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Rockman et al.

(54) ADJUSTMENT OF COMPLEX IMPEDANCE TO COMPENSATE FOR LOST POWER IN AN ARTICULATING ULTRASONIC DEVICE

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(21) Appl. No.: **16/144,418**

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Publication Classification

(51) **Int. Cl.**

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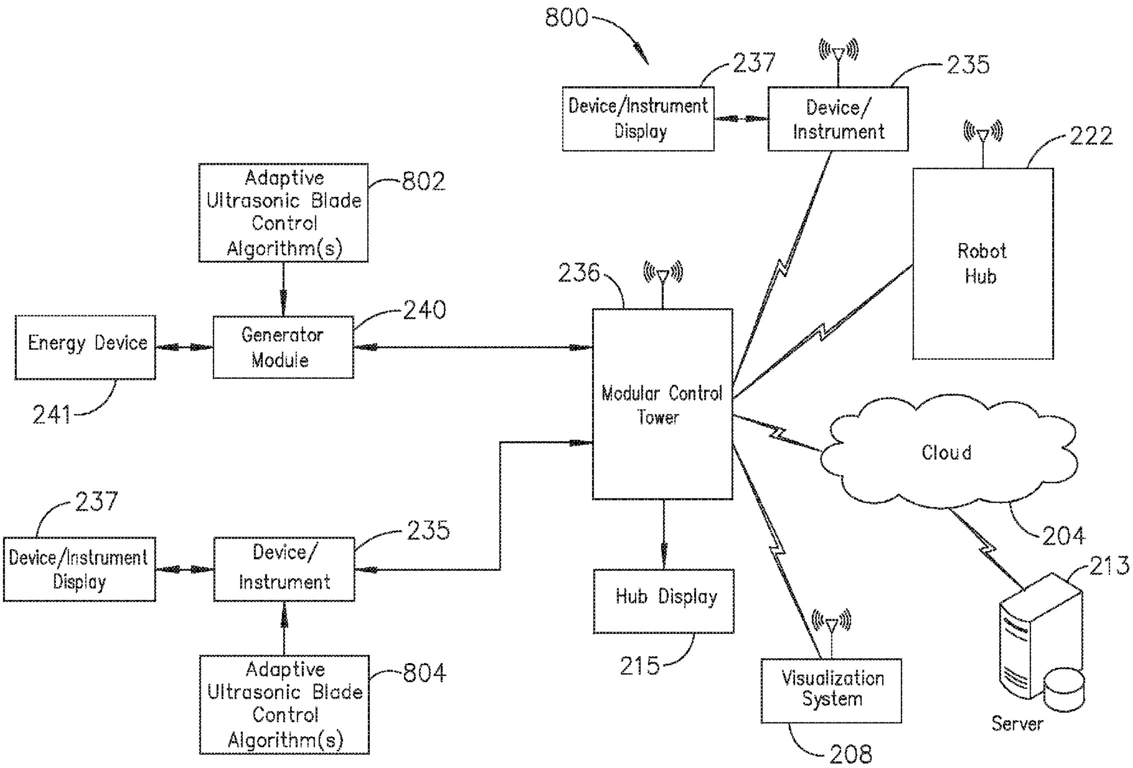
B06B 1/06	(2006.01)
H03H 9/00	(2006.01)

(52) **U.S. Cl.**

CPC *A61B 8/56* (2013.01); *H03H 9/0004* (2013.01); *B06B 1/0644* (2013.01); *A61B 8/4483* (2013.01)

(57) **ABSTRACT**

An ultrasonic device may include an electromechanical ultrasonic system defined by a predetermined resonant frequency, the electromechanical ultrasonic system having an ultrasonic transducer coupled to an ultrasonic blade. A method of compensating power delivered to the ultrasonic device may include determining an articulation angle of an articulatable ultrasonic blade coupled to the ultrasonic transducer, adjusting a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle, and adjusting, a power applied to the ultrasonic transducer based on the articulation angle. The ultrasonic device may include a generator and a control circuit configured to effect the method.



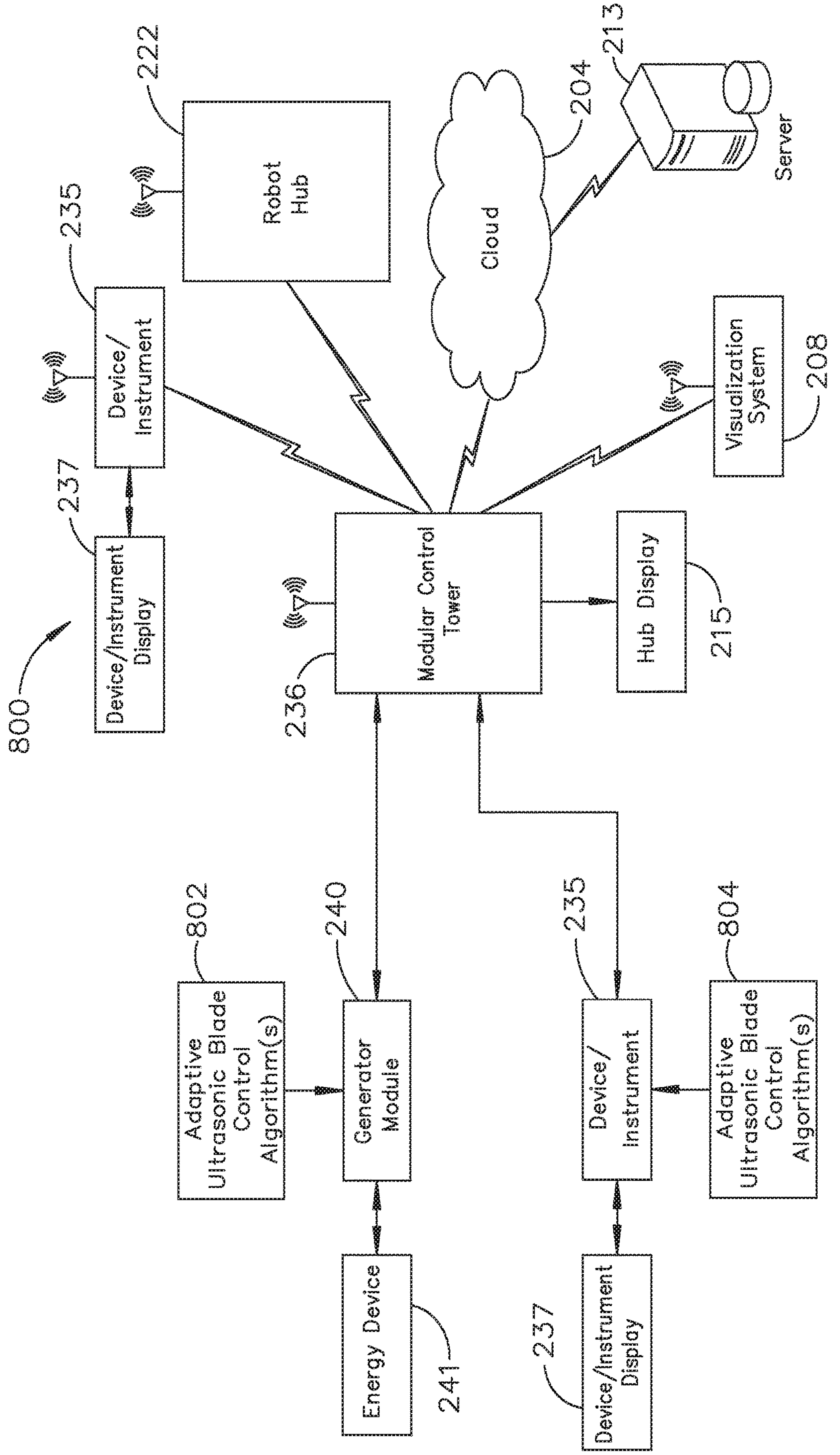
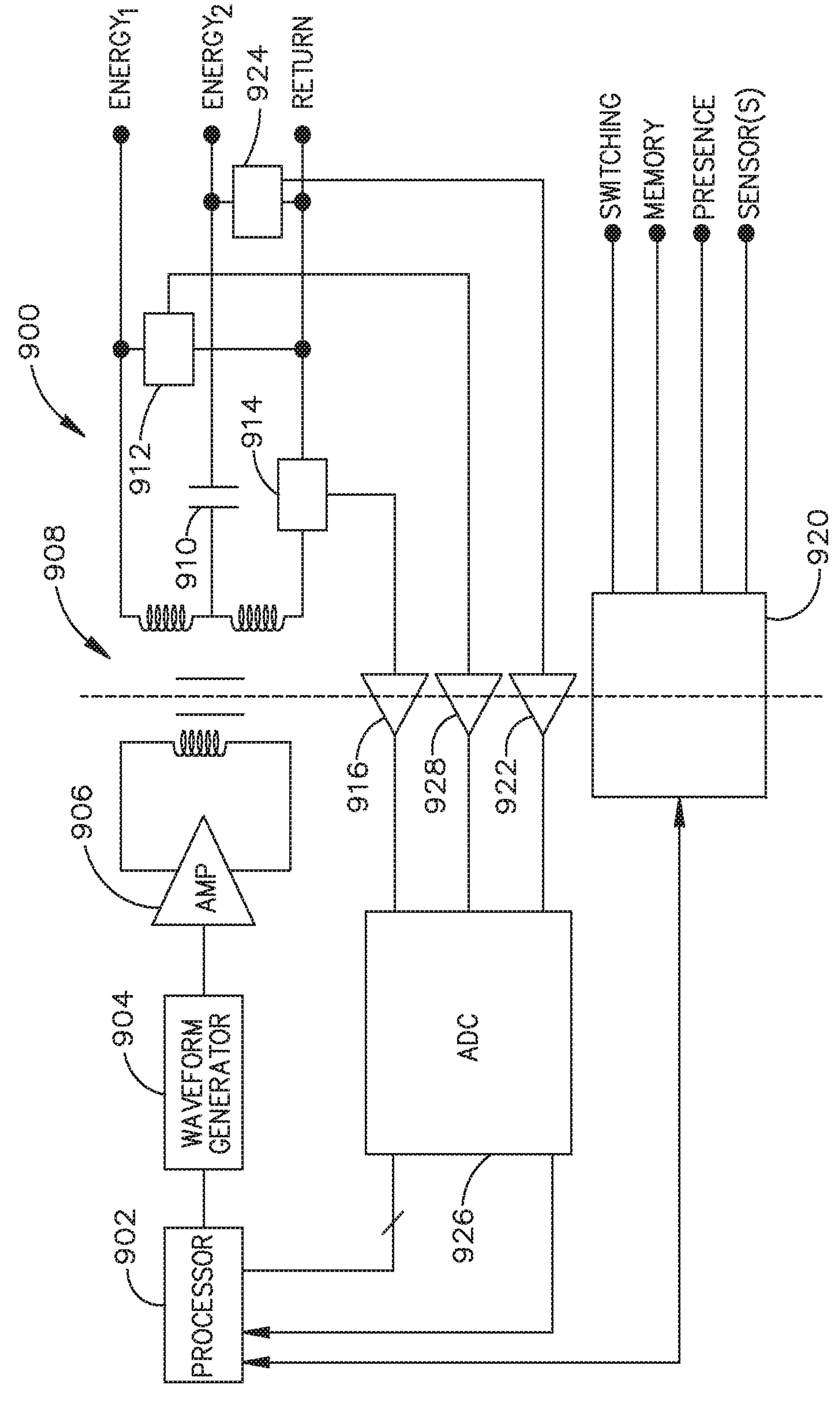

800
Device/Instrument Display
237
Device/ Instrument
235
Robot Hub
222
Cloud
204
213
Server
Visualization System
208
Modular Control Tower
236
Hub Display
215
Adaptive Ultrasonic Blade Control Algorithm(s)
802
Generator Module
240
Energy Device
241
Device/ Instrument
235
Adaptive Ultrasonic Blade Control Algorithm(s)
804
Device/Instrument Display
237

FIG. 1



ENERGY1
ENERGY2
RETURN
924
900
912
914
908
910
SWITCHING
MEMORY
PRESENCE
SENSOR(S)
920
906
AMP
904
WAVEFORM GENERATOR
902
PROCESSOR
ADC
926
916
928
922

FIG. 2

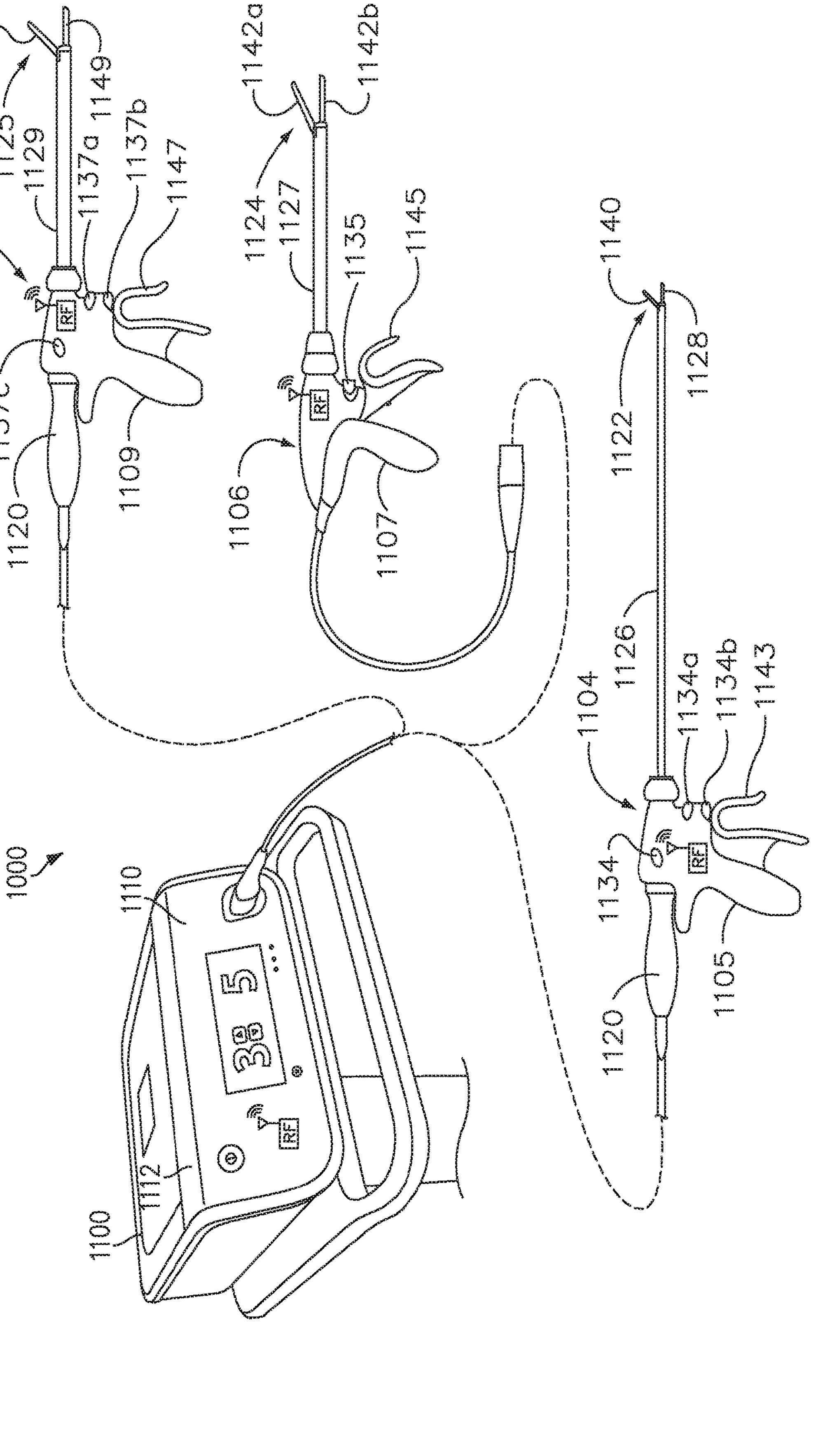

1000
1100
1110
1112
RF
1104
1105
1120
1134
1134a
1134b
1143
1126
1122
1128
1140
1106
1107
1124
1127
1135
1145
1142a
1142b
1108
1109
1125
1129
1137a
1137b
1137c
1146
1147
1149

FIG. 3

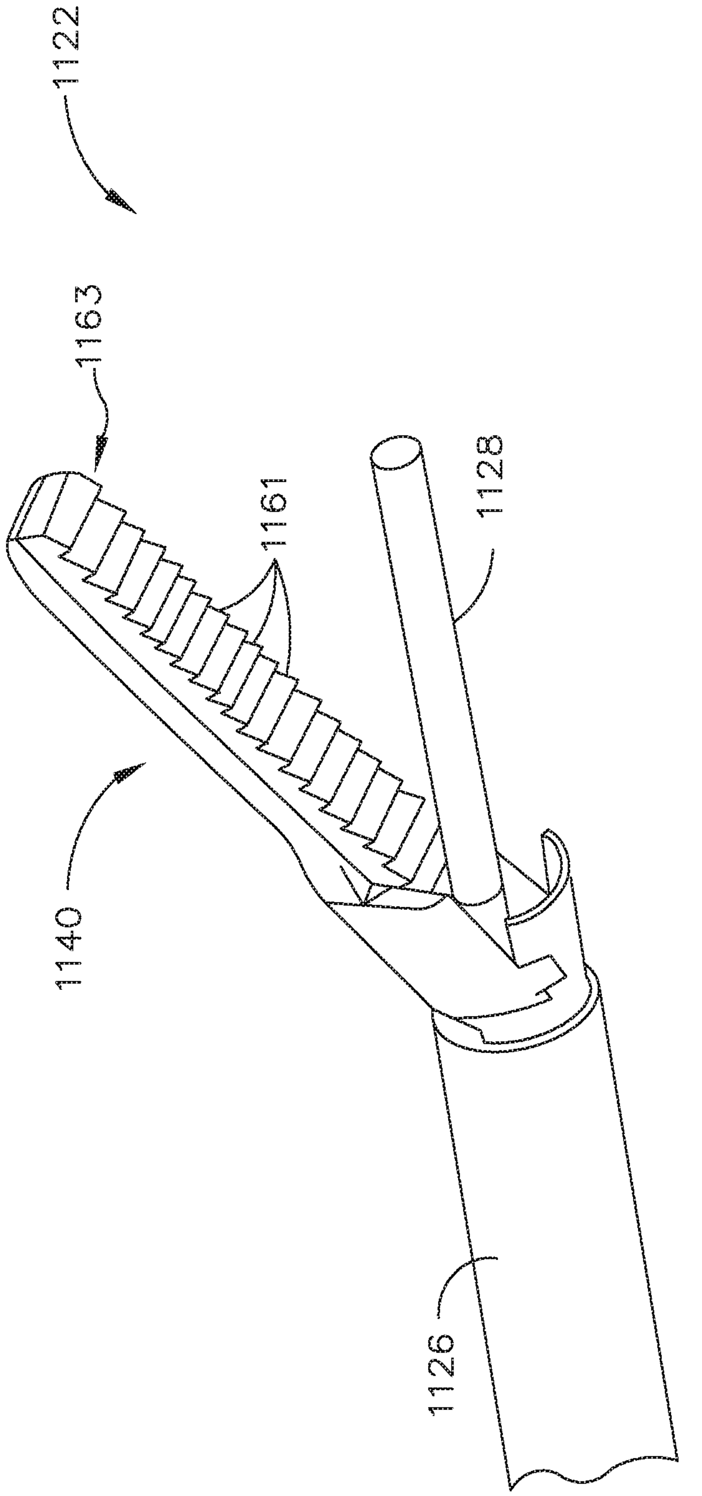


FIG. 4

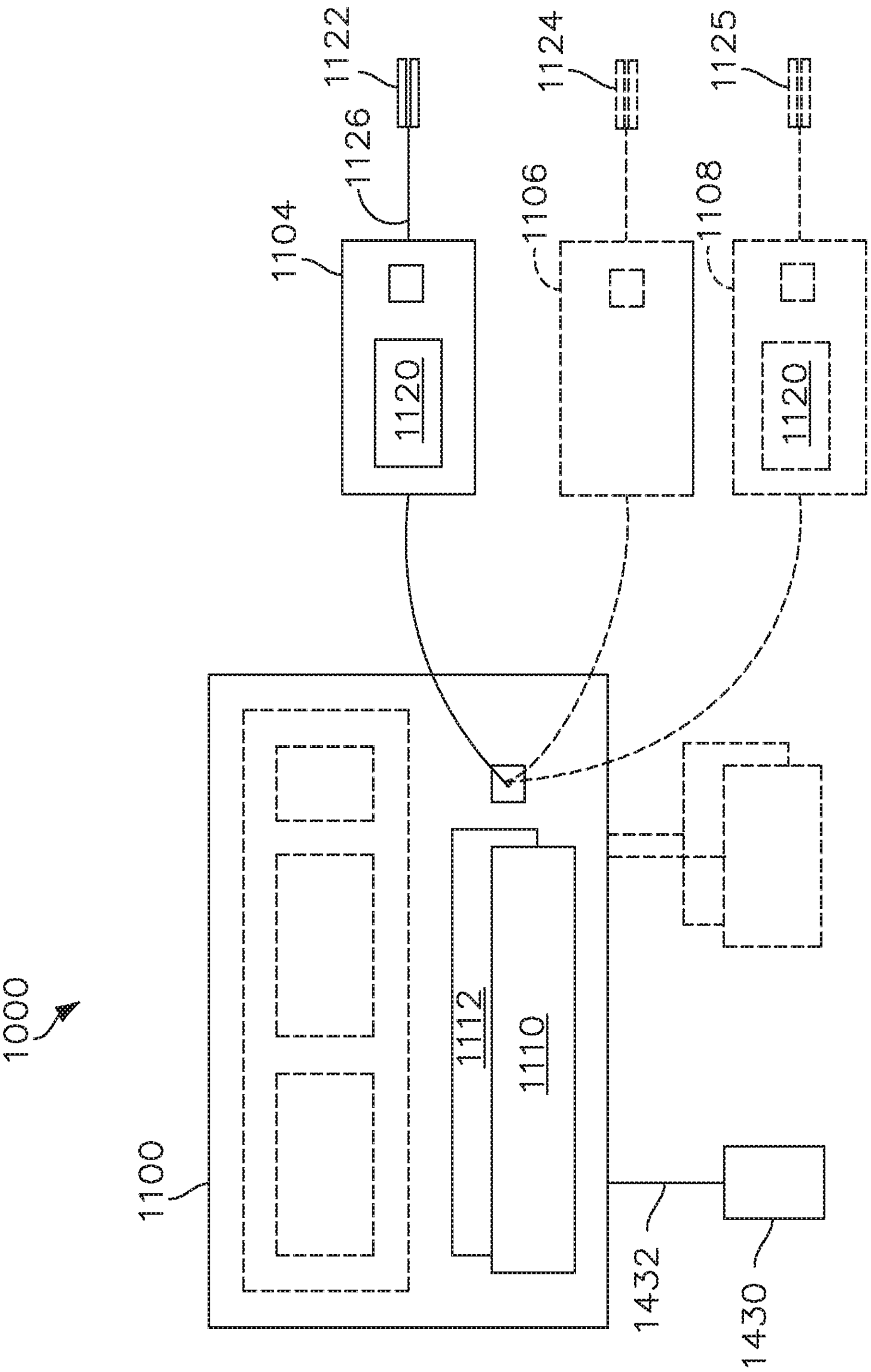

1122
1126
1104
1124
1106
1125
1108
1120
1120
1000
1100
1112
1110
1432
1430

FIG. 5

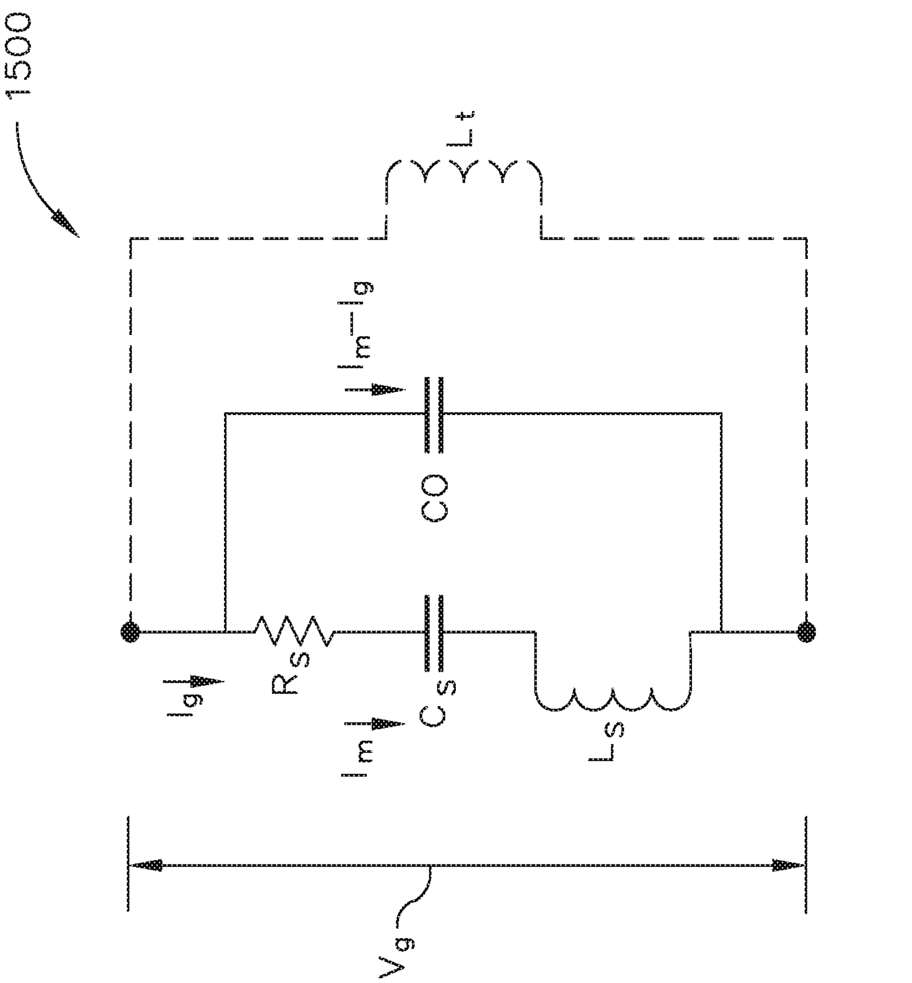
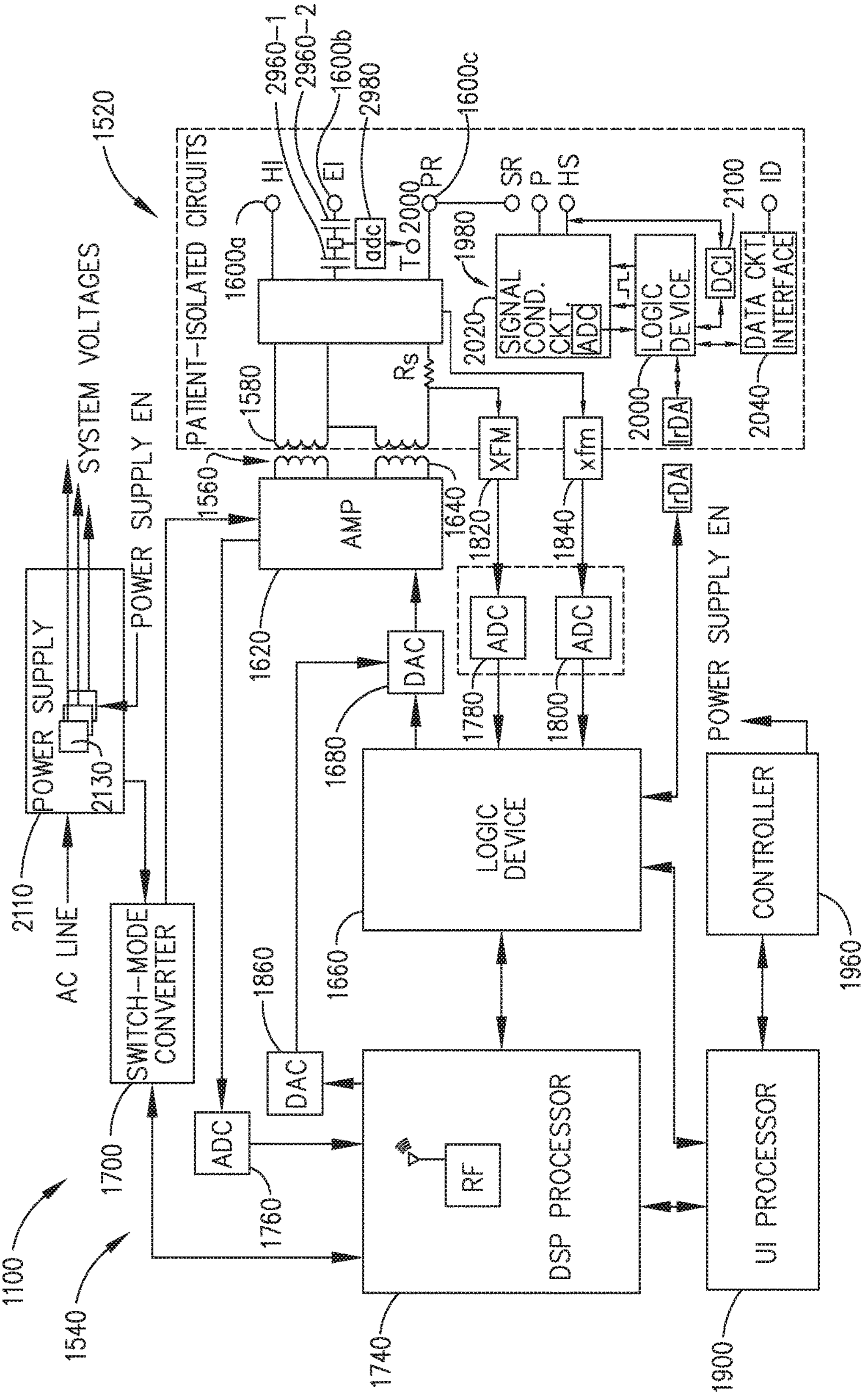


FIG. 6



POWER SUPPLY
AC LINE
SYSTEM VOLTAGES
POWER SUPPLY EN
SWITCH-MODE CONVERTER
PATIENT-ISOLATED CIRCUITS
HI
EI
PR
SR
P
HS
ID
adc
T
SIGNAL COND. CKT.
ADC
LOGIC DEVICE
DCI
DATA CKT. INTERFACE
IrDA
Rs
XFM
xfm
AMP
DAC
ADC
LOGIC DEVICE
CONTROLLER
DSP PROCESSOR
RF
UI PROCESSOR
1100
1520
1540
1560
1580
1600a
1600b
1600c
1620
1640
1660
1680
1700
1740
1760
1780
1800
1820
1840
1860
1900
1960
1980
2000
2020
2040
2100
2110
2130
2960-1
2960-2
2980

FIG. 7

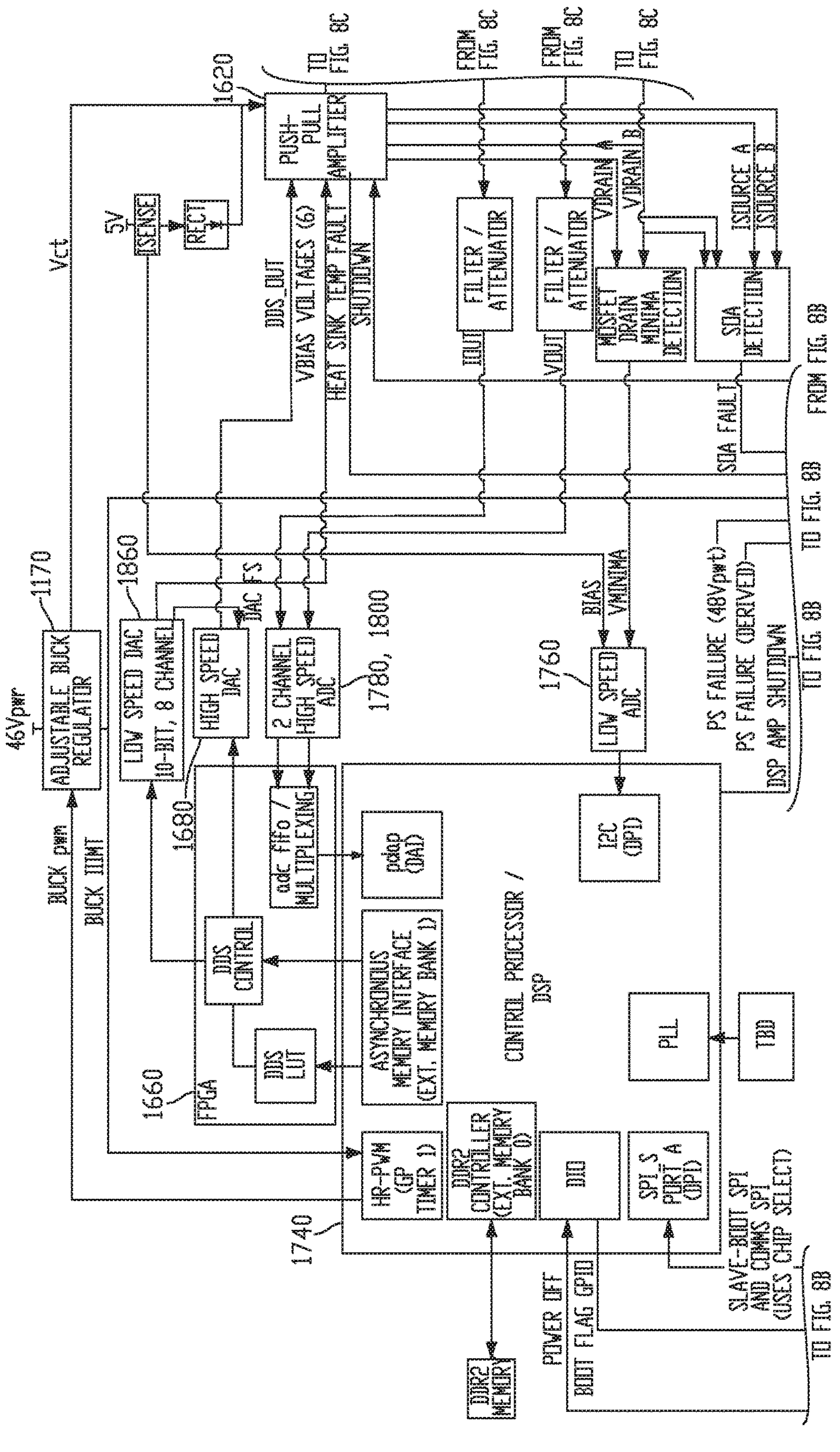

46Vpwr
ADJUSTABLE BUCK REGULATOR
1170
Vct
BUCK pwm
BUCK ILIMIT
5V
ISENSE
RECT
1620
PUSH-PULL AMPLIFIER
TO FIG. 8C
FROM FIG. 8C
FROM FIG. 8C
TO FIG. 8C
DDS_OUT
VBIAS VOLTAGES (6)
HEAT SINK TEMP FAULT
SHUTDOWN
FILTER / ATTENUATOR
IOUT
FILTER / ATTENUATOR
VOUT
VDRAIN A
VDRAIN B
ISOURCE A
ISOURCE B
MOSFET DRAIN MINIMA DETECTION
SOA DETECTION
FROM FIG. 8B
SOA FAULT
TO FIG. 8B
1860
LOW SPEED DAC
10-BIT, 8 CHANNEL
DAC FS
HIGH SPEED DAC
2 CHANNEL HIGH SPEED ADC
1780, 1800
BIAS
VMINIMA
1760
LOW SPEED ADC
PS FAILURE (48Vpwt)
PS FAILURE (DERIVED)
DSP AMP SHUTDOWN
TO FIG. 8B
TO FIG. 8B
1680
adc fifo / MULTIPLEXING
pdap (DAI)
I2C (DPI)
DDS CONTROL
ASYNCHRONOUS MEMORY INTERFACE (EXT. MEMORY BANK 1)
CONTROL PROCESSOR / DSP
1660
FPGA
DDS LUT
PLL
TBD
1740
HR-PWM (GP TIMER 1)
DDR2 CONTROLLER (EXT. MEMORY BANK 0)
DIO
SPI_S PORT A (DPI)
DDR2 MEMORY
POWER OFF
BOOT FLAG GPIO
SLAVE-BOOT SPI AND COMMS SPI (USES CHIP SELECT)
TO FIG. 8B

FIG. 8A

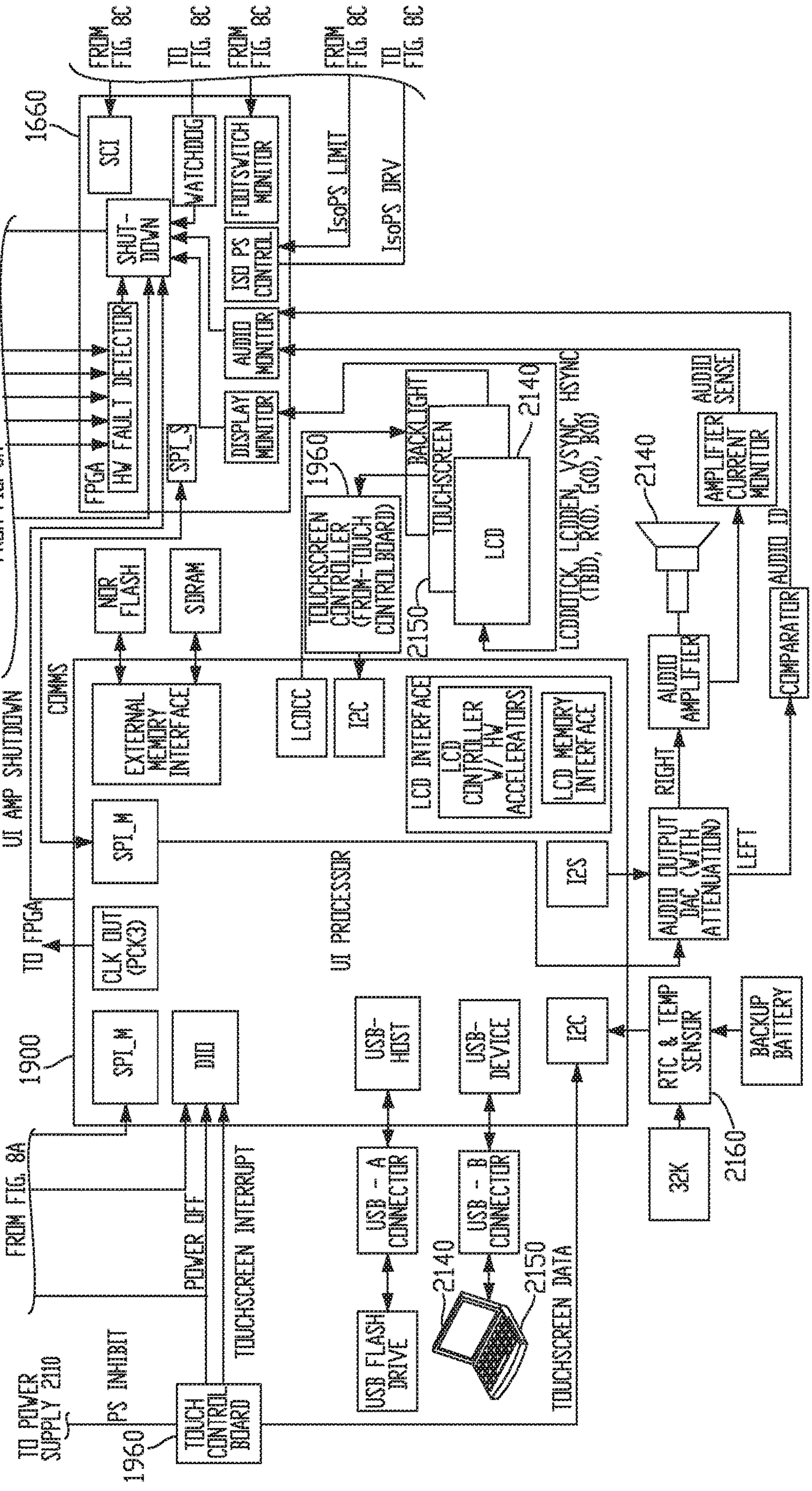

FROM FIG. 8C
TO FIG. 8C
FROM FIG. 8C
FROM FIG. 8C
TO FIG. 8C
1660
SCI
WATCHDOG
FOOTSWITCH MONITOR
IsoPS LIMIT
IsoPS DRV
TO FIG. 8A
SHUT-DOWN
ISO PS CONTROL
FROM FIG. 8A
FPGA
HV FAULT DETECTOR
AUDIO MONITOR
SPI_S
DISPLAY MONITOR
BACKLIGHT
2140
FROM FIG. 8A
1960
TOUCHSCREEN
TOUCHSCREEN CONTROLLER (FROM-TOUCH CONTROLBOARD)
LCD
2150
LCDDTCK, LCDDEN, VSYNC, HSYNC (TBD), R(0), G(0), B(0)
2140
AUDIO SENSE
AMPLIFIER CURRENT MONITOR
AUDIO ID
NOR FLASH
SDRAM
UI AMP SHUTDOWN
COMMS
EXTERNAL MEMORY INTERFACE
LCDCC
I2C
LCD INTERFACE
LCD CONTROLLER W/ HW ACCELERATORS
LCD MEMORY INTERFACE
AUDIO AMPLIFIER
COMPARATOR
RIGHT
SPI_M
I2S
AUDIO OUTPUT DAC (WITH ATTENUATION)
LEFT
TO FPGA
CLK OUT (PCK3)
UI PROCESSOR
1900
SPI_M
DIO
USB-HOST
USB-DEVICE
I2C
RTC & TEMP SENSOR
BACKUP BATTERY
FROM FIG. 8A
2160
32K
POWER OFF
TOUCHSCREEN INTERRUPT
USB - A CONNECTOR
USB - B CONNECTOR
2140
2150
TOUCHSCREEN DATA
USB FLASH DRIVE
TO POWER SUPPLY 2110
PS INHIBIT
1960
TOUCH CONTROL BOARD

FIG. 8B

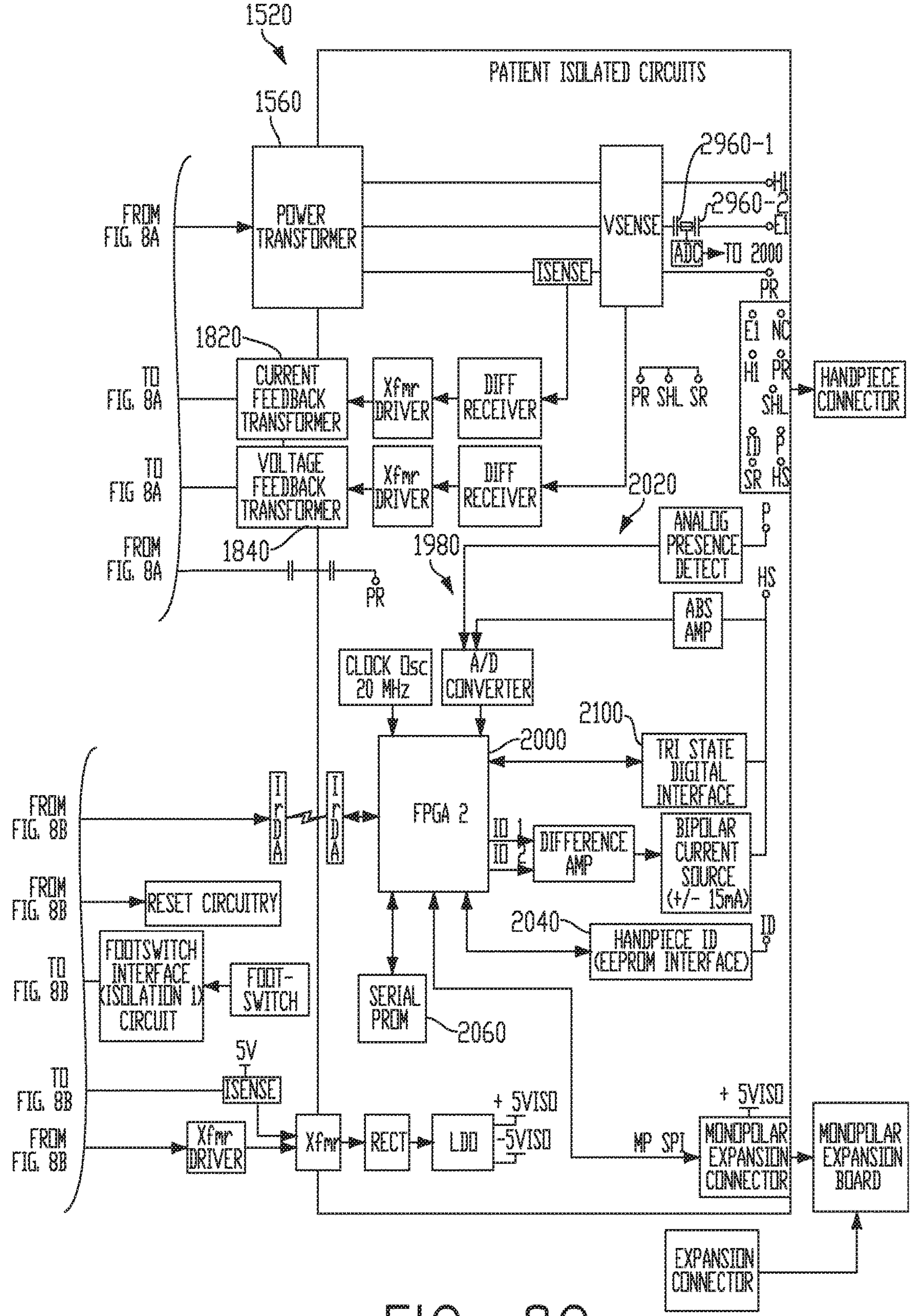

1520
PATIENT ISOLATED CIRCUITS
1560
FROM FIG. 8A
POWER TRANSFORMER
VSENSE
2960-1
2960-2
H1
E1
ADC
TO 2000
ISENSE
PR
1820
TO FIG. 8A
CURRENT FEEDBACK TRANSFORMER
Xfmr DRIVER
DIFF RECEIVER
PR SHL SR
E1 NC
H1 PR
SHL
ID P
SR HS
HANDPIECE CONNECTOR
TO FIG 8A
VOLTAGE FEEDBACK TRANSFORMER
Xfmr DRIVER
DIFF RECEIVER
2020
ANALOG PRESENCE DETECT
P
1840
FROM FIG. 8A
PR
1980
HS
ABS AMP
CLOCK Osc 20 MHz
A/D CONVERTER
2100
2000
TRI STATE DIGITAL INTERFACE
FROM FIG. 8B
IrDA
IrDA
FPGA 2
ID 1
ID 2
DIFFERENCE AMP
BIPOLAR CURRENT SOURCE (+/- 15mA)
FROM FIG. 8B
RESET CIRCUITRY
2040
HANDPIECE ID (EEPROM INTERFACE)
ID
TO FIG. 8B
FOOTSWITCH INTERFACE ISOLATION 1X CIRCUIT
FOOT-SWITCH
SERIAL PROM
2060
5V
TO FIG. 8B
ISENSE
+ 5VISO
+ 5VISO
FROM FIG. 8B
Xfmr DRIVER
Xfmr
RECT
LDO
-5VISO
MP SPI
MONOPOLAR EXPANSION CONNECTOR
MONOPOLAR EXPANSION BOARD
EXPANSION CONNECTOR

FIG. 8C

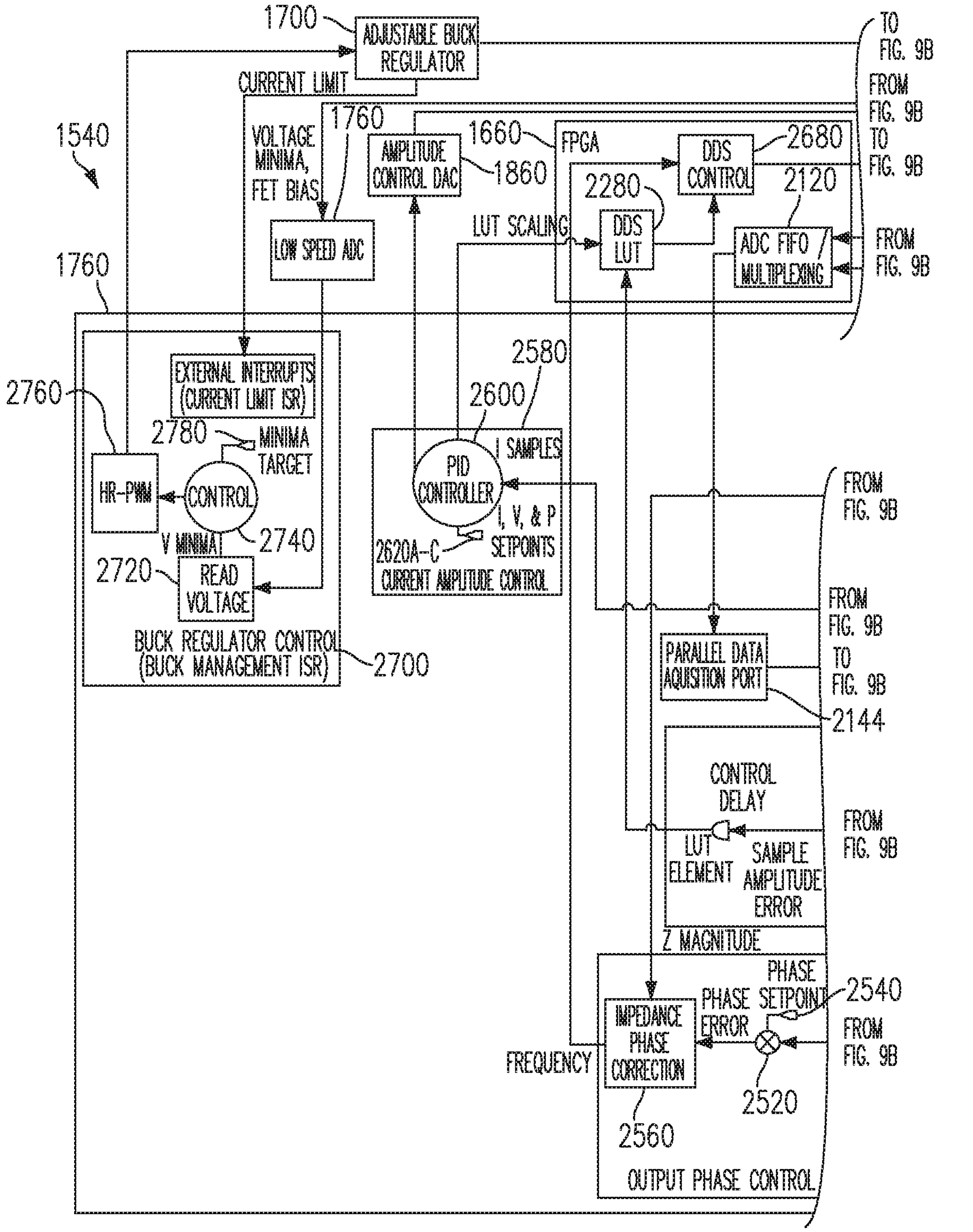

1700
ADJUSTABLE BUCK REGULATOR
TO FIG. 9B
FROM FIG. 9B
TO FIG. 9B
CURRENT LIMIT
1540
VOLTAGE MINIMA, FET BIAS
1760
AMPLITUDE CONTROL DAC
1660
FPGA
DDS CONTROL
2680
1860
2280
2120
LUT SCALING
DDS LUT
ADC FIFO / MULTIPLEXING
FROM FIG. 9B
LOW SPEED ADC
1760
2580
EXTERNAL INTERRUPTS (CURRENT LIMIT ISR)
2760
2600
2780
MINIMA TARGET
I SAMPLES
HR-PWM
CONTROL
PID CONTROLLER
FROM FIG. 9B
V MINIMA
2740
2620A-C
I, V, & P SETPOINTS
2720
READ VOLTAGE
CURRENT AMPLITUDE CONTROL
FROM FIG. 9B
BUCK REGULATOR CONTROL (BUCK MANAGEMENT ISR)
2700
PARALLEL DATA AQUISITION PORT
TO FIG. 9B
2144
CONTROL DELAY
FROM FIG. 9B
LUT ELEMENT
SAMPLE AMPLITUDE ERROR
Z MAGNITUDE
PHASE SETPOINT
2540
PHASE ERROR
IMPEDANCE PHASE CORRECTION
FREQUENCY
FROM FIG. 9B
2520
2560
OUTPUT PHASE CONTROL

FIG. 9A

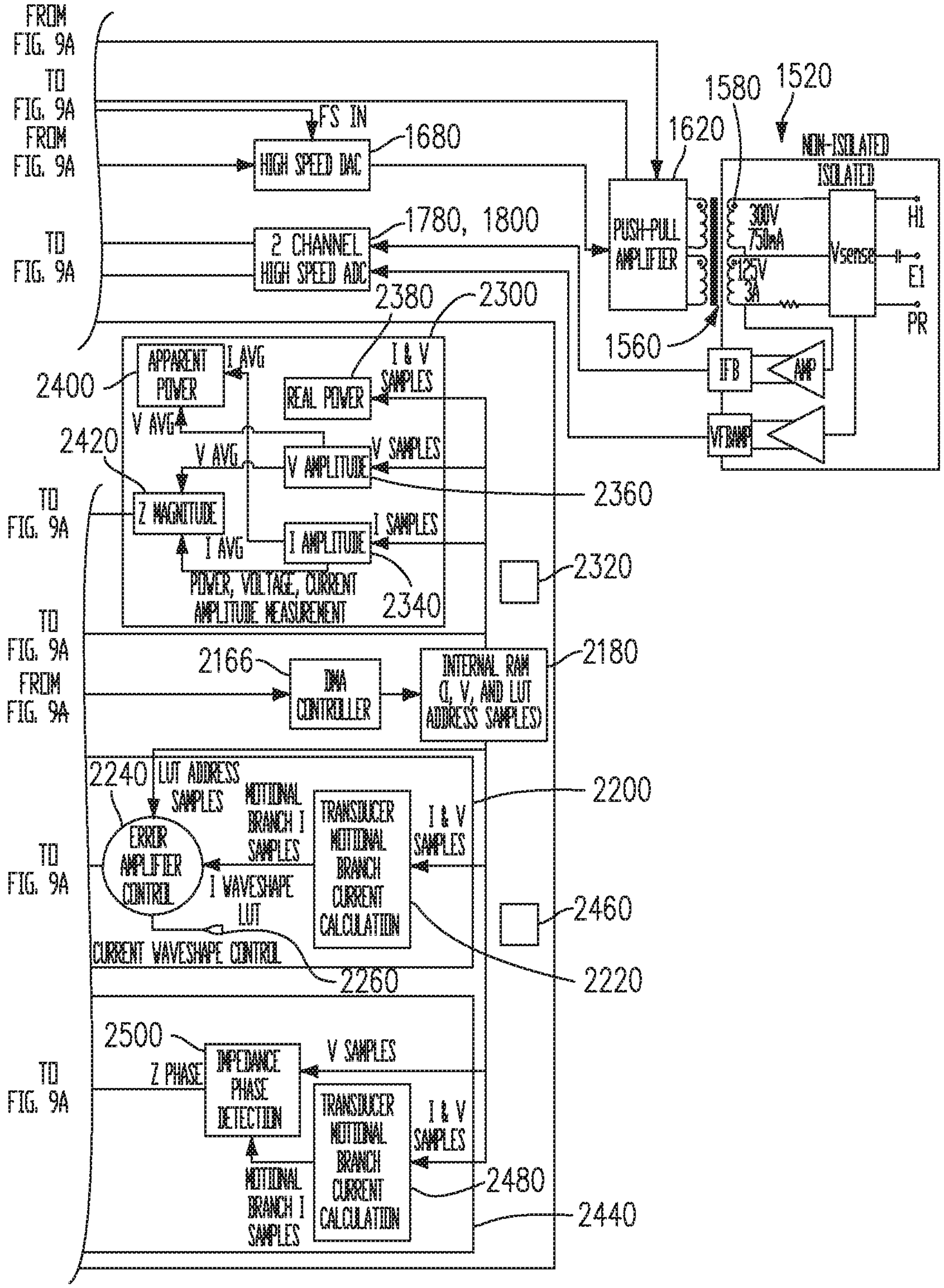

FROM FIG. 9A
TO FIG. 9A
FROM FIG. 9A
TO FIG. 9A
FS IN
HIGH SPEED DAC
1680
2 CHANNEL HIGH SPEED ADC
1780, 1800
PUSH-PULL AMPLIFIER
1620
1580
1520
NON-ISOLATED
ISOLATED
300V 750mA
125V 3A
Vsense
H1
E1
PR
1560
IFB
AMP
VFBAMP
2380
2300
APPARENT POWER
I AVG
REAL POWER
I & V SAMPLES
2400
V AVG
2420
V AVG
V AMPLITUDE
V SAMPLES
2360
Z MAGNITUDE
I AMPLITUDE
I SAMPLES
I AVG
POWER, VOLTAGE, CURRENT AMPLITUDE MEASUREMENT
2340
2320
TO FIG. 9A
TO FIG. 9A
FROM FIG. 9A
2166
DMA CONTROLLER
INTERNAL RAM (I, V, AND LUT ADDRESS SAMPLES)
2180
2240
LUT ADDRESS SAMPLES
NOTIONAL BRANCH I SAMPLES
TRANSDUCER NOTIONAL BRANCH CURRENT CALCULATION
I & V SAMPLES
2200
TO FIG. 9A
ERROR AMPLIFIER CONTROL
I WAVESHAPE LUT
2460
CURRENT WAVESHAPE CONTROL
2260
2220
2500
IMPEDANCE PHASE DETECTION
V SAMPLES
Z PHASE
TO FIG. 9A
TRANSDUCER NOTIONAL BRANCH CURRENT CALCULATION
I & V SAMPLES
2480
NOTIONAL BRANCH I SAMPLES
2440

FIG. 9B

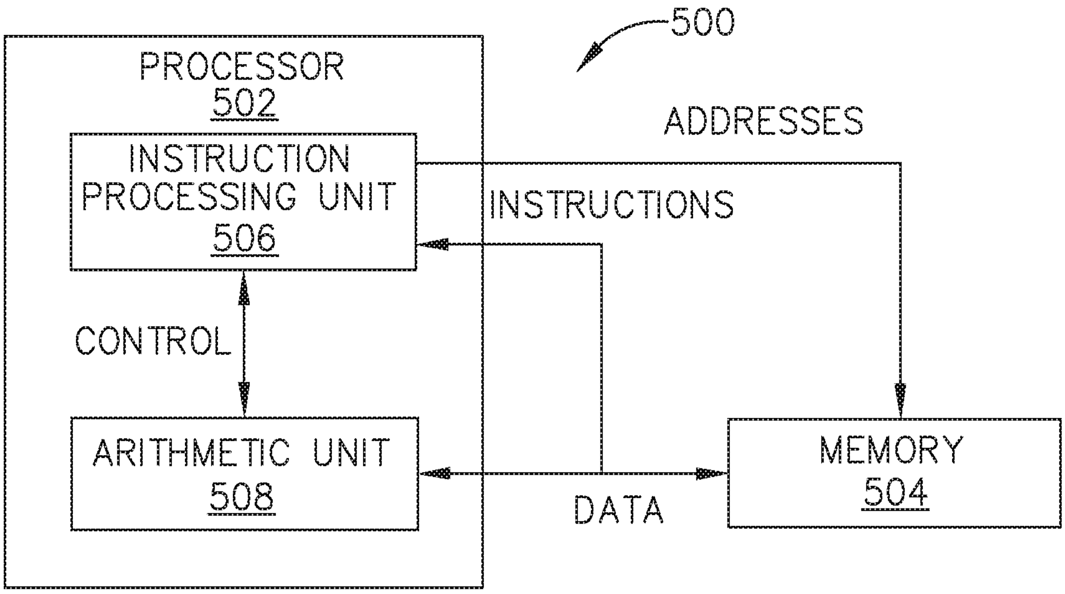


FIG. 10

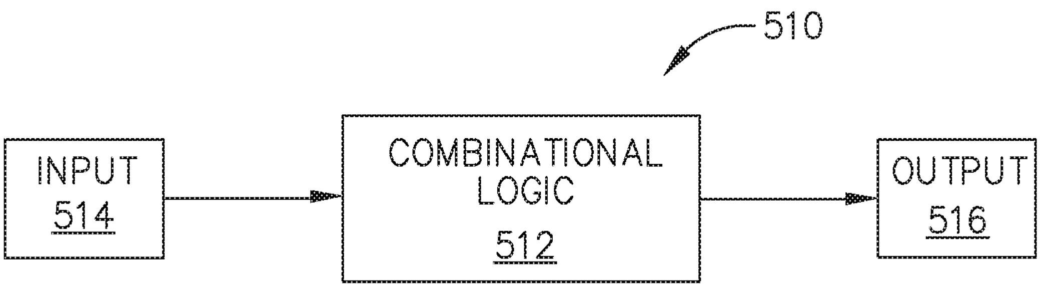


FIG. 11

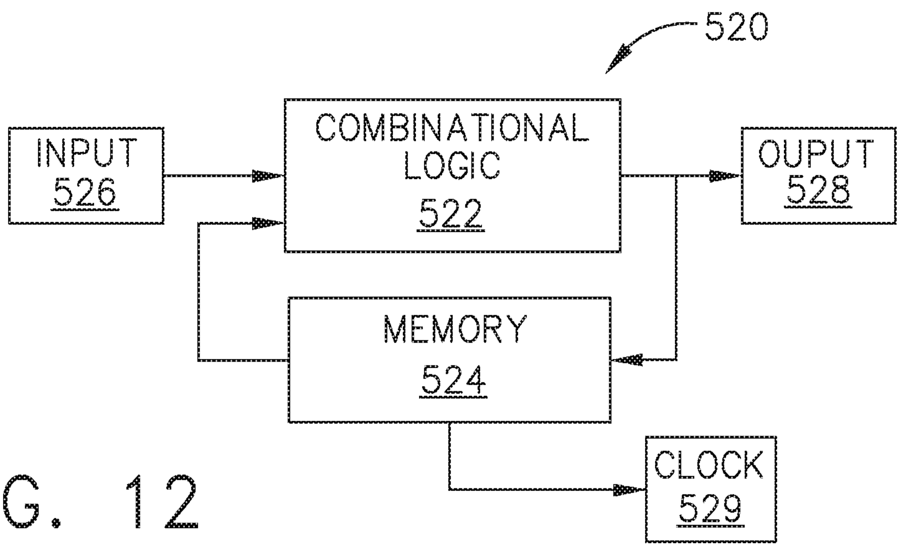


FIG. 12

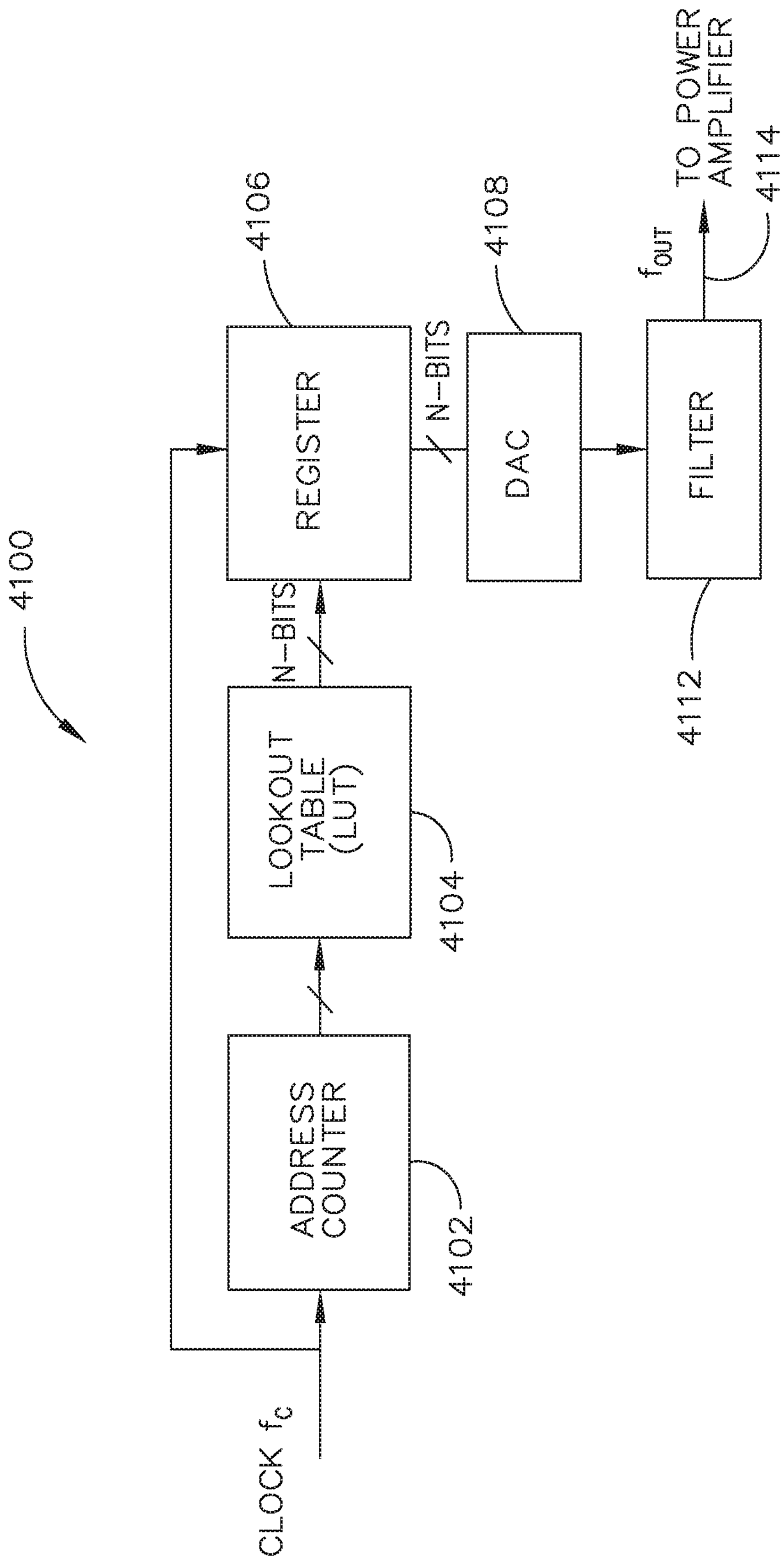

4100
CLOCK f_C
ADDRESS COUNTER
4102
LOOKOUT TABLE (LUT)
4104
N-BITS
REGISTER
4106
N-BITS
DAC
4108
FILTER
4112
f_{OUT}
TO POWER AMPLIFIER
4114

FIG. 13

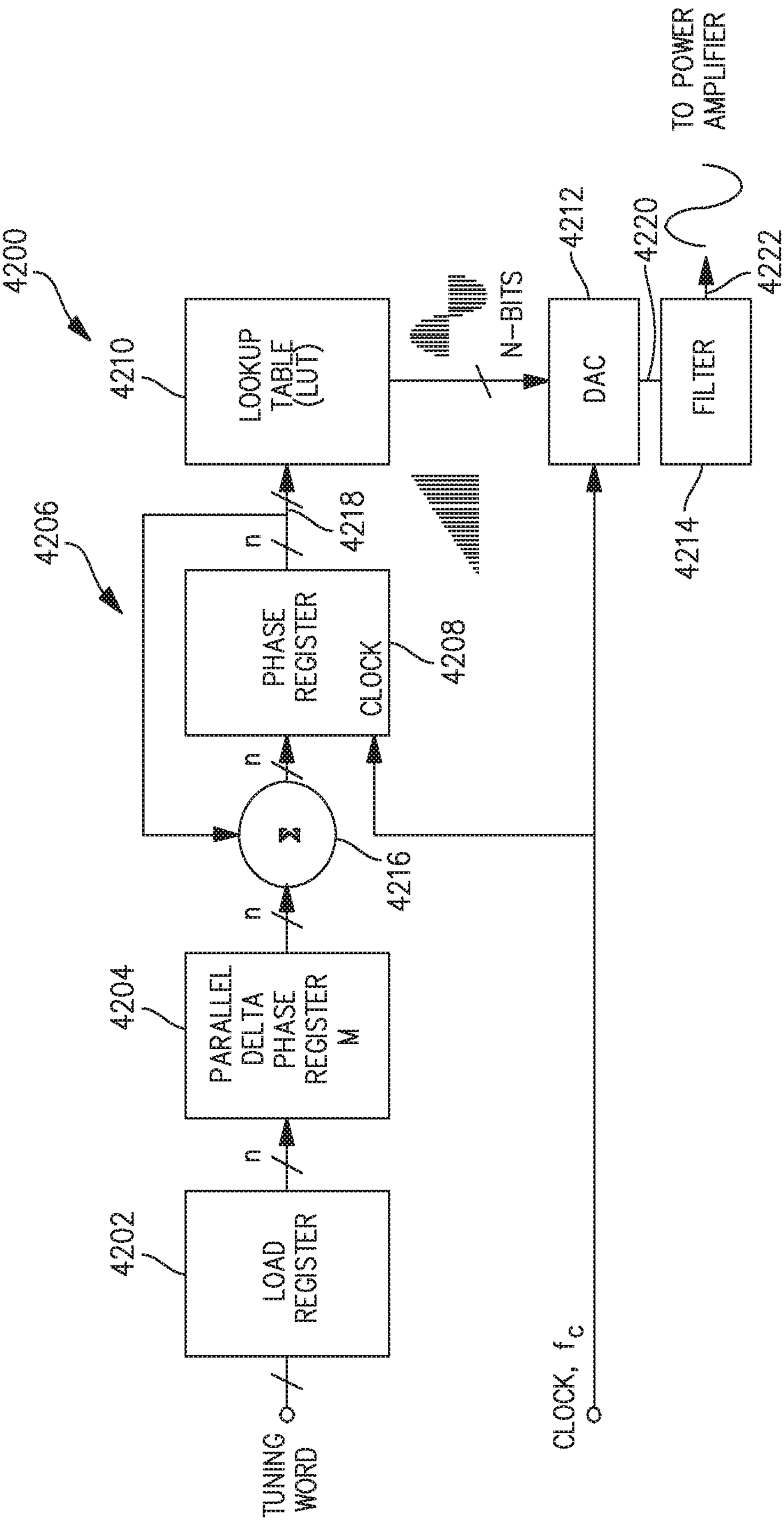

4200
TUNING WORD
LOAD REGISTER
4202
n
PARALLEL DELTA PHASE REGISTER M
4204
n
Σ
4216
4206
n
PHASE REGISTER
CLOCK
4208
n
4218
LOOKUP TABLE (LUT)
4210
N-BITS
DAC
4212
4220
FILTER
4214
4222
TO POWER AMPLIFIER
CLOCK, f_c

FIG. 14

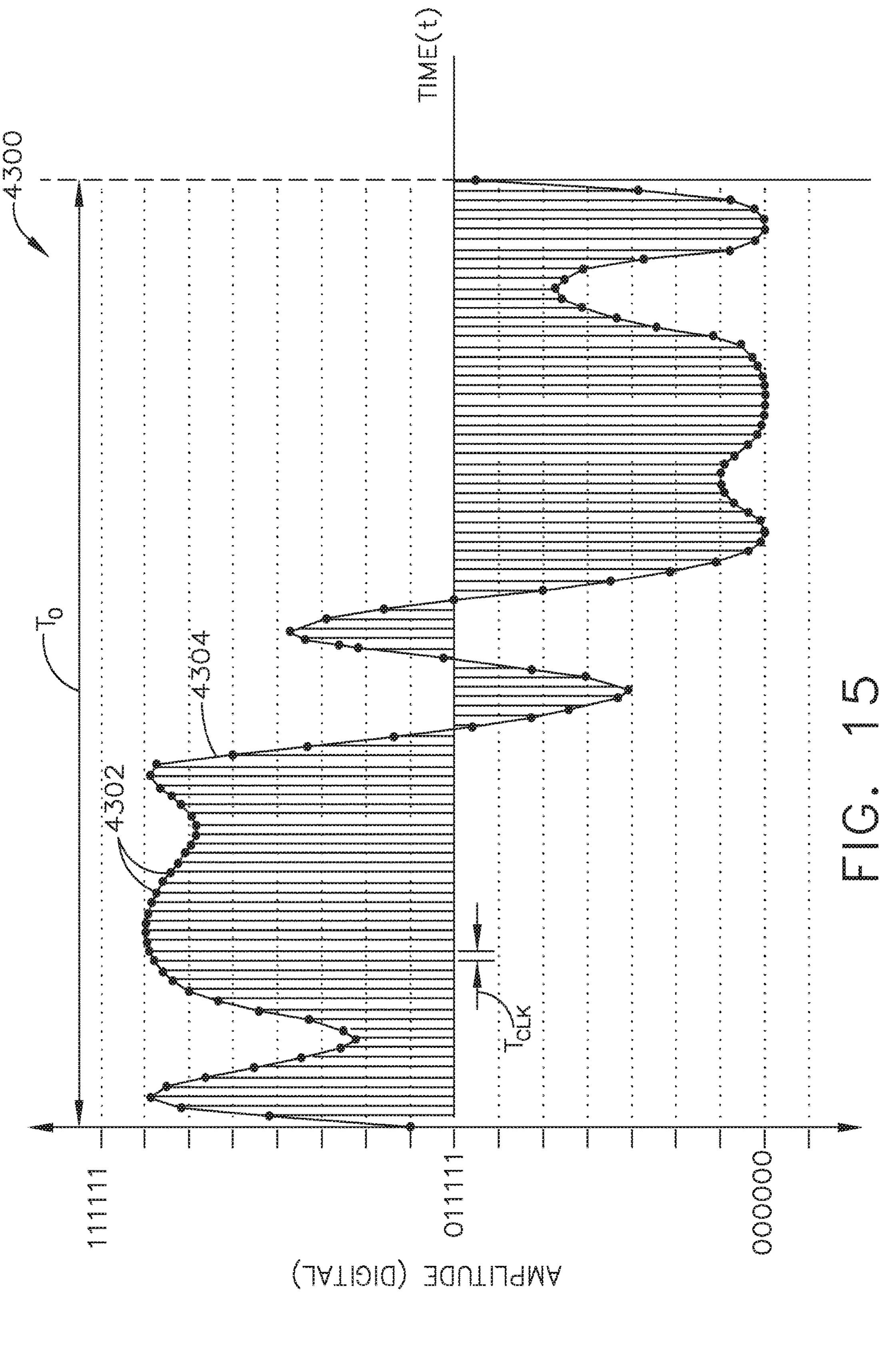

4300
TIME(t)
T0
4304
4302
TCLK
111111
011111
000000
AMPLITUDE (DIGITAL)

FIG. 15

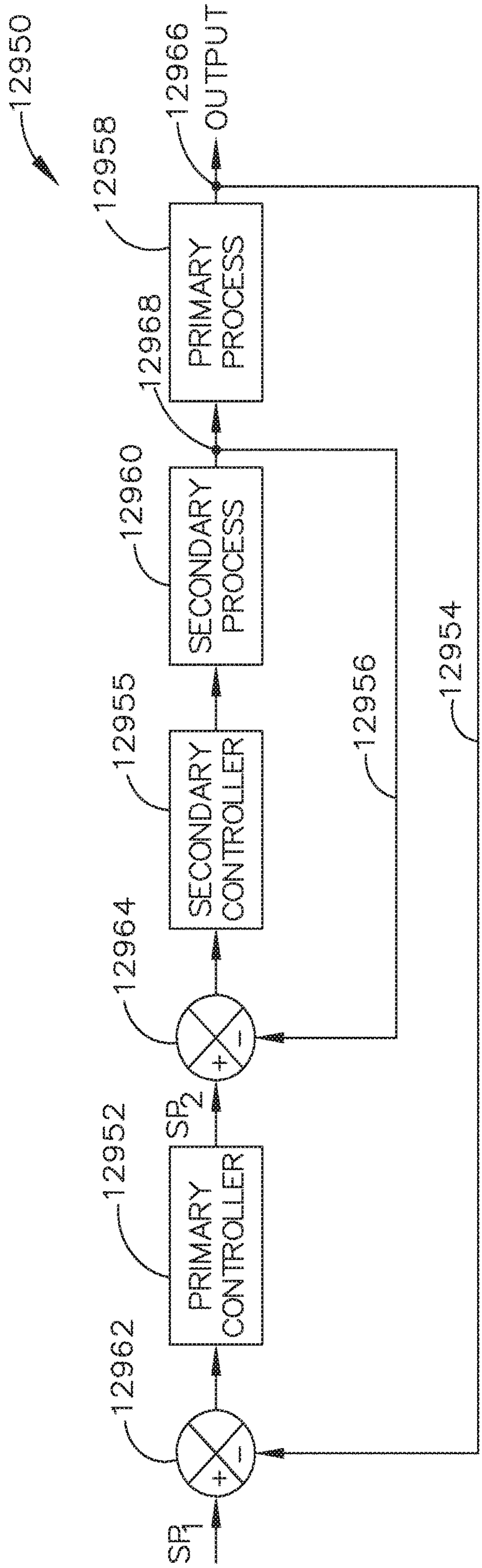

12950
12958
12966
OUTPUT
PRIMARY PROCESS
12968
12960
SECONDARY PROCESS
12955
SECONDARY CONTROLLER
12956
12954
12964
12952
PRIMARY CONTROLLER
SP_2
12962
SP_1

FIG. 16

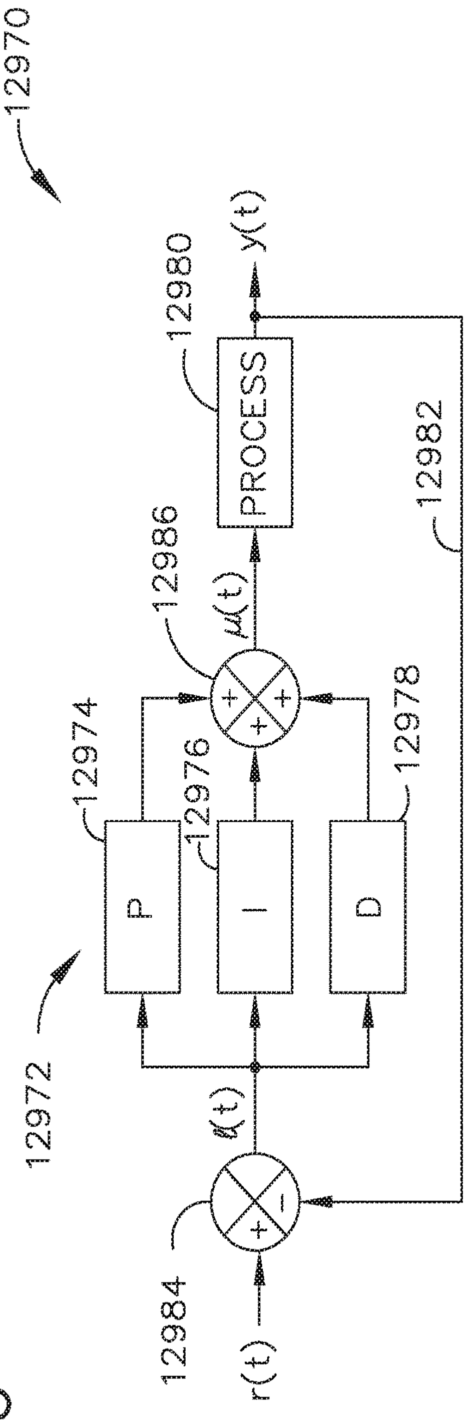

12970
12980
y(t)
PROCESS
12982
12986
μ(t)
12974
12976
12978
P
I
D
12972
e(t)
12984
r(t)

FIG. 17

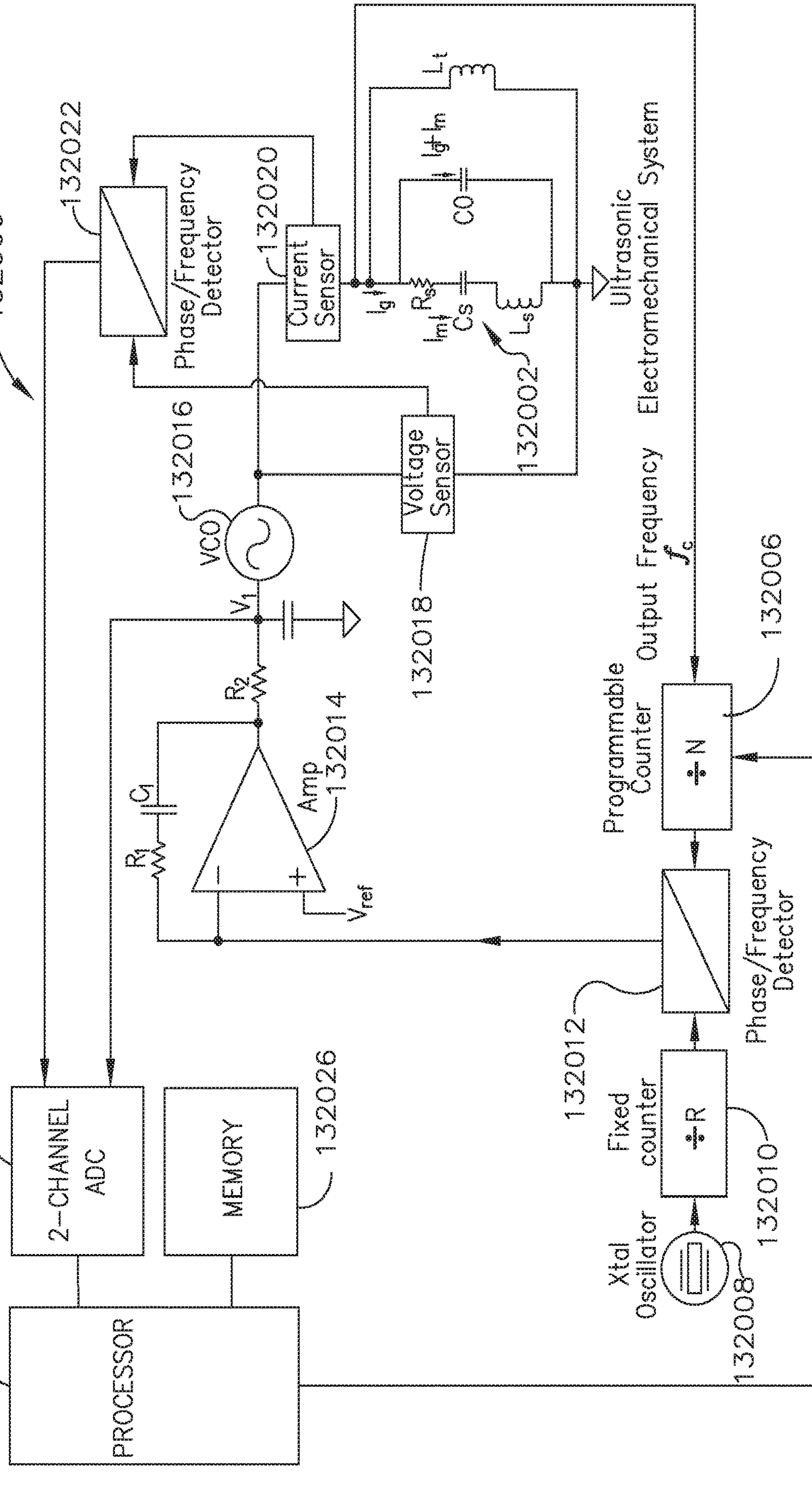

132000
132022
Phase/Frequency Detector
132020
Current Sensor
132016
VCO
V_1
Voltage Sensor
132018
132002
L_t
I_g
I_m
I_g-I_m
R_s
C_s
C0
L_s
Ultrasonic Electromechanical System
Output Frequency
f_c
R_2
R_1
C_1
Amp
132014
V_{ref}
Programmable Counter
÷ N
132006
Phase/Frequency Detector
132012
Fixed counter
÷ R
132010
Xtal Oscillator
132008
132024
2-CHANNEL ADC
132026
MEMORY
132004
PROCESSOR

FIG. 18

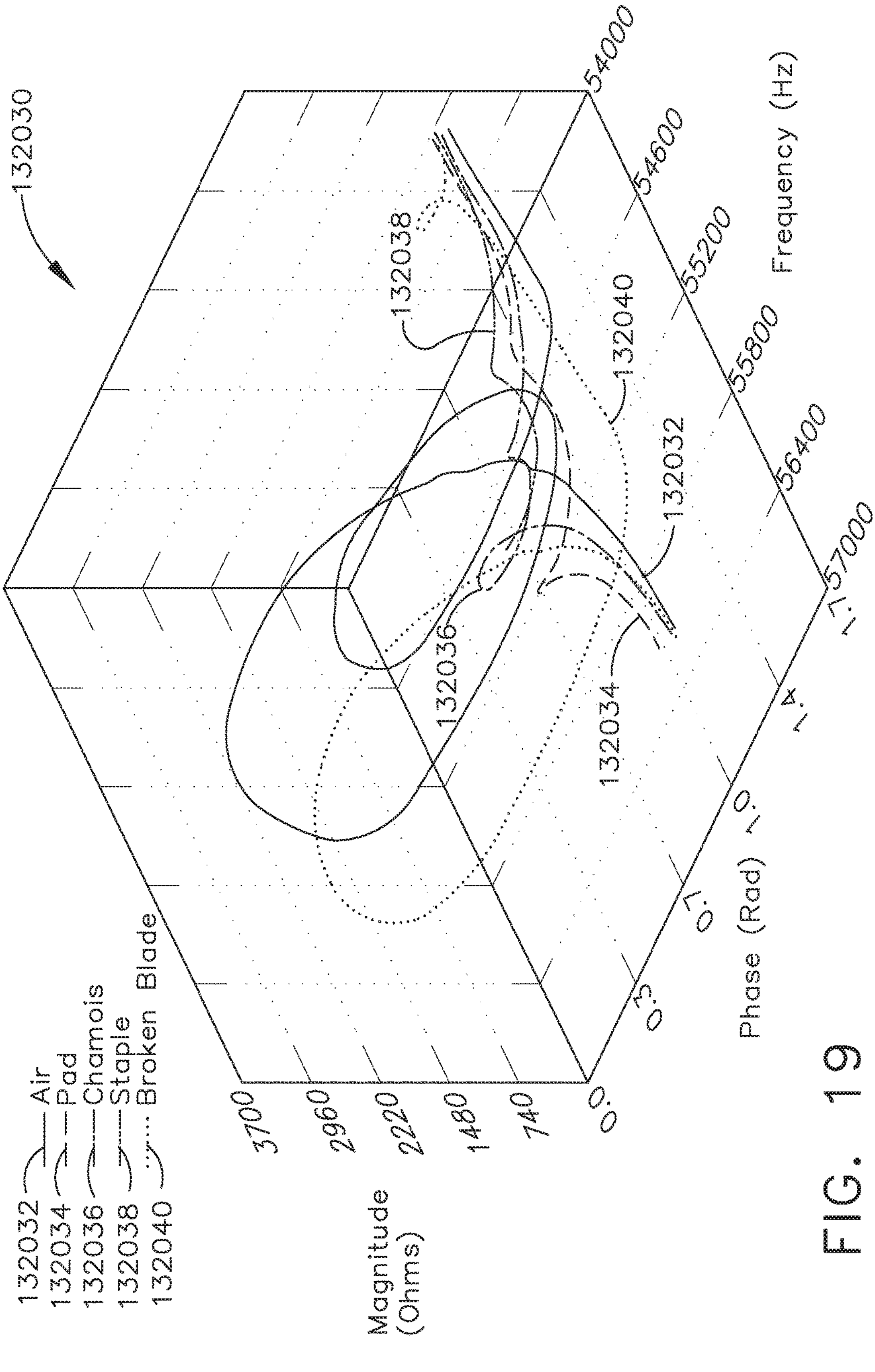

132030
132032 Air
132034 Pad
132036 Chamois
132038 Staple
132040 Broken Blade
Magnitude (Ohms)
3700
2960
2220
1480
740
0.0
Phase (Rad)
0.3
1.0
1.7
2.4
3.1
Frequency (Hz)
54000
54600
55200
55800
56400
57000
132038
132040
132032
132036
132034

FIG. 19

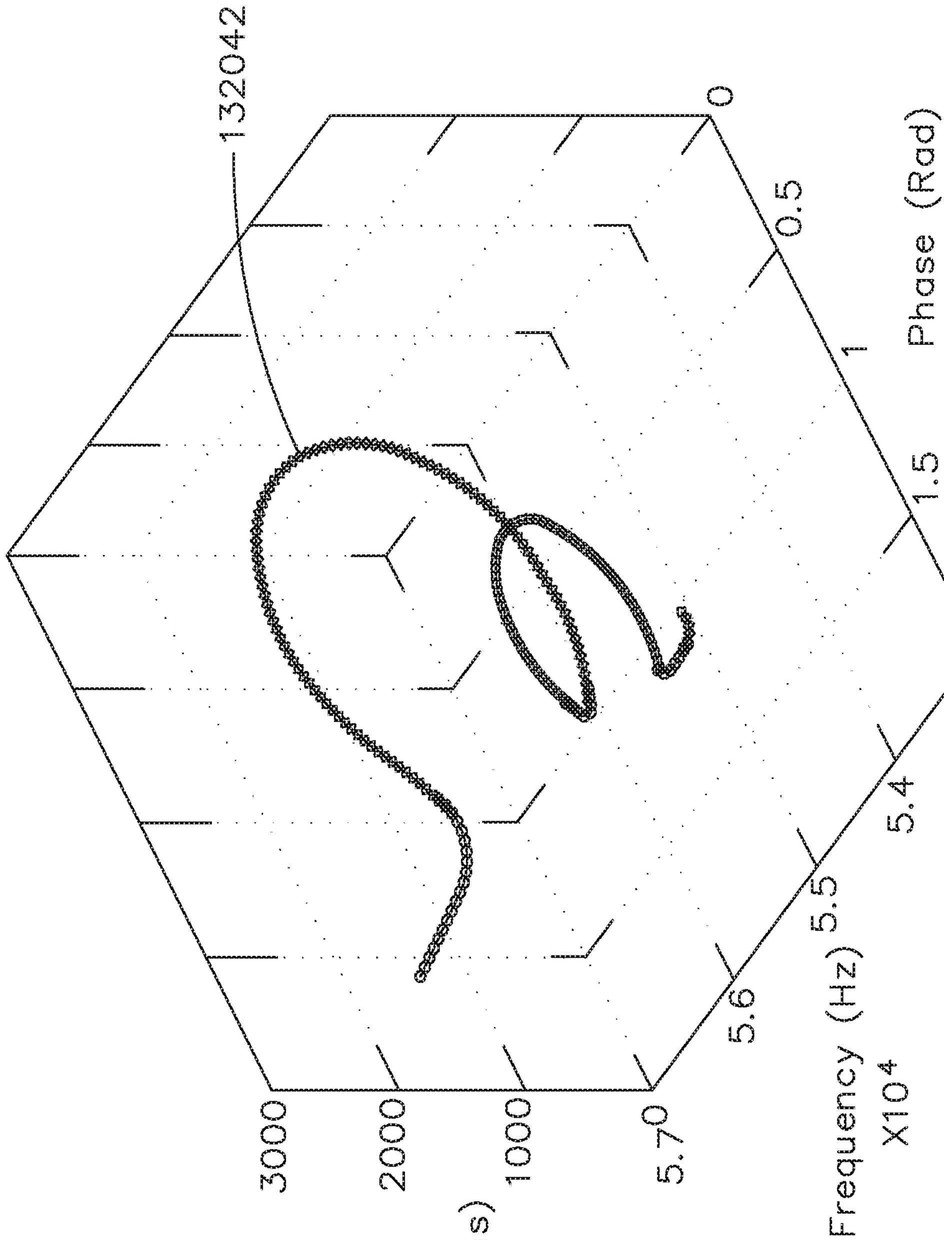

132042
Phase (Rad)
0
0.5
1
1.5
2
5.3
5.4
5.5
5.6
5.7
Frequency (Hz)
X10⁴
Mag (Ohms)
3000
2000
1000
0

FIG. 20

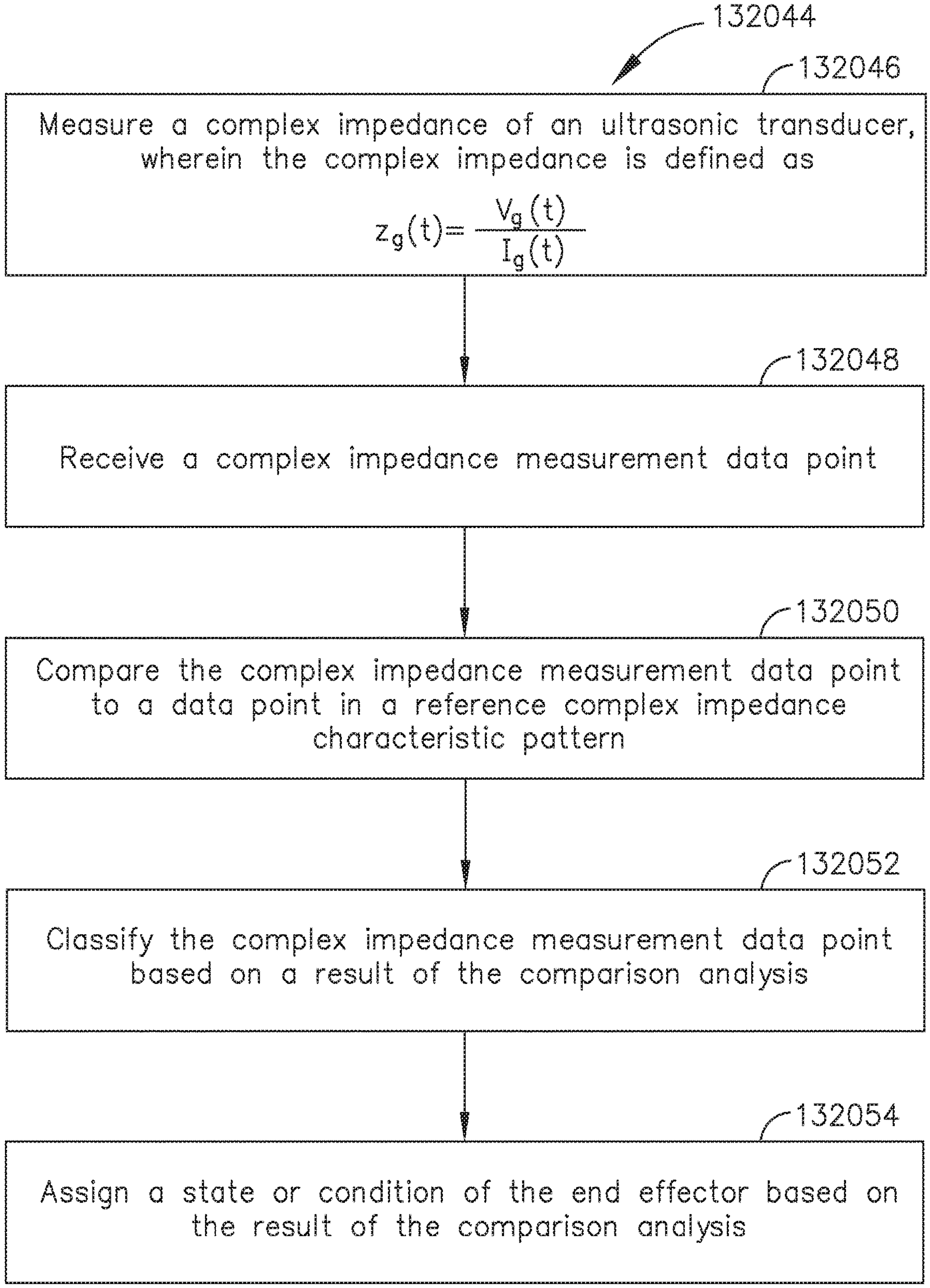

132044
132046
Measure a complex impedance of an ultrasonic transducer, wherein the complex impedance is defined as
$z_g(t)=\frac{V_g(t)}{I_g(t)}$
132048
Receive a complex impedance measurement data point
132050
Compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern
132052
Classify the complex impedance measurement data point based on a result of the comparison analysis
132054
Assign a state or condition of the end effector based on the result of the comparison analysis

FIG. 21

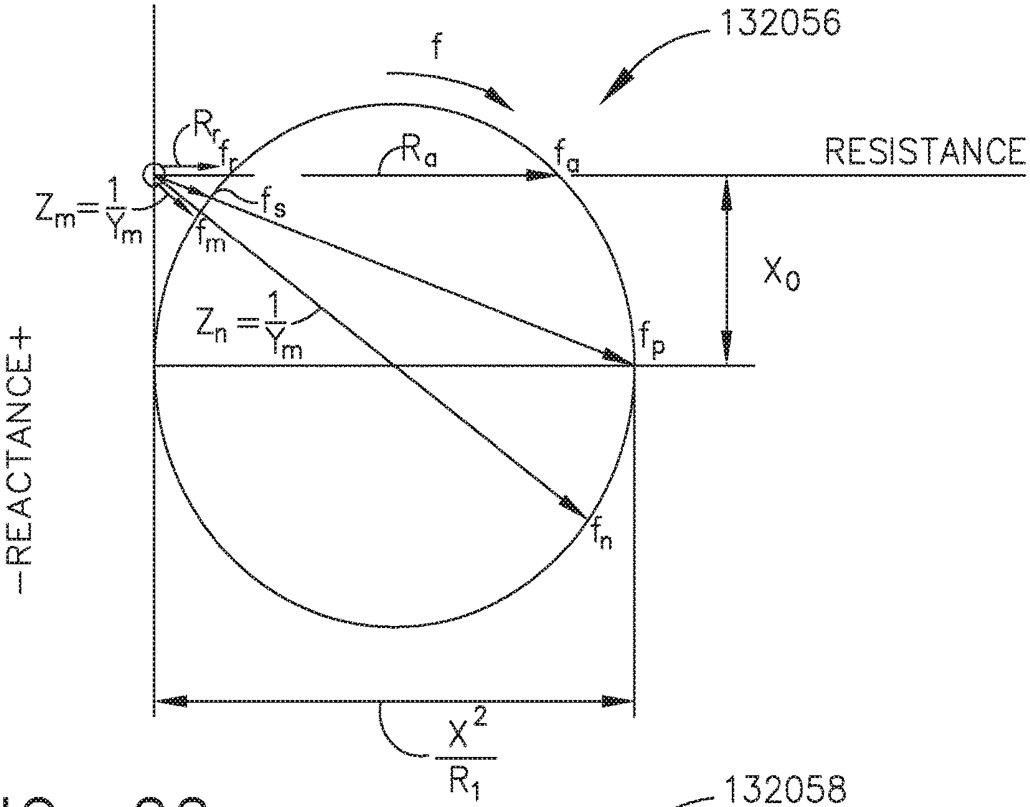

132056
f
R_r
f_r
R_a
f_a
RESISTANCE
$Z_m = \frac{1}{Y_m}$
f_s
f_m
X_0
$Z_n = \frac{1}{Y_m}$
f_p
-REACTANCE+
f_n
$\frac{X^2}{R_1}$

FIG. 22

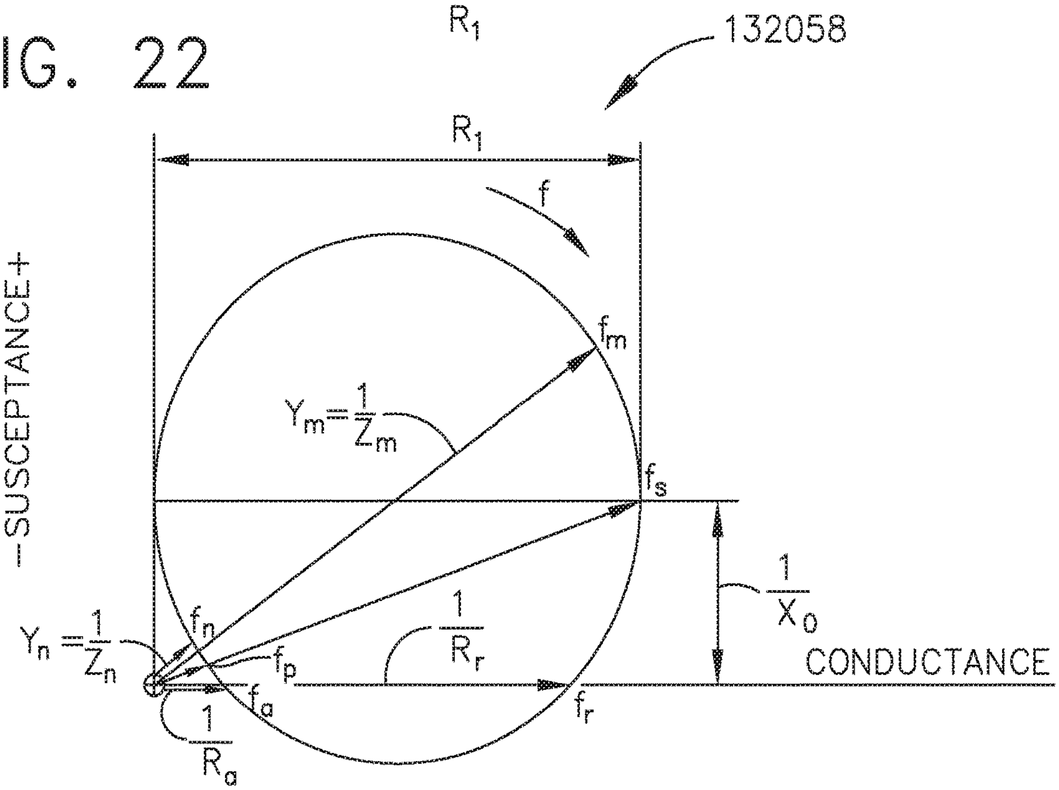

132058
R_1
f
-SUSCEPTANCE+
f_m
$Y_m = \frac{1}{Z_m}$
f_s
$\frac{1}{X_0}$
f_n
$Y_n = \frac{1}{Z_n}$
$\frac{1}{R_r}$
f_p
CONDUCTANCE
f_a
f_r
$\frac{1}{R_a}$

FIG. 23

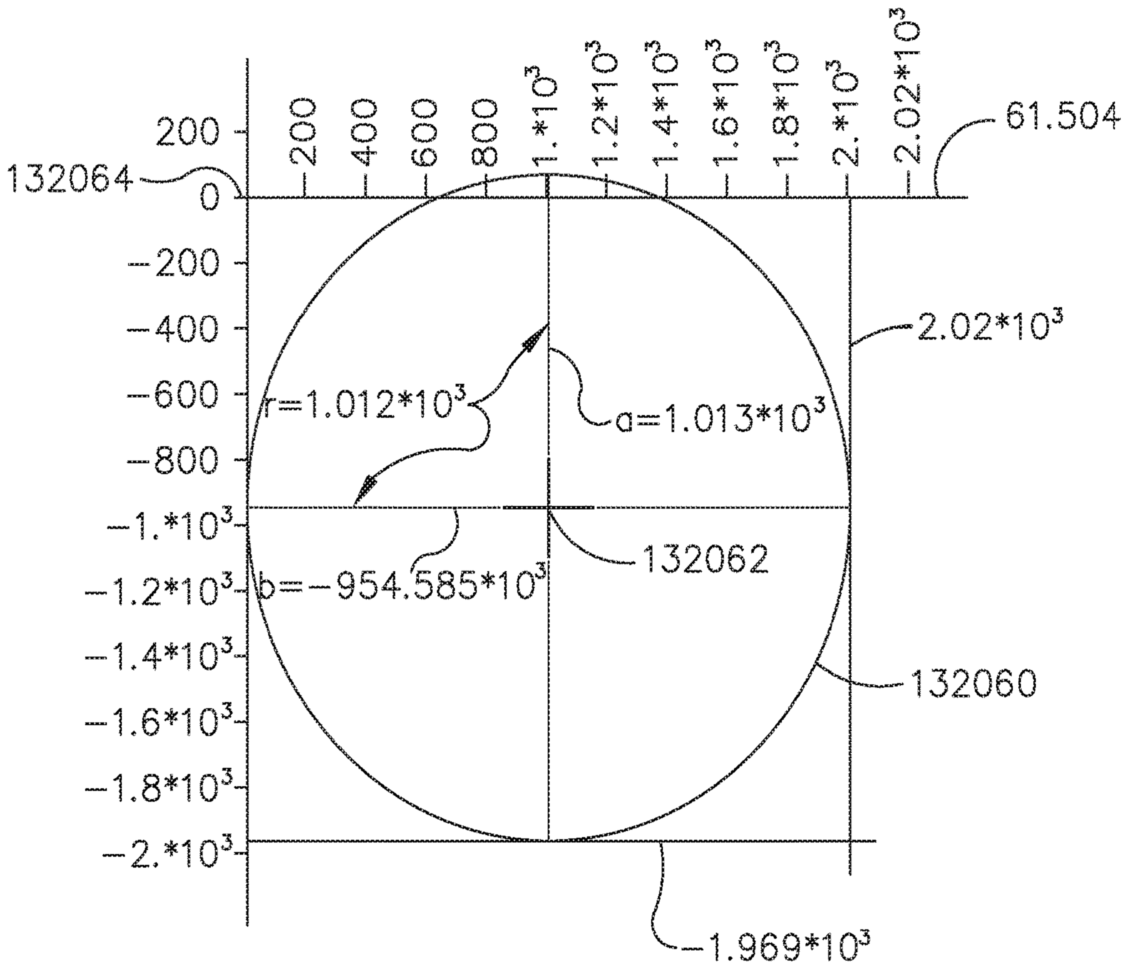

200
400
600
800
1.*10³
1.2*10³
1.4*10³
1.6*10³
1.8*10³
2.*10³
2.02*10³
61.504
132064
0
−200
−400
−600
−800
−1.*10³
−1.2*10³
−1.4*10³
−1.6*10³
−1.8*10³
−2.*10³
2.02*10³
r=1.012*10³
a=1.013*10³
132062
b=−954.585*10³
132060
1.969*10³

FIG. 24

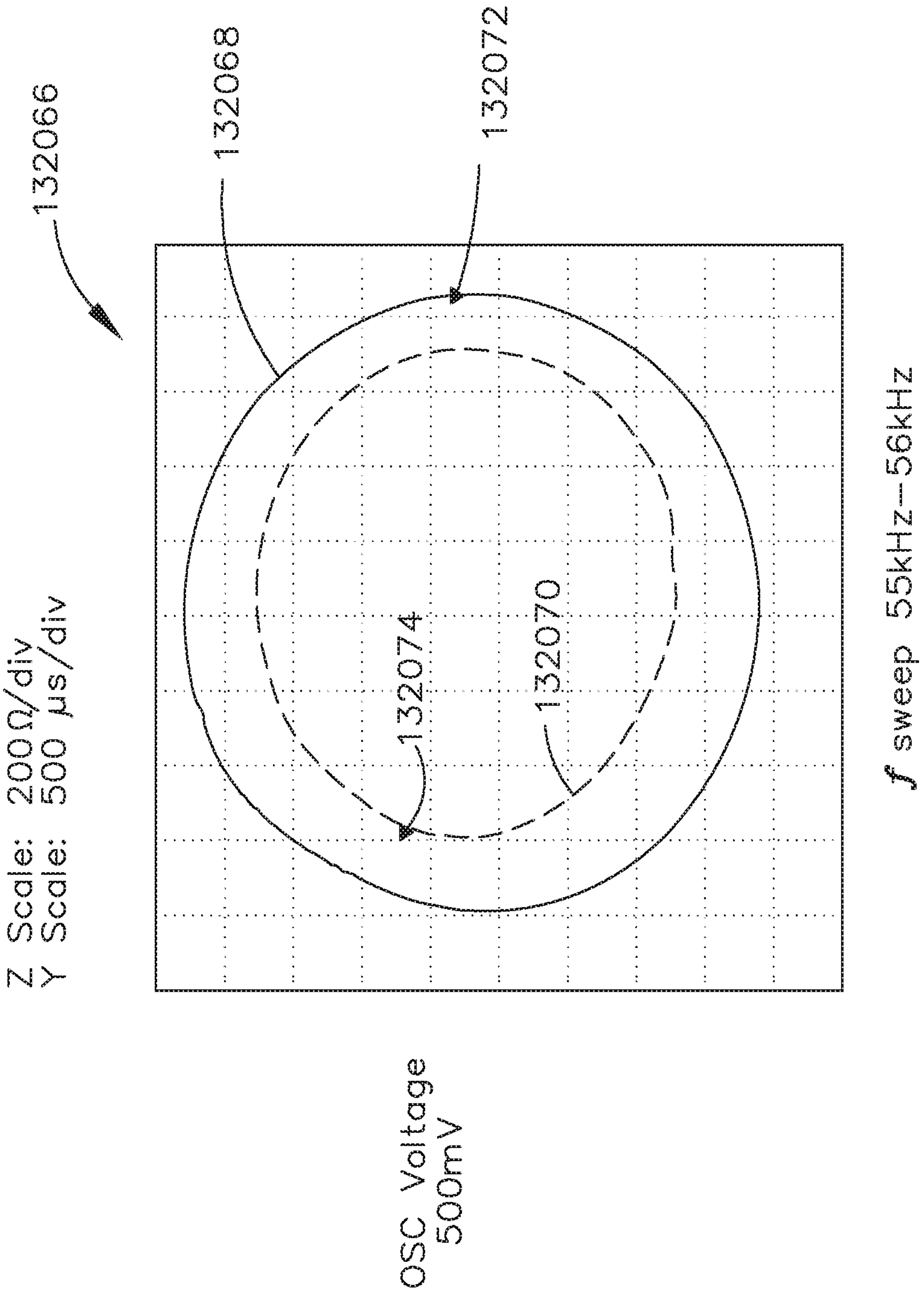

132066
132068
132072
Z Scale: 200Ω/div
Y Scale: 500 μs/div
132074
132070
OSC Voltage
500mV
f sweep 55kHz–56kHz

FIG. 25

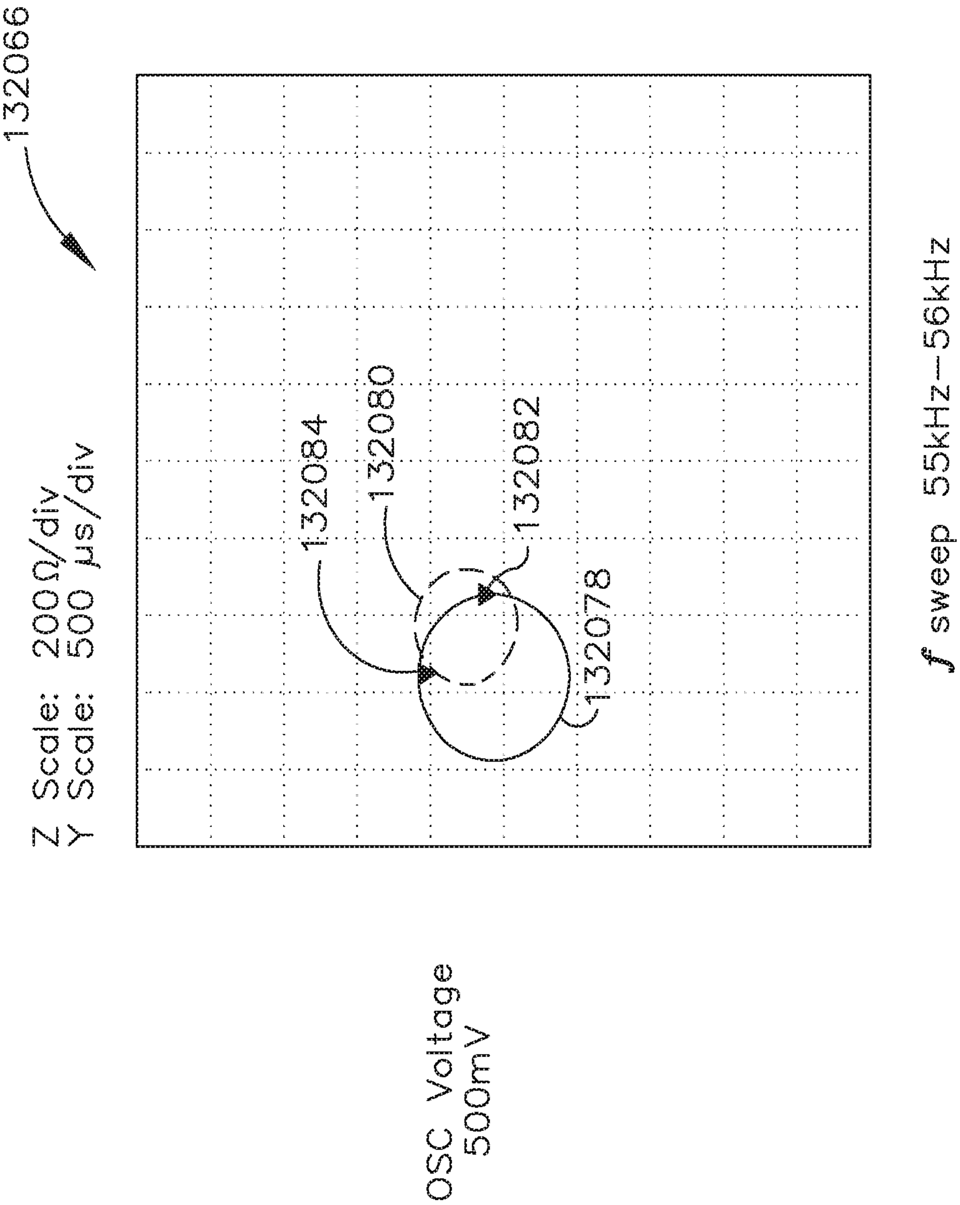

132066
Z Scale: 200Ω/div
Y Scale: 500 μs/div
132084
132080
132082
132078
OSC Voltage
500mV
f sweep 55kHz–56kHz

FIG. 26

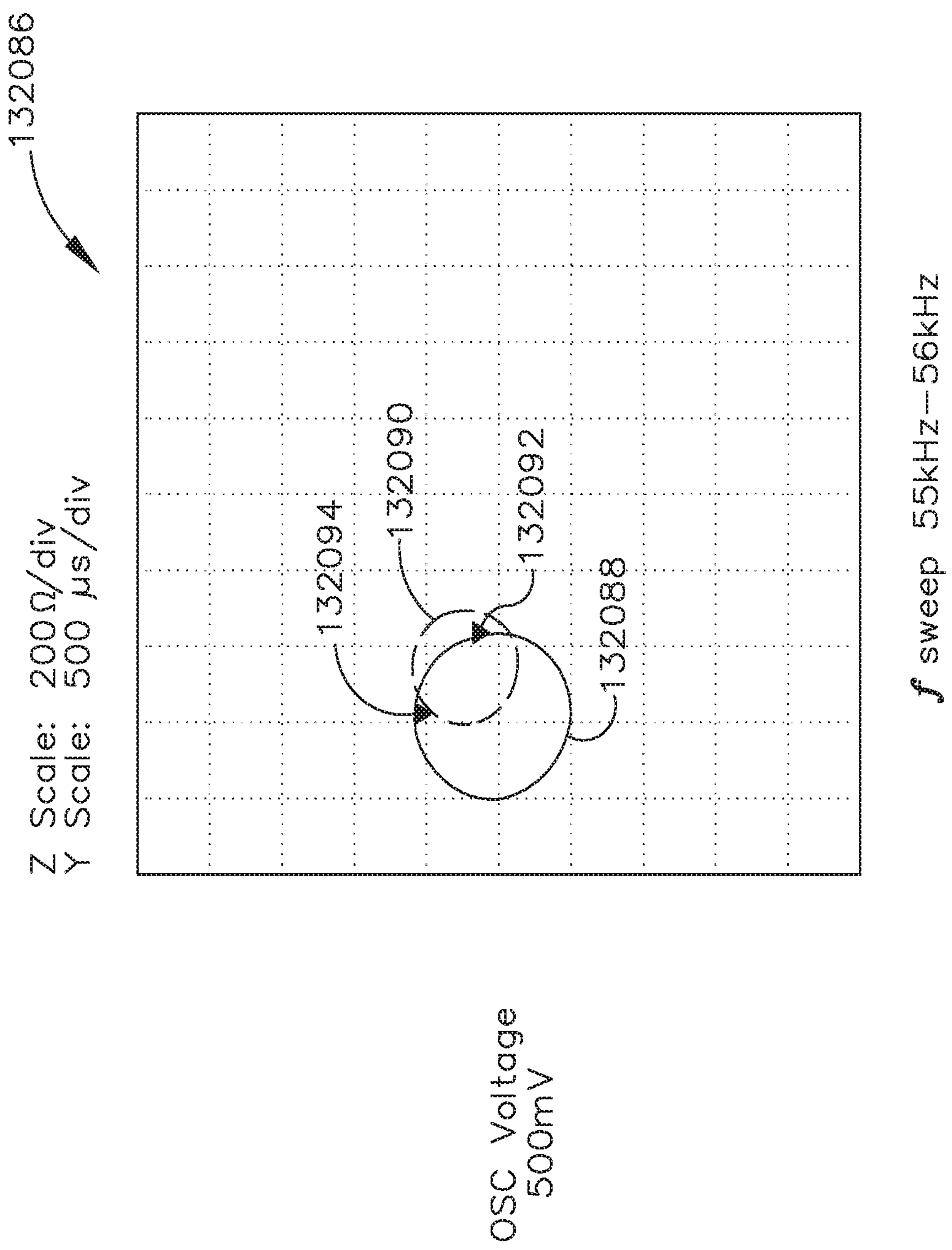

132086
Z Scale: 200Ω/div
Y Scale: 500 μs/div
132094
132090
132092
132088
OSC Voltage
500mV
f sweep 55kHz–56kHz

FIG. 27

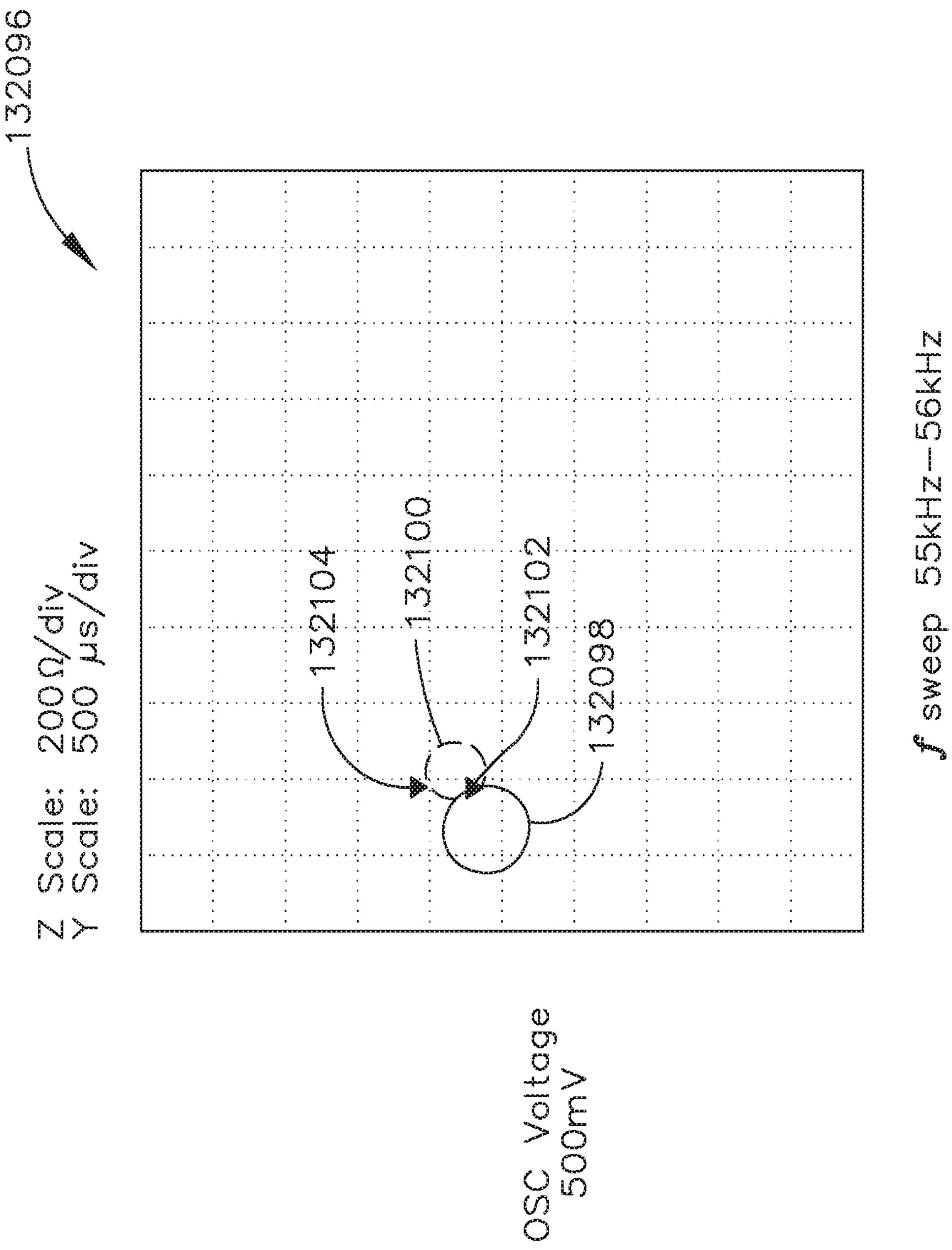

132096
Z Scale: 200Ω/div
Y Scale: 500 μs/div
132104
132100
132102
132098
OSC Voltage
500mV
f sweep 55kHz–56kHz

FIG. 28

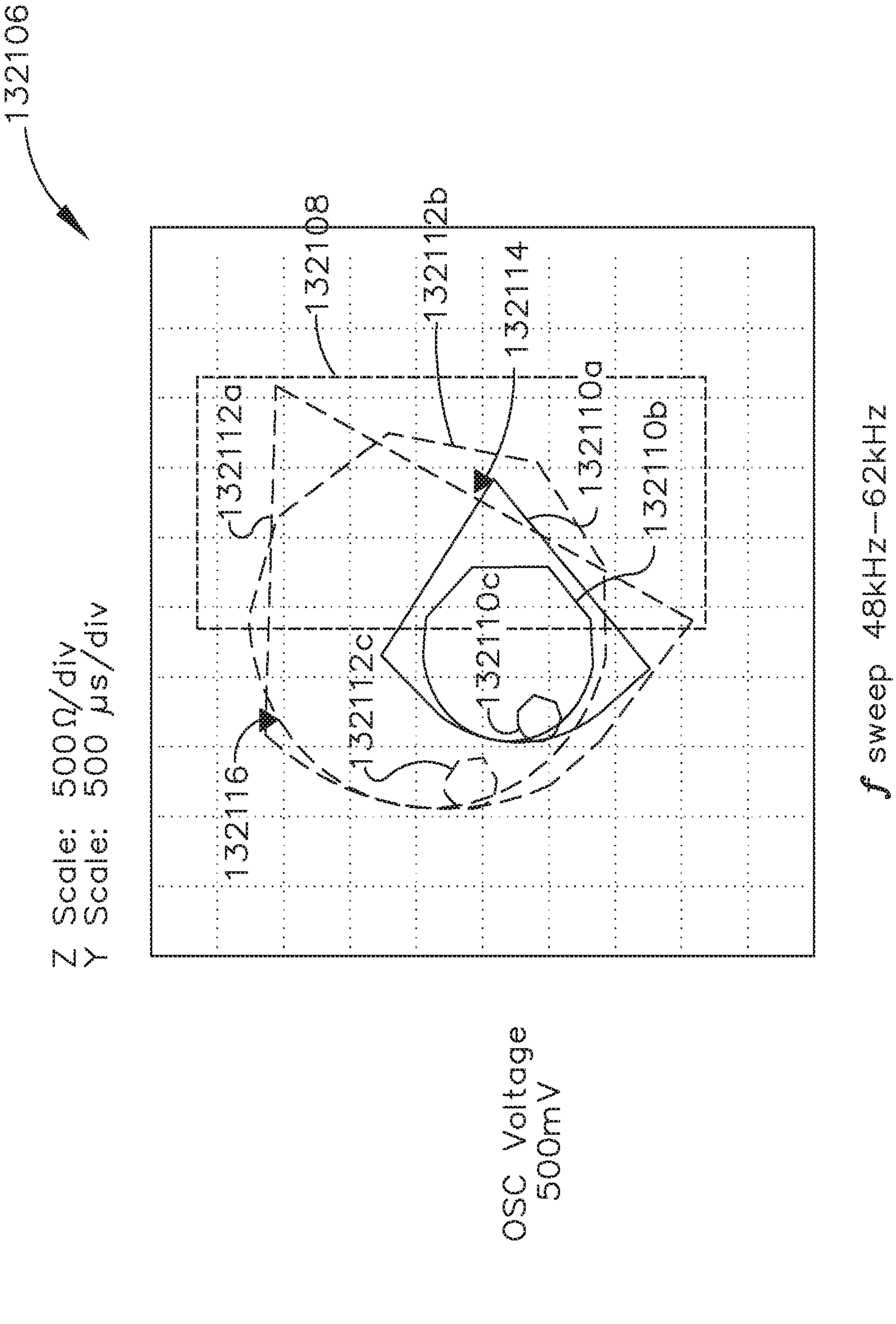

132106
Z Scale: 500Ω/div
Y Scale: 500 μs/div
132108
132112b
132114
132112a
132110a
132110b
132110c
132112c
132116
OSC Voltage
500mV
f sweep 48kHz–62kHz

FIG. 29

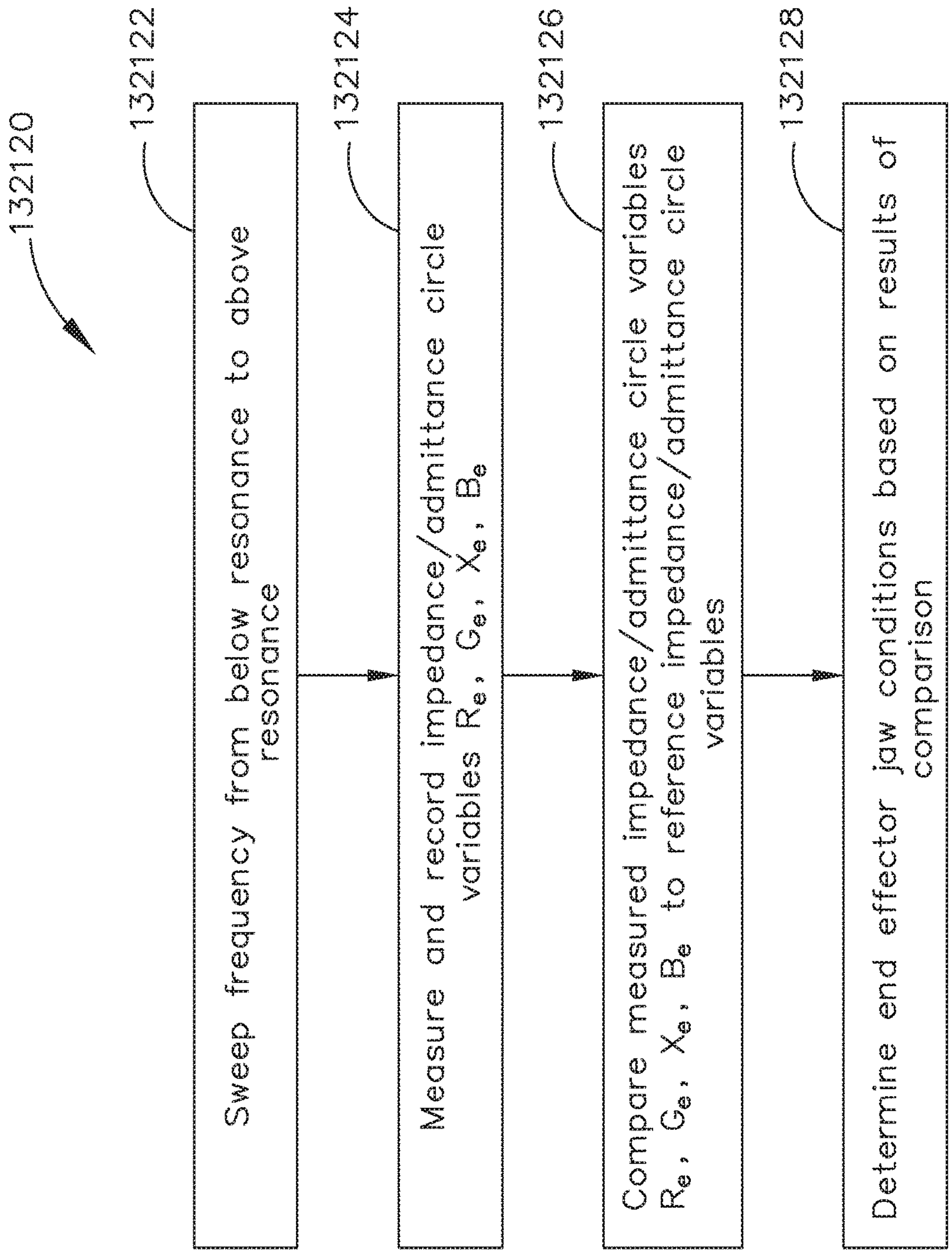

132120
132122
Sweep frequency from below resonance to above resonance
132124
Measure and record impedance/admittance circle variables Re, Ge, Xe, Be
132126
Compare measured impedance/admittance circle variables Re, Ge, Xe, Be to reference impedance/admittance circle variables
132128
Determine end effector jaw conditions based on results of comparison

FIG. 30

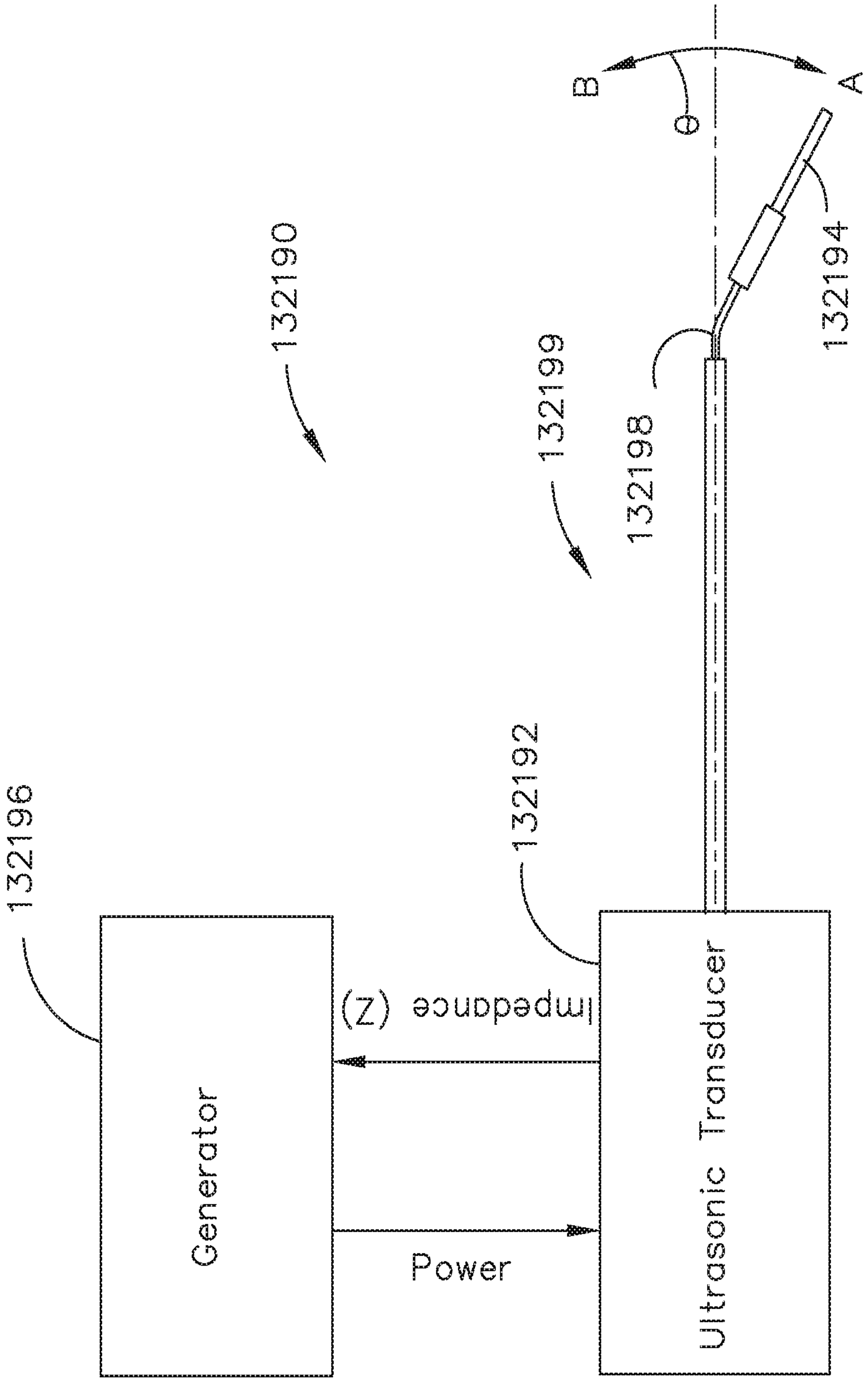

132190
132199
132198
132194
B
A
θ
132192
132196
Generator
Ultrasonic Transducer
Impedance (Z)
Power

FIG. 31

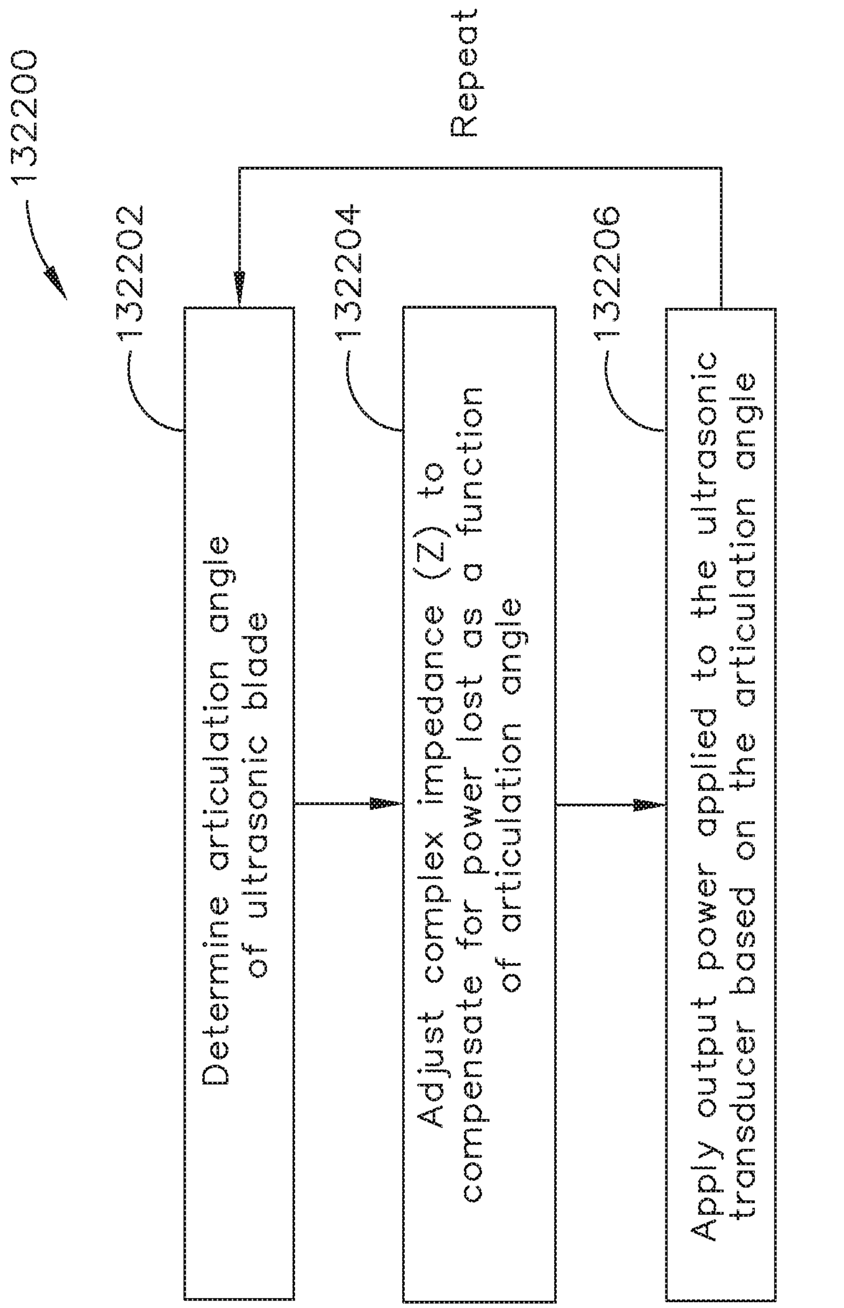

132200
Repeat
132202
Determine articulation angle of ultrasonic blade
132204
Adjust complex impedance (Z) to compensate for power lost as a function of articulation angle
132206
Apply output power applied to the ultrasonic transducer based on the articulation angle

FIG. 32

ADJUSTMENT OF COMPLEX IMPEDANCE TO COMPENSATE FOR LOST POWER IN AN ARTICULATING ULTRASONIC DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of priority under 35 U.S.C. § 119(e) to U.S. Provisional Patent Application Ser. No. 62/640,415, titled ESTIMATING STATE OF ULTRASONIC END EFFECTOR AND CONTROL SYSTEM THEREFOR, filed Mar. 8, 2018, the disclosure of which is herein incorporated by reference in its entirety.

BACKGROUND

[0002] In a surgical environment, smart energy devices may be needed in a smart energy architecture environment. Ultrasonic surgical devices, such as ultrasonic scalpels, are finding increasingly widespread applications in surgical procedures by virtue of their unique performance characteristics. Depending upon specific device configurations and operational parameters, ultrasonic surgical devices can provide substantially simultaneous transection of tissue and homeostasis by coagulation, desirably minimizing patient trauma. An ultrasonic surgical device may comprise a handpiece containing an ultrasonic transducer, and an instrument coupled to the ultrasonic transducer having a distally-mounted end effector (e.g., a blade tip) to cut and seal tissue. In some cases, the instrument may be permanently affixed to the handpiece. In other cases, the instrument may be detachable from the handpiece, as in the case of a disposable instrument or an interchangeable instrument. The end effector transmits ultrasonic energy to tissue brought into contact with the end effector to realize cutting and sealing action. Ultrasonic surgical devices of this nature can be configured for open surgical use, laparoscopic, or endoscopic surgical procedures including robotic-assisted procedures.

[0003] Ultrasonic energy cuts and coagulates tissue using temperatures lower than those used in electrosurgical procedures and can be transmitted to the end effector by an ultrasonic generator in communication with the handpiece. Vibrating at high frequencies (e.g., 55,500 cycles per second), the ultrasonic blade denatures protein in the tissue to form a sticky coagulum. Pressure exerted on tissue by the blade surface collapses blood vessels and allows the coagulum to form a hemostatic seal. A surgeon can control the cutting speed and coagulation by the force applied to the tissue by the end effector, the time over which the force is applied, and the selected excursion level of the end effector.

[0004] The ultrasonic transducer may be modeled as an equivalent circuit comprising a first branch having a static capacitance and a second "motional" branch having a serially connected inductance, resistance and capacitance that define the electromechanical properties of a resonator. Known ultrasonic generators may include a tuning inductor for tuning out the static capacitance at a resonant frequency so that substantially all of a generator's drive signal current flows into the motional branch. Accordingly, by using a tuning inductor, the generator's drive signal current represents the motional branch current, and the generator is thus able to control its drive signal to maintain the ultrasonic transducer's resonant frequency. The tuning inductor may also transform the phase impedance plot of the ultrasonic transducer to improve the generator's frequency lock capabilities. However, the tuning inductor must be matched with the specific static capacitance of an ultrasonic transducer at the operational resonant frequency. In other words, a different ultrasonic transducer having a different static capacitance requires a different tuning inductor.

[0005] Additionally, in some ultrasonic generator architectures, the generator's drive signal exhibits asymmetrical harmonic distortion that complicates impedance magnitude and phase measurements. For example, the accuracy of impedance phase measurements may be reduced due to harmonic distortion in the current and voltage signals.

[0006] Moreover, electromagnetic interference in noisy environments decreases the ability of the generator to maintain lock on the ultrasonic transducer's resonant frequency, increasing the likelihood of invalid control algorithm inputs.

[0007] Electrosurgical devices for applying electrical energy to tissue in order to treat and/or destroy the tissue are also finding increasingly widespread applications in surgical procedures. An electrosurgical device may comprise a handpiece and an instrument having a distally-mounted end effector (e.g., one or more electrodes). The end effector can be positioned against the tissue such that electrical current is introduced into the tissue. Electrosurgical devices can be configured for bipolar or monopolar operation. During bipolar operation, current is introduced into and returned from the tissue by active and return electrodes, respectively, of the end effector. During monopolar operation, current is introduced into the tissue by an active electrode of the end effector and returned through a return electrode (e.g., a grounding pad) separately located on a patient's body. Heat generated by the current flowing through the tissue may form hemostatic seals within the tissue and/or between tissues and thus may be particularly useful for sealing blood vessels, for example. The end effector of an electrosurgical device may also comprise a cutting member that is movable relative to the tissue and the electrodes to transect the tissue.

[0008] Electrical energy applied by an electrosurgical device can be transmitted to the instrument by a generator in communication with the handpiece. The electrical energy may be in the form of radio frequency (RF) energy. RF energy is a form of electrical energy that may be in the frequency range of 300 kHz to 1 MHz, as described in EN60601-2-2:2009+A11:2011, Definition 201.3.218—HIGH FREQUENCY. For example, the frequencies in monopolar RF applications are typically restricted to less than 5 MHz. However, in bipolar RF applications, the frequency can be almost any value. Frequencies above 200 kHz are typically used for monopolar applications in order to avoid the unwanted stimulation of nerves and muscles which would result from the use of low frequency current. Lower frequencies may be used for bipolar techniques if a risk analysis shows the possibility of neuromuscular stimulation has been mitigated to an acceptable level. Normally, frequencies above 5 MHz are not used in order to minimize the problems associated with high frequency leakage currents. It is generally recognized that 10 mA is the lower threshold of thermal effects on tissue.

[0009] During its operation, an electrosurgical device can transmit low frequency RF energy through tissue, which causes ionic agitation, or friction, in effect resistive heating, thereby increasing the temperature of the tissue. Because a sharp boundary may be created between the affected tissue and the surrounding tissue, surgeons can operate with a high level of precision and control, without sacrificing un-targeted adjacent tissue. The low operating temperatures of RF energy may be useful for removing, shrinking, or sculpting soft tissue while simultaneously sealing blood vessels. RF energy may work particularly well on connective tissue, which is primarily comprised of collagen and shrinks when contacted by heat.

[0010] Due to their unique drive signal, sensing and feedback needs, ultrasonic and electrosurgical devices have generally required different generators. Additionally, in cases where the instrument is disposable or interchangeable with a handpiece, ultrasonic and electrosurgical generators are limited in their ability to recognize the particular instrument configuration being used and to optimize control and diagnostic processes accordingly. Moreover, capacitive coupling between the non-isolated and patient-isolated circuits of the generator, especially in cases where higher voltages and frequencies are used, may result in exposure of a patient to unacceptable levels of leakage current.

[0011] Furthermore, due to their unique drive signal, sensing and feedback needs, ultrasonic and electrosurgical devices have generally required different user interfaces for the different generators. In such conventional ultrasonic and electrosurgical devices, one user interface is configured for use with an ultrasonic instrument whereas a different user interface may be configured for use with an electrosurgical instrument. Such user interfaces include hand and/or foot activated user interfaces such as hand activated switches and/or foot activated switches. As various aspects of combined generators for use with both ultrasonic and electrosurgical instruments are contemplated in the subsequent disclosure, additional user interfaces that are configured to operate with both ultrasonic and/or electrosurgical instrument generators also are contemplated.

[0012] Additional user interfaces for providing feedback, whether to the user or other machine, are contemplated within the subsequent disclosure to provide feedback indicating an operating mode or status of either an ultrasonic and/or electrosurgical instrument. Providing user and/or machine feedback for operating a combination ultrasonic and/or electrosurgical instrument will require providing sensory feedback to a user and electrical/mechanical/electromechanical feedback to a machine. Feedback devices that incorporate visual feedback devices (e.g., an LCD display screen, LED indicators), audio feedback devices (e.g., a speaker, a buzzer) or tactile feedback devices (e.g., haptic actuators) for use in combined ultrasonic and/or electrosurgical instruments are contemplated in the subsequent disclosure.

[0013] Other electrical surgical instruments include, without limitation, irreversible and/or reversible electroporation, and/or microwave technologies, among others. Accordingly, the techniques disclosed herein are applicable to ultrasonic, bipolar or monopolar RF (electrosurgical), irreversible and/or reversible electroporation, and/or microwave based surgical instruments, among others.

SUMMARY

[0014] An aspect of an ultrasonic device may include an electromechanical ultrasonic system defined by a predetermined resonant frequency, the electromechanical ultrasonic system having an ultrasonic transducer coupled to an ultrasonic blade. An aspect of a method of compensating power delivered to the ultrasonic device may include determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer, adjusting, by the processor or control circuit, a value of a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle, and adjusting, by the processor or control circuit, a power applied to the ultrasonic transducer based on the articulation angle.

[0015] In one aspect of the method, determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade may include measuring, by the processor or control circuit, a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as $Z_g(t)=V_g(t)/V_g(t)$, receiving, by the processor or control circuit, a complex impedance measurement data point, comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern, classifying, by the processor or control circuit, the complex impedance measurement data point based on a result of the comparison analysis, and assigning, by the processor or control circuit, an articulation angle of the end effector based on the result of the comparison analysis.

[0016] In one aspect of the method, comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern may include comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

[0017] In one aspect of the method, determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade may include applying, by a drive circuit, a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency, sweeping, by a processor or control circuit, the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system, measuring and recording, by the processor or control circuit, impedance/admittance circle variables R_e, G_e, X_e, and B_e, comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}, and determining, by the processor or control circuit, an articulation angle of the end effector based on the result of the comparison analysis.

[0018] In one aspect of the method, comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} may include comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

[0019] In one aspect, the method may further include sweeping, by the processor or control circuit, the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments, activating, by the processor or control circuit, the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments, measuring, by the processor or control circuit, a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments, recording, by the processor or control circuit, a set of complex impedance measurements at each of the one or more predetermined angular increments, generating, by the processor or control circuit, reference complex impedance characteristic patterns as a function of articulation angle, and storing, by the processor or control circuit, the reference complex impedance characteristic patterns in a memory or database;

[0020] In one aspect of the method, activating, by the processor or control circuit, the ultrasonic transducer at an energy level may include activating, by the processor or control circuit, the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

[0021] In one aspect of the method, storing the reference complex impedance characteristic patterns in a memory or database may include storing the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

[0022] An aspect of an ultrasonic surgical instrument may include an ultrasonic electromechanical system having an ultrasonic transducer coupled to an ultrasonic blade via an ultrasonic waveguide and a generator configured to supply power to the ultrasonic transducer. An aspect of the generator may include a control circuit configured to determine an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer, adjust a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle, and adjust a power applied to the ultrasonic transducer based on the articulation angle.

[0023] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to measure a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)},$$

receive a complex impedance measurement data point, compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern, classify the complex impedance measurement data point based on a result of the comparison analysis, and assign an articulation angle of the end effector based on the result of the comparison analysis.

[0024] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

[0025] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to cause a drive circuit to apply a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency, sweep the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system, measure and record impedance/admittance circle variables R_e, G_e, X_e, and B_e, compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}, and determine an articulation angle of the end effector based on the result of the comparison analysis.

[0026] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

[0027] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to sweep the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments, activate the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments, measure a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments, record a set of complex impedance measurements at each of the one or more predetermined angular increments, generate reference complex impedance characteristic patterns as a function of articulation angle, and store the reference complex impedance characteristic patterns in a memory or database;

[0028] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to activate the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

[0029] In one aspect of the ultrasonic surgical instrument, the generator may include a control circuit further configured to store the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

[0030] An aspect of a generator for an ultrasonic surgical instrument may include a control circuit configured to determine an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer, adjust a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle, and adjust a power applied to the ultrasonic transducer based on the articulation angle.

[0031] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to measure a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)},$$

receive a complex impedance measurement data point, compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern, classify the complex impedance measurement data point based on a result of the comparison analysis and assign an articulation angle of the end effector based on the result of the comparison analysis.

[0032] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

[0033] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to cause a drive circuit to apply a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency, sweep the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system, measure and record impedance/admittance circle variables R_e, G_e, X_e, and B_e, compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}, and determine an articulation angle of the end effector based on the result of the comparison analysis.

[0034] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

[0035] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to sweep the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments, activate the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments, measure a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments, record a set of complex impedance measurements at each of the one or more predetermined angular increments, generate reference complex impedance characteristic patterns as a function of articulation angle, and store the reference complex impedance characteristic patterns in a memory or database.

[0036] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to activate the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

[0037] In one aspect of the generator for an ultrasonic surgical instrument, the control circuit may be further configured to store the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

FIGURES

[0038] The features of various aspects are set forth with particularity in the appended claims. The various aspects, however, both as to organization and methods of operation, together with further objects and advantages thereof, may best be understood by reference to the following description, taken in conjunction with the accompanying drawings as follows.

[0039] FIG. **1** is a system configured to execute adaptive ultrasonic blade control algorithms in a surgical data network comprising a modular communication hub, in accordance with at least one aspect of the present disclosure.

[0040] FIG. **2** illustrates an example of a generator, in accordance with at least one aspect of the present disclosure.

[0041] FIG. **3** is a surgical system comprising a generator and various surgical instruments usable therewith, in accordance with at least one aspect of the present disclosure.

[0042] FIG. **4** is an end effector, in accordance with at least one aspect of the present disclosure.

[0043] FIG. **5** is a diagram of the surgical system of FIG. **3**, in accordance with at least one aspect of the present disclosure.

[0044] FIG. **6** is a model illustrating motional branch current, in accordance with at least one aspect of the present disclosure.

[0045] FIG. **7** is a structural view of a generator architecture, in accordance with at least one aspect of the present disclosure.

[0046] FIGS. **8**A-**8**C are functional views of a generator architecture, in accordance with at least one aspect of the present disclosure.

[0047] FIGS. **9**A-**9**B are structural and functional aspects of a generator, in accordance with at least one aspect of the present disclosure.

[0048] FIG. **10** illustrates a control circuit configured to control aspects of the surgical instrument or tool, in accordance with at least one aspect of the present disclosure.

[0049] FIG. **11** illustrates a combinational logic circuit configured to control aspects of the surgical instrument or tool, in accordance with at least one aspect of the present disclosure.

[0050] FIG. **12** illustrates a sequential logic circuit configured to control aspects of the surgical instrument or tool, in accordance with at least one aspect of the present disclosure.

[0051] FIG. **13** illustrates one aspect of a fundamental architecture for a digital synthesis circuit such as a direct digital synthesis (DDS) circuit configured to generate a plurality of wave shapes for the electrical signal waveform for use in a surgical instrument, in accordance with at least one aspect of the present disclosure.

[0052] FIG. **14** illustrates one aspect of direct digital synthesis (DDS) circuit configured to generate a plurality of wave shapes for the electrical signal waveform for use in surgical instrument, in accordance with at least one aspect of the present disclosure.

[0053] FIG. **15** illustrates one cycle of a discrete time digital electrical signal waveform, in accordance with at least one aspect of the present disclosure of an analog waveform (shown superimposed over a discrete time digital electrical signal waveform for comparison purposes), in accordance with at least one aspect of the present disclosure.

[0054] FIG. **16** is a diagram of a control system in accordance with one aspect of this disclosure.

[0055] FIG. **17** illustrates a proportional-integral-derivative (PID) controller feedback control system in accordance with one aspect of this disclosure.

[0056] FIG. **18** is an alternative system for controlling the frequency of an ultrasonic electromechanical system and detecting the impedance thereof, in accordance with at least one aspect of the present disclosure.

[0057] FIG. **19** is a spectra of the same ultrasonic device with a variety of different states and conditions of the end effector where phase and magnitude of the impedance of an ultrasonic transducer are plotted as a function of frequency, in accordance with at least one aspect of the present disclosure.

[0058] FIG. **20** is a graphical representation of a plot of a set of 3D training data S, where ultrasonic transducer impedance magnitude and phase are plotted as a function of frequency, in accordance with at least one aspect of the present disclosure.

[0059] FIG. **21** is a logic flow diagram depicting a control program or a logic configuration to determine jaw conditions based on the complex impedance characteristic pattern (fingerprint), in accordance with at least one aspect of the present disclosure.

[0060] FIG. **22** is a circle plot of complex impedance plotted as an imaginary component versus real components of a piezoelectric vibrator, in accordance with at least one aspect of the present disclosure.

[0061] FIG. **23** is a circle plot of complex admittance plotted as an imaginary component versus real components of a piezoelectric vibrator, in accordance with at least one aspect of the present disclosure.

[0062] FIG. **24** is a circle plot of complex admittance for a 55.5 kHz ultrasonic piezoelectric transducer.

[0063] FIG. **25** is a graphical display of an impedance analyzer showing impedance/admittance circle plots for an ultrasonic device with the jaw open and no loading where complex admittance is depicted in broken line and complex impedance is depicted in solid line, in accordance with at least one aspect of the present disclosure.

[0064] FIG. **26** is a graphical display of an impedance analyzer showing impedance/admittance circle plots for an ultrasonic device with the jaw clamped on dry chamois where complex admittance is depicted in broken line and complex impedance is depicted in solid line, in accordance with at least one aspect of the present disclosure.

[0065] FIG. **27** is a graphical display of an impedance analyzer showing impedance/admittance circle plots for an ultrasonic device with the jaw tip clamped on moist chamois where complex admittance is depicted in broken line and complex impedance is depicted in solid line, in accordance with at least one aspect of the present disclosure.

[0066] FIG. **28** is a graphical display of an impedance analyzer showing impedance/admittance circle plots for an ultrasonic device with the jaw fully clamped on moist chamois where complex admittance is depicted in broken line and complex impedance is depicted in solid line, in accordance with at least one aspect of the present disclosure.

[0067] FIG. **29** is a graphical display of an impedance analyzer showing impedance/admittance plots where frequency is swept from 48 kHz to 62 kHz to capture multiple resonances of an ultrasonic device with the jaw open where the rectangular overlay shown in broken line is to help see the circles, in accordance with at least one aspect of the present disclosure.

[0068] FIG. **30** is a logic flow diagram of a process depicting a control program or a logic configuration to determine jaw conditions based on estimates of the radius and offsets of an impedance/admittance circle, in accordance with at least one aspect of the present disclosure.

[0069] FIG. **31** is a system for adjusting complex impedance of the ultrasonic transducer to compensate for power lost when the ultrasonic blade is articulated, in accordance with at least one aspect of the present disclosure.

[0070] FIG. **32** is a logic flow diagram of a process depicting a control program or a logic configuration to compensate output power as a function of articulation angle, in accordance with at least one aspect of the present disclosure.

DESCRIPTION

[0071] Applicant of the present patent application also owns the following contemporaneously-filed U.S. patent applications, each of which is herein incorporated by reference in its entirety:

[0072] U.S. Provisional Patent Application titled METHODS FOR CONTROLLING TEMPERATURE IN ULTRASONIC DEVICE, Attorney Docket No. END8560USNP1/180106-1M;

[0073] U.S. Provisional Patent Application titled ULTRASONIC SEALING ALGORITHM WITH TEMPERATURE CONTROL, Attorney Docket No. END8560USNP3/180106-3;

[0074] U.S. Provisional Patent Application titled APPLICATION OF SMART ULTRASONIC BLADE TECHNOLOGY, Attorney Docket No. END8560USNP4/180106-4;

[0075] U.S. Provisional Patent Application titled ADAPTIVE ADVANCED TISSUE TREATMENT PAD SAVER MODE, Attorney Docket No. END8560USNP5/180106-5;

[0076] U.S. Provisional Patent Application titled SMART BLADE TECHNOLOGY TO CONTROL BLADE INSTABILITY, Attorney Docket No. END8560USNP6/180106-6; and

[0077] U.S. Provisional Patent Application titled START TEMPERATURE OF BLADE, Attorney Docket No. END8560USNP7/180106-7.

[0078] Applicant of the present patent application also owns the following contemporaneously-filed U.S. patent applications, each of which is herein incorporated by reference in its entirety:

[0079] U.S. Provisional Patent Application titled METHODS FOR ESTIMATING AND CONTROLLING STATE OF ULTRASONIC END EFFECTOR, Attorney Docket No. END8536USNP1/180107-1M;

[0080] U.S. Provisional Patent Application titled IN-THE-JAW CLASSIFIER BASED ON MODEL, Attorney Docket No. END8536USNP3/180107-3;

[0081] U.S. Provisional Patent Application titled APPLICATION OF SMART BLADE TECHNOLOGY, Attorney Docket No. END8536USNP4/180107-4;

[0082] U.S. Provisional Patent Application titled SMART BLADE AND POWER PULSING, Attorney Docket No. END8536USNP5/180107-5;

[0083] U.S. Provisional Patent Application titled USING SPECTROSCOPY TO DETERMINE DEVICE USE STATE IN COMBO INSTRUMENT, Attorney Docket No. EN D8536USN P7/180107-7;

[0084] U.S. Provisional Patent Application titled VESSEL SENSING FOR ADAPTIVE ADVANCED HEMOSTASIS, Attorney Docket No. END8536USNP8/180107-8;

[0085] U.S. Provisional Patent Application titled CALCIFIED VESSEL IDENTIFICATION, Attorney Docket No. END8536USNP9/180107-9;

[0086] U.S. Provisional Patent Application titled DETECTION OF LARGE VESSELS DURING PARENCHYMAL DISSECTION USING A SMART BLADE, Attorney Docket No. END8536U5NP10/180107-10;

[0087] U.S. Provisional Patent Application titled SMART BLADE APPLICATION FOR REUSABLE AND DISPOSABLE DEVICES, Attorney Docket No. EN D8536USN P11/180107-11;

[0088] U.S. Provisional Patent Application titled LIVE TIME TISSUE CLASSIFICATION USING ELEC-

TRICAL PARAMETERS, Attorney Docket No. END8536USNP12/180107-12; and

[0089] U.S. Provisional Patent Application titled FINE DISSECTION MODE FOR TISSUE CLASSIFICATION, Attorney Docket No. END8536USNP13/180107-13.

[0090] Applicant of the present application owns the following U.S. Patent Applications, filed on Sep. 10, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0091] U.S. Provisional Patent Application Ser. No. 62/729,177, titled AUTOMATED DATA SCALING, ALIGNMENT, AND ORGANIZING BASED ON PREDEFINED PARAMETERS WITHIN A SURGICAL NETWORK BEFORE TRANSMISSION;

[0092] U.S. provisional Patent Application Ser. No. 62/729,182, titled SENSING THE PATIENT POSITION AND CONTACT UTILIZING THE MONOPOLAR RETURN PAD ELECTRODE TO PROVIDE SITUATIONAL AWARENESS TO THE HUB;

[0093] U.S. Provisional Patent Application Ser. No. 62/729,184, titled POWERED SURGICAL TOOL WITH A PREDEFINED ADJUSTABLE CONTROL ALGORITHM FOR CONTROLLING AT LEAST ONE END-EFFECTOR PARAMETER AND A MEANS FOR LIMITING THE ADJUSTMENT;

[0094] U.S. Provisional Patent Application Ser. No. 62/729,183, titled SURGICAL NETWORK RECOMMENDATIONS FROM REAL TIME ANALYSIS OF PROCEDURE VARIABLES AGAINST A BASELINE HIGHLIGHTING DIFFERENCES FROM THE OPTIMAL SOLUTION;

[0095] U.S. Provisional Patent Application Ser. No. 62/729,191, titled A CONTROL FOR A SURGICAL NETWORK OR SURGICAL NETWORK CONNECTED DEVICE THAT ADJUSTS ITS FUNCTION BASED ON A SENSED SITUATION OR USAGE;

[0096] U.S. Provisional Patent Application Ser. No. 62/729,176, titled INDIRECT COMMAND AND CONTROL OF A FIRST OPERATING ROOM SYSTEM THROUGH THE USE OF A SECOND OPERATING ROOM SYSTEM WITHIN A STERILE FIELD WHERE THE SECOND OPERATING ROOM SYSTEM HAS PRIMARY AND SECONDARY OPERATING MODES;

[0097] U.S. Provisional Patent Application Ser. No. 62/729,186, titled WIRELESS PAIRING OF A SURGICAL DEVICE WITH ANOTHER DEVICE WITHIN A STERILE SURGICAL FIELD BASED ON THE USAGE AND SITUATIONAL AWARENESS OF DEVICES; and

[0098] U.S. Provisional Patent Application Ser. No. 62/729,185, titled POWERED STAPLING DEVICE THAT IS CAPABLE OF ADJUSTING FORCE, ADVANCEMENT SPEED, AND OVERALL STROKE OF CUTTING MEMBER OF THE DEVICE BASED ON SENSED PARAMETER OF FIRING OR CLAMPING.

[0099] Applicant of the present application owns the following U.S. Patent Applications, filed on Aug. 28, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0100] U.S. patent application Ser. No. 16/115,214, titled ESTIMATING STATE OF ULTRASONIC END EFFECTOR AND CONTROL SYSTEM THEREFOR;

[0101] U.S. patent application Ser. No. 16/115,205, titled TEMPERATURE CONTROL OF ULTRASONIC END EFFECTOR AND CONTROL SYSTEM THEREFOR;

[0102] U.S. patent application Ser. No. 16/115,233, titled RADIO FREQUENCY ENERGY DEVICE FOR DELIVERING COMBINED ELECTRICAL SIGNALS;

[0103] U.S. patent application Ser. No. 16/115,208, titled CONTROLLING AN ULTRASONIC SURGICAL INSTRUMENT ACCORDING TO TISSUE LOCATION;

[0104] U.S. patent application Ser. No. 16/115,220, titled CONTROLLING ACTIVATION OF AN ULTRASONIC SURGICAL INSTRUMENT ACCORDING TO THE PRESENCE OF TISSUE;

[0105] U.S. patent application Ser. No. 16/115,232, titled DETERMINING TISSUE COMPOSITION VIA AN ULTRASONIC SYSTEM;

[0106] U.S. patent application Ser. No. 16/115,239, titled DETERMINING THE STATE OF AN ULTRASONIC ELECTROMECHANICAL SYSTEM ACCORDING TO FREQUENCY SHIFT;

[0107] U.S. patent application Ser. No. 16/115,247, titled DETERMINING THE STATE OF AN ULTRASONIC END EFFECTOR;

[0108] U.S. patent application Ser. No. 16/115,211, titled SITUATIONAL AWARENESS OF ELECTROSURGICAL SYSTEMS;

[0109] U.S. patent application Ser. No. 16/115,226, titled MECHANISMS FOR CONTROLLING DIFFERENT ELECTROMECHANICAL SYSTEMS OF AN ELECTROSURGICAL INSTRUMENT;

[0110] U.S. patent application Ser. No. 16/115,240, titled DETECTION OF END EFFECTOR EMERSION IN LIQUID;

[0111] U.S. patent application Ser. No. 16/115,249, titled INTERRUPTION OF ENERGY DUE TO INADVERTENT CAPACITIVE COUPLING;

[0112] U.S. patent application Ser. No. 16/115,256, titled INCREASING RADIO FREQUENCY TO CREATE PAD-LESS MONOPOLAR LOOP;

[0113] U.S. patent application Ser. No. 16/115,223, titled BIPOLAR COMBINATION DEVICE THAT AUTOMATICALLY ADJUSTS PRESSURE BASED ON ENERGY MODALITY; and

[0114] U.S. patent application Ser. No. 16/115,238, titled ACTIVATION OF ENERGY DEVICES.

[0115] Applicant of the present application owns the following U.S. Patent Applications, filed on Aug. 23, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0116] U.S. Provisional Patent Application No. 62/721,995, titled CONTROLLING AN ULTRASONIC SURGICAL INSTRUMENT ACCORDING TO TISSUE LOCATION;

[0117] U.S. Provisional Patent Application No. 62/721,998, titled SITUATIONAL AWARENESS OF ELECTROSURGICAL SYSTEMS;

[0118] U.S. Provisional Patent Application No. 62/721,999, titled INTERRUPTION OF ENERGY DUE TO INADVERTENT CAPACITIVE COUPLING;

[0119] U.S. Provisional Patent Application No. 62/721,994, titled BIPOLAR COMBINATION DEVICE THAT AUTOMATICALLY ADJUSTS PRESSURE BASED ON ENERGY MODALITY; and

[0120] U.S. Provisional Patent Application No. 62/721,996, titled RADIO FREQUENCY ENERGY DEVICE FOR DELIVERING COMBINED ELECTRICAL SIGNALS.

[0121] Applicant of the present application owns the following U.S. Patent Applications, filed on Jun. 30, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0122] U.S. Provisional Patent Application No. 62/692,747, titled SMART ACTIVATION OF AN ENERGY DEVICE BY ANOTHER DEVICE;

[0123] U.S. Provisional Patent Application No. 62/692,748, titled SMART ENERGY ARCHITECTURE; and

[0124] U.S. Provisional Patent Application No. 62/692,768, titled SMART ENERGY DEVICES.

[0125] Applicant of the present application owns the following U.S. Patent Applications, filed on Jun. 29, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0126] U.S. patent application Ser. No. 16/024,090, titled CAPACITIVE COUPLED RETURN PATH PAD WITH SEPARABLE ARRAY ELEMENTS;

[0127] U.S. patent application Ser. No. 16/024,057, titled CONTROLLING A SURGICAL INSTRUMENT ACCORDING TO SENSED CLOSURE PARAMETERS;

[0128] U.S. patent application Ser. No. 16/024,067, titled SYSTEMS FOR ADJUSTING END EFFECTOR PARAMETERS BASED ON PERIOPERATIVE INFORMATION;

[0129] U.S. patent application Ser. No. 16/024,075, titled SAFETY SYSTEMS FOR SMART POWERED SURGICAL STAPLING;

[0130] U.S. patent application Ser. No. 16/024,083, titled SAFETY SYSTEMS FOR SMART POWERED SURGICAL STAPLING;

[0131] U.S. patent application Ser. No. 16/024,094, titled SURGICAL SYSTEMS FOR DETECTING END EFFECTOR TISSUE DISTRIBUTION IRREGULARITIES;

[0132] U.S. patent application Ser. No. 16/024,138, titled SYSTEMS FOR DETECTING PROXIMITY OF SURGICAL END EFFECTOR TO CANCEROUS TISSUE;

[0133] U.S. patent application Ser. No. 16/024,150, titled SURGICAL INSTRUMENT CARTRIDGE SENSOR ASSEMBLIES;

[0134] U.S. patent application Ser. No. 16/024,160, titled VARIABLE OUTPUT CARTRIDGE SENSOR ASSEMBLY;

[0135] U.S. patent application Ser. No. 16/024,124, titled SURGICAL INSTRUMENT HAVING A FLEXIBLE ELECTRODE;

[0136] U.S. patent application Ser. No. 16/024,132, titled SURGICAL INSTRUMENT HAVING A FLEXIBLE CIRCUIT;

[0137] U.S. patent application Ser. No. 16/024,141, titled SURGICAL INSTRUMENT WITH A TISSUE MARKING ASSEMBLY;

[0138] U.S. patent application Ser. No. 16/024,162, titled SURGICAL SYSTEMS WITH PRIORITIZED DATA TRANSMISSION CAPABILITIES;

[0139] U.S. patent application Ser. No. 16/024,066, titled SURGICAL EVACUATION SENSING AND MOTOR CONTROL;

[0140] U.S. patent application Ser. No. 16/024,096, titled SURGICAL EVACUATION SENSOR ARRANGEMENTS;

[0141] U.S. patent application Ser. No. 16/024,116, titled SURGICAL EVACUATION FLOW PATHS;

[0142] U.S. patent application Ser. No. 16/024,149, titled SURGICAL EVACUATION SENSING AND GENERATOR CONTROL;

[0143] U.S. patent application Ser. No. 16/024,180, titled SURGICAL EVACUATION SENSING AND DISPLAY;

[0144] U.S. patent application Ser. No. 16/024,245, titled COMMUNICATION OF SMOKE EVACUATION SYSTEM PARAMETERS TO HUB OR CLOUD IN SMOKE EVACUATION MODULE FOR INTERACTIVE SURGICAL PLATFORM;

[0145] U.S. patent application Ser. No. 16/024,258, titled SMOKE EVACUATION SYSTEM INCLUDING A SEGMENTED CONTROL CIRCUIT FOR INTERACTIVE SURGICAL PLATFORM;

[0146] U.S. patent application Ser. No. 16/024,265, titled SURGICAL EVACUATION SYSTEM WITH A COMMUNICATION CIRCUIT FOR COMMUNICATION BETWEEN A FILTER AND A SMOKE EVACUATION DEVICE; and

[0147] U.S. patent application Ser. No. 16/024,273, titled DUAL IN-SERIES LARGE AND SMALL DROPLET FILTERS.

[0148] Applicant of the present application owns the following U.S. Provisional Patent Applications, filed on Jun. 28, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0149] U.S. Provisional Patent Application Ser. No. 62/691,228, titled A METHOD OF USING REINFORCED FLEX CIRCUITS WITH MULTIPLE SENSORS WITH ELECTROSURGICAL DEVICES;

[0150] U.S. Provisional Patent Application Ser. No. 62/691,227, titled CONTROLLING A SURGICAL INSTRUMENT ACCORDING TO SENSED CLOSURE PARAMETERS;

[0151] U.S. Provisional Patent Application Ser. No. 62/691,230, titled SURGICAL INSTRUMENT HAVING A FLEXIBLE ELECTRODE;

[0152] U.S. Provisional Patent Application Ser. No. 62/691,219, titled SURGICAL EVACUATION SENSING AND MOTOR CONTROL;

[0153] U.S. Provisional Patent Application Ser. No. 62/691,257, titled COMMUNICATION OF SMOKE EVACUATION SYSTEM PARAMETERS TO HUB OR CLOUD IN SMOKE EVACUATION MODULE FOR INTERACTIVE SURGICAL PLATFORM;

[0154] U.S. Provisional Patent Application Ser. No. 62/691,262, titled SURGICAL EVACUATION SYSTEM WITH A COMMUNICATION CIRCUIT FOR

COMMUNICATION BETWEEN A FILTER AND A SMOKE EVACUATION DEVICE; and

[0155] U.S. Provisional Patent Application Ser. No. 62/691,251, titled DUAL IN-SERIES LARGE AND SMALL DROPLET FILTERS.

[0156] Applicant of the present application owns the following U.S. Provisional Patent Application, filed on Apr. 19, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0157] U.S. Provisional Patent Application Ser. No. 62/659,900, titled METHOD OF HUB COMMUNICATION.

[0158] Applicant of the present application owns the following U.S. Provisional Patent Applications, filed on Mar. 30, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0159] U.S. Provisional Patent Application No. 62/650,898 filed on Mar. 30, 2018, titled CAPACITIVE COUPLED RETURN PATH PAD WITH SEPARABLE ARRAY ELEMENTS;

[0160] U.S. Provisional Patent Application Ser. No. 62/650,887, titled SURGICAL SYSTEMS WITH OPTIMIZED SENSING CAPABILITIES;

[0161] U.S. Provisional Patent Application Ser. No. 62/650,882, titled SMOKE EVACUATION MODULE FOR INTERACTIVE SURGICAL PLATFORM; and

[0162] U.S. Provisional Patent Application Ser. No. 62/650,877, titled SURGICAL SMOKE EVACUATION SENSING AND CONTROLS

[0163] Applicant of the present application owns the following U.S. Patent Applications, filed on Mar. 29, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0164] U.S. patent application Ser. No. 15/940,641, titled INTERACTIVE SURGICAL SYSTEMS WITH ENCRYPTED COMMUNICATION CAPABILITIES;

[0165] U.S. patent application Ser. No. 15/940,648, titled INTERACTIVE SURGICAL SYSTEMS WITH CONDITION HANDLING OF DEVICES AND DATA CAPABILITIES;

[0166] U.S. patent application Ser. No. 15/940,656, titled SURGICAL HUB COORDINATION OF CONTROL AND COMMUNICATION OF OPERATING ROOM DEVICES;

[0167] U.S. patent application Ser. No. 15/940,666, titled SPATIAL AWARENESS OF SURGICAL HUBS IN OPERATING ROOMS;

[0168] U.S. patent application Ser. No. 15/940,670, titled COOPERATIVE UTILIZATION OF DATA DERIVED FROM SECONDARY SOURCES BY INTELLIGENT SURGICAL HUBS;

[0169] U.S. patent application Ser. No. 15/940,677, titled SURGICAL HUB CONTROL ARRANGEMENTS;

[0170] U.S. patent application Ser. No. 15/940,632, titled DATA STRIPPING METHOD TO INTERROGATE PATIENT RECORDS AND CREATE ANONYMIZED RECORD;

[0171] U.S. patent application Ser. No. 15/940,640, titled COMMUNICATION HUB AND STORAGE DEVICE FOR STORING PARAMETERS AND STATUS OF A SURGICAL DEVICE TO BE SHARED WITH CLOUD BASED ANALYTICS SYSTEMS;

[0172] U.S. patent application Ser. No. 15/940,645, titled SELF DESCRIBING DATA PACKETS GENERATED AT AN ISSUING INSTRUMENT;

[0173] U.S. patent application Ser. No. 15/940,649, titled DATA PAIRING TO INTERCONNECT A DEVICE MEASURED PARAMETER WITH AN OUTCOME;

[0174] U.S. patent application Ser. No. 15/940,654, titled SURGICAL HUB SITUATIONAL AWARENESS;

[0175] U.S. patent application Ser. No. 15/940,663, titled SURGICAL SYSTEM DISTRIBUTED PROCESSING;

[0176] U.S. patent application Ser. No. 15/940,668, titled AGGREGATION AND REPORTING OF SURGICAL HUB DATA;

[0177] U.S. patent application Ser. No. 15/940,671, titled SURGICAL HUB SPATIAL AWARENESS TO DETERMINE DEVICES IN OPERATING THEATER;

[0178] U.S. patent application Ser. No. 15/940,686, titled DISPLAY OF ALIGNMENT OF STAPLE CARTRIDGE TO PRIOR LINEAR STAPLE LINE;

[0179] U.S. patent application Ser. No. 15/940,700, titled STERILE FIELD INTERACTIVE CONTROL DISPLAYS;

[0180] U.S. patent application Ser. No. 15/940,629, titled COMPUTER IMPLEMENTED INTERACTIVE SURGICAL SYSTEMS;

[0181] U.S. patent application Ser. No. 15/940,704, titled USE OF LASER LIGHT AND RED-GREEN-BLUE COLORATION TO DETERMINE PROPERTIES OF BACK SCATTERED LIGHT;

[0182] U.S. patent application Ser. No. 15/940,722, titled CHARACTERIZATION OF TISSUE IRREGULARITIES THROUGH THE USE OF MONO-CHROMATIC LIGHT REFRACTIVITY; and

[0183] U.S. patent application Ser. No. 15/940,742, titled DUAL CMOS ARRAY IMAGING.

[0184] U.S. patent application Ser. No. 15/940,636, titled ADAPTIVE CONTROL PROGRAM UPDATES FOR SURGICAL DEVICES;

[0185] U.S. patent application Ser. No. 15/940,653, titled ADAPTIVE CONTROL PROGRAM UPDATES FOR SURGICAL HUBS;

[0186] U.S. patent application Ser. No. 15/940,660, titled CLOUD-BASED MEDICAL ANALYTICS FOR CUSTOMIZATION AND RECOMMENDATIONS TO A USER;

[0187] U.S. patent application Ser. No. 15/940,679, titled CLOUD-BASED MEDICAL ANALYTICS FOR LINKING OF LOCAL USAGE TRENDS WITH THE RESOURCE ACQUISITION BEHAVIORS OF LARGER DATA SET;

[0188] U.S. patent application Ser. No. 15/940,694, titled CLOUD-BASED MEDICAL ANALYTICS FOR MEDICAL FACILITY SEGMENTED INDIVIDUALIZATION OF INSTRUMENT FUNCTION;

[0189] U.S. patent application Ser. No. 15/940,634, titled CLOUD-BASED MEDICAL ANALYTICS FOR SECURITY AND AUTHENTICATION TRENDS AND REACTIVE MEASURES;

[0190] U.S. patent application Ser. No. 15/940,706, titled DATA HANDLING AND PRIORITIZATION IN A CLOUD ANALYTICS NETWORK; and

[0191] U.S. patent application Ser. No. 15/940,675, titled CLOUD INTERFACE FOR COUPLED SURGICAL DEVICES.

[0192] U.S. patent application Ser. No. 15/940,627, titled DRIVE ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0193] U.S. patent application Ser. No. 15/940,637, titled COMMUNICATION ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0194] U.S. patent application Ser. No. 15/940,642, titled CONTROLS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0195] U.S. patent application Ser. No. 15/940,676, titled AUTOMATIC TOOL ADJUSTMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0196] U.S. patent application Ser. No. 15/940,680, titled CONTROLLERS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0197] U.S. patent application Ser. No. 15/940,683, titled COOPERATIVE SURGICAL ACTIONS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0198] U.S. patent application Ser. No. 15/940,690, titled DISPLAY ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS; and

[0199] U.S. patent application Ser. No. 15/940,711, titled SENSING ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS.

[0200] Applicant of the present application owns the following U.S. Provisional Patent Applications, filed on Mar. 28, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0201] U.S. Provisional Patent Application Ser. No. 62/649,302, titled INTERACTIVE SURGICAL SYSTEMS WITH ENCRYPTED COMMUNICATION CAPABILITIES;

[0202] U.S. Provisional Patent Application Ser. No. 62/649,294, titled DATA STRIPPING METHOD TO INTERROGATE PATIENT RECORDS AND CREATE ANONYMIZED RECORD;

[0203] U.S. Provisional Patent Application Ser. No. 62/649,300, titled SURGICAL HUB SITUATIONAL AWARENESS;

[0204] U.S. Provisional Patent Application Ser. No. 62/649,309, titled SURGICAL HUB SPATIAL AWARENESS TO DETERMINE DEVICES IN OPERATING THEATER;

[0205] U.S. Provisional Patent Application Ser. No. 62/649,310, titled COMPUTER IMPLEMENTED INTERACTIVE SURGICAL SYSTEMS;

[0206] U.S. Provisional Patent Application Ser. No. 62/649,291, titled USE OF LASER LIGHT AND RED-GREEN-BLUE COLORATION TO DETERMINE PROPERTIES OF BACK SCATTERED LIGHT;

[0207] U.S. Provisional Patent Application Ser. No. 62/649,296, titled ADAPTIVE CONTROL PROGRAM UPDATES FOR SURGICAL DEVICES;

[0208] U.S. Provisional Patent Application Ser. No. 62/649,333, titled CLOUD-BASED MEDICAL ANALYTICS FOR CUSTOMIZATION AND RECOMMENDATIONS TO A USER;

[0209] U.S. Provisional Patent Application Ser. No. 62/649,327, titled CLOUD-BASED MEDICAL ANALYTICS FOR SECURITY AND AUTHENTICATION TRENDS AND REACTIVE MEASURES;

[0210] U.S. Provisional Patent Application Ser. No. 62/649,315, titled DATA HANDLING AND PRIORITIZATION IN A CLOUD ANALYTICS NETWORK;

[0211] U.S. Provisional Patent Application Ser. No. 62/649,313, titled CLOUD INTERFACE FOR COUPLED SURGICAL DEVICES;

[0212] U.S. Provisional Patent Application Ser. No. 62/649,320, titled DRIVE ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0213] U.S. Provisional Patent Application Ser. No. 62/649,307, titled AUTOMATIC TOOL ADJUSTMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS; and

[0214] U.S. Provisional Patent Application Ser. No. 62/649,323, titled SENSING ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS.

[0215] Applicant of the present application owns the following U.S. Provisional Patent Applications, filed on Mar. 28, 2018, the disclosure of each of which is herein incorporated by reference in its entirety:

[0216] U.S. Provisional Patent Application Ser. No. 62/649,302, titled INTERACTIVE SURGICAL SYSTEMS WITH ENCRYPTED COMMUNICATION CAPABILITIES;

[0217] U.S. Provisional Patent Application Ser. No. 62/649,294, titled DATA STRIPPING METHOD TO INTERROGATE PATIENT RECORDS AND CREATE ANONYMIZED RECORD;

[0218] U.S. Provisional Patent Application Ser. No. 62/649,300, titled SURGICAL HUB SITUATIONAL AWARENESS;

[0219] U.S. Provisional Patent Application Ser. No. 62/649,309, titled SURGICAL HUB SPATIAL AWARENESS TO DETERMINE DEVICES IN OPERATING THEATER;

[0220] U.S. Provisional Patent Application Ser. No. 62/649,310, titled COMPUTER IMPLEMENTED INTERACTIVE SURGICAL SYSTEMS;

[0221] U.S. Provisional Patent Application Ser. No. 62/649,291, titled USE OF LASER LIGHT AND RED-GREEN-BLUE COLORATION TO DETERMINE PROPERTIES OF BACK SCATTERED LIGHT;

[0222] U.S. Provisional Patent Application Ser. No. 62/649,296, titled ADAPTIVE CONTROL PROGRAM UPDATES FOR SURGICAL DEVICES;

[0223] U.S. Provisional Patent Application Ser. No. 62/649,333, titled CLOUD-BASED MEDICAL ANALYTICS FOR CUSTOMIZATION AND RECOMMENDATIONS TO A USER;

[0224] U.S. Provisional Patent Application Ser. No. 62/649,327, titled CLOUD-BASED MEDICAL ANALYTICS FOR SECURITY AND AUTHENTICATION TRENDS AND REACTIVE MEASURES;

[0225] U.S. Provisional Patent Application Ser. No. 62/649,315, titled DATA HANDLING AND PRIORITIZATION IN A CLOUD ANALYTICS NETWORK;

[0226] U.S. Provisional Patent Application Ser. No. 62/649,313, titled CLOUD INTERFACE FOR COUPLED SURGICAL DEVICES;

[0227] U.S. Provisional Patent Application Ser. No. 62/649,320, titled DRIVE ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS;

[0228] U.S. Provisional Patent Application Ser. No. 62/649,307, titled AUTOMATIC TOOL ADJUSTMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS; and

[0229] U.S. Provisional Patent Application Ser. No. 62/649,323, titled SENSING ARRANGEMENTS FOR ROBOT-ASSISTED SURGICAL PLATFORMS.

[0230] Applicant of the present application owns the following U.S. Provisional Patent Applications, filed on Dec. 28, 2017, the disclosure of each of which is herein incorporated by reference in its entirety:

[0231] U.S. Provisional Patent Application Ser. No. U.S. Provisional Patent Application Ser. No. 62/611,341, titled INTERACTIVE SURGICAL PLATFORM;

[0232] U.S. Provisional Patent Application Ser. No. 62/611,340, titled CLOUD-BASED MEDICAL ANALYTICS; and

[0233] U.S. Provisional Patent Application Ser. No. 62/611,339, titled ROBOT ASSISTED SURGICAL PLATFORM.

[0234] Before explaining various aspects of surgical devices and generators in detail, it should be noted that the illustrative examples are not limited in application or use to the details of construction and arrangement of parts illustrated in the accompanying drawings and description. The illustrative examples may be implemented or incorporated in other aspects, variations and modifications, and may be practiced or carried out in various ways. Further, unless otherwise indicated, the terms and expressions employed herein have been chosen for the purpose of describing the illustrative examples for the convenience of the reader and are not for the purpose of limitation thereof. Also, it will be appreciated that one or more of the following-described aspects, expressions of aspects, and/or examples, can be combined with any one or more of the other following-described aspects, expressions of aspects and/or examples.

[0235] Various aspects are directed to improved ultrasonic surgical devices, electrosurgical devices and generators for use therewith. Aspects of the ultrasonic surgical devices can be configured for transecting and/or coagulating tissue during surgical procedures, for example. Aspects of the electrosurgical devices can be configured for transecting, coagulating, scaling, welding and/or desiccating tissue during surgical procedures, for example.

Adaptive Ultrasonic Blade Control Algorithms

[0236] In various aspects smart ultrasonic energy devices may comprise adaptive algorithms to control the operation of the ultrasonic blade. In one aspect, the ultrasonic blade adaptive control algorithms are configured to identify tissue type and adjust device parameters. In one aspect, the ultrasonic blade control algorithms are configured to parameterize tissue type. An algorithm to detect the collagen/elastic ratio of tissue to tune the amplitude of the distal tip of the ultrasonic blade is described in the following section of the present disclosure. Various aspects of smart ultrasonic energy devices are described herein in connection with FIGS. **1-2**, for example. Accordingly, the following description of adaptive ultrasonic blade control algorithms should be read in conjunction with FIGS. **1-2** and the description associated therewith.

[0237] In certain surgical procedures it would be desirable to employ adaptive ultrasonic blade control algorithms. In one aspect, adaptive ultrasonic blade control algorithms may be employed to adjust the parameters of the ultrasonic device based on the type of tissue in contact with the ultrasonic blade. In one aspect, the parameters of the ultrasonic device may be adjusted based on the location of the tissue within the jaws of the ultrasonic end effector, for example, the location of the tissue between the clamp arm and the ultrasonic blade. The impedance of the ultrasonic transducer may be employed to differentiate what percentage of the tissue is located in the distal or proximal end of the end effector. The reactions of the ultrasonic device may be based on the tissue type or compressibility of the tissue. In another aspect, the parameters of the ultrasonic device may be adjusted based on the identified tissue type or parameterization. For example, the mechanical displacement amplitude of the distal tip of the ultrasonic blade may be tuned based on the ration of collagen to elastin tissue detected during the tissue identification procedure. The ratio of collagen to elastin tissue may be detected used a variety of techniques including infrared (IR) surface reflectance and emissivity. The force applied to the tissue by the clamp arm and/or the stroke of the clamp arm to produce gap and compression. Electrical continuity across a jaw equipped with electrodes may be employed to determine what percentage of the jaw is covered with tissue.

[0238] FIG. **1** is a system **800** configured to execute adaptive ultrasonic blade control algorithms in a surgical data network comprising a modular communication hub, in accordance with at least one aspect of the present disclosure. In one aspect, the generator module **240** is configured to execute the adaptive ultrasonic blade control algorithm(s) **802** as described herein. In another aspect, the device/instrument **235** is configured to execute the adaptive ultrasonic blade control algorithm(s) **804** as described herein with reference to FIGS. **19-32**. In another aspect, both the device/instrument **235** and the device/instrument **235** are configured to execute the adaptive ultrasonic blade control algorithms **802**, **804** as described herein with reference to FIGS. **19-32**.

[0239] The generator module **240** may comprise a patient isolated stage in communication with a non-isolated stage via a power transformer. A secondary winding of the power transformer is contained in the isolated stage and may comprise a tapped configuration (e.g., a center-tapped or a non-center-tapped configuration) to define drive signal outputs for delivering drive signals to different surgical instruments, such as, for example, an ultrasonic surgical instrument, an RF electrosurgical instrument, and a multifunction surgical instrument which includes ultrasonic and RF energy modes that can be delivered alone or simultaneously. In particular, the drive signal outputs may output an ultrasonic drive signal (e.g., a 420V root-mean-square (RMS) drive signal) to an ultrasonic surgical instrument **241**, and the drive signal outputs may output an RF electrosurgical drive signal (e.g., a 100V RMS drive signal) to an RF electrosurgical instrument **241**. Aspects of the generator module **240** are described herein with reference to FIGS. **7-12**.

[0240] The generator module **240** or the device/instrument **235** or both are coupled to the modular control tower **236** connected to multiple operating theater devices such as, for example, intelligent surgical instruments, robots, and other computerized devices located in the operating theater. In some aspects, a surgical data network may include a modular communication hub configured to connect modular devices located in one or more operating theaters of a healthcare facility, or any room in a healthcare facility specially equipped for surgical operations, to a cloud-based system (e.g., the cloud **204** that may include a remote server **213** coupled to a storage device).

[0241] Modular devices located in the operating theater may be coupled to the modular communication hub. The network hub and/or the network switch may be coupled to a network router to connect the devices to the cloud **204** or a local computer system. Data associated with the devices may be transferred to cloud-based computers via the router for remote data processing and manipulation. Data associated with the devices may also be transferred to a local computer system for local data processing and manipulation. Modular devices located in the same operating theater also may be coupled to a network switch. The network switch may be coupled to the network hub and/or the network router to connect to the devices to the cloud **204**. Data associated with the devices may be transferred to the cloud **204** via the network router for data processing and manipulation. Data associated with the devices may also be transferred to the local computer system for local data processing and manipulation.

[0242] It will be appreciated that cloud computing relies on sharing computing resources rather than having local servers or personal devices to handle software applications. The word "cloud" may be used as a metaphor for "the Internet," although the term is not limited as such. Accordingly, the term "cloud computing" may be used herein to refer to "a type of Internet-based computing," where different services—such as servers, storage, and applications—are delivered to the modular communication hub and/or computer system located in the surgical theater (e.g., a fixed, mobile, temporary, or field operating room or space) and to devices connected to the modular communication hub and/or computer system through the Internet. The cloud infrastructure may be maintained by a cloud service provider. In this context, the cloud service provider may be the entity that coordinates the usage and control of the devices located in one or more operating theaters. The cloud computing services can perform a large number of calculations based on the data gathered by smart surgical instruments, robots, and other computerized devices located in the operating theater. The hub hardware enables multiple devices or connections to be connected to a computer that communicates with the cloud computing resources and storage.

[0243] FIG. **1** further illustrates some aspects of a computer-implemented interactive surgical system comprising a modular communication hub that may include the system **800** configured to execute adaptive ultrasonic blade control algorithms in a surgical data network. The surgical system may include at least one surgical hub in communication with a cloud **204** that may include a remote server **213**. In one aspect, the computer-implemented interactive surgical system comprises a modular control tower **236** connected to multiple operating theater devices such as, for example, intelligent surgical instruments, robots, and other computerized devices located in the operating theater. The modular control tower **236** may comprise a modular communication hub coupled to a computer system. In some aspects, the modular control tower **236** is coupled to an imaging module that is coupled to an endoscope, a generator module **240** that is coupled to an energy device **241**, and a smart device/instrument **235** optionally coupled to a display **237**. The operating theater devices are coupled to cloud computing resources and data storage via the modular control tower **236**. A robot hub **222** also may be connected to the modular control tower **236** and to the cloud computing resources. The devices/instruments **235**, visualization systems **208**, among others, may be coupled to the modular control tower **236** via wired or wireless communication standards or protocols, as described herein. The modular control tower **236** may be coupled to a hub display **215** (e.g., monitor, screen) to display and overlay images received from the imaging module, device/instrument display, and/or other visualization systems **208**. The hub display **215** also may display data received from devices connected to the modular control tower in conjunction with images and overlaid images.

Generator Hardware

[0244] FIG. **2** illustrates an example of a generator **900**, which is one form of a generator configured to couple to an ultrasonic instrument and further configured to execute adaptive ultrasonic blade control algorithms in a surgical data network comprising a modular communication hub as shown in FIG. **1**. The generator **900** is configured to deliver multiple energy modalities to a surgical instrument. The generator **900** provides RF and ultrasonic signals for delivering energy to a surgical instrument either independently or simultaneously. The RF and ultrasonic signals may be provided alone or in combination and may be provided simultaneously. As noted above, at least one generator output can deliver multiple energy modalities (e.g., ultrasonic, bipolar or monopolar RF, irreversible and/or reversible electroporation, and/or microwave energy, among others) through a single port, and these signals can be delivered separately or simultaneously to the end effector to treat tissue. The generator **900** comprises a processor **902** coupled to a waveform generator **904**. The processor **902** and waveform generator **904** are configured to generate a variety of signal waveforms based on information stored in a memory coupled to the processor **902**, not shown for clarity of disclosure. The digital information associated with a waveform is provided to the waveform generator **904** which includes one or more DAC circuits to convert the digital input into an analog output. The analog output is fed to an amplifier **906** for signal conditioning and amplification. The conditioned and amplified output of the amplifier **906** is coupled to a power transformer **908**. The signals are coupled across the power transformer **908** to the secondary side, which is in the patient isolation side. A first signal of a first energy modality is provided to the surgical instrument between the terminals labeled $ENERGY_1$ and RETURN. A second signal of a second energy modality is coupled across a capacitor **910** and is provided to the surgical instrument between the terminals labeled $ENERGY_2$ and RETURN. It will be appreciated that more than two energy modalities may be output and thus the subscript "n" may be used to designate that up to n $ENERGY_n$ terminals may be provided, where n is a positive integer greater than 1. It also will be appreciated that up to "n" return paths $RETURN_n$ may be provided without departing from the scope of the present disclosure.

[0245] A first voltage sensing circuit **912** is coupled across the terminals labeled $ENERGY_1$ and the RETURN path to measure the output voltage therebetween. A second voltage sensing circuit **924** is coupled across the terminals labeled $ENERGY_2$ and the RETURN path to measure the output voltage therebetween. A current sensing circuit **914** is disposed in series with the RETURN leg of the secondary side of the power transformer **908** as shown to measure the output current for either energy modality. If different return paths are provided for each energy modality, then a separate current sensing circuit should be provided in each return leg. The outputs of the first and second voltage sensing circuits **912**, **924** are provided to respective isolation transformers **916**, **922** and the output of the current sensing circuit **914** is provided to another isolation transformer **918**. The outputs of the isolation transformers **916**, **928**, **922** in the on the primary side of the power transformer **908** (non-patient isolated side) are provided to a one or more ADC circuit **926**. The digitized output of the ADC circuit **926** is provided to the processor **902** for further processing and computation. The output voltages and output current feedback information can be employed to adjust the output voltage and current provided to the surgical instrument and to compute output impedance, among other parameters. Input/output communications between the processor **902** and patient isolated circuits is provided through an interface circuit **920**. Sensors also may be in electrical communication with the processor **902** by way of the interface circuit **920**.

[0246] In one aspect, the impedance may be determined by the processor **902** by dividing the output of either the first voltage sensing circuit **912** coupled across the terminals labeled $ENERGY_1$/RETURN or the second voltage sensing circuit **924** coupled across the terminals labeled $ENERGY_2$/RETURN by the output of the current sensing circuit **914** disposed in series with the RETURN leg of the secondary side of the power transformer **908**. The outputs of the first and second voltage sensing circuits **912**, **924** are provided to separate isolations transformers **916**, **922** and the output of the current sensing circuit **914** is provided to another isolation transformer **916**. The digitized voltage and current sensing measurements from the ADC circuit **926** are provided the processor **902** for computing impedance. As an example, the first energy modality $ENERGY_1$ may be ultrasonic energy and the second energy modality $ENERGY_2$ may be RF energy. Nevertheless, in addition to ultrasonic and bipolar or monopolar RF energy modalities, other energy modalities include irreversible and/or reversible electroporation and/or microwave energy, among others. Also, although the example illustrated in FIG. **2** shows a single return path RETURN may be provided for two or more energy modalities, in other aspects, multiple return paths $RETURN_n$ may be provided for each energy modality $ENERGY_n$. Thus, as described herein, the ultrasonic transducer impedance may be measured by dividing the output of the first voltage sensing circuit **912** by the current sensing circuit **914** and the tissue impedance may be measured by dividing the output of the second voltage sensing circuit **924** by the current sensing circuit **914**.

[0247] As shown in FIG. **2**, the generator **900** comprising at least one output port can include a power transformer **908** with a single output and with multiple taps to provide power in the form of one or more energy modalities, such as ultrasonic, bipolar or monopolar RF, irreversible and/or reversible electroporation, and/or microwave energy, among others, for example, to the end effector depending on the type of treatment of tissue being performed. For example, the generator **900** can deliver energy with higher voltage and lower current to drive an ultrasonic transducer, with lower voltage and higher current to drive RF electrodes for sealing tissue, or with a coagulation waveform for spot coagulation using either monopolar or bipolar RF electrosurgical electrodes. The output waveform from the generator **900** can be steered, switched, or filtered to provide the frequency to the end effector of the surgical instrument. The connection of an ultrasonic transducer to the generator **900** output would be preferably located between the output labeled $ENERGY_1$ and RETURN as shown in FIG. **2**. In one example, a connection of RF bipolar electrodes to the generator **900** output would be preferably located between the output labeled $ENERGY_2$ and RETURN. In the case of monopolar output, the preferred connections would be active electrode (e.g., pencil or other probe) to the $ENERGY_2$ output and a suitable return pad connected to the RETURN output.

[0248] Additional details are disclosed in U.S. Patent Application Publication No. 2017/0086914, titled TECHNIQUES FOR OPERATING GENERATOR FOR DIGITALLY GENERATING ELECTRICAL SIGNAL WAVEFORMS AND SURGICAL INSTRUMENTS, which published on Mar. 30, 2017, which is herein incorporated by reference in its entirety.

[0249] As used throughout this description, the term "wireless" and its derivatives may be used to describe circuits, devices, systems, methods, techniques, communications channels, etc., that may communicate data through the use of modulated electromagnetic radiation through a non-solid medium. The term does not imply that the associated devices do not contain any wires, although in some aspects they might not. The communication module may implement any of a number of wireless or wired communication standards or protocols, including but not limited to W-Fi (IEEE 802.11 family), WiMAX (IEEE 802.16 family), IEEE 802.20, long term evolution (LTE), Ev-DO, HSPA+, HSDPA+, HSUPA+, EDGE, GSM, GPRS, CDMA, TDMA, DECT, Bluetooth, Ethernet derivatives thereof, as well as any other wireless and wired protocols that are designated as 3G, 4G, 5G, and beyond. The computing module may include a plurality of communication modules. For instance, a first communication module may be dedicated to shorter range wireless communications such as W-Fi and Bluetooth and a second communication module may be dedicated to longer range wireless communications such as GPS, EDGE, GPRS, CDMA, WiMAX, LTE, Ev-DO, and others.

[0250] As used herein a processor or processing unit is an electronic circuit which performs operations on some external data source, usually memory or some other data stream. The term is used herein to refer to the central processor (central processing unit) in a system or computer systems (especially systems on a chip (SoCs)) that combine a number of specialized "processors."

[0251] As used herein, a system on a chip or system on chip (SoC or SOC) is an integrated circuit (also known as an "IC" or "chip") that integrates all components of a computer or other electronic systems. It may contain digital, analog, mixed-signal, and often radio-frequency functions—all on a single substrate. A SoC integrates a microcontroller (or microprocessor) with advanced peripherals like graphics processing unit (GPU), Wi-Fi module, or coprocessor. A SoC may or may not contain built-in memory.

[0252] As used herein, a microcontroller or controller is a system that integrates a microprocessor with peripheral circuits and memory. A microcontroller (or MCU for microcontroller unit) may be implemented as a small computer on a single integrated circuit. It may be similar to a SoC; an SoC may include a microcontroller as one of its components. A microcontroller may contain one or more core processing units (CPUs) along with memory and programmable input/output peripherals. Program memory in the form of Ferroelectric RAM, NOR flash or OTP ROM is also often included on chip, as well as a small amount of RAM. Microcontrollers may be employed for embedded applications, in contrast to the microprocessors used in personal computers or other general purpose applications consisting of various discrete chips.

[0253] As used herein, the term controller or microcontroller may be a stand-alone IC or chip device that interfaces with a peripheral device. This may be a link between two parts of a computer or a controller on an external device that manages the operation of (and connection with) that device.

[0254] Any of the processors or microcontrollers described herein, may be implemented by any single core or multicore processor such as those known under the trade name ARM Cortex by Texas Instruments. In one aspect, the processor may be an LM4F230H5QR ARM Cortex-M4F Processor Core, available from Texas Instruments, for example, comprising on-chip memory of 256 KB single-cycle flash memory, or other non-volatile memory, up to 40 MHz, a prefetch buffer to improve performance above 40 MHz, a 32 KB single-cycle serial random access memory (SRAM), internal read-only memory (ROM) loaded with StellarisWare® software, 2 KB electrically erasable programmable read-only memory (EEPROM), one or more pulse width modulation (PWM) modules, one or more quadrature encoder inputs (QEI) analog, one or more 12-bit Analog-to-Digital Converters (ADC) with 12 analog input channels, details of which are available for the product datasheet.

[0255] In one aspect, the processor may comprise a safety controller comprising two controller-based families such as TMS570 and RM4x known under the trade name Hercules ARM Cortex R4, also by Texas Instruments. The safety controller may be configured specifically for IEC 61508 and ISO 26262 safety critical applications, among others, to provide advanced integrated safety features while delivering scalable performance, connectivity, and memory options.

[0256] Modular devices include the modules (as described in connection with FIG. **3**, for example) that are receivable within a surgical hub and the surgical devices or instruments that can be connected to the various modules in order to connect or pair with the corresponding surgical hub. The modular devices include, for example, intelligent surgical instruments, medical imaging devices, suction/irrigation devices, smoke evacuators, energy generators, ventilators, insufflators, and displays. The modular devices described herein can be controlled by control algorithms. The control algorithms can be executed on the modular device itself, on the surgical hub to which the particular modular device is paired, or on both the modular device and the surgical hub (e.g., via a distributed computing architecture). In some exemplifications, the modular devices' control algorithms control the devices based on data sensed by the modular device itself (i.e., by sensors in, on, or connected to the modular device). This data can be related to the patient being operated on (e.g., tissue properties or insufflation pressure) or the modular device itself (e.g., the rate at which a knife is being advanced, motor current, or energy levels). For example, a control algorithm for a surgical stapling and cutting instrument can control the rate at which the instrument's motor drives its knife through tissue according to resistance encountered by the knife as it advances.

[0257] FIG. **3** illustrates one form of a surgical system **1000** comprising a generator **1100** and various surgical instruments **1104**, **1106**, **1108** usable therewith, where the surgical instrument **1104** is an ultrasonic surgical instrument, the surgical instrument **1106** is an RF electrosurgical instrument, and the multifunction surgical instrument **1108** is a combination ultrasonic/RF electrosurgical instrument. The generator **1100** is configurable for use with a variety of surgical instruments. According to various forms, the generator **1100** may be configurable for use with different surgical instruments of different types including, for example, ultrasonic surgical instruments **1104**, RF electrosurgical instruments **1106**, and multifunction surgical instruments **1108** that integrate RF and ultrasonic energies delivered simultaneously from the generator **1100**. Although in the form of FIG. **3** the generator **1100** is shown separate from the surgical instruments **1104**, **1106**, **1108** in one form, the generator **1100** may be formed integrally with any of the surgical instruments **1104**, **1106**, **1108** to form a unitary surgical system. The generator **1100** comprises an input device **1110** located on a front panel of the generator **1100** console. The input device **1110** may comprise any suitable device that generates signals suitable for programming the operation of the generator **1100**. The generator **1100** may be configured for wired or wireless communication.

[0258] The generator **1100** is configured to drive multiple surgical instruments **1104**, **1106**, **1108**. The first surgical instrument is an ultrasonic surgical instrument **1104** and comprises a handpiece **1105** (HP), an ultrasonic transducer **1120**, a shaft **1126**, and an end effector **1122**. The end effector **1122** comprises an ultrasonic blade **1128** acoustically coupled to the ultrasonic transducer **1120** and a clamp arm **1140**. The handpiece **1105** comprises a trigger **1143** to operate the clamp arm **1140** and a combination of the toggle buttons **1134***a*, **1134***b*, **1134***c* to energize and drive the ultrasonic blade **1128** or other function. The toggle buttons **1134***a*, **1134***b*, **1134***c* can be configured to energize the ultrasonic transducer **1120** with the generator **1100**.

[0259] The generator **1100** also is configured to drive a second surgical instrument **1106**. The second surgical instrument **1106** is an RF electrosurgical instrument and comprises a handpiece **1107** (HP), a shaft **1127**, and an end effector **1124**. The end effector **1124** comprises electrodes in clamp arms **1142***a*, **1142***b* and return through an electrical conductor portion of the shaft **1127**. The electrodes are coupled to and energized by a bipolar energy source within the generator **1100**. The handpiece **1107** comprises a trigger **1145** to operate the clamp arms **1142***a*, **1142***b* and an energy button **1135** to actuate an energy switch to energize the electrodes in the end effector **1124**.

[0260] The generator **1100** also is configured to drive a multifunction surgical instrument **1108**. The multifunction surgical instrument **1108** comprises a handpiece **1109** (HP), a shaft **1129**, and an end effector **1125**. The end effector **1125** comprises an ultrasonic blade **1149** and a clamp arm **1146**. The ultrasonic blade **1149** is acoustically coupled to the ultrasonic transducer **1120**. The handpiece **1109** comprises a trigger **1147** to operate the clamp arm **1146** and a combination of the toggle buttons **1137***a*, **1137***b*, **1137***c* to energize and drive the ultrasonic blade **1149** or other function. The toggle buttons **1137***a,* **1137***b,* **1137***c* can be configured to energize the ultrasonic transducer **1120** with the generator **1100** and energize the ultrasonic blade **1149** with a bipolar energy source also contained within the generator **1100**.

[0261] The generator **1100** is configurable for use with a variety of surgical instruments. According to various forms, the generator **1100** may be configurable for use with different surgical instruments of different types including, for example, the ultrasonic surgical instrument **1104**, the RF electrosurgical instrument **1106**, and the multifunction surgical instrument **1108** that integrates RF and ultrasonic energies delivered simultaneously from the generator **1100**. Although in the form of FIG. **3** the generator **1100** is shown separate from the surgical instruments **1104**, **1106**, **1108**, in another form the generator **1100** may be formed integrally with any one of the surgical instruments **1104**, **1106**, **1108** to form a unitary surgical system. As discussed above, the generator **1100** comprises an input device **1110** located on a front panel of the generator **1100** console. The input device **1110** may comprise any suitable device that generates signals suitable for programming the operation of the generator **1100**. The generator **1100** also may comprise one or more output devices **1112**. Further aspects of generators for digitally generating electrical signal waveforms and surgical instruments are described in US patent publication US-2017-0086914-A1, which is herein incorporated by reference in its entirety.

[0262] FIG. **4** is an end effector **1122** of the example ultrasonic device **1104**, in accordance with at least one aspect of the present disclosure. The end effector **1122** may comprise a blade **1128** that may be coupled to the ultrasonic transducer **1120** via a wave guide. When driven by the ultrasonic transducer **1120**, the blade **1128** may vibrate and, when brought into contact with tissue, may cut and/or coagulate the tissue, as described herein. According to various aspects, and as illustrated in FIG. **4**, the end effector **1122** may also comprise a clamp arm **1140** that may be configured for cooperative action with the blade **1128** of the end effector **1122**. With the blade **1128**, the clamp arm **1140** may comprise a set of jaws. The clamp arm **1140** may be pivotally connected at a distal end of a shaft **1126** of the instrument portion **1104**. The clamp arm **1140** may include a clamp arm tissue pad **1163**, which may be formed from TEFLON® or other suitable low-friction material. The pad **1163** may be mounted for cooperation with the blade **1128**, with pivotal movement of the clamp arm **1140** positioning the clamp pad **1163** in substantially parallel relationship to, and in contact with, the blade **1128**. By this construction, a tissue bite to be clamped may be grasped between the tissue pad **1163** and the blade **1128**. The tissue pad **1163** may be provided with a sawtooth-like configuration including a plurality of axially spaced, proximally extending gripping teeth **1161** to enhance the gripping of tissue in cooperation with the blade **1128**. The clamp arm **1140** may transition from the open position shown in FIG. **4** to a closed position (with the clamp arm **1140** in contact with or proximity to the blade **1128**) in any suitable manner. For example, the handpiece **1105** may comprise a jaw closure trigger. When actuated by a clinician, the jaw closure trigger may pivot the clamp arm **1140** in any suitable manner.

[0263] The generator **1100** may be activated to provide the drive signal to the ultrasonic transducer **1120** in any suitable manner. For example, the generator **1100** may comprise a foot switch **1430** (FIG. **5**) coupled to the generator **1100** via a footswitch cable **1432**. A clinician may activate the ultrasonic transducer **1120**, and thereby the ultrasonic transducer **1120** and blade **1128**, by depressing the foot switch **1430**. In addition, or instead of the foot switch **1430**, some aspects of the device **1104** may utilize one or more switches positioned on the handpiece **1105** that, when activated, may cause the generator **1100** to activate the ultrasonic transducer **1120**. In one aspect, for example, the one or more switches may comprise a pair of toggle buttons **1134**, **1134***a,* **1134***b* (FIG. **3**), for example, to determine an operating mode of the device **1104**. When the toggle button **1134***a* is depressed, for example, the ultrasonic generator **1100** may provide a maximum drive signal to the ultrasonic transducer **1120**, causing it to produce maximum ultrasonic energy output. Depressing toggle button **1134***b* may cause the ultrasonic generator **1100** to provide a user-selectable drive signal to the ultrasonic transducer **1120**, causing it to produce less than the maximum ultrasonic energy output. The device **1104** additionally or alternatively may comprise a second switch to, for example, indicate a position of a jaw closure trigger for operating the jaws via the clamp arm **1140** of the end effector **1122**. Also, in some aspects, the ultrasonic generator **1100** may be activated based on the position of the jaw closure trigger, (e.g., as the clinician depresses the jaw closure trigger to close the jaws via the clamp arm **1140**, ultrasonic energy may be applied).

[0264] Additionally or alternatively, the one or more switches may comprise a toggle button **1134** that, when depressed, causes the generator **1100** to provide a pulsed output (FIG. **3**). The pulses may be provided at any suitable frequency and grouping, for example. In certain aspects, the power level of the pulses may be the power levels associated with toggle buttons **1134***a,* **1134***b* (maximum, less than maximum), for example.

[0265] It will be appreciated that a device **1104** may comprise any combination of the toggle buttons **1134***a,* **1134***b,* **1134** (FIG. **3**). For example, the device **1104** could be configured to have only two toggle buttons: a toggle button **1134***a* for producing maximum ultrasonic energy output and a toggle button **1134** for producing a pulsed output at either the maximum or less than maximum power level per. In this way, the drive signal output configuration of the generator **1100** could be five continuous signals, or any discrete number of individual pulsed signals (1, 2, 3, 4, or 5). In certain aspects, the specific drive signal configuration may be controlled based upon, for example, EEPROM settings in the generator **1100** and/or user power level selection(s).

[0266] In certain aspects, a two-position switch may be provided as an alternative to a toggle button **1134** (FIG. **3**). For example, a device **1104** may include a toggle button **1134***a* for producing a continuous output at a maximum power level and a two-position toggle button **1134***b*. In a first detented position, toggle button **1134***b* may produce a continuous output at a less than maximum power level, and in a second detented position the toggle button **1134***b* may produce a pulsed output (e.g., at either a maximum or less than maximum power level, depending upon the EEPROM settings).

[0267] In some aspects, the RF electrosurgical end effector **1124**, **1125** (FIG. **3**) may also comprise a pair of electrodes. The electrodes may be in communication with the generator **1100**, for example, via a cable. The electrodes may be used, for example, to measure an impedance of a tissue bite present between the clamp arm **1142***a,* **1146** and the blade

1142*b*, **1149**. The generator **1100** may provide a signal (e.g., a non-therapeutic signal) to the electrodes. The impedance of the tissue bite may be found, for example, by monitoring the current, voltage, etc. of the signal.

[0268] In various aspects, the generator **1100** may comprise several separate functional elements, such as modules and/or blocks, as shown in FIG. **5**, a diagram of the surgical system **1000** of FIG. **3**. Different functional elements or modules may be configured for driving the different kinds of surgical devices **1104**, **1106**, **1108**. For example an ultrasonic generator module may drive an ultrasonic device, such as the ultrasonic device **1104**. An electrosurgery/RF generator module may drive the electrosurgical device **1106**. The modules may generate respective drive signals for driving the surgical devices **1104**, **1106**, **1108**. In various aspects, the ultrasonic generator module and/or the electrosurgery/RF generator module each may be formed integrally with the generator **1100**. Alternatively, one or more of the modules may be provided as a separate circuit module electrically coupled to the generator **1100**. (The modules are shown in phantom to illustrate this option.) Also, in some aspects, the electrosurgery/RF generator module may be formed integrally with the ultrasonic generator module, or vice versa.

[0269] In accordance with the described aspects, the ultrasonic generator module may produce a drive signal or signals of particular voltages, currents, and frequencies (e.g. 55,500 cycles per second, or Hz). The drive signal or signals may be provided to the ultrasonic device **1104**, and specifically to the transducer **1120**, which may operate, for example, as described above. In one aspect, the generator **1100** may be configured to produce a drive signal of a particular voltage, current, and/or frequency output signal that can be stepped with high resolution, accuracy, and repeatability.

[0270] In accordance with the described aspects, the electrosurgery/RF generator module may generate a drive signal or signals with output power sufficient to perform bipolar electrosurgery using radio frequency (RF) energy. In bipolar electrosurgery applications, the drive signal may be provided, for example, to the electrodes of the electrosurgical device **1106**, for example, as described above. Accordingly, the generator **1100** may be configured for therapeutic purposes by applying electrical energy to the tissue sufficient for treating the tissue (e.g., coagulation, cauterization, tissue welding, etc.).

[0271] The generator **1100** may comprise an input device **2150** (FIG. **8**B) located, for example, on a front panel of the generator **1100** console. The input device **2150** may comprise any suitable device that generates signals suitable for programming the operation of the generator **1100**. In operation, the user can program or otherwise control operation of the generator **1100** using the input device **2150**. The input device **2150** may comprise any suitable device that generates signals that can be used by the generator (e.g., by one or more processors contained in the generator) to control the operation of the generator **1100** (e.g., operation of the ultrasonic generator module and/or electrosurgery/RF generator module). In various aspects, the input device **2150** includes one or more of: buttons, switches, thumbwheels, keyboard, keypad, touch screen monitor, pointing device, remote connection to a general purpose or dedicated computer. In other aspects, the input device **2150** may comprise a suitable user interface, such as one or more user interface screens displayed on a touch screen monitor, for example. Accordingly, by way of the input device **2150**, the user can set or program various operating parameters of the generator, such as, for example, current (I), voltage (V), frequency (f), and/or period (T) of a drive signal or signals generated by the ultrasonic generator module and/or electrosurgery/RF generator module.

[0272] The generator **1100** may also comprise an output device **2140** (FIG. **8**B) located, for example, on a front panel of the generator **1100** console. The output device **2140** includes one or more devices for providing a sensory feedback to a user. Such devices may comprise, for example, visual feedback devices (e.g., an LCD display screen, LED indicators), audio feedback devices (e.g., a speaker, a buzzer) or tactile feedback devices (e.g., haptic actuators).

[0273] Although certain modules and/or blocks of the generator **1100** may be described by way of example, it can be appreciated that a greater or lesser number of modules and/or blocks may be used and still fall within the scope of the aspects. Further, although various aspects may be described in terms of modules and/or blocks to facilitate description, such modules and/or blocks may be implemented by one or more hardware components, e.g., processors, Digital Signal Processors (DSPs), Programmable Logic Devices (PLDs), Application Specific Integrated Circuits (ASICs), circuits, registers and/or software components, e.g., programs, subroutines, logic and/or combinations of hardware and software components.

[0274] In one aspect, the ultrasonic generator drive module and electrosurgery/RF drive module **1110** (FIG. **3**) may comprise one or more embedded applications implemented as firmware, software, hardware, or any combination thereof. The modules may comprise various executable modules such as software, programs, data, drivers, application program interfaces (APIs), and so forth. The firmware may be stored in nonvolatile memory (NVM), such as in bit-masked read-only memory (ROM) or flash memory. In various implementations, storing the firmware in ROM may preserve flash memory. The NVM may comprise other types of memory including, for example, programmable ROM (PROM), erasable programmable ROM (EPROM), electrically erasable programmable ROM (EEPROM), or battery backed random-access memory (RAM) such as dynamic RAM (DRAM), Double-Data-Rate DRAM (DDRAM), and/or synchronous DRAM (SDRAM).

[0275] In one aspect, the modules comprise a hardware component implemented as a processor for executing program instructions for monitoring various measurable characteristics of the devices **1104**, **1106**, **1108** and generating a corresponding output drive signal or signals for operating the devices **1104**, **1106**, **1108**. In aspects in which the generator **1100** is used in conjunction with the device **1104**, the drive signal may drive the ultrasonic transducer **1120** in cutting and/or coagulation operating modes. Electrical characteristics of the device **1104** and/or tissue may be measured and used to control operational aspects of the generator **1100** and/or provided as feedback to the user. In aspects in which the generator **1100** is used in conjunction with the device **1106**, the drive signal may supply electrical energy (e.g., RF energy) to the end effector **1124** in cutting, coagulation and/or desiccation modes. Electrical characteristics of the device **1106** and/or tissue may be measured and used to control operational aspects of the generator **1100** and/or provided as feedback to the user. In various aspects, as previously discussed, the hardware components may be implemented as DSP, PLD, ASIC, circuits, and/or registers. In one aspect, the processor may be configured to store and execute computer software program instructions to generate the step function output signals for driving various components of the devices **1104**, **1106**, **1108**, such as the ultrasonic transducer **1120** and the end effectors **1122**, **1124**, **1125**.

[0276] An electromechanical ultrasonic system includes an ultrasonic transducer, a waveguide, and an ultrasonic blade. The electromechanical ultrasonic system has an initial resonant frequency defined by the physical properties of the ultrasonic transducer, the waveguide, and the ultrasonic blade. The ultrasonic transducer is excited by an alternating voltage $V_g(t)$ and current $I_g(t)$ signal equal to the resonant frequency of the electromechanical ultrasonic system. When the electromechanical ultrasonic system is at resonance, the phase difference between the voltage $V_g(t)$ and current $I_g(t)$ signals is zero. Stated another way, at resonance the inductive impedance is equal to the capacitive impedance. As the ultrasonic blade heats up, the compliance of the ultrasonic blade (modeled as an equivalent capacitance) causes the resonant frequency of the electromechanical ultrasonic system to shift. Thus, the inductive impedance is no longer equal to the capacitive impedance causing a mismatch between the drive frequency and the resonant frequency of the electromechanical ultrasonic system. The system is now operating "off-resonance." The mismatch between the drive frequency and the resonant frequency is manifested as a phase difference between the voltage $V_g(t)$ and current $I_g(t)$ signals applied to the ultrasonic transducer. The generator electronics can easily monitor the phase difference between the voltage $V_g(t)$ and current $I_g(t)$ signals and can continuously adjust the drive frequency until the phase difference is once again zero. At this point, the new drive frequency is equal to the new resonant frequency of the electromechanical ultrasonic system. The change in phase and/or frequency can be used as an indirect measurement of the ultrasonic blade temperature.

[0277] As shown in FIG. **6**, the electromechanical properties of the ultrasonic transducer may be modeled as an equivalent circuit comprising a first branch having a static capacitance and a second "motional" branch having a serially connected inductance, resistance and capacitance that define the electromechanical properties of a resonator. Known ultrasonic generators may include a tuning inductor for tuning out the static capacitance at a resonant frequency so that substantially all of generator's drive signal current flows into the motional branch. Accordingly, by using a tuning inductor, the generator's drive signal current represents the motional branch current, and the generator is thus able to control its drive signal to maintain the ultrasonic transducer's resonant frequency. The tuning inductor may also transform the phase impedance plot of the ultrasonic transducer to improve the generator's frequency lock capabilities. However, the tuning inductor must be matched with the specific static capacitance of an ultrasonic transducer at the operational resonance frequency. In other words, a different ultrasonic transducer having a different static capacitance requires a different tuning inductor.

[0278] FIG. **6** illustrates an equivalent circuit **1500** of an ultrasonic transducer, such as the ultrasonic transducer **1120**, according to one aspect. The circuit **1500** comprises a first "motional" branch having a serially connected inductance L_s, resistance R_s and capacitance C_s that define the electromechanical properties of the resonator, and a second capacitive branch having a static capacitance C_0. Drive current $I_g(t)$ may be received from a generator at a drive voltage $V_g(t)$, with motional current $I_m(t)$ flowing through the first branch and current $I_g(t\text{-}I_m(t)$ flowing through the capacitive branch. Control of the electromechanical properties of the ultrasonic transducer may be achieved by suitably controlling $I_g(t)$ and $V_g(t)$. As explained above, known generator architectures may include a tuning inductor L_t (shown in phantom in FIG. **6**) in a parallel resonance circuit for tuning out the static capacitance C_0 at a resonant frequency so that substantially all of the generator's current output $I_g(t)$ flows through the motional branch. In this way, control of the motional branch current $I_m(t)$ is achieved by controlling the generator current output $I_g(t)$. The tuning inductor L_t is specific to the static capacitance C_0 of an ultrasonic transducer, however, and a different ultrasonic transducer having a different static capacitance requires a different tuning inductor L_t. Moreover, because the tuning inductor L_t is matched to the nominal value of the static capacitance C_0 at a single resonant frequency, accurate control of the motional branch current $I_m(t)$ is assured only at that frequency. As frequency shifts down with transducer temperature, accurate control of the motional branch current is compromised.

[0279] Various aspects of the generator **1100** may not rely on a tuning inductor L_t to monitor the motional branch current $I_m(t)$. Instead, the generator **1100** may use the measured value of the static capacitance C_0 in between applications of power for a specific ultrasonic surgical device **1104** (along with drive signal voltage and current feedback data) to determine values of the motional branch current $I_m(t)$ on a dynamic and ongoing basis (e.g., in real-time). Such aspects of the generator **1100** are therefore able to provide virtual tuning to simulate a system that is tuned or resonant with any value of static capacitance C_0 at any frequency, and not just at a single resonant frequency dictated by a nominal value of the static capacitance C_0.

[0280] FIG. **7** is a simplified block diagram of one aspect of the generator **1100** for providing inductorless tuning as described above, among other benefits. FIGS. **8**A-**8**C illustrate an architecture of the generator **1100** of FIG. **7** according to one aspect. With reference to FIG. **7**, the generator **1100** may comprise a patient isolated stage **1520** in communication with a non-isolated stage **1540** via a power transformer **1560**. A secondary winding **1580** of the power transformer **1560** is contained in the isolated stage **1520** and may comprise a tapped configuration (e.g., a center-tapped or non-center tapped configuration) to define drive signal outputs **1600***a*, **1600***b*, **1600***c* for outputting drive signals to different surgical devices, such as, for example, an ultrasonic surgical device **1104** and an electrosurgical device **1106**. In particular, drive signal outputs **1600***a*, **1600***b*, **1600***c* may output a drive signal (e.g., a 420V RMS drive signal) to an ultrasonic surgical device **1104**, and drive signal outputs **1600***a*, **1600***b*, **1600***c* may output a drive signal (e.g., a 100V RMS drive signal) to an electrosurgical device **1106**, with output **1600***b* corresponding to the center tap of the power transformer **1560**. The non-isolated stage **1540** may comprise a power amplifier **1620** having an output connected to a primary winding **1640** of the power transformer **1560**. In certain aspects the power amplifier **1620** may comprise a push-pull amplifier, for example. The non-isolated stage **1540** may further comprise a programmable logic device **1660** for supplying a digital output to a digital-to-analog converter (DAC) **1680**, which in turn supplies a corresponding analog signal to an input of the power amplifier **1620**. In certain aspects the programmable logic device **1660** may comprise a field-programmable gate array (FPGA), for example. The programmable logic device **1660**, by virtue of controlling the power amplifier's **1620** input via the DAC **1680**, may therefore control any of a number of parameters (e.g., frequency, waveform shape, waveform amplitude) of drive signals appearing at the drive signal outputs **1600***a*, **1600***b*, **1600***c*. In certain aspects and as discussed below, the programmable logic device **1660**, in conjunction with a processor (e.g., processor **1740** discussed below), may implement a number of digital signal processing (DSP)-based and/or other control algorithms to control parameters of the drive signals output by the generator **1100**.

[0281] Power may be supplied to a power rail of the power amplifier **1620** by a switch-mode regulator **1700**. In certain aspects the switch-mode regulator **1700** may comprise an adjustable buck regulator, for example. As discussed above, the non-isolated stage **1540** may further comprise a processor **1740**, which in one aspect may comprise a DSP processor such as an ADSP-21469 SHARC DSP, available from Analog Devices, Norwood, Mass., for example. In certain aspects the processor **1740** may control operation of the switch-mode power converter **1700** responsive to voltage feedback data received from the power amplifier **1620** by the processor **1740** via an analog-to-digital converter (ADC) **1760**. In one aspect, for example, the processor **1740** may receive as input, via the ADC **1760**, the waveform envelope of a signal (e.g., an RF signal) being amplified by the power amplifier **1620**. The processor **1740** may then control the switch-mode regulator **1700** (e.g., via a pulse-width modulated (PWM) output) such that the rail voltage supplied to the power amplifier **1620** tracks the waveform envelope of the amplified signal. By dynamically modulating the rail voltage of the power amplifier **1620** based on the waveform envelope, the efficiency of the power amplifier **1620** may be significantly improved relative to a fixed rail voltage amplifier scheme. The processor **1740** may be configured for wired or wireless communication.

[0282] In certain aspects and as discussed in further detail in connection with FIGS. **9**A-**9**B, the programmable logic device **1660**, in conjunction with the processor **1740**, may implement a direct digital synthesizer (DDS) control scheme to control the waveform shape, frequency and/or amplitude of drive signals output by the generator **1100**. In one aspect, for example, the programmable logic device **1660** may implement a DDS control algorithm **2680** (FIG. **9**A) by recalling waveform samples stored in a dynamically-updated look-up table (LUT), such as a RAM LUT which may be embedded in an FPGA. This control algorithm is particularly useful for ultrasonic applications in which an ultrasonic transducer, such as the ultrasonic transducer **1120**, may be driven by a clean sinusoidal current at its resonant frequency. Because other frequencies may excite parasitic resonances, minimizing or reducing the total distortion of the motional branch current may correspondingly minimize or reduce undesirable resonance effects. Because the waveform shape of a drive signal output by the generator **1100** is impacted by various sources of distortion present in the output drive circuit (e.g., the power transformer **1560**, the power amplifier **1620**), voltage and current feedback data based on the drive signal may be input into an algorithm, such as an error control algorithm implemented by the processor **1740**, which compensates for distortion by suitably pre-distorting or modifying the waveform samples stored in the LUT on a dynamic, ongoing basis (e.g., in real-time). In one aspect, the amount or degree of pre-distortion applied to the LUT samples may be based on the error between a computed motional branch current and a desired current waveform shape, with the error being determined on a sample-by sample basis. In this way, the pre-distorted LUT samples, when processed through the drive circuit, may result in a motional branch drive signal having the desired waveform shape (e.g., sinusoidal) for optimally driving the ultrasonic transducer. In such aspects, the LUT waveform samples will therefore not represent the desired waveform shape of the drive signal, but rather the waveform shape that is required to ultimately produce the desired waveform shape of the motional branch drive signal when distortion effects are taken into account.

[0283] The non-isolated stage **1540** may further comprise an ADC **1780** and an ADC **1800** coupled to the output of the power transformer **1560** via respective isolation transformers **1820**, **1840** for respectively sampling the voltage and current of drive signals output by the generator **1100**. In certain aspects, the ADCs **1780**, **1800** may be configured to sample at high speeds (e.g., 80 Msps) to enable oversampling of the drive signals. In one aspect, for example, the sampling speed of the ADCs **1780**, **1800** may enable approximately 200× (depending on drive frequency) oversampling of the drive signals. In certain aspects, the sampling operations of the ADCs **1780**, **1800** may be performed by a single ADC receiving input voltage and current signals via a two-way multiplexer. The use of high-speed sampling in aspects of the generator **1100** may enable, among other things, calculation of the complex current flowing through the motional branch (which may be used in certain aspects to implement DDS-based waveform shape control described above), accurate digital filtering of the sampled signals, and calculation of real power consumption with a high degree of precision. Voltage and current feedback data output by the ADCs **1780**, **1800** may be received and processed (e.g., FIFO buffering, multiplexing) by the programmable logic device **1660** and stored in data memory for subsequent retrieval by, for example, the processor **1740**. As noted above, voltage and current feedback data may be used as input to an algorithm for pre-distorting or modifying LUT waveform samples on a dynamic and ongoing basis. In certain aspects, this may require each stored voltage and current feedback data pair to be indexed based on, or otherwise associated with, a corresponding LUT sample that was output by the programmable logic device **1660** when the voltage and current feedback data pair was acquired. Synchronization of the LUT samples and the voltage and current feedback data in this manner contributes to the correct timing and stability of the pre-distortion algorithm.

[0284] In certain aspects, the voltage and current feedback data may be used to control the frequency and/or amplitude (e.g., current amplitude) of the drive signals. In one aspect, for example, voltage and current feedback data may be used to determine impedance phase, e.g., the phase difference between the voltage and current drive signals. The frequency of the drive signal may then be controlled to minimize or reduce the difference between the determined impedance phase and an impedance phase setpoint (e.g., 0°), thereby minimizing or reducing the effects of harmonic distortion and correspondingly enhancing impedance phase measurement accuracy. The determination of phase impedance and a frequency control signal may be implemented in the processor **1740**, for example, with the frequency control signal being supplied as input to a DDS control algorithm implemented by the programmable logic device **1660**.

[0285] The impedance phase may be determined through Fourier analysis. In one aspect, the phase difference between the generator voltage $V_g(t)$ and generator current $I_g(t)$ driving signals may be determined using the Fast Fourier Transform (FFT) or the Discrete Fourier Transform (DFT) as follows:

$$V_g(t) = A_1\cos(2\pi f_0 t + \varphi_1)$$

$$I_g(t) = A_2\cos(2\pi f_0 t + \varphi_2)$$

$$V_g(f) = \frac{A_1}{2}(\delta(f - f_0) + \delta(f + f_0))\exp\left(j2\pi f\frac{\varphi_1}{2\pi f_0}\right)$$

$$I_g(f) = \frac{A_2}{2}(\delta(f - f_0) + \delta(f + f_0))\exp\left(j2\pi f\frac{\varphi_2}{2\pi f_0}\right)$$

Evaluating the Fourier Transform at the frequency of the sinusoid yields:

$$V_g(f_0) = \frac{A_1}{2}\delta(0)\exp(j\varphi_1) \quad \arg V(f_0) = \varphi_1$$

$$I_g(f_0) = \frac{A_2}{2}\delta(0)\exp(j\varphi_2) \quad \arg I(f_0) = \varphi_2$$

[0286] Other approaches include weighted least-squares estimation, Kalman filtering, and space-vector-based techniques. Virtually all of the processing in an FFT or DFT technique may be performed in the digital domain with the aid of the 2-channel high speed ADC **1780**, **1800**, for example. In one technique, the digital signal samples of the voltage and current signals are Fourier transformed with an FFT or a DFT. The phase angle φ at any point in time can be calculated by:

$$\varphi = 2\pi ft + \varphi_0$$

where φ is the phase angle, f is the frequency, t is time, and φ_0 is the phase at t=0.

[0287] Another technique for determining the phase difference between the voltage $V_g(t)$ and current $I_g(t)$ signals is the zero-crossing method and produces highly accurate results. For voltage $V_g(t)$ and current $I_g(t)$ signals having the same frequency, each negative to positive zero-crossing of voltage signal $V_g(t)$ triggers the start of a pulse, while each negative to positive zero-crossing of current signal $I_g(t)$ triggers the end of the pulse. The result is a pulse train with a pulse width proportional to the phase angle between the voltage signal and the current signal. In one aspect, the pulse train may be passed through an averaging filter to yield a measure of the phase difference. Furthermore, if the positive to negative zero crossings also are used in a similar manner, and the results averaged, any effects of DC and harmonic components can be reduced. In one implementation, the analog voltage $V_g(t)$ and current $I_g(t)$ signals are converted to digital signals that are high if the analog signal is positive and low if the analog signal is negative. High accuracy phase estimates require sharp transitions between high and low. In one aspect, a Schmitt trigger along with an RC stabilization network may be employed to convert the analog signals into digital signals. In other aspects, an edge triggered RS flip-flop and ancillary circuitry may be employed. In yet another aspect, the zero-crossing technique may employ an eXclusive OR (XOR) gate.

[0288] Other techniques for determining the phase difference between the voltage and current signals include Lissajous figures and monitoring the image; methods such as the three-voltmeter method, the crossed-coil method, vector voltmeter and vector impedance methods; and using phase standard instruments, phase-locked loops, and other techniques as described in Phase Measurement, Peter O'Shea, 2000 CRC Press LLC, <http://www.engnetbase.com>, which is incorporated herein by reference.

[0289] In another aspect, for example, the current feedback data may be monitored in order to maintain the current amplitude of the drive signal at a current amplitude setpoint. The current amplitude setpoint may be specified directly or determined indirectly based on specified voltage amplitude and power setpoints. In certain aspects, control of the current amplitude may be implemented by control algorithm, such as, for example, a proportional-integral-derivative (PID) control algorithm, in the processor **1740**. Variables controlled by the control algorithm to suitably control the current amplitude of the drive signal may include, for example, the scaling of the LUT waveform samples stored in the programmable logic device **1660** and/or the full-scale output voltage of the DAC **1680** (which supplies the input to the power amplifier **1620**) via a DAC **1860**.

[0290] The non-isolated stage **1540** may further comprise a processor **1900** for providing, among other things, user interface (UI) functionality. In one aspect, the processor **1900** may comprise an Atmel AT91 SAM9263 processor having an ARM 926EJ-S core, available from Atmel Corporation, San Jose, Calif., for example. Examples of UI functionality supported by the processor **1900** may include audible and visual user feedback, communication with peripheral devices (e.g., via a Universal Serial Bus (USB) interface), communication with a foot switch **1430**, communication with an input device **2150** (e.g., a touch screen display) and communication with an output device **2140** (e.g., a speaker). The processor **1900** may communicate with the processor **1740** and the programmable logic device (e.g., via a serial peripheral interface (SPI) bus). Although the processor **1900** may primarily support UI functionality, it may also coordinate with the processor **1740** to implement hazard mitigation in certain aspects. For example, the processor **1900** may be programmed to monitor various aspects of user input and/or other inputs (e.g., touch screen inputs **2150**, foot switch **1430** inputs, temperature sensor inputs **2160**) and may disable the drive output of the generator **1100** when an erroneous condition is detected.

[0291] In certain aspects, both the processor **1740** (FIGS. **7**, **8**A) and the processor **1900** (FIGS. **7**, **8**B) may determine and monitor the operating state of the generator **1100**. For processor **1740**, the operating state of the generator **1100** may dictate, for example, which control and/or diagnostic processes are implemented by the processor **1740**. For processor **1900**, the operating state of the generator **1100** may dictate, for example, which elements of a user interface (e.g., display screens, sounds) are presented to a user. The processors **1740**, **1900** may independently maintain the current operating state of the generator **1100** and recognize and evaluate possible transitions out of the current operating state. The processor **1740** may function as the master in this relationship and determine when transitions between operating states are to occur. The processor **1900** may be aware of valid transitions between operating states and may confirm if a particular transition is appropriate. For example, when the processor **1740** instructs the processor **1900** to transition to a specific state, the processor **1900** may verify that the requested transition is valid. In the event that a requested transition between states is determined to be invalid by the processor **1900**, the processor **1900** may cause the generator **1100** to enter a failure mode.

[0292] The non-isolated stage **1540** may further comprise a controller **1960** (FIGS. **7**, **8**B) for monitoring input devices **2150** (e.g., a capacitive touch sensor used for turning the generator **1100** on and off, a capacitive touch screen). In certain aspects, the controller **1960** may comprise at least one processor and/or other controller device in communication with the processor **1900**. In one aspect, for example, the controller **1960** may comprise a processor (e.g., a Mega168 8-bit controller available from Atmel) configured to monitor user input provided via one or more capacitive touch sensors. In one aspect, the controller **1960** may comprise a touch screen controller (e.g., a QT5480 touch screen controller available from Atmel) to control and manage the acquisition of touch data from a capacitive touch screen.

[0293] In certain aspects, when the generator **1100** is in a "power off" state, the controller **1960** may continue to receive operating power (e.g., via a line from a power supply of the generator **1100**, such as the power supply **2110** (FIG. **7**) discussed below). In this way, the controller **1960** may continue to monitor an input device **2150** (e.g., a capacitive touch sensor located on a front panel of the generator **1100**) for turning the generator **1100** on and off. When the generator **1100** is in the "power off" state, the controller **1960** may wake the power supply (e.g., enable operation of one or more DC/DC voltage converters **2130** (FIG. **7**) of the power supply **2110**) if activation of the "on/off" input device **2150** by a user is detected. The controller **1960** may therefore initiate a sequence for transitioning the generator **1100** to a "power on" state. Conversely, the controller **1960** may initiate a sequence for transitioning the generator **1100** to the "power off" state if activation of the "on/off" input device **2150** is detected when the generator **1100** is in the "power on" state. In certain aspects, for example, the controller **1960** may report activation of the "on/off" input device **2150** to the processor **1900**, which in turn implements the necessary process sequence for transitioning the generator **1100** to the "power off" state. In such aspects, the controller **1960** may have no independent ability for causing the removal of power from the generator **1100** after its "power on" state has been established.

[0294] In certain aspects, the controller **1960** may cause the generator **1100** to provide audible or other sensory feedback for alerting the user that a "power on" or "power off" sequence has been initiated. Such an alert may be provided at the beginning of a "power on" or "power off" sequence and prior to the commencement of other processes associated with the sequence.

[0295] In certain aspects, the isolated stage **1520** may comprise an instrument interface circuit **1980** to, for example, provide a communication interface between a control circuit of a surgical device (e.g., a control circuit comprising handpiece switches) and components of the non-isolated stage **1540**, such as, for example, the programmable logic device **1660**, the processor **1740** and/or the processor **1900**. The instrument interface circuit **1980** may exchange information with components of the non-isolated stage **1540** via a communication link that maintains a suitable degree of electrical isolation between the stages **1520**, **1540**, such as, for example, an infrared (IR)-based communication link. Power may be supplied to the instrument interface circuit **1980** using, for example, a low-dropout voltage regulator powered by an isolation transformer driven from the non-isolated stage **1540**.

[0296] In one aspect, the instrument interface circuit **1980** may comprise a programmable logic device **2000** (e.g., an FPGA) in communication with a signal conditioning circuit **2020** (FIG. **7** and FIG. **8**C). The signal conditioning circuit **2020** may be configured to receive a periodic signal from the programmable logic device **2000** (e.g., a 2 kHz square wave) to generate a bipolar interrogation signal having an identical frequency. The interrogation signal may be generated, for example, using a bipolar current source fed by a differential amplifier. The interrogation signal may be communicated to a surgical device control circuit (e.g., by using a conductive pair in a cable that connects the generator **1100** to the surgical device) and monitored to determine a state or configuration of the control circuit. For example, the control circuit may comprise a number of switches, resistors and/or diodes to modify one or more characteristics (e.g., amplitude, rectification) of the interrogation signal such that a state or configuration of the control circuit is uniquely discernible based on the one or more characteristics. In one aspect, for example, the signal conditioning circuit **2020** may comprise an ADC for generating samples of a voltage signal appearing across inputs of the control circuit resulting from passage of interrogation signal therethrough. The programmable logic device **2000** (or a component of the non-isolated stage **1540**) may then determine the state or configuration of the control circuit based on the ADC samples.

[0297] In one aspect, the instrument interface circuit **1980** may comprise a first data circuit interface **2040** to enable information exchange between the programmable logic device **2000** (or other element of the instrument interface circuit **1980**) and a first data circuit disposed in or otherwise associated with a surgical device. In certain aspects, for example, a first data circuit **2060** may be disposed in a cable integrally attached to a surgical device handpiece, or in an adaptor for interfacing a specific surgical device type or model with the generator **1100**. In certain aspects, the first data circuit may comprise a non-volatile storage device, such as an electrically erasable programmable read-only memory (EEPROM) device. In certain aspects and referring again to FIG. **7**, the first data circuit interface **2040** may be implemented separately from the programmable logic device **2000** and comprise suitable circuitry (e.g., discrete logic devices, a processor) to enable communication between the programmable logic device **2000** and the first data circuit. In other aspects, the first data circuit interface **2040** may be integral with the programmable logic device **2000**.

[0298] In certain aspects, the first data circuit **2060** may store information pertaining to the particular surgical device with which it is associated. Such information may include, for example, a model number, a serial number, a number of operations in which the surgical device has been used, and/or any other type of information. This information may be read by the instrument interface circuit **1980** (e.g., by the programmable logic device **2000**), transferred to a component of the non-isolated stage **1540** (e.g., to programmable logic device **1660**, processor **1740** and/or processor **1900**) for presentation to a user via an output device **2140** and/or for controlling a function or operation of the generator **1100**. Additionally, any type of information may be communicated to first data circuit **2060** for storage therein via the first data circuit interface **2040** (e.g., using the programmable logic device **2000**). Such information may comprise, for example, an updated number of operations in which the surgical device has been used and/or dates and/or times of its usage.

[0299] As discussed previously, a surgical instrument may be detachable from a handpiece (e.g., instrument **1106** may be detachable from handpiece **1107**) to promote instrument interchangeability and/or disposability. In such cases, known generators may be limited in their ability to recognize particular instrument configurations being used and to optimize control and diagnostic processes accordingly. The addition of readable data circuits to surgical device instruments to address this issue is problematic from a compatibility standpoint, however. For example, it may be impractical to design a surgical device to maintain backward compatibility with generators that lack the requisite data reading functionality due to, for example, differing signal schemes, design complexity and cost. Other aspects of instruments address these concerns by using data circuits that may be implemented in existing surgical instruments economically and with minimal design changes to preserve compatibility of the surgical devices with current generator platforms.

[0300] Additionally, aspects of the generator **1100** may enable communication with instrument-based data circuits. For example, the generator **1100** may be configured to communicate with a second data circuit (e.g., a data circuit) contained in an instrument (e.g., instrument **1104**, **1106** or **1108**) of a surgical device. The instrument interface circuit **1980** may comprise a second data circuit interface **2100** to enable this communication. In one aspect, the second data circuit interface **2100** may comprise a tri-state digital interface, although other interfaces may also be used. In certain aspects, the second data circuit may generally be any circuit for transmitting and/or receiving data. In one aspect, for example, the second data circuit may store information pertaining to the particular surgical instrument with which it is associated. Such information may include, for example, a model number, a serial number, a number of operations in which the surgical instrument has been used, and/or any other type of information. Additionally or alternatively, any type of information may be communicated to the second data circuit for storage therein via the second data circuit interface **2100** (e.g., using the programmable logic device **2000**). Such information may comprise, for example, an updated number of operations in which the instrument has been used and/or dates and/or times of its usage. In certain aspects, the second data circuit may transmit data acquired by one or more sensors (e.g., an instrument-based temperature sensor). In certain aspects, the second data circuit may receive data from the generator **1100** and provide an indication to a user (e.g., an LED indication or other visible indication) based on the received data.

[0301] In certain aspects, the second data circuit and the second data circuit interface **2100** may be configured such that communication between the programmable logic device **2000** and the second data circuit can be effected without the need to provide additional conductors for this purpose (e.g., dedicated conductors of a cable connecting a handpiece to the generator **1100**). In one aspect, for example, information may be communicated to and from the second data circuit using a one-wire bus communication scheme implemented on existing cabling, such as one of the conductors used transmit interrogation signals from the signal conditioning circuit **2020** to a control circuit in a handpiece. In this way, design changes or modifications to the surgical device that might otherwise be necessary are minimized or reduced. Moreover, because different types of communications can be implemented over a common physical channel (either with or without frequency-band separation), the presence of a second data circuit may be "invisible" to generators that do not have the requisite data reading functionality, thus enabling backward compatibility of the surgical device instrument.

[0302] In certain aspects, the isolated stage **1520** may comprise at least one blocking capacitor **2960-1** (FIG. **8**C) connected to the drive signal output **1600*b*** to prevent passage of DC current to a patient. A single blocking capacitor may be required to comply with medical regulations or standards, for example. While failure in single-capacitor designs is relatively uncommon, such failure may nonetheless have negative consequences. In one aspect, a second blocking capacitor **2960-2** may be provided in series with the blocking capacitor **2960-1**, with current leakage from a point between the blocking capacitors **2960-1**, **2960-2** being monitored by, for example, an ADC **2980** for sampling a voltage induced by leakage current. The samples may be received by the programmable logic device **2000**, for example. Based on changes in the leakage current (as indicated by the voltage samples in the aspect of FIG. **7**), the generator **1100** may determine when at least one of the blocking capacitors **2960-1**, **2960-2** has failed. Accordingly, the aspect of FIG. **7** may provide a benefit over single-capacitor designs having a single point of failure.

[0303] In certain aspects, the non-isolated stage **1540** may comprise a power supply **2110** for outputting DC power at a suitable voltage and current. The power supply may comprise, for example, a 400 W power supply for outputting a 48 VDC system voltage. As discussed above, the power supply **2110** may further comprise one or more DC/DC voltage converters **2130** for receiving the output of the power supply to generate DC outputs at the voltages and currents required by the various components of the generator **1100**. As discussed above in connection with the controller **1960**, one or more of the DC/DC voltage converters **2130** may receive an input from the controller **1960** when activation of the "on/off" input device **2150** by a user is detected by the controller **1960** to enable operation of, or wake, the DC/DC voltage converters **2130**.

[0304] FIGS. **9**A-**9**B illustrate certain functional and structural aspects of one aspect of the generator **1100**. Feedback indicating current and voltage output from the secondary winding **1580** of the power transformer **1560** is received by the ADCs **1780**, **1800**, respectively. As shown, the ADCs **1780**, **1800** may be implemented as a 2-channel ADC and may sample the feedback signals at a high speed (e.g., 80 Msps) to enable oversampling (e.g., approximately 200× oversampling) of the drive signals. The current and voltage feedback signals may be suitably conditioned in the analog domain (e.g., amplified, filtered) prior to processing by the

ADCs **1780**, **1800**. Current and voltage feedback samples from the ADCs **1780**, **1800** may be individually buffered and subsequently multiplexed or interleaved into a single data stream within block **2120** of the programmable logic device **1660**. In the aspect of FIGS. **9**A-**9**B, the programmable logic device **1660** comprises an FPGA.

[0305] The multiplexed current and voltage feedback samples may be received by a parallel data acquisition port (PDAP) implemented within block **2144** of the processor **1740**. The PDAP may comprise a packing unit for implementing any of a number of methodologies for correlating the multiplexed feedback samples with a memory address. In one aspect, for example, feedback samples corresponding to a particular LUT sample output by the programmable logic device **1660** may be stored at one or more memory addresses that are correlated or indexed with the LUT address of the LUT sample. In another aspect, feedback samples corresponding to a particular LUT sample output by the programmable logic device **1660** may be stored, along with the LUT address of the LUT sample, at a common memory location. In any event, the feedback samples may be stored such that the address of the LUT sample from which a particular set of feedback samples originated may be subsequently ascertained. As discussed above, synchronization of the LUT sample addresses and the feedback samples in this way contributes to the correct timing and stability of the pre-distortion algorithm. A direct memory access (DMA) controller implemented at block **2166** of the processor **1740** may store the feedback samples (and any LUT sample address data, where applicable) at a designated memory location **2180** of the processor **1740** (e.g., internal RAM).

[0306] Block **2200** of the processor **1740** may implement a pre-distortion algorithm for pre-distorting or modifying the LUT samples stored in the programmable logic device **1660** on a dynamic, ongoing basis. As discussed above, pre-distortion of the LUT samples may compensate for various sources of distortion present in the output drive circuit of the generator **1100**. The pre-distorted LUT samples, when processed through the drive circuit, will therefore result in a drive signal having the desired waveform shape (e.g., sinusoidal) for optimally driving the ultrasonic transducer.

[0307] At block **2220** of the pre-distortion algorithm, the current through the motional branch of the ultrasonic transducer is determined. The motional branch current may be determined using Kirchhoff's Current Law based on, for example, the current and voltage feedback samples stored at memory location **2180** (which, when suitably scaled, may be representative of I_g and V_g in the model of FIG. **6** discussed above), a value of the ultrasonic transducer static capacitance C_0 (measured or known a priori) and a known value of the drive frequency. A motional branch current sample for each set of stored current and voltage feedback samples associated with a LUT sample may be determined.

[0308] At block **2240** of the pre-distortion algorithm, each motional branch current sample determined at block **2220** is compared to a sample of a desired current waveform shape to determine a difference, or sample amplitude error, between the compared samples. For this determination, the sample of the desired current waveform shape may be supplied, for example, from a waveform shape LUT **2260** containing amplitude samples for one cycle of a desired current waveform shape. The particular sample of the desired current waveform shape from the LUT **2260** used for the comparison may be dictated by the LUT sample address associated with the motional branch current sample used in the comparison. Accordingly, the input of the motional branch current to block **2240** may be synchronized with the input of its associated LUT sample address to block **2240**. The LUT samples stored in the programmable logic device **1660** and the LUT samples stored in the waveform shape LUT **2260** may therefore be equal in number. In certain aspects, the desired current waveform shape represented by the LUT samples stored in the waveform shape LUT **2260** may be a fundamental sine wave. Other waveform shapes may be desirable. For example, it is contemplated that a fundamental sine wave for driving main longitudinal motion of an ultrasonic transducer superimposed with one or more other drive signals at other frequencies, such as a third order harmonic for driving at least two mechanical resonances for beneficial vibrations of transverse or other modes, could be used.

[0309] Each value of the sample amplitude error determined at block **2240** may be transmitted to the LUT of the programmable logic device **1660** (shown at block **2280** in FIG. **9**A) along with an indication of its associated LUT address. Based on the value of the sample amplitude error and its associated address (and, optionally, values of sample amplitude error for the same LUT address previously received), the LUT **2280** (or other control block of the programmable logic device **1660**) may pre-distort or modify the value of the LUT sample stored at the LUT address such that the sample amplitude error is reduced or minimized. It will be appreciated that such pre-distortion or modification of each LUT sample in an iterative manner across the entire range of LUT addresses will cause the waveform shape of the generator's output current to match or conform to the desired current waveform shape represented by the samples of the waveform shape LUT **2260**.

[0310] Current and voltage amplitude measurements, power measurements and impedance measurements may be determined at block **2300** of the processor **1740** based on the current and voltage feedback samples stored at memory location **2180**. Prior to the determination of these quantities, the feedback samples may be suitably scaled and, in certain aspects, processed through a suitable filter **2320** to remove noise resulting from, for example, the data acquisition process and induced harmonic components. The filtered voltage and current samples may therefore substantially represent the fundamental frequency of the generator's drive output signal. In certain aspects, the filter **2320** may be a finite impulse response (FIR) filter applied in the frequency domain. Such aspects may use the Fast Fourier Transform (FFT) of the output drive signal current and voltage signals. In certain aspects, the resulting frequency spectrum may be used to provide additional generator functionality. In one aspect, for example, the ratio of the second and/or third order harmonic component relative to the fundamental frequency component may be used as a diagnostic indicator.

[0311] At block **2340** (FIG. **9**B), a root mean square (RMS) calculation may be applied to a sample size of the current feedback samples representing an integral number of cycles of the drive signal to generate a measurement I_{rms} representing the drive signal output current.

[0312] At block **2360**, a root mean square (RMS) calculation may be applied to a sample size of the voltage feedback samples representing an integral number of cycles of the drive signal to determine a measurement V_{rms} representing the drive signal output voltage.

[0313] At block **2380**, the current and voltage feedback samples may be multiplied point by point, and a mean calculation is applied to samples representing an integral number of cycles of the drive signal to determine a measurement P_r of the generator's real output power.

[0314] At block **2400**, measurement P_a of the generator's apparent output power may be determined as the product $V_{rms} \cdot I_{rms}$.

[0315] At block **2420**, measurement Z_m of the load impedance magnitude may be determined as the quotient V_{rms}/I_{rms}.

[0316] In certain aspects, the quantities I_{rms}, V_{rms}, P_r, P_a and Z_m determined at blocks **2340**, **2360**, **2380**, **2400** and **2420** may be used by the generator **1100** to implement any of a number of control and/or diagnostic processes. In certain aspects, any of these quantities may be communicated to a user via, for example, an output device **2140** integral with the generator **1100** or an output device **2140** connected to the generator **1100** through a suitable communication interface (e.g., a USB interface). Various diagnostic processes may include, without limitation, handpiece integrity, instrument integrity, instrument attachment integrity, instrument overload, approaching instrument overload, frequency lock failure, over-voltage condition, over-current condition, over-power condition, voltage sense failure, current sense failure, audio indication failure, visual indication failure, short circuit condition, power delivery failure, or blocking capacitor failure, for example.

[0317] Block **2440** of the processor **1740** may implement a phase control algorithm for determining and controlling the impedance phase of an electrical load (e.g., the ultrasonic transducer) driven by the generator **1100**. As discussed above, by controlling the frequency of the drive signal to minimize or reduce the difference between the determined impedance phase and an impedance phase setpoint (e.g., 0°), the effects of harmonic distortion may be minimized or reduced, and the accuracy of the phase measurement increased.

[0318] The phase control algorithm receives as input the current and voltage feedback samples stored in the memory location **2180**. Prior to their use in the phase control algorithm, the feedback samples may be suitably scaled and, in certain aspects, processed through a suitable filter **2460** (which may be identical to filter **2320**) to remove noise resulting from the data acquisition process and induced harmonic components, for example. The filtered voltage and current samples may therefore substantially represent the fundamental frequency of the generator's drive output signal.

[0319] At block **2480** of the phase control algorithm, the current through the motional branch of the ultrasonic transducer is determined. This determination may be identical to that described above in connection with block **2220** of the pre-distortion algorithm. The output of block **2480** may thus be, for each set of stored current and voltage feedback samples associated with a LUT sample, a motional branch current sample.

[0320] At block **2500** of the phase control algorithm, impedance phase is determined based on the synchronized input of motional branch current samples determined at block **2480** and corresponding voltage feedback samples. In certain aspects, the impedance phase is determined as the average of the impedance phase measured at the rising edge of the waveforms and the impedance phase measured at the falling edge of the waveforms.

[0321] At block **2520** of the of the phase control algorithm, the value of the impedance phase determined at block **2220** is compared to phase setpoint **2540** to determine a difference, or phase error, between the compared values.

[0322] At block **2560** (FIG. **9**A) of the phase control algorithm, based on a value of phase error determined at block **2520** and the impedance magnitude determined at block **2420**, a frequency output for controlling the frequency of the drive signal is determined. The value of the frequency output may be continuously adjusted by the block **2560** and transferred to a DDS control block **2680** (discussed below) in order to maintain the impedance phase determined at block **2500** at the phase setpoint (e.g., zero phase error). In certain aspects, the impedance phase may be regulated to a 0° phase setpoint. In this way, any harmonic distortion will be centered about the crest of the voltage waveform, enhancing the accuracy of phase impedance determination.

[0323] Block **2580** of the processor **1740** may implement an algorithm for modulating the current amplitude of the drive signal in order to control the drive signal current, voltage and power in accordance with user specified setpoints, or in accordance with requirements specified by other processes or algorithms implemented by the generator **1100**. Control of these quantities may be realized, for example, by scaling the LUT samples in the LUT **2280** and/or by adjusting the full-scale output voltage of the DAC **1680** (which supplies the input to the power amplifier **1620**) via a DAC **1860**. Block **2600** (which may be implemented as a PID controller in certain aspects) may receive, as input, current feedback samples (which may be suitably scaled and filtered) from the memory location **2180**. The current feedback samples may be compared to a "current demand" I_d value dictated by the controlled variable (e.g., current, voltage or power) to determine if the drive signal is supplying the necessary current. In aspects in which drive signal current is the control variable, the current demand I_d may be specified directly by a current setpoint **2620**A (I_{sp}). For example, an RMS value of the current feedback data (determined as in block **2340**) may be compared to user-specified RMS current setpoint I_{sp} to determine the appropriate controller action. If, for example, the current feedback data indicates an RMS value less than the current setpoint I_{sp}, LUT scaling and/or the full-scale output voltage of the DAC **1680** may be adjusted by the block **2600** such that the drive signal current is increased. Conversely, block **2600** may adjust LUT scaling and/or the full-scale output voltage of the DAC **1680** to decrease the drive signal current when the current feedback data indicates an RMS value greater than the current setpoint I.

[0324] In aspects in which the drive signal voltage is the control variable, the current demand I_d may be specified indirectly, for example, based on the current required to maintain a desired voltage setpoint **2620**B (V_{sp}) given the load impedance magnitude Z_m measured at block **2420** (e.g. $I_d=V_{sp}/Z_m$). Similarly, in aspects in which drive signal power is the control variable, the current demand I_d may be specified indirectly, for example, based on the current required to maintain a desired power setpoint **2620**C (P_{sp}) given the voltage V_{rms} measured at blocks **2360** (e.g. $I_d=P_{sp}/V_{rms}$).

[0325] Block **2680** (FIG. **9**A) may implement a DDS control algorithm for controlling the drive signal by recalling LUT samples stored in the LUT **2280**. In certain aspects, the DDS control algorithm may be a numerically-controlled oscillator (NCO) algorithm for generating samples of a waveform at a fixed clock rate using a point (memory location)-skipping technique. The NCO algorithm may implement a phase accumulator, or frequency-to-phase converter, that functions as an address pointer for recalling LUT samples from the LUT **2280**. In one aspect, the phase accumulator may be a D step size, modulo N phase accumulator, where D is a positive integer representing a frequency control value, and N is the number of LUT samples in the LUT **2280**. A frequency control value of D=1, for example, may cause the phase accumulator to sequentially point to every address of the LUT **2280**, resulting in a waveform output replicating the waveform stored in the LUT **2280**. When D>1, the phase accumulator may skip addresses in the LUT **2280**, resulting in a waveform output having a higher frequency. Accordingly, the frequency of the waveform generated by the DDS control algorithm may therefore be controlled by suitably varying the frequency control value. In certain aspects, the frequency control value may be determined based on the output of the phase control algorithm implemented at block **2440**. The output of block **2680** may supply the input of DAC **1680**, which in turn supplies a corresponding analog signal to an input of the power amplifier **1620**.

[0326] Block **2700** of the processor **1740** may implement a switch-mode converter control algorithm for dynamically modulating the rail voltage of the power amplifier **1620** based on the waveform envelope of the signal being amplified, thereby improving the efficiency of the power amplifier **1620**. In certain aspects, characteristics of the waveform envelope may be determined by monitoring one or more signals contained in the power amplifier **1620**. In one aspect, for example, characteristics of the waveform envelope may be determined by monitoring the minima of a drain voltage (e.g., a MOSFET drain voltage) that is modulated in accordance with the envelope of the amplified signal. A minima voltage signal may be generated, for example, by a voltage minima detector coupled to the drain voltage. The minima voltage signal may be sampled by ADC **1760**, with the output minima voltage samples being received at block **2720** of the switch-mode converter control algorithm. Based on the values of the minima voltage samples, block **2740** may control a PWM signal output by a PWM generator **2760**, which, in turn, controls the rail voltage supplied to the power amplifier **1620** by the switch-mode regulator **1700**. In certain aspects, as long as the values of the minima voltage samples are less than a minima target **2780** input into block **2720**, the rail voltage may be modulated in accordance with the waveform envelope as characterized by the minima voltage samples. When the minima voltage samples indicate low envelope power levels, for example, block **2740** may cause a low rail voltage to be supplied to the power amplifier **1620**, with the full rail voltage being supplied only when the minima voltage samples indicate maximum envelope power levels. When the minima voltage samples fall below the minima target **2780**, block **2740** may cause the rail voltage to be maintained at a minimum value suitable for ensuring proper operation of the power amplifier **1620**.

[0327] FIG. **10** illustrates a control circuit **500** configured to control aspects of the surgical instrument or tool according to one aspect of this disclosure. The control circuit **500** can be configured to implement various processes described herein. The control circuit **500** may comprise a microcontroller comprising one or more processors **502** (e.g., microprocessor, microcontroller) coupled to at least one memory circuit **504**. The memory circuit **504** stores machine-executable instructions that, when executed by the processor **502**, cause the processor **502** to execute machine instructions to implement various processes described herein. The processor **502** may be any one of a number of single-core or multicore processors known in the art. The memory circuit **504** may comprise volatile and non-volatile storage media. The processor **502** may include an instruction processing unit **506** and an arithmetic unit **508**. The instruction processing unit may be configured to receive instructions from the memory circuit **504** of this disclosure.

[0328] FIG. **11** illustrates a combinational logic circuit **510** configured to control aspects of the surgical instrument or tool according to one aspect of this disclosure. The combinational logic circuit **510** can be configured to implement various processes described herein. The combinational logic circuit **510** may comprise a finite state machine comprising a combinational logic **512** configured to receive data associated with the surgical instrument or tool at an input **514**, process the data by the combinational logic **512**, and provide an output **516**.

[0329] FIG. **12** illustrates a sequential logic circuit **520** configured to control aspects of the surgical instrument or tool according to one aspect of this disclosure. The sequential logic circuit **520** or the combinational logic **522** can be configured to implement various processes described herein. The sequential logic circuit **520** may comprise a finite state machine. The sequential logic circuit **520** may comprise a combinational logic **522**, at least one memory circuit **524**, and a clock **529**, for example. The at least one memory circuit **524** can store a current state of the finite state machine. In certain instances, the sequential logic circuit **520** may be synchronous or asynchronous. The combinational logic **522** is configured to receive data associated with the surgical instrument or tool from an input **526**, process the data by the combinational logic **522**, and provide an output **528**. In other aspects, the circuit may comprise a combination of a processor (e.g., processor **502**, FIG. **13**) and a finite state machine to implement various processes herein. In other aspects, the finite state machine may comprise a combination of a combinational logic circuit (e.g., combinational logic circuit **510**, FIG. **14**) and the sequential logic circuit **520**.

[0330] In one aspect, the ultrasonic or high-frequency current generators of the surgical system **1000** may be configured to generate the electrical signal waveform digitally such that the desired using a predetermined number of phase points stored in a lookup table to digitize the wave shape. The phase points may be stored in a table defined in a memory, a field programmable gate array (FPGA), or any suitable non-volatile memory. FIG. **13** illustrates one aspect of a fundamental architecture for a digital synthesis circuit such as a direct digital synthesis (DDS) circuit **4100** configured to generate a plurality of wave shapes for the electrical signal waveform. The generator software and digital controls may command the FPGA to scan the addresses in the lookup table **4104** which in turn provides varying digital input values to a DAC circuit **4108** that feeds a power amplifier. The addresses may be scanned according to a frequency of interest. Using such a lookup table **4104** enables generating various types of wave shapes that can be fed into tissue or into a transducer, an RF electrode, multiple transducers simultaneously, multiple RF electrodes simultaneously, or a combination of RF and ultrasonic instruments. Furthermore, multiple lookup tables **4104** that represent multiple wave shapes can be created, stored, and applied to tissue from a generator.

[0331] The waveform signal may be configured to control at least one of an output current, an output voltage, or an output power of an ultrasonic transducer and/or an RF electrode, or multiples thereof (e.g. two or more ultrasonic transducers and/or two or more RF electrodes). Further, where the surgical instrument comprises an ultrasonic components, the waveform signal may be configured to drive at least two vibration modes of an ultrasonic transducer of the at least one surgical instrument. Accordingly, a generator may be configured to provide a waveform signal to at least one surgical instrument wherein the waveform signal corresponds to at least one wave shape of a plurality of wave shapes in a table. Further, the waveform signal provided to the two surgical instruments may comprise two or more wave shapes. The table may comprise information associated with a plurality of wave shapes and the table may be stored within the generator. In one aspect or example, the table may be a direct digital synthesis table, which may be stored in an FPGA of the generator. The table may be addressed by anyway that is convenient for categorizing wave shapes. According to one aspect, the table, which may be a direct digital synthesis table, is addressed according to a frequency of the waveform signal. Additionally, the information associated with the plurality of wave shapes may be stored as digital information in the table.

[0332] The analog electrical signal waveform may be configured to control at least one of an output current, an output voltage, or an output power of an ultrasonic transducer and/or an RF electrode, or multiples thereof (e.g., two or more ultrasonic transducers and/or two or more RF electrodes). Further, where the surgical instrument comprises ultrasonic components, the analog electrical signal waveform may be configured to drive at least two vibration modes of an ultrasonic transducer of the at least one surgical instrument. Accordingly, the generator circuit may be configured to provide an analog electrical signal waveform to at least one surgical instrument wherein the analog electrical signal waveform corresponds to at least one wave shape of a plurality of wave shapes stored in a lookup table **4104**. Further, the analog electrical signal waveform provided to the two surgical instruments may comprise two or more wave shapes. The lookup table **4104** may comprise information associated with a plurality of wave shapes and the lookup table **4104** may be stored either within the generator circuit or the surgical instrument. In one aspect or example, the lookup table **4104** may be a direct digital synthesis table, which may be stored in an FPGA of the generator circuit or the surgical instrument. The lookup table **4104** may be addressed by anyway that is convenient for categorizing wave shapes. According to one aspect, the lookup table **4104**, which may be a direct digital synthesis table, is addressed according to a frequency of the desired analog electrical signal waveform. Additionally, the information associated with the plurality of wave shapes may be stored as digital information in the lookup table **4104**.

[0333] With the widespread use of digital techniques in instrumentation and communications systems, a digitally-controlled method of generating multiple frequencies from a reference frequency source has evolved and is referred to as direct digital synthesis. The basic architecture is shown in FIG. **13**. In this simplified block diagram, a DDS circuit is coupled to a processor, controller, or a logic device of the generator circuit and to a memory circuit located in the generator circuit of the surgical system **1000**. The DDS circuit **4100** comprises an address counter **4102**, lookup table **4104**, a register **4106**, a DAC circuit **4108**, and a filter **4112**. A stable clock f_c is received by the address counter **4102** and the register **4106** drives a programmable-read-only-memory (PROM) which stores one or more integral number of cycles of a sinewave (or other arbitrary waveform) in a lookup table **4104**. As the address counter **4102** steps through memory locations, values stored in the lookup table **4104** are written to the register **4106**, which is coupled to the DAC circuit **4108**. The corresponding digital amplitude of the signal at the memory location of the lookup table **4104** drives the DAC circuit **4108**, which in turn generates an analog output signal **4110**. The spectral purity of the analog output signal **4110** is determined primarily by the DAC circuit **4108**. The phase noise is basically that of the reference clock f_c. The first analog output signal **4110** output from the DAC circuit **4108** is filtered by the filter **4112** and a second analog output signal **4114** output by the filter **4112** is provided to an amplifier having an output coupled to the output of the generator circuit. The second analog output signal has a frequency f_{out}.

[0334] Because the DDS circuit **4100** is a sampled data system, issues involved in sampling must be considered: quantization noise, aliasing, filtering, etc. For instance, the higher order harmonics of the DAC circuit **4108** output frequencies fold back into the Nyquist bandwidth, making them unfilterable, whereas, the higher order harmonics of the output of phase-locked-loop (PLL) based synthesizers can be filtered. The lookup table **4104** contains signal data for an integral number of cycles. The final output frequency f_{out} can be changed changing the reference clock frequency f_c or by reprogramming the PROM.

[0335] The DDS circuit **4100** may comprise multiple lookup tables **4104** where the lookup table **4104** stores a waveform represented by a predetermined number of samples, wherein the samples define a predetermined shape of the waveform. Thus multiple waveforms having a unique shape can be stored in multiple lookup tables **4104** to provide different tissue treatments based on instrument settings or tissue feedback. Examples of waveforms include high crest factor RF electrical signal waveforms for surface tissue coagulation, low crest factor RF electrical signal waveform for deeper tissue penetration, and electrical signal waveforms that promote efficient touch-up coagulation. In one aspect, the DDS circuit **4100** can create multiple wave shape lookup tables **4104** and during a tissue treatment procedure (e.g., "on-the-fly" or in virtual real time based on user or sensor inputs) switch between different wave shapes stored in separate lookup tables **4104** based on the tissue effect desired and/or tissue feedback. Accordingly, switching between wave shapes can be based on tissue impedance and other factors, for example. In other aspects, the lookup tables **4104** can store electrical signal waveforms shaped to maximize the power delivered into the tissue per cycle (i.e., trapezoidal or square wave). In other aspects, the lookup tables **4104** can store wave shapes synchronized in such way that they make maximizing power delivery by the multifunction surgical instrument of surgical system **1000** while delivering RF and ultrasonic drive signals. In yet other aspects, the lookup tables **4104** can store electrical signal waveforms to drive ultrasonic and RF therapeutic, and/or sub-therapeutic, energy simultaneously while maintaining ultrasonic frequency lock. Custom wave shapes specific to different instruments and their tissue effects can be stored in the non-volatile memory of the generator circuit or in the non-volatile memory (e.g., EEPROM) of the surgical system **1000** and be fetched upon connecting the multifunction surgical instrument to the generator circuit. An example of an exponentially damped sinusoid, as used in many high crest factor "coagulation" waveforms is shown in FIG. **15**.

[0336] A more flexible and efficient implementation of the DDS circuit **4100** employs a digital circuit called a Numerically Controlled Oscillator (NCO). A block diagram of a more flexible and efficient digital synthesis circuit such as a DDS circuit **4200** is shown in FIG. **14**. In this simplified block diagram, a DDS circuit **4200** is coupled to a processor, controller, or a logic device of the generator and to a memory circuit located either in the generator or in any of the surgical instruments of surgical system **1000**. The DDS circuit **4200** comprises a load register **4202**, a parallel delta phase register **4204**, an adder circuit **4216**, a phase register **4208**, a lookup table **4210** (phase-to-amplitude converter), a DAC circuit **4212**, and a filter **4214**. The adder circuit **4216** and the phase register **4208** form part of a phase accumulator **4206**. A clock frequency f_c is applied to the phase register **4208** and a DAC circuit **4212**. The load register **4202** receives a tuning word that specifies output frequency as a fraction of the reference clock frequency signal f_c. The output of the load register **4202** is provided to the parallel delta phase register **4204** with a tuning word M.

[0337] The DDS circuit **4200** includes a sample clock that generates the clock frequency f_c, the phase accumulator **4206**, and the lookup table **4210** (e.g., phase to amplitude converter). The content of the phase accumulator **4206** is updated once per clock cycle f_c. When time the phase accumulator **4206** is updated, the digital number, M, stored in the parallel delta phase register **4204** is added to the number in the phase register **4208** by the adder circuit **4216**. Assuming that the number in the parallel delta phase register **4204** is 00 . . . 01 and that the initial contents of the phase accumulator **4206** is 00 . . . 00. The phase accumulator **4206** is updated by 00 . . . 01 per clock cycle. If the phase accumulator **4206** is 32-bits wide, 232 clock cycles (over 4 billion) are required before the phase accumulator **4206** returns to 00 . . . 00, and the cycle repeats.

[0338] A truncated output **4218** of the phase accumulator **4206** is provided to a phase-to amplitude converter lookup table **4210** and the output of the lookup table **4210** is coupled to a DAC circuit **4212**. The truncated output **4218** of the phase accumulator **4206** serves as the address to a sine (or cosine) lookup table. An address in the lookup table corresponds to a phase point on the sinewave from 0° to 360°. The lookup table **4210** contains the corresponding digital amplitude information for one complete cycle of a sinewave. The lookup table **4210** therefore maps the phase information from the phase accumulator **4206** into a digital amplitude word, which in turn drives the DAC circuit **4212**. The output of the DAC circuit is a first analog signal **4220** and is filtered by a filter **4214**. The output of the filter **4214** is a second analog signal **4222**, which is provided to a power amplifier coupled to the output of the generator circuit.

[0339] In one aspect, the electrical signal waveform may be digitized into 1024 (210) phase points, although the wave shape may be digitized is any suitable number of 2n phase points ranging from 256 (28) to 281,474,976,710,656 (248), where n is a positive integer, as shown in TABLE 1. The electrical signal waveform may be expressed as $A_n(\theta_n)$, where a normalized amplitude A_n at a point n is represented by a phase angle θ_n is referred to as a phase point at point n. The number of discrete phase points n determines the tuning resolution of the DDS circuit **4200** (as well as the DDS circuit **4100** shown in FIG. **13**).

[0340] TABLE 1 specifies the electrical signal waveform digitized into a number of phase points.

TABLE 1

N	Number of Phase Points 2^n
8	256
10	1,024
12	4,096
14	16,384
16	65,536
18	262,144
20	1,048,576
22	4,194,304
24	16,777,216
26	67,108,864
28	268,435,456
. . .	. . .
32	4,294,967,296
. . .	. . .
48	281,474,976,710,656
. . .	. . .

[0341] The generator circuit algorithms and digital control circuits scan the addresses in the lookup table **4210**, which in turn provides varying digital input values to the DAC circuit **4212** that feeds the filter **4214** and the power amplifier. The addresses may be scanned according to a frequency of interest. Using the lookup table enables generating various types of shapes that can be converted into an analog output signal by the DAC circuit **4212**, filtered by the filter **4214**, amplified by the power amplifier coupled to the output of the generator circuit, and fed to the tissue in the form of RF energy or fed to an ultrasonic transducer and applied to the tissue in the form of ultrasonic vibrations which deliver energy to the tissue in the form of heat. The output of the amplifier can be applied to an RF electrode, multiple RF electrodes simultaneously, an ultrasonic transducer, multiple ultrasonic transducers simultaneously, or a combination of RF and ultrasonic transducers, for example. Furthermore, multiple wave shape tables can be created, stored, and applied to tissue from a generator circuit.

[0342] With reference back to FIG. **13**, for n=32, and M=1, the phase accumulator **4206** steps through **232** possible outputs before it overflows and restarts. The corresponding output wave frequency is equal to the input clock frequency divided by 232. If M=2, then the phase register **1708** "rolls over" twice as fast, and the output frequency is doubled. This can be generalized as follows.

[0343] For a phase accumulator **4206** configured to accumulate n-bits (n generally ranges from 24 to 32 in most DDS systems, but as previously discussed n may be selected from a wide range of options), there are 2^n possible phase points. The digital word in the delta phase register, M, represents the amount the phase accumulator is incremented per clock cycle. If f_c is the clock frequency, then the frequency of the output sinewave is equal to:

$$f_0 = \frac{M \cdot f_c}{2^n}$$

[0344] The above equation is known as the DDS "tuning equation." Note that the frequency resolution of the system is equal to

$$\frac{f_o}{2^n}.$$

For n=2, the resolution is greater than one part in four billion. In one aspect of the DDS circuit **4200**, not all of the bits out of the phase accumulator **4206** are passed on to the lookup table **4210**, but are truncated, leaving only the first 13 to 15 most significant bits (MSBs), for example. This reduces the size of the lookup table **4210** and does not affect the frequency resolution. The phase truncation only adds a small but acceptable amount of phase noise to the final output.

[0345] The electrical signal waveform may be characterized by a current, voltage, or power at a predetermined frequency. Further, where any one of the surgical instruments of surgical system **1000** comprises ultrasonic components, the electrical signal waveform may be configured to drive at least two vibration modes of an ultrasonic transducer of the at least one surgical instrument. Accordingly, the generator circuit may be configured to provide an electrical signal waveform to at least one surgical instrument wherein the electrical signal waveform is characterized by a predetermined wave shape stored in the lookup table **4210** (or lookup table **4104** FIG. **13**). Further, the electrical signal waveform may be a combination of two or more wave shapes. The lookup table **4210** may comprise information associated with a plurality of wave shapes. In one aspect or example, the lookup table **4210** may be generated by the DDS circuit **4200** and may be referred to as a direct digital synthesis table. DDS works by first storing a large repetitive waveform in onboard memory. A cycle of a waveform (sine, triangle, square, arbitrary) can be represented by a predetermined number of phase points as shown in TABLE 1 and stored into memory. Once the waveform is stored into memory, it can be generated at very precise frequencies. The direct digital synthesis table may be stored in a non-volatile memory of the generator circuit and/or may be implemented with a FPGA circuit in the generator circuit. The lookup table **4210** may be addressed by any suitable technique that is convenient for categorizing wave shapes. According to one aspect, the lookup table **4210** is addressed according to a frequency of the electrical signal waveform. Additionally, the information associated with the plurality of wave shapes may be stored as digital information in a memory or as part of the lookup table **4210**.

[0346] In one aspect, the generator circuit may be configured to provide electrical signal waveforms to at least two surgical instruments simultaneously. The generator circuit also may be configured to provide the electrical signal waveform, which may be characterized two or more wave shapes, via an output channel of the generator circuit to the two surgical instruments simultaneously. For example, in one aspect the electrical signal waveform comprises a first electrical signal to drive an ultrasonic transducer (e.g., ultrasonic drive signal), a second RF drive signal, and/or a combination thereof. In addition, an electrical signal waveform may comprise a plurality of ultrasonic drive signals, a plurality of RF drive signals, and/or a combination of a plurality of ultrasonic and RF drive signals.

[0347] In addition, a method of operating the generator circuit according to the present disclosure comprises generating an electrical signal waveform and providing the generated electrical signal waveform to any one of the surgical instruments of surgical system **1000**, where generating the electrical signal waveform comprises receiving information associated with the electrical signal waveform from a memory. The generated electrical signal waveform comprises at least one wave shape. Furthermore, providing the generated electrical signal waveform to the at least one surgical instrument comprises providing the electrical signal waveform to at least two surgical instruments simultaneously.

[0348] The generator circuit as described herein may allow for the generation of various types of direct digital synthesis tables. Examples of wave shapes for RF/Electrosurgery signals suitable for treating a variety of tissue generated by the generator circuit include RF signals with a high crest factor (which may be used for surface coagulation in RF mode), a low crest factor RF signals (which may be used for deeper tissue penetration), and waveforms that promote efficient touch-up coagulation. The generator circuit also may generate multiple wave shapes employing a direct digital synthesis lookup table **4210** and, on the fly, can switch between particular wave shapes based on the desired tissue effect. Switching may be based on tissue impedance and/or other factors.

[0349] In addition to traditional sine/cosine wave shapes, the generator circuit may be configured to generate wave shape(s) that maximize the power into tissue per cycle (i.e., trapezoidal or square wave). The generator circuit may provide wave shape(s) that are synchronized to maximize the power delivered to the load when driving RF and ultrasonic signals simultaneously and to maintain ultrasonic frequency lock, provided that the generator circuit includes a circuit topology that enables simultaneously driving RF and ultrasonic signals. Further, custom wave shapes specific to instruments and their tissue effects can be stored in a non-volatile memory (NVM) or an instrument EEPROM and can be fetched upon connecting any one of the surgical instruments of surgical system **1000** to the generator circuit.

[0350] The DDS circuit **4200** may comprise multiple lookup tables **4104** where the lookup table **4210** stores a waveform represented by a predetermined number of phase points (also may be referred to as samples), wherein the phase points define a predetermined shape of the waveform. Thus multiple waveforms having a unique shape can be stored in multiple lookup tables **4210** to provide different tissue treatments based on instrument settings or tissue feedback. Examples of waveforms include high crest factor RF electrical signal waveforms for surface tissue coagulation, low crest factor RF electrical signal waveform for deeper tissue penetration, and electrical signal waveforms that promote efficient touch-up coagulation. In one aspect, the DDS circuit **4200** can create multiple wave shape lookup tables **4210** and during a tissue treatment procedure (e.g., "on-the-fly" or in virtual real time based on user or sensor inputs) switch between different wave shapes stored in different lookup tables **4210** based on the tissue effect desired and/or tissue feedback. Accordingly, switching between wave shapes can be based on tissue impedance and other factors, for example. In other aspects, the lookup tables **4210** can store electrical signal waveforms shaped to maximize the power delivered into the tissue per cycle (i.e., trapezoidal or square wave). In other aspects, the lookup tables **4210** can store wave shapes synchronized in such way that they make maximizing power delivery by any one of the surgical instruments of surgical system **1000** when delivering RF and ultrasonic drive signals. In yet other aspects, the lookup tables **4210** can store electrical signal waveforms to drive ultrasonic and RF therapeutic, and/or sub-therapeutic, energy simultaneously while maintaining ultrasonic frequency lock. Generally, the output wave shape may be in the form of a sine wave, cosine wave, pulse wave, square wave, and the like. Nevertheless, the more complex and custom wave shapes specific to different instruments and their tissue effects can be stored in the non-volatile memory of the generator circuit or in the non-volatile memory (e.g., EEPROM) of the surgical instrument and be fetched upon connecting the surgical instrument to the generator circuit. One example of a custom wave shape is an exponentially damped sinusoid as used in many high crest factor "coagulation" waveforms, as shown in FIG. **43**.

[0351] FIG. **15** illustrates one cycle of a discrete time digital electrical signal waveform **4300**, in accordance with at least one aspect of the present disclosure of an analog waveform **4304** (shown superimposed over the discrete time digital electrical signal waveform **4300** for comparison purposes). The horizontal axis represents Time (t) and the vertical axis represents digital phase points. The digital electrical signal waveform **4300** is a digital discrete time version of the desired analog waveform **4304**, for example. The digital electrical signal waveform **4300** is generated by storing an amplitude phase point **4302** that represents the amplitude per clock cycle T_{clk} over one cycle or period T_0. The digital electrical signal waveform **4300** is generated over one period T_0 by any suitable digital processing circuit. The amplitude phase points are digital words stored in a memory circuit. In the example illustrated in FIGS. **13**, **14**, the digital word is a six-bit word that is capable of storing the amplitude phase points with a resolution of 26 or 64 bits. It will be appreciated that the examples shown in FIGS. **13**, **14** is for illustrative purposes and in actual implementations the resolution can be much higher. The digital amplitude phase points **4302** over one cycle T_0 are stored in the memory as a string of string words in a lookup table **4104**, **4210** as described in connection with FIGS. **13**, **14**, for example. To generate the analog version of the analog waveform **4304**, the amplitude phase points **4302** are read sequentially from the memory from 0 to T_0 per clock cycle T_{clk} and are converted by a DAC circuit **4108**, **4212**, also described in connection with FIGS. **13**, **14**. Additional cycles can be generated by repeatedly reading the amplitude phase points **4302** of the digital electrical signal waveform **4300** the from 0 to T_0 for as many cycles or periods as may be desired. The smooth analog version of the analog waveform **4304** is achieved by filtering the output of the DAC circuit **4108**, **4212** by a filter **4112**, **4214** (FIGS. **13** and **14**). The filtered analog output signal **4114**, **4222** (FIGS. **13** and **14**) is applied to the input of a power amplifier.

[0352] FIG. **16** is a diagram of a control system **12950** that may be implemented as a nested PID feedback controller. A PID controller is a control loop feedback mechanism (controller) to continuously calculate an error value as the difference between a desired set point and a measured process variable and applies a correction based on proportional, integral, and derivative terms (sometimes denoted P, I, and D respectively). The nested PID controller feedback control system **12950** includes a primary controller **12952**, in a primary (outer) feedback loop **12954** and a secondary controller **12955** in a secondary (inner) feedback loop **12956**. The primary controller **12952** may be a PID controller **12972** as shown in FIG. **17**, and the secondary controller **12955** also may be a PID controller **12972** as shown in FIG. **17**. The primary controller **12952** controls a primary process **12958** and the secondary controller **12955** controls a secondary process **12960**. The output **12966** of the primary process **12958** is subtracted from a primary set point SP_1 by a first summer **12962**. The first summer **12962** produces a single sum output signal which is applied to the primary controller **12952**. The output of the primary controller **12952** is the secondary set point SP_2. The output **12968** of the secondary process **12960** is subtracted from the secondary set point SP_2 by a second summer **12964**.

[0353] FIG. **17** illustrates a PID feedback control system **12970** according to one aspect of this disclosure. The primary controller **12952** or the secondary controller **12955**, or both, may be implemented as a PID controller **12972**. In one aspect, the PID controller **12972** may comprise a proportional element **12974** (P), an integral element **12976** (I), and a derivative element **12978** (D). The outputs of the P, I, D elements **12974**, **12976**, **12978** are summed by a summer **12986**, which provides the control variable p(t) to the process **12980**. The output of the process **12980** is the process variable y(t). A summer **12984** calculates the difference between a desired set point r(t) and a measured process variable y(t). The PID controller **12972** continuously calculates an error value e(t) (e.g., difference between closure force threshold and measured closure force) as the difference between a desired set point r(t) (e.g., closure force threshold) and a measured process variable y(t) (e.g., velocity and direction of closure tube) and applies a correction based on the proportional, integral, and derivative terms calculated by the proportional element **12974** (P), integral element **12976** (I), and derivative element **12978** (D), respectively. The PID controller **12972** attempts to minimize the error e(t) over time by adjustment of the control variable μ(t) (e.g., velocity and direction of the closure tube).

[0354] In accordance with the PID algorithm, the "P" element **12974** accounts for present values of the error. For example, if the error is large and positive, the control output will also be large and positive. In accordance with the present disclosure, the error term e(t) is the different between the desired closure force and the measured closure force of the closure tube. The "I" element **12976** accounts for past values of the error. For example, if the current output is not sufficiently strong, the integral of the error will accumulate over time, and the controller will respond by applying a stronger action. The "D" element **12978** accounts for possible future trends of the error, based on its current rate of change. For example, continuing the P example above, when the large positive control output succeeds in bringing the error closer to zero, it also puts the process on a path to large negative error in the near future. In this case, the derivative turns negative and the D module reduces the strength of the action to prevent this overshoot.

[0355] It will be appreciated that other variables and set points may be monitored and controlled in accordance with the feedback control systems **12950**, **12970**. For example, the adaptive closure member velocity control algorithm described herein may measure at least two of the following parameters: firing member stroke location, firing member load, displacement of cutting element, velocity of cutting element, closure tube stroke location, closure tube load, among others.

[0356] FIG. **18** is an alternative system **132000** for controlling the frequency of an ultrasonic electromechanical system **132002** and detecting the impedance thereof, in accordance with at least one aspect of the present disclosure. The system **132000** may be incorporated into a generator. A processor **132004** coupled to a memory **132026** programs a programmable counter **132006** to tune to the output frequency f_0 of the ultrasonic electromechanical system **132002**. The input frequency is generated by a crystal oscillator **132008** and is input into a fixed counter **132010** to scale the frequency to a suitable value. The outputs of the fixed counter **132010** and the programmable counter **132006** are applied to a phase/frequency detector **132012**. The output of the phase/frequency detector **132012** is applied to an amplifier/active filter circuit **132014** to generate a tuning voltage V_t that is applied to a voltage controlled oscillator **132016** (VCO). The VCO **132016** applies the output frequency f_0 to an ultrasonic transducer portion of the ultrasonic electromechanical system **132002**, shown here modeled as an equivalent electrical circuit. The voltage and current signals applied to the ultrasonic transducer are monitored by a voltage sensor **132018** and a current sensor **132020**.

[0357] The outputs of the voltage and current sensors **132018**, **13020** are applied to another phase/frequency detector **132022** to determine the phase angle between the voltage and current as measured by the voltage and current sensors **132018**, **13020**. The output of the phase/frequency detector **132022** is applied to one channel of a high speed analog to digital converter **132024** (ADC) and is provided to the processor **132004** therethrough. Optionally, the outputs of the voltage and current sensors **132018**, **132020** may be applied to respective channels of the two-channel ADC **132024** and provided to the processor **132004** for zero crossing, FFT, or other algorithm described herein for determining the phase angle between the voltage and current signals applied to the ultrasonic electromechanical system **132002**.

[0358] Optionally the tuning voltage V_t, which is proportional to the output frequency f_0, may be fed back to the processor **132004** via the ADC **132024**. This provides the processor **132004** with a feedback signal proportional to the output frequency f_0 and can use this feedback to adjust and control the output frequency f_0.

Estimating the State of the Jaw (Pad Burn Through, Staples, Broken Blade, Bone in Jaw, Tissue in Jaw)

[0359] A challenge with ultrasonic energy delivery is that ultrasonic acoustics applied on the wrong materials or the wrong tissue can result in device failure, for example, clamp arm pad burn through or ultrasonic blade breakage. It is also desirable to detect what is located in the jaws of an end effector of an ultrasonic device and the state of the jaws without adding additional sensors in the jaws. Locating sensors in the jaws of an ultrasonic end effector poses reliability, cost, and complexity challenges.

[0360] Ultrasonic spectroscopy smart blade algorithm techniques may be employed for estimating the state of the jaw (clamp arm pad burn through, staples, broken blade, bone in jaw, tissue in jaw, back-cutting with jaw closed, etc.) based on the impedance

$$Z_g(t) = \frac{V_g(t)}{I_g(t)}$$

of an ultrasonic transducer configured to drive an ultrasonic transducer blade, in accordance with at least one aspect of the present disclosure. The impedance $Z_g(t)$, magnitude $|Z|$, and phase φ are plotted as a function of frequency f.

[0361] Dynamic mechanical analysis (DMA), also known as dynamic mechanical spectroscopy or simply mechanical spectroscopy, is a technique used to study and characterize materials. A sinusoidal stress is applied to a material, and the strain in the material is measured, allowing the determination of the complex modulus of the material. The spectroscopy as applied to ultrasonic devices includes exciting the tip of the ultrasonic blade with a sweep of frequencies (compound signals or traditional frequency sweeps) and measuring the resulting complex impedance at each frequency. The complex impedance measurements of the ultrasonic transducer across a range of frequencies are used in a classifier or model to infer the characteristics of the ultrasonic end effector. In one aspect, the present disclosure provides a technique for determining the state of an ultrasonic end effector (clamp arm, jaw) to drive automation in the ultrasonic device (such as disabling power to protect the device, executing adaptive algorithms, retrieving information, identifying tissue, etc.).

[0362] FIG. **19** is a spectra **132030** of an ultrasonic device with a variety of different states and conditions of the end effector where the impedance $Z_g(t)$, magnitude $|Z|$, and phase φ are plotted as a function of frequency f, in accordance with at least one aspect of the present disclosure. The spectra **132030** is plotted in three-dimensional space where frequency (Hz) is plotted along the x-axis, phase (Rad) is plotted along the y-axis, and magnitude (Ohms) is plotted along the z-axis.

[0363] Spectral analysis of different jaw bites and device states produces different complex impedance characteristic patterns (fingerprints) across a range of frequencies for different conditions and states. Each state or condition has a different characteristic pattern in 3D space when plotted. These characteristic patterns can be used to estimate the condition and state of the end effector. FIG. **19** shows the spectra for air **132032**, clamp arm pad **132034**, chamois **132036**, staple **132038**, and broken blade **132040**. The chamois **132036** may be used to characterize different types of tissue.

[0364] The spectra **132030** can be evaluated by applying a low-power electrical signal across the ultrasonic transducer to produce a non-therapeutic excitation of the ultrasonic blade. The low-power electrical signal can be applied in the form of a sweep or a compound Fourier series to measure the impedance

$$Z_g(t) = \frac{V_g(t)}{I_g(t)}$$

across the ultrasonic transducer at a range of frequencies in series (sweep) or in parallel (compound signal) using an FFT.

Methods of Classification of New Data

[0365] For each characteristic pattern, a parametric line can be fit to the data used for training using a polynomial, a Fourier series, or any other form of parametric equation as may be dictated by convenience. A new data point is then received and is classified by using the Euclidean perpendicular distance from the new data point to the trajectory that has been fitted to the characteristic pattern training data. The perpendicular distance of the new data point to each of the trajectories (each trajectory representing a different state or condition) is used to assign the point to a state or condition.

[0366] The probability distribution of distance of each point in the training data to the fitted curve can be used to estimate the probability of a correctly classified new data point. This essentially constructs a two-dimensional probability distribution in a plane perpendicular to the fitted trajectory at each new data point of the fitted trajectory. The new data point can then be included in the training set based on its probability of correct classification to make an adaptive, learning classifier that readily detects high-frequency changes in states but adapts to slow occurring deviations in system performance, such as a device getting dirty or the pad wearing out.

[0367] FIG. **20** is a graphical representation of a plot **132042** of a set of 3D training data set (S), where ultrasonic transducer impedance $Z_g(t)$, magnitude $|Z|$, and phase φ are plotted as a function of frequency f, in accordance with at least one aspect of the present disclosure. The 3D training data set (S) plot **132042** is graphically depicted in three-dimensional space where phase (Rad) is plotted along the x-axis, frequency (Hz) is plotted along the y-axis, magnitude (Ohms) is plotted along the z-axis, and a parametric Fourier series is fit to the 3D training data set (S). A methodology for classifying data is based on the 3D training data set (S0 is used to generate the plot **132042**).

[0368] The parametric Fourier series fit to the 3D training data set (S) is defined by:

$$\vec{p} = \vec{a}_0 + \sum_{n=1}^{\infty}\left(\vec{a}_n\cos\frac{n\pi t}{L} + \vec{b}_n\sin\frac{n\pi t}{L}\right)$$

[0369] For a new point $\vec{z}$, the perpendicular distance from $\vec{p}$ to $\vec{z}$ is found by:

$$D = \|\vec{p} - \vec{z}\|$$

[0370] When:

$$\frac{\partial D}{\partial T} = 0$$

[0371] Then:

$$D = D_{\perp}$$

[0372] A probability distribution of D can be used to estimate the probability of a data point $\vec{z}$ belonging to the group S.

Control

[0373] Based on the classification of data measured before, during, or after activation of the ultrasonic transducer/ultrasonic blade, a variety of automated tasks and safety measures can be implemented. Similarly, the state of the tissue located in the end effector and temperature of the ultrasonic blade also can be inferred to some degree, and used to better inform the user of the state of the ultrasonic device or protect critical structures, etc. Temperature control of an ultrasonic blade is described in commonly owned U.S. Provisional Patent Application No. 62/640,417, filed Mar. 8, 2018, titled TEMPERATURE CONTROL IN ULTRASONIC DEVICE AND CONTROL SYSTEM THEREFOR, which is incorporated herein by reference in its entirety.

[0374] Similarly, power delivery can be reduced when there is a high probability that the ultrasonic blade is contacting the clamp arm pad (e.g., without tissue in between) or if there is a probability that the ultrasonic blade has broken or that the ultrasonic blade is touching metal (e.g., a staple). Furthermore, back-cutting can be disallowed if the jaw is closed and no tissue is detected between the ultrasonic blade and the clamp arm pad.

Integration of Other Data to Improve Classification

[0375] This system can be used in conjunction with other information provided by sensors, the user, metrics on the patient, environmental factors, etc., by combing the data from this process with the aforementioned data using probability functions and a Kalman filter. The Kalman filter determines the maximum likelihood of a state or condition occurring given a plethora of uncertain measurements of varying confidence. Since this method allows for an assignment of probability to a newly classified data point, this algorithm's information can be implemented with other measures or estimates in a Kalman filter.

[0376] FIG. **21** is a logic flow diagram **132044** depicting a control program or a logic configuration to determine jaw conditions based on the complex impedance characteristic pattern (fingerprint), in accordance with at least one aspect of the present disclosure. Prior to determining jaw conditions based on the complex impedance characteristic pattern (fingerprint), a database is populated with reference complex impedance characteristic patterns or a training data sets (S) that characterize various jaw conditions, including, without limitation, air **132032**, clamp arm pad **132034**, chamois **132036**, staple **132038**, broken blade **132040**, as shown in FIG. **82**, and a variety of tissue types and conditions. The chamois dry or wet, full byte or tip, may be used to characterize different types of tissue. The data points used to generate reference complex impedance characteristic patterns or a training data set (S) are obtained by applying a sub-therapeutic drive signal to the ultrasonic transducer, sweeping the driving frequency over a predetermined range of frequencies from below resonance to above resonance, measuring the complex impedance at each of the frequencies, and recording the data points. The data points are then fit to a curve using a variety of numerical methods including polynomial curve fit, Fourier series, and/or parametric equation. A parametric Fourier series fit to the reference complex impedance characteristic patterns or a training data set (S) is described herein.

[0377] Once the reference complex impedance characteristic patterns or a training data sets (S) are generated, the ultrasonic instrument measures new data points, classifies the new points, and determines whether the new data points should be added to the reference complex impedance characteristic patterns or a training data sets (S).

[0378] Turning now to the logic flow diagram of FIG. **21**, in one aspect, the control circuit measures **132046** a complex impedance of an ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)}.$$

The control circuit receives **132048** a complex impedance measurement data point and compares **132050** the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern. The control circuit classifies **132052** the complex impedance measurement data point based on a result of the comparison analysis and assigns **132054** a state or condition of the end effector based on the result of the comparison analysis.

[0379] In one aspect, the control circuit receives the reference complex impedance characteristic pattern from a database or memory coupled to the processor. In one aspect, the control circuit generates the reference complex impedance characteristic pattern as follows. A drive circuit coupled to the control circuit applies a nontherapeutic drive signal to the ultrasonic transducer starting at an initial frequency, ending at a final frequency, and at a plurality of frequencies therebetween. The control circuit measures the impedance of the ultrasonic transducer at each frequency and stores a data point corresponding to each impedance measurement. The control circuit curve fits a plurality of data points to generate a three-dimensional curve of representative of the reference complex impedance characteristic pattern, wherein the magnitude $|Z|$ and phase φ are plotted as a function of frequency f. The curve fitting includes a polynomial curve fit, a Fourier series, and/or a parametric equation.

[0380] In one aspect, the control circuit receives a new impedance measurement data point and classifies the new impedance measurement data point using a Euclidean perpendicular distance from the new impedance measurement data point to a trajectory that has been fitted to the reference complex impedance characteristic pattern. The control circuit estimates a probability that the new impedance measurement data point is correctly classified. The control circuit adds the new impedance measurement data point to the reference complex impedance characteristic pattern based on the probability of the estimated correct classification of the new impedance measurement data point. In one aspect, the control circuit classifies data based on a training data set (S), where the training data set (S) comprises a plurality of complex impedance measurement data, and curve fits the training data set (S) using a parametric Fourier series, wherein S is defined herein and wherein the probability distribution is used to estimate the probability of the new impedance measurement data point belonging to the group S.

State Of Jaw Classifier Based On Model

[0381] There has been an existing interest in classifying matter located within the jaws of an ultrasonic device including tissue types and condition. In various aspects, it can be shown that with high data sampling and sophisticated pattern recognition this classification is possible. The approach is based on impedance as a function of frequency, where magnitude, phase, and frequency are plotted in 3D the patterns look like ribbons as shown in FIGS. **19** and **20** and the logic flow diagram of FIG. **21**. This disclosure provides an alternative smart blade algorithm approach that is based on a well-established model for piezoelectric transducers.

[0382] By way of example, the equivalent electrical lumped parameter model is known to be an accurate model of the physical piezoelectric transducer. It is based on the Mittag-Leffler expansion of a tangent near a mechanical resonance. When the complex impedance or the complex admittance is plotted as an imaginary component versus a real component, circles are formed. FIG. **22** is a circle plot **132056** of complex impedance plotted as an imaginary component versus real components of a piezoelectric vibrator, in accordance with at least one aspect of the present disclosure. FIG. **23** is a circle plot **132058** of complex admittance plotted as an imaginary component versus real components of a piezoelectric vibrator, in accordance with at least one aspect of the present disclosure. The circles depicted in FIGS. **22** and **23** are taken from the IEEE 177 Standard, which is incorporated herein by reference in its entirety. Tables 1-4 are taken from the IEEE 177 Standard and disclosed herein for completeness.

[0383] The circle is created as the frequency is swept from below resonance to above resonance. Rather than stretching the circle out in 3D, a circle is identified and the radius (r) and offsets (a, b) of the circle are estimated. These values are then compared with established values for given conditions. These conditions may be: 1) open nothing in jaws, 2) tip bite 3) full bite and staple in jaws. If the sweep generates multiple resonances, circles of different characteristics will be present for each resonance. Each circle will be drawn out before the next if the resonances are separated. Rather than fitting a 3D curve with a series approximation, the data is fitted with a circle. The radius (r) and offsets (a, b) can be calculated using a processor programmed to execute a variety of mathematical or numerical techniques described below. These values may be estimated by capturing an image of a circle and, using image processing techniques, the radius (r) and offsets (a, b) that define the circle are estimated.

[0384] FIG. **24** is a circle plot **132060** of complex admittance for a 55.5 kHz ultrasonic piezoelectric transducer for lumped parameters inputs and outputs specified hereinbelow. Values for a lumped parameter model were used to generate the complex admittance. A moderate load was applied in the model. The obtained admittance circle generated in MathCad is shown in FIG. **24**. The circle plot **132060** is formed when the frequency is swept from 54 to 58 kHz.

[0385] The lumped parameter input values are:

[0386] Co=3.0 nF

[0387] Cs=8.22 pF

[0388] Ls=1.0 H

[0389] Rs=450Ω

[0390] The outputs of the model based on the inputs are:

$$am = \frac{D \cdot C - B \cdot C}{A \cdot C - B^2} = 1.013 \cdot 10^3$$

$$bm = \frac{A \cdot E - B \cdot D}{A \cdot C - B^2} = -954.585$$

$$rm = \frac{1}{fpts}\left(\sum_{i}^{fpts} \sqrt[2]{((Zout_{1,i} = am)^2 + (Zout_{2,i} - bm)^2)}\right) = 1.012 \cdot 10^3$$

[0391] The output values are used to plot the circle plot **132060** shown in FIG. **24**. The circle plot **132060** has a radius (r) and the center **132062** is offset (a, b) from the origin **132064** as follows:

$$r = 1.012*10^3$$

$$a = 1.013*10^3$$

$$b = -954.585$$

[0392] The summations A-E specified below are needed to estimate the circle plot **132060** plot for the example given in FIG. **24**, in accordance with at least one aspect of the present disclosure. Several algorithms exist to calculate a fit to a circle. A circle is defined by its radius (r) and offsets (a, b) of the center from the origin:

$$r^2 = (x-a)^2 + (y-b)^2$$

[0393] The modified least squares method (Umbach and Jones) is convenient in that there a simple close formed solution for a, b, and r.

$$\hat{a} = \frac{DC - BE}{AC - B^2}$$

$$\hat{b} = \frac{AE - BD}{AC - B^2}$$

$$\hat{r} = \frac{1}{n}\sum_{i=1}^{n} \sqrt{(x_i - \hat{a})^2 + (y_i - \hat{b})^2}$$

[0394] The caret symbol over the variable "a" indicates an estimate of the true value. A, B, C, D, and E are summations of various products which are calculated from the data. They are included herein for completeness as follows:

$$A := fpts \cdot \sum_{i}^{fpts} (Zout_{1,i})^2 - \left(\sum_{i}^{fpts} (Zout_{1,i})\right)^2 = 5.463 \cdot 10^{10}$$

-continued

$$B := fpts \sum_{i}^{fpts} (Zout_{1,i} \cdot Zout_{2,i}) - \left(\left(\sum_{i}^{fpts} (Zout_{1,i})\right) \cdot \left(\sum_{i}^{fpts} (Zout_{2,i})\right)\right) = 5.461 \cdot 10^7$$

$$C := fpts \sum_{i}^{fpts} (Zout_{2,i})^2 - \left(\sum_{i}^{fpts} (Zout_{2,i})\right)^2 = 5.445 \cdot 10^{10}$$

$$D := 0.5 \cdot \left(fpts \sum_{i}^{fpts} (Zout_{1,i} \cdot (Zout_{2,i})^2) - \left(\sum_{i}^{fpts} (Zout_{1,i})\right) \cdot \left(\sum_{i}^{fpts} (Zout_{2,i})^2\right) + fpts \sum_{i}^{fpts} (Zout_{1,i}^3) - \left(\sum_{i}^{fpts} (Zout_{1,i})\right) \cdot \left(\sum_{i}^{fpts} (Zout_{1,i})\right) \cdot \left(\sum_{i}^{fpts} (Zout_{1,i})^2\right)\right) = 5.529 \cdot 10^3$$

$$E := 0.5 \cdot \left(fpts \sum_{i}^{fpts} (Zout_{2,i} \cdot (Zout_{1,i})^2) - \left(\sum_{i}^{fpts} (Zout_{2,i})\right) \cdot \left(\sum_{i}^{fpts} (Zout_{1,i})^2\right) + fpts \sum_{i}^{fpts} (Zout_{2,i}^3) - \left(\sum_{i}^{fpts} (Zout_{2,i})\right) \cdot \sum_{i}^{fpts} (Zout_{2,i})^2 \right) = -5.192 \cdot 10^{13}$$

[0395] Z1,i is a first vector of the real components referred to as conductance;

[0396] Z2,i is a second of the imaginary components referred to as susceptance; and

[0397] Z3,i is a third vector that represents the frequencies at which admittances are calculated.

[0398] This disclosure will work for ultrasonic systems and may possibly be applied to electrosurgical systems, even though electrosurgical systems do not rely on a resonance.

[0399] FIGS. **25-29** illustrate images taken from an impedance analyzer showing impedance/admittance circle plots for an ultrasonic device with the end effector jaw in various open or closed configurations and loading. The circle plots in solid line depict impedance and the circle plots in broken lines depict admittance, in accordance with at least one aspect of the present disclosure. By way of example, the impedance/admittance circle plots are generated by connecting an ultrasonic device to an impedance analyzer. The display of the impedance analyzer is set to complex impedance and complex admittance, which can be selectable from the front panel of the impedance analyzer. An initial display may be obtained with the jaw of the ultrasonic end effector in an open position and the ultrasonic device in an unloaded state, as described below in connection with FIG. **25**, for example. The autoscale display function of the impedance analyzer may be used to generate both the complex impedance and admittance circle plots. The same display is used for subsequent runs of the ultrasonic device with different loading conditions as shown in the subsequent FIGS. **25-29**. A LabVIEW application may be employed to upload the data files. In another technique, the display images may be captured with a camera, such as a smartphone camera, like an iPhone or Android. As such, the image of the display may include some "keystone-ing" and in general may not appear to be parallel to the screen. Using this technique, the circle plot traces on the display will appear distorted in the captured image. With this approach, the material located in the jaws of the ultrasonic end effector can be classified.

[0400] The complex impedance and complex admittance are just the reciprocal of one another. No new information should be added by looking at both. Another consideration includes determining how sensitive the estimates are to noise when using complex impedance or complex admittance.

[0401] In the examples illustrated in FIGS. **25-29**, the impedance analyzer is set up with a range to just capture the main resonance. By scanning over a wider range of frequencies more resonances may be encountered and multiple circle plots may be formed. An equivalent circuit of an ultrasonic transducer may be modeled by a first "motional" branch having a serially connected inductance Ls, resistance Rs and capacitance Cs that define the electromechanical properties of the resonator, and a second capacitive branch having a static capacitance CO. In the impedance/admittance plots shown in FIGS. **25-29** that follow, the values of the components of the equivalent circuit are:

$$Ls=L1=1.1068\text{ H}$$

$$Rs=R1=311.352\Omega$$

$$Cs=C1=7.43265\text{ pF}$$

$$C0=C0=3.64026\text{ nF}$$

[0402] The oscillator voltage applied to the ultrasonic transducer is 500 mV and the frequency is swept from 55 kHz to 56 kHz. The impedance (Z) scale is 200 Ω/div and the admittance (Y) scale is 500 μS/div. Measurements of values that may characterize the impedance (Z) and admittance (Y) circle plots may be obtained at the locations on the circle plots as indicated by an impedance cursor and an admittance cursor.

State of Jaw: Open with No Loading

[0403] FIG. **25** is a graphical display **132066** of an impedance analyzer showing complex impedance (Z)/admittance (Y) circle plots **132068**, **132070** for an ultrasonic device with the jaw open and no loading where a circle plot **132068** in solid line depicts complex impedance and a circle plot **132070** in broken line depicts complex admittance, in accordance with at least one aspect of the present disclosure. The oscillator voltage applied to the ultrasonic transducer is 500 mV and the frequency is swept from 55 kHz to 56 kHz. The impedance (Z) scale is 200 Ω/div and the admittance (Y) scale is 500 μS/div. Measurements of values that may characterize the complex impedance (Z) and admittance (Y) circle plots **132068**, **132070** may be obtained at locations on the circle plots **132068**, **132070** as indicated by the impedance cursor **132072** and the admittance cursor **132074**. Thus, the impedance cursor **132072** is located at a portion of the impedance circle plot **132068** that is equivalent to about 55.55 kHz, and the admittance cursor **132074** is located at a portion of the admittance circle plot **132070** that is equivalent to about 55.29 kHz. As depicted in FIG. **25**, the position of the impedance cursor **132072** corresponds to values of:

[0404] R=1.66026Ω

[0405] X=−697.309Ω

[0406] Where R is the resistance (real value) and X is the reactance (imaginary value). Similarly, the position of the admittance cursor **132074** corresponds to values of:

[0407] G=64.0322 μS

[0408] B=1.63007 mS

[0409] Where G is the conductance (real value) and B is susceptance (imaginary value).

State of Jaw: Clamped on Dry Chamois

[0410] FIG. **26** is a graphical display **132076** of an impedance analyzer showing complex impedance (Z)/admittance (Y) circle plots **132078**, **132080** for an ultrasonic device with the jaw of the end effector clamped on dry chamois where the impedance circle plot **132078** is shown in solid line and the admittance circle plot **132080** is shown in broken line, in accordance with at least one aspect of the present disclosure. The voltage applied to the ultrasonic transducer is 500 mV and the frequency is swept from 55 kHz to 56 kHz. The impedance (Z) scale is 200 Ω/div and the admittance (Y) scale is 500 μS/div.

[0411] Measurements of values that may characterize the complex impedance (Z) and admittance (Y) circle pots **132078**, **132080** may be obtained at locations on the circle plots **132078**, **132080** as indicated by the impedance cursor **132082** and the admittance cursor **132084**. Thus, the impedance cursor **132082** is located at a portion of the impedance circle plot **132078** that is equivalent to about 55.68 kHz, and the admittance cursor **132084** is located at a portion of the admittance circle plot **132080** that is equivalent to about 55.29 kHz. As depicted in FIG. **26**, the position of the impedance cursor **132082** corresponds to values of:

[0412] R=434.577Ω

[0413] X=−758.772Ω

[0414] Where R is the resistance (real value) and X is the reactance (imaginary value).

[0415] Similarly, the position of the admittance cursor **132084** corresponds to values of:

[0416] G=85.1712 μS

[0417] B=1.49569 mS

[0418] Where G is the conductance (real value) and B is susceptance (imaginary value).

State of Jaw: Tip Clamped on Moist Chamois

[0419] FIG. **27** is a graphical display **132086** of an impedance analyzer showing complex impedance (Z)/admittance (Y) circle plots **132098**, **132090** for an ultrasonic device with the jaw tip clamped on moist chamois where the impedance circle plot **132088** is shown in solid line and the admittance circle plot **132090** is shown in broken line, in accordance with at least one aspect of the present disclosure. The voltage applied to the ultrasonic transducer is 500 mV and the frequency is swept from 55 kHz to 56 kHz. The impedance (Z) scale is 200 Ω/div and the admittance (Y) scale is 500 μS/div.

[0420] Measurements of values that may characterize the complex impedance (Z) and complex admittance (Y) circle plots **132088**, **132090** may be obtained at locations on the circle plots **132088**, **132090** as indicated by the impedance cursor **132092** and the admittance cursor **132094**. Thus, the impedance cursor **132092** is located at a portion of the impedance circle plot **132088** that is equivalent to about 55.68 kHz, and the admittance cursor **132094** is located at a portion of the admittance circle plot **132090** that is equivalent to about 55.29 kHz. As depicted in FIG. **28**, the impedance cursor **132092** corresponds to values of:

[0421] R=445.259Ω

[0422] X=−750.082Ω

[0423] Where R is the resistance (real value) and X is the reactance (imaginary value). Similarly, the admittance cursor **132094** corresponds to values of:

[0424] G=96.2179 μS

[0425] B=1.50236 mS

[0426] Where G is the conductance (real value) and B is susceptance (imaginary value).

State of Jaw: Fully Clamped on Moist Chamois

[0427] FIG. **28** is a graphical display **132096** of an impedance analyzer showing complex impedance (Z)/admittance (Y) circle plots **132098**, **132100** for an ultrasonic device with the jaw fully clamped on moist chamois where the impedance circle plot **132098** is shown in solid line and the admittance circle plot **132100** is shown in broken line, in accordance with at least one aspect of the present disclosure. The voltage applied to the ultrasonic transducer is 500 mV and the frequency is swept from 55 kHz to 56 kHz. The impedance (Z) scale is 200 Ω/div and the admittance (Y) scale is 500 μS/div.

[0428] Measurements of values that may characterize the impedance and admittance circle plots **132098**, **132100** may be obtained at locations on the circle plots **132098**, **1332100** as indicated by the impedance cursor **13212** and admittance cursor **132104**. Thus, the impedance cursor **132102** is located at a portion of the impedance circle plot **132098** equivalent to about 55.63 kHz, and the admittance cursor **132104** is located at a portion of the admittance circle plot **132100** equivalent to about 55.29 kHz. As depicted in FIG. **28**, the impedance cursor **132102** corresponds to values of R, the resistance (real value, not shown), and X, the reactance (imaginary value, also not shown).

[0429] Similarly, the admittance cursor **132104** corresponds to values of:

[0430] G=137.272 μS

[0431] B=1.48481 mS

[0432] Where G is the conductance (real value) and B is susceptance (imaginary value).

State of Jaw: Open with No Loading

[0433] FIG. **29** is a graphical display **132106** of an impedance analyzer showing impedance (Z)/admittance (Y) circle plots where frequency is swept from 48 kHz to 62 kHz to capture multiple resonances of an ultrasonic device with the jaw open and no loading where the area designated by the rectangle **132108** shown in broken line is to help see the impedance circle plots **132110***a*, **132110***b*, **132110***c* shown in solid line and the admittance circle plots **132112***a*, **132112***b*, **132112***c*, in accordance with at least one aspect of the present disclosure. The voltage applied to the ultrasonic transducer is 500 mV and the frequency is swept from 48 kHz to 62 kHz. The impedance (Z) scale is 500 Ω/div and the admittance (Y) scale is 500 μS/div.

[0434] Measurements of values that may characterize the impedance and admittance circle plots **132110***a-c*, **132112***a-c* may be obtained at locations on the impedance and admittance circle plots **132110***a-c*, **132112***a-c* as indicated by the impedance cursor **132114** and the admittance cursor **132116**. Thus, the impedance cursor **132114** is located at a portion of the impedance circle plots **132110***a-c* equivalent to about 55.52 kHz, and the admittance cursor **132116** is located at a portion of the admittance circle plot **132112***a-c* equivalent to about 59.55 kHz. As depicted in FIG. **29**, the impedance cursor **132114** corresponds to values of:

[0435] R=1.86163 kΩ

[0436] X=−536.229Ω

[0437] Where R is the resistance (real value) and X is the reactance (imaginary value). Similarly, the admittance cursor **132116** corresponds to values of:

[0438] G=649.956 μS

[0439] B=2.51975 mS

[0440] Where G is the conductance (real value) and B is susceptance (imaginary value).

[0441] Because there are only 400 samples across the sweep range of the impedance analyzer, there are only a few points about a resonance. So, the circle on the right side becomes choppy. But this is only due to the impedance analyzer and the settings used to cover multiple resonances.

[0442] When multiple resonances are present, there is more information to improve the classifier. The circle plots **132110***a-c*, **132112***a-c* fit can be calculated for each as encountered to keep the algorithm running fast. So once there is a cross of the complex admittance, which implies a circle, during the sweep, a fit can be calculated.

[0443] Benefits include in-the-jaw classifier based on data and a well-known model for ultrasonic systems. Count and characterizations of circles are well known in vision systems. So data processing is readily available. For example, a closed form solution exists to calculate the radius and axes' offsets for a circle. This technique can be relatively fast.

[0444] TABLE 2 is a list of symbols used for lumped parameter model of a piezoelectric transducer (from IEEE 177 Standard).

			References		
Symbols	Meaning	SI Units	Equations	Tables	Figures
B_p	Equivalent parallel susceptance of vibrator	mho		2	
	Shunt (parallel) capacitance	farad			
C_0	in the equivalent electric circuit		2, 3, 4, 8	5	1, 4
C_1	Motional capacitance in the	farad	2, 3, 4, 6, 8, 9	5	1, 4
	equivalent electric circuit				
f	Frequency	hertz			3
f_a	Antiresonance frequency, zero susceptance	hertz		2, 4	2, 3
	Frequency of maximum	hertz			
f_m	admittance (minimum impedance)			2, 4	2, 3
f_n	Frequency of minimum admittance	hertz		2, 4	2, 3
	(maximum impedance)				
	Parallel resonance frequency	hertz			

-continued

Symbols	Meaning	SI Units	References: Equations	References: Tables	References: Figures
f_p	(lossless) $= \dfrac{1}{2\pi\sqrt{L_1\dfrac{C_1C_0}{C_1+C_0}}}$		2, 3	2, 4	2
f_r	Resonance frequency, zero substance	hertz		2, 4	2,3
f_B	Motional (series) resonance frequency $\frac{1}{2}$	hertz	2, 3, 6, 7, 9, 11a, 11b, 11c, 12,	2, 4	2, 3, 6, 8
G_p	Equivalent parallel conductance of vibrator		1		
L_1	Motional inductance in the equivalent electric circuit	henry	8, 9		1, 4, 5
M	Figure of merit of a vibrator $= \frac{Q}{r}$ $M = \frac{1}{\omega_s C_0 R_1}$	dimensionless	10, 11a, 11b	3, 4, 5	
Q	Quality factor Q $= \frac{\omega_s L_1}{R_1} = \frac{1}{\omega_s C_1 R_1} = rM$	dimensionless	12	3	6, 8
r	Capacitance ratio $r = \frac{C_0}{C_1}$	dimensionless	2, 3, 10, 11	2, 3, 4, 5	8
R_a	Impedance at zero phase angle near antiresonance	ohm			2, 3
R_e	Equivalent series resistance of vibrator	ohm			1, 2
R_r	Impedance at fr zero phase angle	ohm			2, 3
R_1	Motional resistance in the equivalent electric circuit	ohm	4, 8, 10, 11a, 11b, 11c, 12	2, 5	1, 3, 4, 6, 7, 8
X_e	Equivalent series reactance of vibrator	ohm			1, 2
X_0	Reactance of shunt (parallel) capacitance at series resonance $= \frac{1}{\omega_s C_0}$	ohm	1, 4, 5	5	3, 7
X_1	Reactance of motional (series) arm of vibrator $X_1 = \omega L_1 - \frac{1}{\omega C_1}$	ohm		2	2
Y	Admittance of vibrator $Y = G_p + {}_jB_p = \frac{1}{z}$	mho 1			
Y_m	Maximum admittance of vibrator	mho			3
Y_n	Minimum admittance of vibrator	mho			3
Z	Impedance of vibrator $Z = R_e + {}_jX_e$	ohm	1		
Z_m	Minimum impedance of vibrator	ohm			3
Z_n	Maximum impedance of vibrator	ohm			3
	Absolute value of impedance of vibrator $Z = \sqrt{R_e^2 + X_e^2}$	ohm		2	2
	Absolute value of impedance at f_m (minimum impedance)	ohm			2

-continued

Symbols	Meaning	SI Units	References		
			Equations	Tables	Figures
	Absolute value of impedance at f_n (maximum impedance)	ohm			2
δ	Normalized damping factorδ = ${}_{\omega}C_oR_1$	dimensionless	1	2	
Ω	Normalized frequency factor $\Omega = \frac{f^2 - f_s^2}{f_p^2 - f_s^2}$	dimensionless	1	2	
ω	Circular (angular) frequency ω = 2πf	hertz		2	
ω_s	Circular frequency at motional resonance $\omega_s = 2\pi f_s$	hertz			

TABLE 3 is a list of symbols for the transmission network (from IEEE 177 Standard).

TABLE 3

Symbols	Meaning	SI Units	References		
			Equations	Tables	Figures
b	Normalized compensation factor $1 - \frac{1}{4\pi^2 f_s^2 C_0 L_0}$	dimensionless	4, 10	5	
B	Normalized admittance factor dimensionless	10	5		
C	Normalized admittance factor dimensionless	10	5		
C_{A-B}	Stray capacitance between the terminals A-B (Figure 4)	farad			
C_L	Load capacitance	farad	6		4
C_T	Shunt capacitance terminating transmission circuit	farad	4, 10	5	4
C_{L1}	Load capacitance	farad	7		
C_{L2}	Load capacitance	farad	7		
e_2	Output voltage of transmission network	volt			4
f_{mT}	Frequency of maximum transmission	hertz	10		
F_{sL1}	Motional resonance frequency of combination of vibrator and C_{L1}	hertz	7		
F_{sL2}	Motional resonance frequency of combination of vibrator and C_{L2}	hertz	7		
i_1	Input current to transmission network	ampere			4
L_0	Compensation inductance shunting vibrator	henry			4
M_T	Figure of merit of transmission network termination $\text{termination} = \frac{1}{2_\pi f_s C_T R_T} = \frac{X_T}{R_T}$	dimensionless	4, 10	5	
R_T	Shunt resistance termination of transmission network	ohm	4, 11a, 11b, 11c, 12	5	4, 6, 7, 8
R_{sL2}	Standard resistor	ohm	4, 5	5	7
S	Detector sensitivity smallest detectable current change /current	dimensionless	12		6
x	Normalized frequency factor $x = \frac{f^2}{f_s^2} - 1 = \frac{\Omega}{r}$	dimensionless	12		
X_{A-B}	Reactance of stray capacitance CA-B	ohm			
X_T	Reactance of CT at the motional resonance frequency $X_T = \frac{1}{2_\pi f_s C_T}$	ohm	4	5	

TABLE 3-continued

Symbols	Meaning	SI Units	References: Equations	References: Tables	References: Figures
x_{mT}	Normalized frequency factor at the frequency of maximum transmission	dimensionless		5	
ΔC_L	$\Delta C_L = C_{L2} - C_{L1}$	farad	6, 7		
Δf	$\Delta f_1 = f_{sL1} - f_{sL2}$	hertz	6, 7		6, 8
Δf_1	$\Delta f_1 = f_{sL1} - f_s$	hertz	6, 7		
Δf_2	$\Delta f_1 = f_{sL2} - f_s$	hertz	6, 7		

*Refers to real roots; complex roots to be disregarded.

[0445] TABLE 4 is a list of solutions for various characteristic frequencies (from IEEE 177 Standard).

Solutions for the Various Characteristic Frequencies

[0446]

TABLE 4

Characteristic Frequencies	Meaning	Condition	Constituent Equation for Frequency	Root	57 IEEE 14.S1[1]
f_m	Frequency of maximum admittance (minimum impedance)	= O	$-2\delta^2(\Omega + r) - 2\Omega r(1 - \Omega) - \Omega^2 = 0$	lower*	f_m
f_a	Motional (series) resonance frequency	X_1 = O	$\Omega = 0$		f_a
f_r	Resonance frequency	$X_e = B_p$ = O	$\Omega(1 - \Omega) - \delta^2 = 0$	lower	f_r
f_a	Antiresonance frequency	$X_e = B_p$ = O	$\Omega(1 - \Omega) - \delta^2 = 0$	upper	f_a
f_p	Parallel resonance frequency (lossless)	$\| = \infty \| R_1 = 0$	$\Omega = 1$		f_p
f_n	Frequency of minimum admittance (maximum impedance)	= O	$-2\delta^2(\Omega + r) - 2\Omega r(1 - \Omega) - \Omega^2 = 0$	upper*	f_n

*Refers to real roots; complex roots to be disregarded

[0447] TABLE 5 is a list of losses of three classes of piezoelectric materials.

TABLE 5

Type of Piezoelectric Vibrator	Q = Mr	r	Q″/r min
Piezoelectric Ceramics	90-500	2-40	200
Water-Soluble Piezoelectric Crystals	200-50,000	3-500	80
Quartz	10^4-10^7	100-50,000	2000

Minimum Values for the Ratio Q″/r to be Expected for Various Types of Piezoelectric Vibrators

[0448] TABLE 6 illustrates jaw conditions, estimated parameters of a circle based on real time measurements of complex impedance/admittance, radius (re) and offsets (ae and be) of the circle represented by measured variables Re, Ge, Xe, Be, and parameters of a reference circle plots, as described in FIGS. **25-29**, based on real time measurements of complex impedance/admittance, radius (rr) and offsets (ar, br) of the reference circle represented by reference variables Rref, Gref, Xref, Bref. These values are then compared with established values for given conditions. These conditions may be: 1) open with nothing in jaws, 2) tip bite 3) full bite and staple in jaws. The equivalent circuit of the ultrasonic transducer was modeled as follows and the frequency was swept from 55 kHz to 56 kHz:

$$Ls=L1=1.1068\ \text{H}$$

$$Rs=R1=311.352\Omega$$

$$Cs=C1=7.43265\ \text{pF and}$$

$$C0=C0=3.64026\ \text{nF}$$

TABLE 6

Reference	Reference Circle Plot			
Jaw Conditions	R_{ref} (Ω)	G_{ref} (μS)	X_{ref} (Ω)	B_{ref} (mS)
Jaw open and no loading	1.66026	64.0322	−697.309	1.63007
Jaw clamped on dry chamois	434.577	85.1712	−758.772	1.49569
Jaw tip clamped on moist chamois	445.259	96.2179	−750.082	1.50236
Jaw fully clamped on moist chamois		137.272		1.48481

[0449] In use, the ultrasonic generator sweeps the frequency, records the measured variables, and determines estimates Re, Ge, Xe, Be. These estimates are then compared to reference variables Rref, Gref, Xref, Bref stored in memory (e.g., stored in a look-up table) and determines the jaw conditions. The reference jaw conditions shown in TABLE 6 are examples only. Additional or fewer reference jaw conditions may be classified and stored in memory.

These variables can be used to estimate the radius and offsets of the impedance/admittance circle.

[0450] FIG. **30** is a logic flow diagram **132120** of a process depicting a control program or a logic configuration to determine jaw conditions based on estimates of the radius (r) and offsets (a, b) of an impedance/admittance circle, in accordance with at least one aspect of the present disclosure. Initially a data base or lookup table is populated with reference values based on reference jaw conditions as described in connection with FIGS. **25-29** and TABLE 6. A reference jaw condition is set and the frequency is swept from a value below resonance to a value above resonance. The reference values Rref, Gref, Xref, Bref that define the corresponding impedance/admittance circle plot are stored in a database or lookup table. During use, under control of a control program or logic configuration a control circuit of the generator or instrument causes the frequency to sweep **132122** from below resonance to above resonance. The control circuit measures and records **132124** (e.g., stores in memory) the variables Re, Ge, Xe, Be that define the corresponding impedance/admittance circle plot and compares **132126** them to the reference values Rref, Gref, Xref, Bref stored in the database or lookup table. The control circuit determines **132128**, e.g., estimates, the end effector jaw conditions based on the results of the comparison.

Adjustment of Complex Impedance to Compensate for Lost Power in an Articulating Ultrasonic Device

[0451] FIG. **31** is a system **132190** for adjusting complex impedance of the ultrasonic transducer **132192** to compensate for power lost when the ultrasonic blade **132194** is articulated, in accordance with at least one aspect of the present disclosure. The performance of an articulatable ultrasonic blade **132194** is inconsistent throughout the full articulation angle θ from A-B. For example, power is lost when the ultrasonic blade **132194** is articulated. Knowing the articulation angle θ that the ultrasonic blade **132194** is at, the generator **132196** or the surgical instrument **132199** can adjust the complex impedance (Z) to compensate for the power lost when the ultrasonic blade **132194** is articulated. Also, by analyzing the performance of the ultrasonic blade **132194** through its full articulation angle θ, the generator **132196** can execute an algorithm to adjust the complex impedance (Z) to compensate for power loss.

[0452] Adjusting complex impedance of the ultrasonic transducer **132192** to compensate for power lost when the ultrasonic blade **132194** may employ the techniques described in FIGS. **19-21** under the heading ESTIMATING THE STATE OF THE JAW (PAD BURN THROUGH, STAPLES, BROKEN BLADE, BONE IN JAW, TISSUE IN JAW and/or FIGS. **22-30** under the heading STATE OF JAW CLASSIFIER BASED ON MODEL and/or techniques for estimating the temperature of the ultrasonic blade are described in related U.S. Provisional Patent Application No. 62/640,417, titled TEMPERATURE CONTROL IN ULTRASONIC DEVICE AND CONTROL SYSTEM THEREFOR, to Nott et al, which is incorporated herein by reference in its entirety.

[0453] These techniques may be employed to determine the articulation angle θ of the ultrasonic blade **132194** by sweeping through a range of articulation angles θ from A-B at a predetermined angular increment. At each angular increment, activating the ultrasonic transducer **132192** at either a therapeutic or non-therapeutic energy level, measuring the complex impedance (Z) of the ultrasonic transducer **132192**, recording a set of complex impedance (Z) measurements, generating reference complex impedance characteristic patterns or a training data sets S as a function of articulation angle θ, and storing the reference complex impedance characteristic patterns or a training data sets S in a memory or database that is accessible by the ultrasonic instrument **132199** during a surgical procedure. During a surgical procedure, the ultrasonic instrument **132199** can determine articulation angle θ by comparing real time complex impedance (Z) measurements of the ultrasonic transducer **132192** with the reference complex impedance characteristic patterns or a training data sets S.

[0454] Articulatable ultrasonic waveguides **132198** are described in U.S. Pat. No. 9,095,367 titled Flexible Harmonic Waveguides/Blades For Surgical Instruments, which is incorporated herein by reference. See FIGS. 47-66B and associated description. Measurement of articulation angle is described in U.S. Pat. No. 9,808,244 titled Sensor Arrangements For Absolute Positioning System For Surgical Instruments, which is incorporated herein by reference. See FIGS. 193-196 and associated description.

[0455] FIG. **32** is a logic flow diagram **132200** of a process depicting a control program or a logic configuration to compensate output power as a function of articulation angle, in accordance with at least one aspect of the present disclosure. Accordingly, in conjunction with FIG. **31**, during use, a control circuit of the generator **132196** or instrument determines **132202** the articulation angle θ of the ultrasonic blade **132194**. The control circuit adjusts **132204** the complex impedance (Z) to compensate for power lost as a function of articulation angle θ. The control circuit applies **132206** the output power of the generator **132196** applied to the ultrasonic transducer **132192** based on the articulation angle θ of the ultrasonic blade **132194**.

[0456] While several forms have been illustrated and described, it is not the intention of the applicant to restrict or limit the scope of the appended claims to such detail. Numerous modifications, variations, changes, substitutions, combinations, and equivalents to those forms may be implemented and will occur to those skilled in the art without departing from the scope of the present disclosure. Moreover, the structure of each element associated with the described forms can be alternatively described as a means for providing the function performed by the element. Also, where materials are disclosed for certain components, other materials may be used. It is therefore to be understood that the foregoing description and the appended claims are intended to cover all such modifications, combinations, and variations as falling within the scope of the disclosed forms. The appended claims are intended to cover all such modifications, variations, changes, substitutions, modifications, and equivalents.

[0457] The foregoing detailed description has set forth various forms of the devices and/or processes via the use of block diagrams, flowcharts, and/or examples. Insofar as such block diagrams, flowcharts, and/or examples contain one or more functions and/or operations, it will be understood by those within the art that each function and/or operation within such block diagrams, flowcharts, and/or examples can be implemented, individually and/or collectively, by a wide range of hardware, software, firmware, or virtually any combination thereof. Those skilled in the art will recognize that some aspects of the forms disclosed herein, in whole or in part, can be equivalently implemented in integrated circuits, as one or more computer programs running on one or more computers (e.g., as one or more programs running on one or more computer systems), as one or more programs running on one or more processors (e.g., as one or more programs running on one or more microprocessors), as firmware, or as virtually any combination thereof, and that designing the circuitry and/or writing the code for the software and or firmware would be well within the skill of one of skill in the art in light of this disclosure. In addition, those skilled in the art will appreciate that the mechanisms of the subject matter described herein are capable of being distributed as one or more program products in a variety of forms, and that an illustrative form of the subject matter described herein applies regardless of the particular type of signal bearing medium used to actually carry out the distribution.

[0458] Instructions used to program logic to perform various disclosed aspects can be stored within a memory in the system, such as dynamic random access memory (DRAM), cache, flash memory, or other storage. Furthermore, the instructions can be distributed via a network or by way of other computer readable media. Thus a machine-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computer), but is not limited to, floppy diskettes, optical disks, compact disc, read-only memory (CD-ROMs), and magneto-optical disks, read-only memory (ROMs), random access memory (RAM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), magnetic or optical cards, flash memory, or a tangible, machine-readable storage used in the transmission of information over the Internet via electrical, optical, acoustical or other forms of propagated signals (e.g., carrier waves, infrared signals, digital signals, etc.). Accordingly, the non-transitory computer-readable medium includes any type of tangible machine-readable medium suitable for storing or transmitting electronic instructions or information in a form readable by a machine (e.g., a computer).

[0459] As used in any aspect herein, the term “control circuit” may refer to, for example, hardwired circuitry, programmable circuitry (e.g., a computer processor comprising one or more individual instruction processing cores, processing unit, processor, microcontroller, microcontroller unit, controller, digital signal processor (DSP), programmable logic device (PLD), programmable logic array (PLA), or field programmable gate array (FPGA)), state machine circuitry, firmware that stores instructions executed by programmable circuitry, and any combination thereof. The control circuit may, collectively or individually, be embodied as circuitry that forms part of a larger system, for example, an integrated circuit (IC), an application-specific integrated circuit (ASIC), a system on-chip (SoC), desktop computers, laptop computers, tablet computers, servers, smart phones, etc. Accordingly, as used herein “control circuit” includes, but is not limited to, electrical circuitry having at least one discrete electrical circuit, electrical circuitry having at least one integrated circuit, electrical circuitry having at least one application specific integrated circuit, electrical circuitry forming a general purpose computing device configured by a computer program (e.g., a general purpose computer configured by a computer program which at least partially carries out processes and/or devices described herein, or a microprocessor configured by a computer program which at least partially carries out processes and/or devices described herein), electrical circuitry forming a memory device (e.g., forms of random access memory), and/or electrical circuitry forming a communications device (e.g., a modem, communications switch, or optical-electrical equipment). Those having skill in the art will recognize that the subject matter described herein may be implemented in an analog or digital fashion or some combination thereof.

[0460] As used in any aspect herein, the term “logic” may refer to an app, software, firmware and/or circuitry configured to perform any of the aforementioned operations. Software may be embodied as a software package, code, instructions, instruction sets and/or data recorded on non-transitory computer readable storage medium. Firmware may be embodied as code, instructions or instruction sets and/or data that are hard-coded (e.g., nonvolatile) in memory devices.

[0461] As used in any aspect herein, the terms “component,” “system,” “module” and the like can refer to a computer-related entity, either hardware, a combination of hardware and software, software, or software in execution.

[0462] As used in any aspect herein, an “algorithm” refers to a self-consistent sequence of steps leading to a desired result, where a “step” refers to a manipulation of physical quantities and/or logic states which may, though need not necessarily, take the form of electrical or magnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. It is common usage to refer to these signals as bits, values, elements, symbols, characters, terms, numbers, or the like. These and similar terms may be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities and/or states.

[0463] A network may include a packet switched network. The communication devices may be capable of communicating with each other using a selected packet switched network communications protocol. One example communications protocol may include an Ethernet communications protocol which may be capable permitting communication using a Transmission Control Protocol/Internet Protocol (TCP/IP). The Ethernet protocol may comply or be compatible with the Ethernet standard published by the Institute of Electrical and Electronics Engineers (IEEE) titled “IEEE 802.3 Standard”, published in December 2008 and/or later versions of this standard. Alternatively or additionally, the communication devices may be capable of communicating with each other using an X.5 communications protocol. The X.5 communications protocol may comply or be compatible with a standard promulgated by the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T). Alternatively or additionally, the communication devices may be capable of communicating with each other using a frame relay communications protocol. The frame relay communications protocol may comply or be compatible with a standard promulgated by Consultative Committee for International Telegraph and Telephone (CCITT) and/or the American National Standards Institute (ANSI). Alternatively or additionally, the transceivers may be capable of communicating with each other using an Asynchronous Transfer Mode (ATM) communications protocol. The ATM communications protocol may comply or be compatible with an ATM standard published by the ATM

Forum titled "ATM-MPLS Network Interworking 2.0" published August 2001, and/or later versions of this standard. Of course, different and/or after-developed connection-oriented network communication protocols are equally contemplated herein.

[0464] Unless specifically stated otherwise as apparent from the foregoing disclosure, it is appreciated that, throughout the foregoing disclosure, discussions using terms such as "processing," "computing," "calculating," "determining," "displaying," or the like, refer to the action and processes of a computer system, or similar electronic computing device, that manipulates and transforms data represented as physical (electronic) quantities within the computer system's registers and memories into other data similarly represented as physical quantities within the computer system memories or registers or other such information storage, transmission or display devices.

[0465] One or more components may be referred to herein as "configured to," "configurable to," "operable/operative to," "adapted/adaptable," "able to," "conformable/conformed to," etc. Those skilled in the art will recognize that "configured to" can generally encompass active-state components and/or inactive-state components and/or standby-state components, unless context requires otherwise.

[0466] The terms "proximal" and "distal" are used herein with reference to a clinician manipulating the handle portion of the surgical instrument. The term "proximal" refers to the portion closest to the clinician and the term "distal" refers to the portion located away from the clinician. It will be further appreciated that, for convenience and clarity, spatial terms such as "vertical", "horizontal", "up", and "down" may be used herein with respect to the drawings. However, surgical instruments are used in many orientations and positions, and these terms are not intended to be limiting and/or absolute.

[0467] Those skilled in the art will recognize that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to claims containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations.

[0468] In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that typically a disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms unless context dictates otherwise. For example, the phrase "A or B" will be typically understood to include the possibilities of "A" or "B" or "A and B."

[0469] With respect to the appended claims, those skilled in the art will appreciate that recited operations therein may generally be performed in any order. Also, although various operational flow diagrams are presented in a sequence(s), it should be understood that the various operations may be performed in other orders than those which are illustrated, or may be performed concurrently. Examples of such alternate orderings may include overlapping, interleaved, interrupted, reordered, incremental, preparatory, supplemental, simultaneous, reverse, or other variant orderings, unless context dictates otherwise. Furthermore, terms like "responsive to," "related to," or other past-tense adjectives are generally not intended to exclude such variants, unless context dictates otherwise.

[0470] It is worthy to note that any reference to "one aspect," "an aspect," "an exemplification," "one exemplification," and the like means that a particular feature, structure, or characteristic described in connection with the aspect is included in at least one aspect. Thus, appearances of the phrases "in one aspect," "in an aspect," "in an exemplification," and "in one exemplification" in various places throughout the specification are not necessarily all referring to the same aspect. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more aspects.

[0471] Any patent application, patent, non-patent publication, or other disclosure material referred to in this specification and/or listed in any Application Data Sheet is incorporated by reference herein, to the extent that the incorporated materials is not inconsistent herewith. As such, and to the extent necessary, the disclosure as explicitly set forth herein supersedes any conflicting material incorporated herein by reference. Any material, or portion thereof, that is said to be incorporated by reference herein, but which conflicts with existing definitions, statements, or other disclosure material set forth herein will only be incorporated to the extent that no conflict arises between that incorporated material and the existing disclosure material.

[0472] In summary, numerous benefits have been described which result from employing the concepts described herein. The foregoing description of the one or more forms has been presented for purposes of illustration and description. It is not intended to be exhaustive or limiting to the precise form disclosed. Modifications or variations are possible in light of the above teachings. The one or more forms were chosen and described in order to illustrate principles and practical application to thereby enable one of ordinary skill in the art to utilize the various forms and with various modifications as are suited to the particular use contemplated. It is intended that the claims submitted herewith define the overall scope.

[0473] Various aspects of the subject matter described herein are set out in the following numbered examples:

[0474] Example 1. A method of compensating power delivered to an ultrasonic device, the ultrasonic device comprising an electromechanical ultrasonic system defined by a predetermined resonant frequency, the electromechanical ultrasonic system comprising an ultrasonic transducer coupled to an ultrasonic blade, the method comprising:

[0475] determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer;

[0476] adjusting, by the processor or control circuit, a value of a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle; and

[0477] adjusting, by the processor or control circuit, a power applied to the ultrasonic transducer based on the articulation angle.

[0478] Example 2. The method of Example 1, wherein determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade comprises:

[0479] measuring, by the processor or control circuit, a complex impedance of the ultrasonic

[0480] transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)};$$

[0481] receiving, by the processor or control circuit, a complex impedance measurement data point;

[0482] comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern;

[0483] classifying, by the processor or control circuit, the complex impedance measurement data point based on a result of the comparison analysis; and

[0484] assigning, by the processor or control circuit, an articulation angle of the end effector based on the result of the comparison analysis.

[0485] Example 3. The method of Example 2, wherein comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern comprises comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

[0486] Example 4. The method of any one or more of Examples 1 through 3, wherein determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade comprises:

[0487] applying, by a drive circuit, a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency;

[0488] sweeping, by a processor or control circuit, the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system;

[0489] measuring and recording, by the processor or control circuit, impedance/admittance circle variables R_e, G_e, X_e, and B_e;

[0490] comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}; and

[0491] determining, by the processor or control circuit, an articulation angle of the end effector based on the result of the comparison analysis.

[0492] Example 5. The method of Example 4, wherein comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} comprises comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

[0493] Example 6. The method of any one or more of Examples 1 through 5, further comprising:

[0494] sweeping, by the processor or control circuit, the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments;

[0495] activating, by the processor or control circuit, the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments;

[0496] measuring, by the processor or control circuit, a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments;

[0497] recording, by the processor or control circuit, a set of complex impedance measurements at each of the one or more predetermined angular increments;

[0498] generating, by the processor or control circuit, reference complex impedance characteristic patterns as a function of articulation angle; and

[0499] storing, by the processor or control circuit, the reference complex impedance characteristic patterns in a memory or database;

[0500] Example 7. The method of Example 6, wherein activating, by the processor or control circuit, the ultrasonic transducer at an energy level comprises activating, by the processor or control circuit, the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

[0501] Example 8. The method of any one or more of Examples 6 through 7, wherein storing the reference complex impedance characteristic patterns in a memory or database comprises storing the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

[0502] Example 9. An ultrasonic surgical instrument comprising:

[0503] an ultrasonic electromechanical system comprising an ultrasonic transducer coupled to an ultrasonic blade via an ultrasonic waveguide; and

[0504] a generator configured to supply power to the ultrasonic transducer, wherein the generator comprises a control circuit configured to:

[0505] determine an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer;

[0506] adjust a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle; and

[0507] adjust a power applied to the ultrasonic transducer based on the articulation angle.

[0508] Example 10. The ultrasonic surgical instrument of Example 9, wherein the generator comprises a control circuit further configured to:

[0509] measure a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)};$$

[0510] receive a complex impedance measurement data point;

[0511] compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern;

[0512] classify the complex impedance measurement data point based on a result of the comparison analysis; and

[0513] assign an articulation angle of the end effector based on the result of the comparison analysis.

[0514] Example 11. The ultrasonic surgical instrument of Example 10, wherein the generator comprises a control circuit further configured to compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

[0515] Example 12. The ultrasonic surgical instrument of any one or more of Examples 9 through 11, the generator comprises a control circuit further configured to:

[0516] cause a drive circuit to apply a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency;

[0517] sweep the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system;

[0518] measure and record impedance/admittance circle variables R_e, G_e, X_e, and B_e;

[0519] compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}; and

[0520] determine an articulation angle of the end effector based on the result of the comparison analysis.

[0521] Example 13. The ultrasonic surgical instrument of Example 12, the generator comprises a control circuit further configured to compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables $R_{,f}$, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

[0522] Example 14. The ultrasonic surgical instrument of any one or more of Examples 9 through 13, wherein the generator comprises a control circuit further configured to:

[0523] sweep the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments;

[0524] activate the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments;

[0525] measure a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments;

[0526] record a set of complex impedance measurements at each of the one or more predetermined angular increments;

[0527] generate reference complex impedance characteristic patterns as a function of articulation angle; and

[0528] store the reference complex impedance characteristic patterns in a memory or database;

[0529] Example 15. The ultrasonic surgical instrument of Example 14, the generator comprises a control circuit further configured to activate the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

[0530] Example 16. The ultrasonic surgical instrument of any one or more of Examples 14 through 15, the generator comprises a control circuit further configured to store the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

[0531] Example 17. A generator for an ultrasonic surgical instrument, the generator comprising:

[0532] a control circuit configured to:

[0533] determine an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer;

[0534] adjust a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle; and

[0535] adjust a power applied to the ultrasonic transducer based on the articulation angle.

[0536] Example 18. The generator for an ultrasonic surgical instrument of Example 17, wherein the control circuit is further configured to:

[0537] measure a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)};$$

[0538] receive a complex impedance measurement data point;

[0539] compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern;

[0540] classify the complex impedance measurement data point based on a result of the comparison analysis; and

[0541] assign an articulation angle of the end effector based on the result of the comparison analysis.

[0542] Example 19. The generator for an ultrasonic surgical instrument of Example 18, wherein the control circuit is further configured to compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

[0543] Example 20. The generator for an ultrasonic surgical instrument of any one or more of Examples 17 through 19, wherein the control circuit is further configured to:

[0544] cause a drive circuit to apply a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency;

[0545] sweep the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system;

[0546] measure and record impedance/admittance circle variables R_e, G_e, X_e, and B_e;

[0547] compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}; and

[0548] determine an articulation angle of the end effector based on the result of the comparison analysis.

[0549] Example 21. The generator for an ultrasonic surgical instrument of Example 20, the wherein the control circuit is further configured to compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables $R_{,f}$, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

[0550] Example 22. The generator for an ultrasonic surgical instrument of any one or more of Examples 17 through 21, wherein the control circuit is further configured to:

[0551] sweep the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments;

[0552] activate the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments;

[0553] measure a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments;

[0554] record a set of complex impedance measurements at each of the one or more predetermined angular increments;

[0555] generate reference complex impedance characteristic patterns as a function of articulation angle; and

[0556] store the reference complex impedance characteristic patterns in a memory or database.

[0557] Example 23. The generator for an ultrasonic surgical instrument of Example 22, wherein the control circuit is further configured to activate the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

[0558] Example 24. The generator for an ultrasonic surgical instrument of any one or more of Examples 22 through 23, wherein the control circuit is further configured to store the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

1. A method of compensating power delivered to an ultrasonic device, the ultrasonic device comprising an electromechanical ultrasonic system defined by a predetermined resonant frequency, the electromechanical ultrasonic system comprising an ultrasonic transducer coupled to an ultrasonic blade, the method comprising:

determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer;

adjusting, by the processor or control circuit, a value of a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle; and

adjusting, by the processor or control circuit, a power applied to the ultrasonic transducer based on the articulation angle.

2. The method of claim 1, wherein determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade comprises:

measuring, by the processor or control circuit, a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)};$$

receiving, by the processor or control circuit, a complex impedance measurement data point;

comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern;

classifying, by the processor or control circuit, the complex impedance measurement data point based on a result of the comparison analysis; and

assigning, by the processor or control circuit, an articulation angle of the end effector based on the result of the comparison analysis.

3. The method of claim 2, wherein comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern comprises comparing, by the processor or control circuit, the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

4. The method of claim 1, wherein determining, by a processor or control circuit, an articulation angle of an articulatable ultrasonic blade comprises:

applying, by a drive circuit, a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency;

sweeping, by a processor or control circuit, the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system;

measuring and recording, by the processor or control circuit, impedance/admittance circle variables R_e, G_e, X_e, and B_e;

comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}; and

determining, by the processor or control circuit, an articulation angle of the end effector based on the result of the comparison analysis.

5. The method of claim 4, wherein comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}; G_{ref}; X_{ref}, and B_{ref} comprises comparing, by the processor or control circuit, measured impedance/admittance circle variables R_e,

G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

6. The method of claim **1**, further comprising:

sweeping, by the processor or control circuit, the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments;

activating, by the processor or control circuit, the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments;

measuring, by the processor or control circuit, a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments;

recording, by the processor or control circuit, a set of complex impedance measurements at each of the one or more predetermined angular increments;

generating, by the processor or control circuit, reference complex impedance characteristic patterns as a function of articulation angle; and

storing, by the processor or control circuit, the reference complex impedance characteristic patterns in a memory or database;

7. The method of claim **6**, wherein activating, by the processor or control circuit, the ultrasonic transducer at an energy level comprises activating, by the processor or control circuit, the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

8. The method of claim **6**, wherein storing the reference complex impedance characteristic patterns in a memory or database comprises storing the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

9. An ultrasonic surgical instrument comprising:

an ultrasonic electromechanical system comprising an ultrasonic transducer coupled to an ultrasonic blade via an ultrasonic waveguide; and

a generator configured to supply power to the ultrasonic transducer, wherein the generator comprises a control circuit configured to:

determine an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer;

adjust a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle; and

adjust a power applied to the ultrasonic transducer based on the articulation angle.

10. The ultrasonic surgical instrument of claim **9**, wherein the generator comprises a control circuit further configured to:

measure a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)};$$

receive a complex impedance measurement data point;

compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern;

classify the complex impedance measurement data point based on a result of the comparison analysis; and

assign an articulation angle of the end effector based on the result of the comparison analysis.

11. The ultrasonic surgical instrument of claim **10**, wherein the generator comprises a control circuit further configured to compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

12. The ultrasonic surgical instrument of claim **9**, the generator comprises a control circuit further configured to:

cause a drive circuit to apply a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency;

sweep the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system;

measure and record impedance/admittance circle variables R_e, G_e, X_e, and B_e;

compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}; and

determine an articulation angle of the end effector based on the result of the comparison analysis.

13. The ultrasonic surgical instrument of claim **12**, the generator comprises a control circuit further configured to compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

14. The ultrasonic surgical instrument of claim **9**, wherein the generator comprises a control circuit further configured to:

sweep the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments;

activate the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments;

measure a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments;

record a set of complex impedance measurements at each of the one or more predetermined angular increments;

generate reference complex impedance characteristic patterns as a function of articulation angle; and

store the reference complex impedance characteristic patterns in a memory or database;

15. The ultrasonic surgical instrument of claim **14**, the generator comprises a control circuit further configured to activate the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

16. The ultrasonic surgical instrument of claim **14**, the generator comprises a control circuit further configured to store the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

17. A generator for an ultrasonic surgical instrument, the generator comprising:

a control circuit configured to:

determine an articulation angle of an articulatable ultrasonic blade coupled to an ultrasonic transducer;

adjust a complex impedance of the ultrasonic transducer to compensate for power lost as a function of the articulation angle; and

adjust a power applied to the ultrasonic transducer based on the articulation angle.

18. The generator for an ultrasonic surgical instrument of claim **17**, wherein the control circuit is further configured to:

measure a complex impedance of the ultrasonic transducer, wherein the complex impedance is defined as

$$Z_g(t) = \frac{V_g(t)}{I_g(t)};$$

receive a complex impedance measurement data point;

compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern;

classify the complex impedance measurement data point based on a result of the comparison analysis; and

assign an articulation angle of the end effector based on the result of the comparison analysis.

19. The generator for an ultrasonic surgical instrument of claim **18**, wherein the control circuit is further configured to compare the complex impedance measurement data point to a data point in a reference complex impedance characteristic pattern corresponding to the articulation angle.

20. The generator for an ultrasonic surgical instrument of claim **17**, wherein the control circuit is further configured to:

cause a drive circuit to apply a drive signal to the ultrasonic transducer, wherein the drive signal is a periodic signal defined by a magnitude and frequency;

sweep the frequency of the drive signal from below resonance to above resonance of the electromechanical ultrasonic system;

measure and record impedance/admittance circle variables R_e, G_e, X_e, and B_e;

compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref}; and

determine an articulation angle of the end effector based on the result of the comparison analysis.

21. The generator for an ultrasonic surgical instrument of claim **20**, the wherein the control circuit is further configured to compare measured impedance/admittance circle variables R_e, G_e, X_e, and B_e to reference impedance/admittance circle variables R_{ref}, G_{ref}, X_{ref}, and B_{ref} corresponding to the articulation angle.

22. The generator for an ultrasonic surgical instrument of claim **17**, wherein the control circuit is further configured to:

sweep the articulatable ultrasonic blade through a range of articulation angles from a first articulation angle to a second articulation angle at one or more predetermined angular increments;

activate the ultrasonic transducer at an energy level at each of the one or more predetermined angular increments;

measure a complex impedance of the ultrasonic transducer at each of the one or more predetermined angular increments;

record a set of complex impedance measurements at each of the one or more predetermined angular increments;

generate reference complex impedance characteristic patterns as a function of articulation angle; and

store the reference complex impedance characteristic patterns in a memory or database.

23. The generator for an ultrasonic surgical instrument of claim **22**, wherein the control circuit is further configured to activate the ultrasonic transducer at a therapeutic or a non-therapeutic energy level.

24. The generator for an ultrasonic surgical instrument of claim **22**, wherein the control circuit is further configured to store the reference complex impedance characteristic patterns in a memory or database that is accessible by the ultrasonic instrument during a surgical procedure.

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专利名称(译)	调节复阻抗以补偿铰接超声装置中的功率损失		
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申请号	US16/144418	申请日	2018-09-27
[标]申请(专利权)人(译)	ETHICON , LLC		
申请(专利权)人(译)	ETHICON LLC		
当前申请(专利权)人(译)	ETHICON LLC		
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摘要(译)

超声装置可包括由预定共振频率限定的机电超声系统，该机电超声系统具有耦合到超声刀的超声换能器。补偿传递到超声装置的功率的方法可以包括确定耦合到超声换能器的可铰接超声刀的铰接角度，调节超声换能器的复阻抗以补偿作为关节角度的函数的功率损失，以及调节，基于关节角度施加到超声换能器的功率。超声装置可包括发生器和配置成实现该方法的控制电路。