing logic circuit is controlled by limit switches 146 and 147 which are physically so positioned as to be activated at respective drive 33 travel limit positions corresponding at one limit position to maximum capacitance for series tuning capacitor 29 with switch 146 and minimum capacitance for capacitor 29 with switch 147. With continued reference to FIGURE 2, both switches 146 and 147 are normally open switches subject to being contact actuated by the extension 33b of the motor drive 33 and are both connected to ground. The other normally open terminal of switch 146 is connected through an RF filter 148, of standard construction, to a lead input to NAND gate 149 that is also connected through resistor 150 to positive voltage supply 76. In like manner, the normally open contact of switch 147 is connected through an RF filter 151, of standard construction, to an input line connection to NAND gate 152 that is also connected through resistor 153 to the positive voltage supply 76. The output of NAND gate 152 is connected as an addi-

tional input to NAND gate 149 and the output of NAND gate 149 is connected both back as an additional input to NAND gate 152 and also as the output of the homing logic circuit through resistor 154 to the base of NPN transistor 155. The emitter of NPN transistor 155 is connected to the anode of diode 156 and through the diode to ground, and the collector output of the transistor is connected both through resistor 157 to positive voltage supply 60 and also to the cathode of diode 158 and serially through the diode and resistor 159 to the junction of resistor 52 and the input of DC operational amplifier 53.

With this homing logic circuit, as shown in FIGURE 2, when the series tuning capacitor 29 reaches its maximum capacitance the limit switch 146 is closed to supply a logic 0 input, in other words ground input, to NAND gate 149. This NAND gate 149 supplies a logic 1 output both back as an input to NAND gate 152 and to the base of transistor 155 and for a subsequent interval of time NAND gate 152 continues to receive an additional logic 1 input thereto as long as switch 147 is not closed. Hence, NAND gate 152 having two logic 1 inputs supplies a logic 0 back as the additional input to NAND gate 149. This state of conditions remains this way until the series tuning capacitor 29 is motor driven to its opposite minimum capacitance setting where switch 147 is mechanically closed to thereby supply a logic 0 input to NAND gate 152. NAND gate 152 then supplies a logic 1 input to NAND gate 149 and with a second logic 1 also supplied to NAND gate 149 because limit switch 146 is then in the opened state. NAND gate 149 with the application of both logic 1 inputs thereto is then caused to supply a logic 0 input both back as an input to NAND gate 152 and as a controlling output to the base of transistor 155. Whenever a logic 1 is applied to the base of transistor 155 the transistor is biased to conduction to supply a near ground potential to diode 158 to effectively so bias the input to DC operational amplifier 53 that the servo system drives the servo motor and capacitor to the minimum capacitor limit. When a logic 0 is applied to the base of transistor 155, the transistor biases off and permits the antenna tuning system to seek a null and if the null setting being attained is at the first resonance as shown in FIGURE 6, the coupling system and antenna will be set to substantially the null position consistent with the frequency being transmitted.

The servo control system so controls the tuning mechanism of the antenna that the first resonance as shown in FIGURE 6 is a stable point for the servo system. Taking this a little further this means, in essence, at the onset of the tuning cycle, if the capacitive value of series tuning capacitor 29 is such as to yield a voltage that lies between points A and B on the curve, then the servo motor 32 will reposition the capacitor 29 to the first resonant point. As has been pointed out hereinbefore, point B is an unstable point and the servo motor will cause the capacitor 29 to position either back to the first resonance or to point C at which time limit switch action occurs and the servo system ignores the phase discriminator signal to position the capacitor until point A is reached and switch 147 is closed thereby so activating the system as to return to the search mode of operation for null at first resonance. In the specific embodiment of FIGURE 2, the second resonance crossing of the phase discriminator is a result of the shunt reactive element 26 not being varied and the properties of the combination antenna and matching circuit remaining small in terms of wavelength. In other words, the tuning logic technique required for tuning and matching antennas is limited in bandwidth with the actual bandwidth achievable depending on the electrical size at the lower frequency limit and if one allows electrical size to become extremely small, then increasing larger bandwidths are possible. A practical upper frequency limit occurs when the electrical height of an antenna in accord with the embodiment of FIGURE

2 becomes approximately one-eighth wavelength. Please note, that as long as power as supplied the servo motor 32 holds the last capacitor 29 set position with, however, upon removal of electrical power from the system the vacuum bias of the vacuum variable capacitor 29 being sufficient and so directed as to, even acting against the gear train in drive 33, return capacitor 29 to the maximum capacitance limit drive position. The vacuum bias also minimizes drive system backlash.

It may be well to note at this point that there is an important relationship between the response of the fine tune circuit and the coarse tune drive circuit positioning of the series tuning capacitor 29. With the transistor 66 controlling current flow through the fine tune circuit being of such a nature in its circuit environment as to provide a substantially constant current source as varied primarily by the controlling voltages applied at the base of the transistor 66 from the output of DC operational amplifier 53. This enables the fine tune circuit response to be so much faster than the servo motor tuning capacitor 29 correction drive as to approach a substantially instantaneous response in fine tuning adjustment by comparison.

Component values used in a VHF/FM blade antenna in accord with the embodiment of FIGURE 2 with the antenna providing FM communications with automatic tuning to frequencies from 30 Mega-Hertz to 76 Mega-Hertz and impedance matching to a 50 ohm transmission line include the following:

Variable capacitor 29	3-40 picofarads vacuum variable.
Servo motor 32	IMC Magnetics Corp. Variable reluctance stepping motor with 15° pulse activated steps.
Drive train 33	Includes a 34 to 1 gear reduction.
Coil winding sections 36a and 36b	2,000 turns.
Toroid rings 37a and 37b	Ferrite Q3 material.
Iron bars 39a, 39b, 40a, 40b and 41	Magnetic "Soft" iron.
Diodes 42a, 42b and 124	1N914.
Resistor 43	390 ohms.
Resistor 44	10 ohms.
Capacitors 45, 46 and 125	4700 pf.
Resistors 47, 48, 73, 154 and 157	10K ohms.
Capacitor 49	6 pf.
Coil 50	39 mh.
Resistors 52, 58, 75, 80, 83 and 101	5.6K ohms.
Amplifier 53	RCA high gain DC operational amplifier CA3010.
Voltage supply 55	+6.2 volts DC.
Diodes 56, 57, 69, 97, 98, 111, 127, 130, 138, 138', 138'', 141, 144, 144', 144'', 156 and 158	1N645.
Capacitors 59 and 88	0.02 μ f.
Voltage supply 60	+13.7 volts DC.
Resistors 61, 63, and 105	2.2K ohms.
Zener diode 62	8.2 volt 1N756A.
Zener diode 64	3.9 volt 1N748A.
NPN transistor 66	2N657A.
Resistor 67	120 ohms.
Zener diode 68	3.3 volt 1N746A.
Voltage supply 70	+28 volts DC.
NPN transistors 74, 79, 82, 108, 109, 131, 139, 139', 139'' and 155	2N718A.
Voltage supply 76	+5.1 volts DC.
NAND gates 77, 84 and 91	SG191.
Resistors 78, 140, 140' and 140''	2.7K ohms.
Resistor 81	18K ohms.

Resistor 85	820 ohms.
Zener diode 86	7.5 volt 1N755A.
Zener diode 87	6.2 volt 1N753A.
Resistor 89	160 ohms.
Zener diode 90	5.1 volt 1N3826.
NAND gates 93, 133, 134, 135, 136, 137 and 149	SG141.
Capacitor 94	1500 pf.
Resistors 95, 106, 107 and 110	56K ohms.
NPN transistors 96, 99 and 103	2N956.
Resistors 100 and 104	68K ohms.
Capacitors 102 and 105A	0.068 μ f.
Resistor 112	100K ohms.
Field effect transistor 113	2N2608.
Resistor 115	33K ohms.
Resistors 117, 132, 150 and 153	4.7K ohms.
Coil 118	47 mh.
Capacitors 120 and 123	1000 pf.
Ring counter devices 121 and 122	SF 61 Sylvania Electric Products, Inc.
Resistor 125a	680 ohms.
Capacitor 128	0.01 μ f.
Resistor 129	22K ohms.
NPN transistors 142, 142' and 142''	2N3253.
Resistors 143, 143' and 143''	1.6K ohms.
Resistor 159	1K ohm.

With reference to the embodiment of FIGURE 1 and FIGURE 2, the servo motor 32 is used to servo position variable series capacitor 29 located between one end of the folded monopole antenna radiating element 28 and ground, and the reactive shunt element is a shunt inductance 26 connected between the antenna lead 22 and ground at a location between the phase detector 25 and the series inductance 27 associated with the antenna lead 22. Various changes may be made in the position and the components used in place of various components such as, for example, a fixed capacitor may be used as the reactive shunt element in place of shunt inductance 26 in any number of different antenna and matching circuit combination embodiments. FIGURE 7 shows one of these different embodiments with capacitor 160 connected between an antenna lead 22' and ground, in place of shunt inductance 26, and the mechanically varied tuning element, although still a series tuned capacitor 161, is positioned between the fine tune circuit 35 and the folded monopole radiating element 28', the other end of which is connected directly to ground.

In the embodiment of FIGURE 8, the reactive shunt element that could be either capacitive or inductive is in substantially the same location as capacitor 160 in FIGURE 7 or shunt inductance 26 in the embodiment of FIGURES 1 and 2. The mechanically adjustable element, a mechanically adjustable coil 163 connected to the drive 33a from the servo motor, is located in this embodiment between the fine tune circuit 35 and a radiating element in the form of an antenna monopole 164.

In the embodiment of FIGURE 9, reactive shunt element 162 either capacitive or inductive is connected between the antenna lead 22' and ground and the fine tune circuit 35 is connected to a helical monopole 165 as the radiating element. The mechanically varied element is a series tuned capacitor 29' connected between a wire return lead 166 from the other end of the helical monopole 165 and ground.

In the embodiment of FIGURE 10, a reactive shunt element 162 is connected between the antenna lead 22' and ground. The embodiment is very similar to that of FIGURE 9 with, however, the radiating element being a folded helical monopole 167 in place of the helical monopole 165 and the wire return lead 166 of the FIGURE 9 embodiment. In the FIGURE 11 embodiment, however, the antenna lead 22' after the fine tune circuit 35 is directly connected to monopole radiating element 168 and

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a mechanically adjustable tuning capacitor 169 driven by servo drive branch 33a is connected between the top of the monopole radiating element 168 and a top capacitive loading element 170.

In the FIGURE 12 embodiment, the antenna lead 22' is connected after the fine tune circuit 35 to monopole radiating element 171. The top of element 171 is connected through a transmission line to a mechanically adjustable tuning capacitor 172 driven by servo drive branch 33a and the other side of capacitor 172 is connected to capacitive loading element 173.

Please note that with some of the embodiments the interrelation of the tuning circuits is advantageously such that a function of the fine tune circuit is to substantially eliminate limit cycling that would otherwise be present with the coarse step tune servo system operation.

Whereas this invention is here illustrated and described with respect to specific embodiments thereof, it should be realized that various changes may be made without departing from the essential contribution to the art made by the teachings hereof.

We claim:

1. In an RF terminal to load automatically controlled impedance matching system including a series connected mechanically varied reactive element and an electronically controlled variable series inductance control fine tune circuit in operative association with an RF signal line carrying the RF signal transmitted between the RF terminal and the load, and with the RF signal being subject to being shifted through an RF signal range: a servo motor drive connected to said mechanically varied reactive element; a servo motor drive control system including an amplifier circuit with a DC operational amplifier and developing servo controlling voltages for servo positioning said servo motor and said mechanically varied reactive element; a phase detector located for developing a DC signal proportional to the phase shift between the RF line voltage and RF line current in said signal line from said RF terminal and with the DC signal phase detector output feed as an input to said amplifier circuit; and said electronically controlled variable series inductance control fine tune circuit being connected for control by voltage levels developed out of said DC operational amplifier in the servo motor drive control system.

2. The RF terminal to load automatically controlled impedance matching system of claim 1, wherein the servo motor control system acting through the servo motor in setting said mechanically varied reactive element is a coarse tune servo system; and with the fine tune circuit faster acting than the coarse tune servo system.

3. The RF terminal to load automatically controlled impedance matching system of claim 2, wherein the motor used is a variable reluctance stepping motor with discrete pulse activated steps; voltage pulse developing means in the servo motor drive control system with a maximum pulse rate within the maximum pulse drive speed of said stepping motor; and means in said motor drive control system for varying pulse drive control to the motor as determined by voltage signal inputs to said DC operational amplifier and resulting voltages out of the amplifier.

4. The RF terminal to load automatically controlled impedance matching system of claim 3, wherein said servo motor drive control system includes first and second voltage threshold device circuits with spaced apart voltage threshold to conduction levels with one above and one below the voltage output level of the DC operational amplifier output when the impedance matching system and load are impedance match tuned to the particular set RF frequency being used.

5. The RF terminal to load automatically controlled impedance matching system of claim 4, wherein said first and second voltage threshold device circuits each include a Zener diode.

6. The RF terminal to load automatically controlled impedance matching system of claim 4, wherein said DC

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operational amplifier is a high gain amplifier with a feedback circuit including a gating device connected to said pulse generating means and subject to being gated to conduction and gain of said amplifier being reduced with each pulse generated by said pulse generating means whenever it is activated to pulse generating action with voltage levels out of the amplifier passing from between the voltages of said first and second threshold devices through the threshold of either threshold device and with the direction of servo motor drive being determined by which threshold device is being subject to being activation changed by variation in voltage out of the DC operational amplifier.

7. The RF terminal to load automatically controlled impedance matching system of claim 6, wherein said gating device is a field effect transistor; and with gated circuit electrodes of the field effect transistor connected across a capacitor in the feedback circuit.

8. The RF terminal to load automatically controlled impedance matching system of claim 6, wherein there is a first resonance and a second resonance tuned operational state with the development of opposite direction wrong servo control within the range of RF signals and the tune settings developed; and with servo rotation logic control means, and resetting means provided to servo tune to the first resonance.

9. The RF terminal to load automatically controlled impedance matching system of claim 6, wherein the servo motor is a motor holding the last servo set position as long as power is supplied to the servo control system.

10. The RF terminal to load automatically controlled impedance matching system of claim 2, wherein said mechanically varied reactive element is a mechanically varied series tuning capacitor.

11. The RF terminal to load automatically controlled impedance matching system of claim 2, wherein said mechanically varied reactive element is a mechanically varied series tuning coil.

12. The RF terminal to load automatically controlled impedance matching system of claim 1, wherein RF power level sensing means is connected to said RF signal line and so connected to said servo motor drive control system as to enable the impedance matching system to operation whenever the RF signal in said RF signal line is over a predetermined power level.

13. The RF terminal to load automatically controlled impedance matching system of claim 12, wherein a gear reduction is provided in the drive connecting the servo motor and the mechanically varied reactive element.

14. The RF terminal to load automatically controlled impedance matching system to claim 13, wherein the mechanically varied reactive element is a vacuum variable capacitor with a pressure differential being sufficient to substantially eliminate backlash in said drive and sufficient to return the capacitor and the motor to a limit position when the motor is not being driven and position retaining power lines has been removed.

15. The RF terminal to load automatically controlled impedance matching system of claim 1, wherein said load is an antenna.

16. The RF terminal to load automatically controlled impedance matching system of claim 15, wherein said reactive element is located in said RF signal line between said fine tune circuit and the antenna.

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