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OPTIMIZED, AUTOMATIC IMPEDANCE-MATCHING SYSTEM

STATEMENT OF GOVERNMENT INTEREST

[0001] The embodiments of the invention described herein were made in the performance of official duties by employees of the U.S. Department of the Navy and may be manufactured, used, or licensed by or for the Government of the United States for any governmental purpose without payment of any royalties thereon.

CROSS REFERENCE TO OTHER PATENT APPLICATIONS

[0002] None.

BACKGROUND OF THE INVENTION

(1) FIELD OF THE INVENTION

[0003] The present invention is directed to an optimized, automatic impedance-matching system.

(2) DESCRIPTION OF THE RELATED ART

[0004] For normal underwater tracking applications, a useful device is an electronic transducer that transmits sound into the undersea environment. Those devices that transmit, rather than receive, are called acoustic projectors.

[0005] Acoustic projectors may be represented by an equivalent circuit. The circuit is highly frequency-dependent; for example, at 13 kHz the projector "looks like" an inductor in

series with a resistor, because of its positive net phase angle. At 17 kHz, it is modeled instead by a series resistor and capacitor. At this frequency it has a capacitive phase angle of -42 degrees. In most cases, the equivalent circuit has a net negative phase angle. Because of this reactance, there is a requirement for a tuning component that tunes (cancels) out the reactance, leaving as close to a real, non-reactive part remaining as possible in the load impedance.

[0006] If the net phase angle is negative at the operating frequency, an inductor with reactance $j\omega L$ may be used in series to tune out the capacitive reactance $1/j\omega C$, leaving only the real (resistive) part. The better the matching, the smaller the phase angle for the combined load impedance at the load terminals. This allows the projector to deliver the highest power signal possible to the water environment. It also means that the load current and load voltage are in phase.

[0007] When tracking underwater vehicles on a range, the vehicles are prepped with a sonar generator, such as an acoustic transducer or pinger that transmits a coded signal, allowing the instrumented range to know the vehicle position at all times. Another type of pinger is used on ships or vehicles. A typical pinger puts out an acoustic power of about 150 watts. It uses a transducer, and depending on the operating frequency, typically has a matching unit that contains a high-power inductor or coil

to tune out the capacitive reactance of the transducer. In practice, over the large range of operating frequencies (up to 100 kHz) a sizable spread of inductor values is needed for impedance-matching. These inductors may have thousands of volts across them in the circuit and often must tolerate currents in excess of 1 ampere to drive the transducer at 150 watts. This usually mandates custom-made inductors, built in the past by small companies. Designing high-powered magnetic components is becoming more unusual. There are few companies possessing the high-voltage testing capability in order to qualify a design for a pinger matching inductor. Tapped inductors featuring several different inductances are even more complicated and expensive to build.

SUMMARY OF THE INVENTION

[0008] In exemplary embodiments herein a phase correction apparatus includes an inductor producing inductor output having a load voltage and load current. At least one series capacitor is connected to the inductor. The series capacitor receives the inductor output and alters this output to a phase-corrected output by adding negative reactance to the inductor output. A phase detector is joined to receive the phase-corrected output to determine a phase angle between the phase-corrected load voltage and load current. Switches are connected between the phase detector and parallel capacitors. The parallel capacitors

add or subtract capacitance to the phase corrected output to produce adjusted output. Connecting more of the parallel capacitors adds less of the additional negative reactance to the phase-corrected output. (A higher capacitance has less capacitive reactance.) The switches are set according to the phase angle. In an exemplary embodiment, the phase detector can be switched into the circuit in a low power mode and switched out of the circuit in a high power mode.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

[0010] **FIG. 1** is a diagram illustrating a circuit for reducing or eliminating phase angle;

[0011] **FIG. 2** is a diagram illustrating operations of the phase detector;

[0012] **FIG. 3** is a diagram providing an overview of the parallel capacitor tuning device;

[0013] **FIG. 4** is a flowchart showing processing; and

[0014] **FIG. 5** is a diagram illustrating detector transfer function.

DETAILED DESCRIPTION OF THE INVENTION

[0015] As noted above, few companies possess the high-voltage testing capability in order to qualify a design for a pinger matching inductor. In view of the foregoing, a system is presented for multiple transducer types that switches in the correct components for tuning (depending on the frequency) and that utilize as few custom inductor values as possible. These apparatuses measure the phase of the load current and voltage, see how far out of phase they are, then automatically adjust the circuit to lower the phase angle to a value approaching that of a resistive load.

[0016] Therefore, an electronic circuit is provided which switches in correct tuning components to a high-power, reactive-load transducer, measures the phase difference between the load current and voltage waveforms at low power, fine tunes the matching circuit if necessary to obtain an even better impedance match, as measured by a lower phase angle, then disengages the phase detector circuitry and switches back to high power with the correct matching components in place.

[0017] **FIG. 1** illustrates one embodiment of the invention including components which can be arranged in many ways using

various diverse components (whether conventionally known or developed in the future) to achieve the functionality described herein. Specifically, **FIG. 1** shows that apparatuses herein include any form of amplifier **100** and transformer **102**. In circuit **104** shown in **FIG. 1**, an inductor **106** is connected to a circuit **104**, at least one phase-correction series capacitor **108** is connected to the circuit **104**, and a transducer **118** (e.g., projector-type transducer) is connected to the circuit **104**. The circuit is joined to a ground **120**. A processor **121** is provided to obtain user input and control aspects of circuit **104**. The transformer **102** supplies power to the circuit **104**. Processor **121** selects inductor **106** from a plurality of inductors based upon requirements of the transducer **118** and user input. User input can include the transducer **118** type and an operating frequency or frequency range. Likewise, phase-correction series capacitor **108** is selected in conjunction with inductor **106** by processor **121**. As shown in **FIG. 1**, the phase-correction series capacitor **108** receives inductor **106** output and alters the output to a phase-corrected output by adding negative reactance.

[0018] Additionally, a switch **110** selectably connects a phase detector **112** to the circuit **104**. Processor **121** is used to control the circuit **104** between a low power mode and a high power mode by connection with switch **110** and transducer **118**. Processor **121** uses the switch **110** to connect the phase detector

112 to the circuit **104** when the circuit **104** is operating at a lower power setting. The low power setting is preferably about 1-5% of the high power setting.

[0019] The phase detector **112** outputs a phase angle to an analog/digital (A/D) converter **114**, which supplies a digitized phase angle. Logic circuitry or a processor **121** receives the digitized phase angle and can provide control signals to a parallel capacitor tuning device **116**. The parallel capacitor tuning device **116** utilizes a relay bank to select capacitance to reduce or eliminate the phase angle. This improves the operation of the transducer (load) **118** which can now operate with little or no phase angle (e.g., an impedance magnitude equal to the real part of the transducer).

[0020] **FIG. 2** illustrates the phase detector **112**. As shown in **FIG. 2**, the phase detector **112** uses a voltage phase detector **122** and a current phase detector **124** in combination with a phase comparator **126** to determine the phase angle **128** between load voltage and load current of the phase-corrected output. Specifically, the phase comparator **126** compares the phase detected by the voltage phase detector **122** with the phase detected by the current phase detector **124** to find the phase angle between the two phases. The phase angle **128** can be received by analog to digital convertor **114** for conversion into a digitized phase angle **129**. (Analog to digital convertor **114**

is necessary because phase angle **128** is provided as an analog voltage output. In an embodiment using a digital phase detector, this may not be necessary.) Digitized phase angle **129** is provided to processor **121**.

[0021] **FIG. 3** illustrates the parallel capacitor tuning device **116**. As can be seen in **FIG. 3**, switches **130** are connected to the circuit **104** and to the analog to digital converter **114** and parallel capacitors **132** are connected to the circuit **104** through the switches **130**. The switches **130** are activated and deactivated according to processor **121** in accordance with the digitized phase angle **129**. (In an alternative embodiment logic circuitry, could be utilized in place of processor **121**.) More specifically switches **130** are made from a relay bank having a plurality of switches **130**. Each switch **130** is joined to receive a digital output bit from processor **121**. Each switch **130** is further joined to a capacitance circuit of the parallel capacitors **132** having a value corresponding to the significance of the associated digital bit. As the digitized phase angle **129** increases, switches **130** activate the appropriate capacitance circuits to add additional negative reactance to the phase-corrected output, so as to produce adjusted output.

[0022] Connecting more of the parallel capacitors **132** adds more capacitance, decreases the capacitive reactance, and thus

decreases the negative phase angle. The transducer **118** shown in **FIG. 1** operates using the adjusted output from the parallel capacitor tuning device **116**. The switches **130** are set to reduce the phase angle considering the load exerted by the transducer **118** on the circuit **104**.

[0023] The foregoing apparatus is very useful if the required inductor has a non-standard value because a larger, standard value inductor **106** may be used and the series capacitor **108** may be added to subtract the required inductive reactance out and "down-tune" it to the correct value. Thus, for practicality the series capacitor **108** is shown in **FIG. 1** to allow adjustment of the inductor **106**, with the possibility of adding (or subtracting) additional capacitors in parallel (using the parallel capacitor tuning device **116**) or series capacitor **108** to fine-tune it even further in pursuit of a zero overall phase angle. In one example, if the phase angle of the transducer is $(\arctan (X/R))$, with X being the reactance and R being the real part, it can be seen that the smaller the real part the better the matching is required (lower reactance needed) to achieve a given phase angle.

[0024] This is very useful because it is generally much easier to find high-voltage capacitors with convenient selections of capacitance than it is to obtain odd-value, high power inductors. The alternating current (AC) rating of

capacitors is much lower than the direct current (DC) rating, on the order of one- third. Special high-voltage capacitors with AC specifications and the correct dielectric material can be used with embodiments of the invention.

[0025] Further the embodiments of the invention are optimized to match a large number of transducer/frequency combinations with a single configuration. Load circuit analysis software in processor **121** calculates the impedance magnitude and phase of the circuit looking into the load. The correct tuning components are calculated using this process which can result in an essentially zero phase angle at the load terminals, with an impedance magnitude equal to the real part of the transducer. That is because the inductive and capacitive reactance cancel each other out. This software program may be furnished upon request.

[0026] The phase detector **112** described above allows a true phase measurement between the load voltage and current waveforms. In one example, a perfect phase match between the two inputs gives an output of 1.8 volts; a non-zero phase difference gives a voltage between 0 and 1.8 v. The inputs can be, for example, driven between 200 and 800 millivolts.

[0027] **FIG. 5** illustrates the transfer function (voltage output vs. phase difference input) of a typical phase comparator. As one transits right on the x axis in **FIG. 5**, the

phase becomes more positive (more inductive) and on the left-hand side, more negative (i.e., capacitive). Using this example, if a phase measurement is taken and the output is 1.5 volts, there is an ambiguity as to which side of the curve the measurement represents.

[0028] However, only one more data point is needed to resolve this. Therefore, the parallel capacitor tuning device **116** is used to add capacitive reactance to the circuit to see if voltage increases or decreases. If the output voltage increases, this means the original data point was inductive (right hand part of the curve in **FIG. 5**) because now the negative phase of the added capacitance is moving the detector up towards 1.8 volts. In contrast, if adding capacitive reactance to the load circuit the parallel capacitor tuning device **116** reduces the detector output voltage in the next measurement, then the phase was negative (capacitive) to begin with (left-hand side of the function in **FIG. 5**) and is continuing to become more negative.

[0029] Thus, by reading the phase detector **112** output after adding a parallel capacitor **132** in the parallel capacitor tuning device **116**, the apparatus shown in **FIG. 1** can automatically evaluate the matching process and stop when the phase of the load current approaches 0 degrees. The parallel capacitors **132** are selected so that the tuning steps are small enough to avoid very large "jumps" in the phase response as the matching process

occurs. In one example, a target tuning increment of 5 degrees per step can be used.

[0030] The foregoing shows that there are two sections to the impedance matching system: the phase detector **112** with its signal conditioning, and parallel capacitor tuning device **116** with the tuning capacitors **132** and switches **130** to switch in the correct reactance.

[0031] **FIG. 4** shows operation of the foregoing devices in flowchart form. In item **200** in **FIG. 4** one of many possible inductors or inductor combinations is selected (e.g., using relays). This allows a standard large inductor that does not need custom sizing to be utilized, with subsequent phase-correction using capacitors. In item **202**, the one or more series-connected capacitors is selected to perform the first and larger amount of phase-correction which adds negative reactance. Generally, the phase-correction processes herein add negative reactance (cancels out the reactance) to leave as close to a real, non-reactive part remaining as possible in the load impedance for the transducer.

[0032] Thus, in item **200**, processor **121** decodes a lookup table to determine which inductor to select when the user specifies the transducer and operating frequency via a touch-screen or switch closure. In one example, if a given transducer is selected for a K-frequency exercise, a 4 mH inductor may be

selected and phase-corrected to 3.84 mH with a 0.93 uF series capacitor as a starting point. Thus, the lookup table provides the correct bit pattern that selects the appropriate inductor. The adjacent, series "phase-correction" capacitor is selected along with it in item **202**.

[0033] In item **204**, processor **121** sets the transducer to operate in a relatively low power mode. In item **206**, the second switch is turned on to engage the phase detector. Therefore, as shown above, the transducer (pinger) is put into low-power mode. This ensures that the phase detector (which usually has very low voltage/ampereage limits) is not damaged.

[0034] In item **208**, the phase detector detects the phase angle. In item **210**, the phase angle is used to set the switches that control the parallel capacitors. Processing loops back to item **208** until the phase angle is reduced to zero or at least below an established upper limit. Thus, in items **208** and **210** some of the parallel capacitors are connected to the circuit and then the phase angle is measured again. Parallel capacitor connections (capacitor engagement/disengagements) that decrease phase angle are repeated and connections that increase phase angle are reversed. This processing is repeated until no more decreases in phase angle occur or until the phase angle is below an upper limit (or is at zero).

[0035] In other words, in items **208** and **210**, relays enabling the two phase detector signals are turned on, and a phase angle reading is obtained. If the voltage reading indicates a phase difference of 10 degrees or less then the process stops and the tuning relays hold the correct inductor and capacitors in place. Processor 121 can be programmed by user input to allow coarser or finer phase angle tolerances.

[0036] Once this loop processing is finished, in item **212** the phase detector is disconnected from the circuit. Then, in item **214**, the transducer is returned to high power operation. (High power operation is that which allows the transducer to transmit or project a signal.) The pinger reverts to high power signal transmission using the selected tuning relay values for the capacitor bank. The measured phase angle of the load current is optionally displayed via an LCD or other display device if desired.

[0037] Thus, as shown above, if the phase angle is out of specification then tuning step capacitors may be selected to add or subtract from the present phase angle to get it closer to zero degrees. For fine-tuning, only parallel capacitors in the parallel capacitor tuning device are used. These are in parallel with the initial phase-correction capacitor. The reason for this is that, for small increments of capacitive reactance tuning (i.e., very large capacitor value), series

capacitors would be prohibitively large in size. Capacitor step sizes were worked out beforehand to give, for example, approximately a ± 5 degree phase change. By starting at, say, 0.7 of the "phase-correction" value, the step capacitors may be selected to "ramp up" the total parallel value of capacitance until a better or near- zero phase match is obtained.

[0038] Increasing the capacitance by switching in parallel capacitors, lowers the capacitive reactance and thus the negative phase angle, resulting in a more positive total (composite) phase angle when added with the phase of the inductor. Note: a purely resistive load connected across the transducer terminal pads at the relay board output, should give a load voltage and current in phase, a convenient crosscheck. With these conditions the phase detector output should read 1.8 volts in this example.

[0039] The impedance matching system described herein utilizes a phase detector for maximum accuracy. High-end automatic antenna tuners for radio-frequency utilize phase detectors. The selection of tuning components is performed automatically, rather than manually. These devices/methods use inexpensive, off-the-shelf components to avoid custom, expensive procurements, especially for odd-valued inductors. The circuit avoids tapped inductors by phase-correcting the initial,

standard value inductor with off-the-shelf, high-voltage capacitors in series with the inductor.

[0040] The suite of available tuning circuit components has been optimized with a sorting routine (a macro with multiple nested sorting loops) to provide the most efficient component combinations. This results in more efficient tuning steps and component selection given a finite amount of board space for high-voltage components. Maximum tuning flexibility is achieved with the fewest number of large, high-voltage components possible. Thus, multiple transducers may be tuned and matched with one circuit board. The number of unique-valued inductors has been minimized using a phase-correction technique starting with the maximum-valued inductor necessary for a given group of transducers.

[0041] Instead of using separate current and voltage monitor transformers, that measure the voltage phase at the transformer primary, the devices and methods herein allows a true phase measurement of the actual load current by reducing the waveform power before the phase measurement, measuring the actual load phase, fine-tuning the load as appropriate, and then disconnecting the phase detector before transmitting at full power. Added phase errors resulting from add-on current and voltage transformers are thus avoided.

[0042] If the list of required transducers is reduced, that would leave room on the relay board for more tuning capacitors for finer step sizes. An option in the tuning could stop fine-tuning after three tuning attempts, for example, choosing the best set of matching components and displaying the final load phase. Depending on the available space in the enclosure and the board dimensions, this matching system is expandable to other transformers and inductors as well. That is why, in the final implementation of this system, the transformer and inductors were mounted off-board.

[0043] The invention has been described with references to specific embodiments. While particular values, relationships, materials, and steps have been set forth for purposes of describing concepts of the present disclosure, it will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the disclosed embodiments without departing from the spirit or scope of the basic concepts and operating principles of the invention as broadly described. It should be recognized that, in the light of the above teachings, those skilled in the art could modify those specifics without departing from the invention taught herein. Having now fully set forth certain embodiments and modifications of the concept underlying the present disclosure, various other embodiments as well as

potential variations and modifications of the embodiments shown and described herein will obviously occur to those skilled in the art upon becoming familiar with such underlying concept. It is intended to include all such modifications, alternatives, and other embodiments insofar as they come within the scope of the appended claims or equivalents thereof. It should be understood, therefore, that the invention might be practiced otherwise than as specifically set forth herein. Consequently, the present embodiments are to be considered in all respects as illustrative and not restrictive.

[0044] Finally, any numerical parameters set forth in the specification and attached claims are approximations (for example, by using the term "about") that may vary depending upon the desired properties sought to be obtained by the present disclosure. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of significant digits and by applying ordinary rounding.

OPTIMIZED, AUTOMATIC IMPEDANCE-MATCHING SYSTEM

ABSTRACT OF THE DISCLOSURE

A phase correction apparatus includes an inductor joined to a series capacitor to produce phase-corrected output having a load voltage and a load current. A phase detector is joined to the series capacitor and has a phase angle output proportional to a phase angle between the voltage and current. Logic circuitry or a processor is joined to receive the phase angle output and provide switch control value outputs to switches connected to the logic circuitry. A bank of parallel capacitors are joined to the switches. The switch control value outputs activate joined parallel capacitors to adjust reactance provided to the phase-corrected output to produce an adjusted output. In a further embodiment parallel capacitors are iterated to produce the adjusted output.

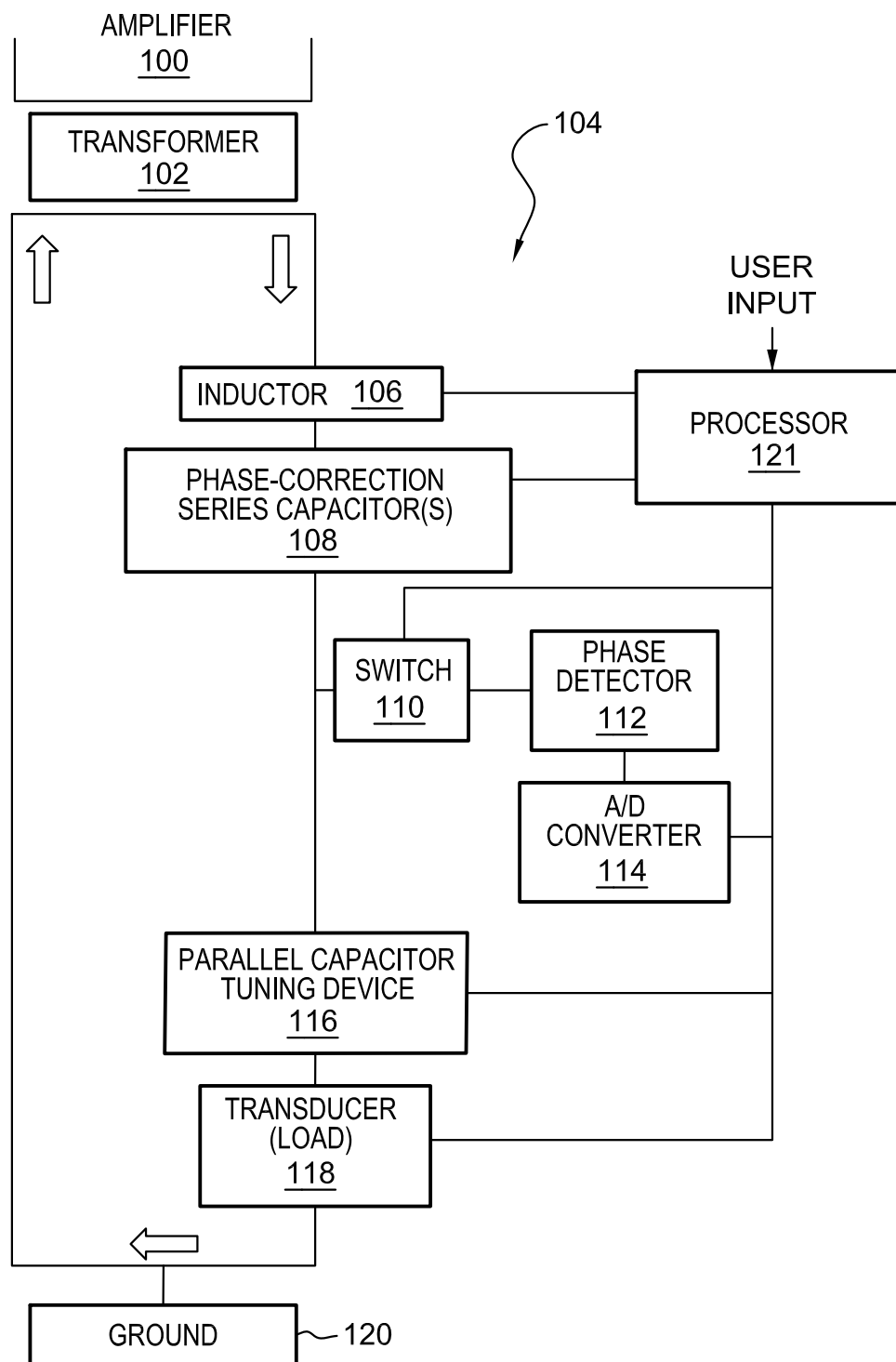


FIG. 1

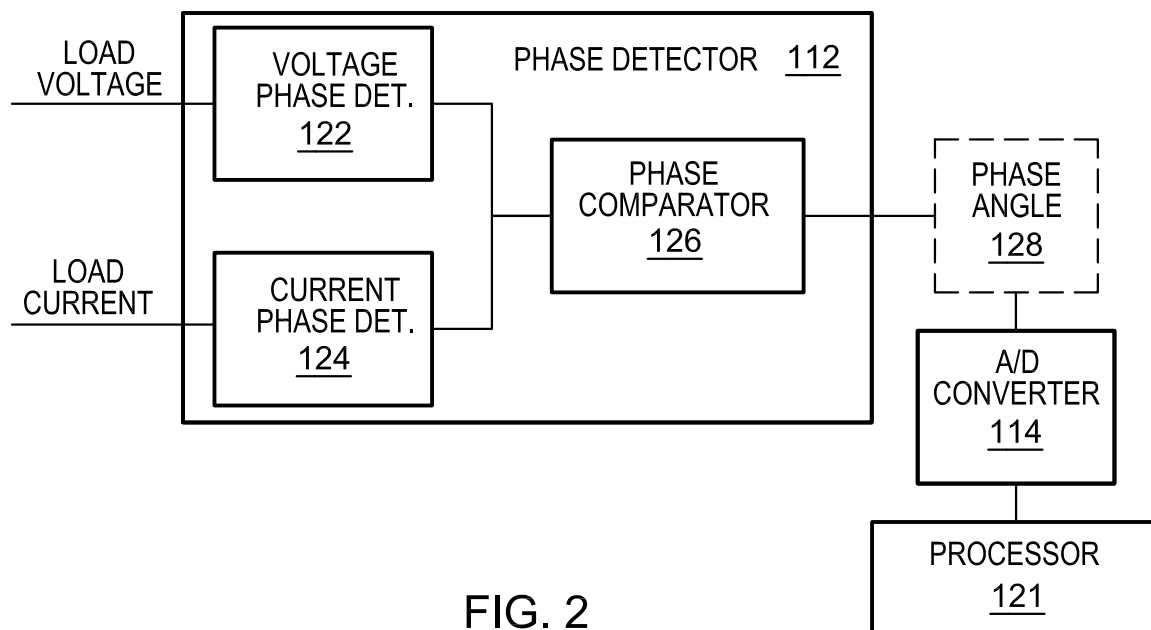


FIG. 2

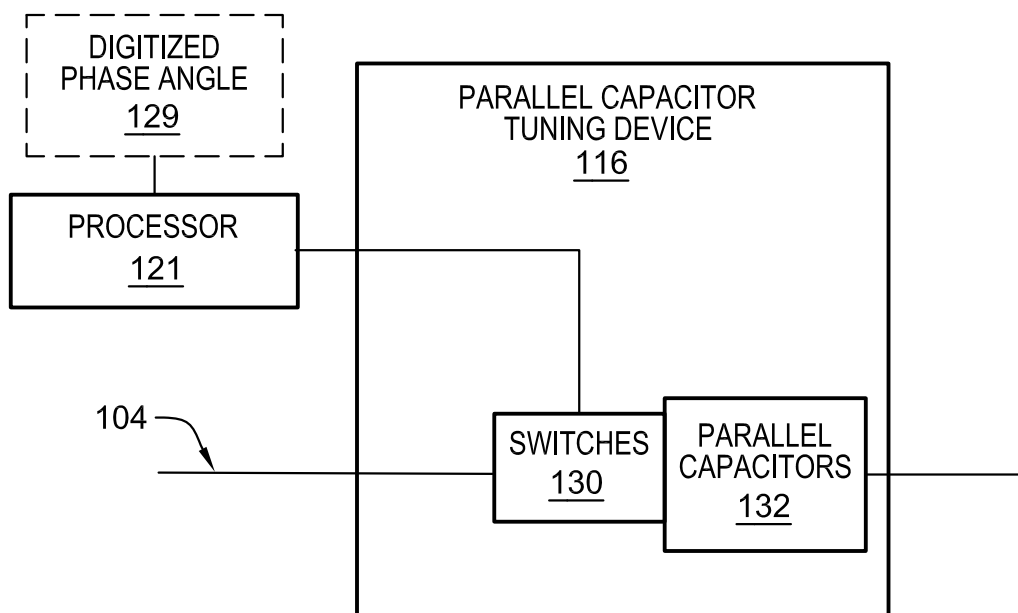


FIG. 3

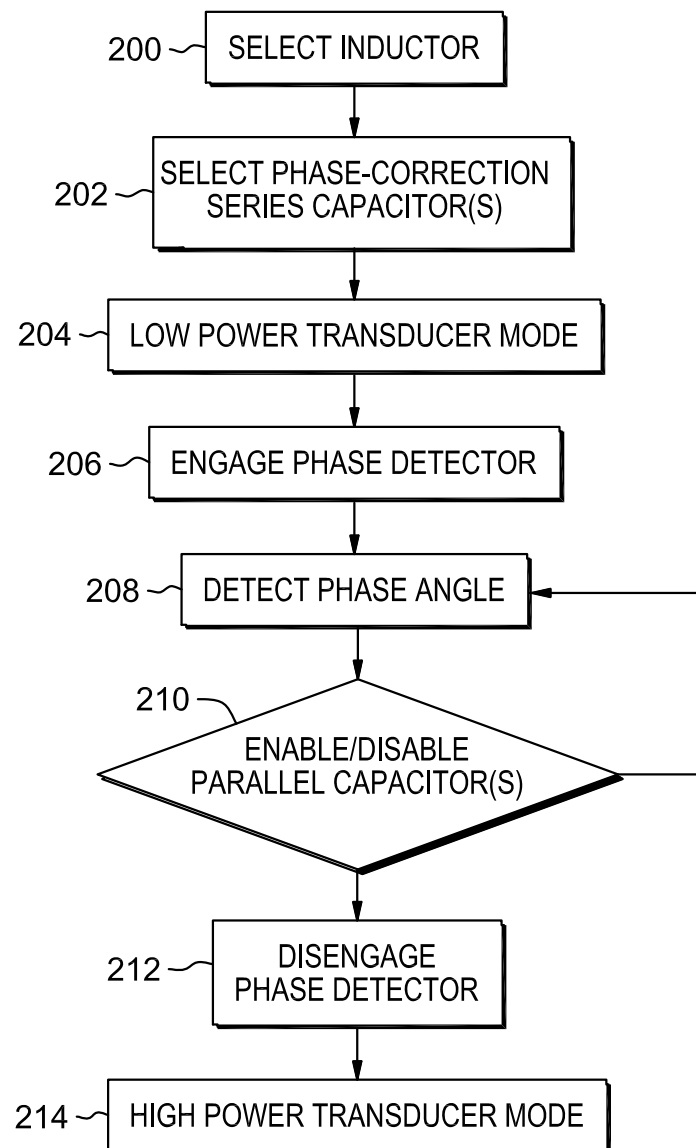


FIG. 4

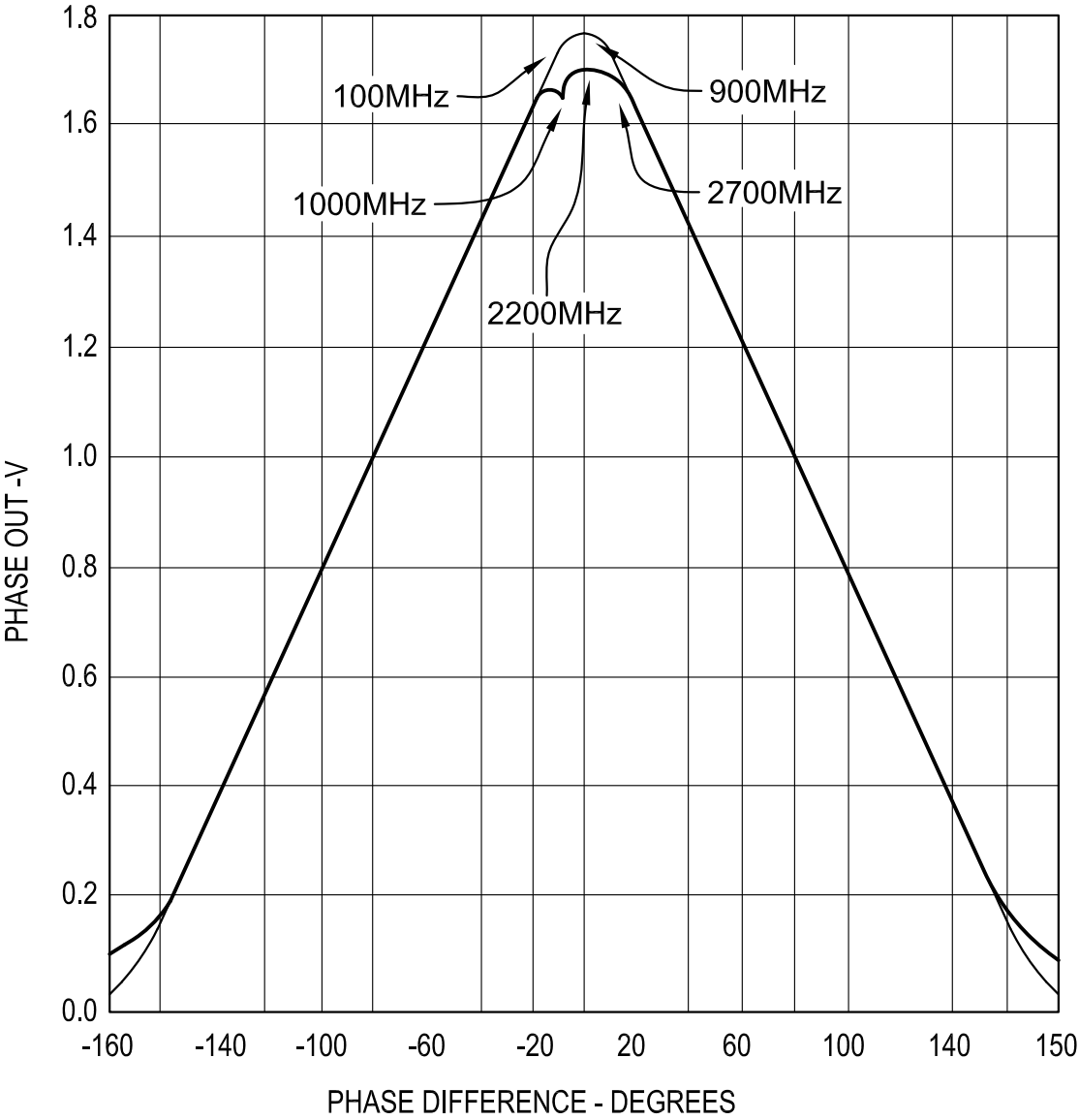


FIG. 5