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System And Methods For Controlling Patient Leakage Current In A Surgical System

Abstract

Control consoles and methods for supplying a drive signal to a surgical tool are provided. The control console comprises a transformer with primary and secondary windings. The primary winding receives an input signal from a power source and induces the drive signal in the secondary winding to supply the drive signal to the surgical tool. A first current source comprising a leakage control winding is coupled to a path of the drive signal. The primary winding induces a first cancellation current in the leakage control winding to inject into the path of the drive signal to cancel leakage current. A sensor coupled to the path of the drive signal outputs a sensed signal to provide feedback related to leakage current. The sensor may connect to a second leakage current cancellation source and/or a fault detection stage. The power source may be variable and may also energize the second current source.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] The subject patent application is a continuation of U.S. patent application Ser. No. 18/670,207, filed on May 21, 2024, which is a continuation of U.S. patent application Ser. No. 16/770,473, filed on Jun. 5, 2020, which is a National Stage Entry of International Patent Application No. PCT/2018/063775, filed on Dec. 4, 2018, which claims priority to and all the benefits of U.S. Provisional Patent Application No. 62/595,235, filed on Dec. 6, 2017, the disclosures of which are hereby incorporated by reference in their entirety.

TECHNICAL FIELD
[0002] The present disclosure generally relates to control consoles that supply drive signals to electrically powered surgical tools, and more specifically, that are designed to reduce patient leakage current of/from drive signals.
BACKGROUND
[0003] A powered surgical tool system can be considered to have three basic components. A control console produces drive signals that have the characteristics necessary to actuate the second component of the system, the power generator. The power generator converts the electrical energy of the drive signals into another form of energy. The types of energy into which the electrical energy is converted include, mechanical energy, thermal energy (heat) and photonic (light) energy. The third component of the tool system is the energy applicator. The energy applicator receives the energy output by the power generator and applies this energy to the targeted tissue to perform a specific therapeutic task. Some tool systems are designed to apply electrical energy directed to the targeted tissue. In this type of system, the power generator is essentially the conductors over which the drive signals are applied to the exposed electrodes over which the current is sourced to the tissue. The electrodes function as the energy applicator. Electrodes may be placed on a patient or integrated into a hand piece. Other tool systems are designed to provide mechanical energy. In this type of system, the power generator converts electrical energy, e.g. an AC drive signal, into mechanical energy, e.g. vibrations, which are applied to the patient through the hand piece.
[0004] An integral part of many surgical tool systems is the surgical tool, which can be a hand piece. At a minimum, the hand piece is the physical component designed to be held by the practitioner from which the energy applicator extends. Often the power generator is contained in the surgical tool. One such surgical tool system so designed is an ultrasonic surgical tool system. The surgical tool of this system includes a power generator that includes one or more drivers. Each driver, in response to the application of an AC signal, vibrates. A horn is closely mechanically coupled to the drivers. A tip, which functions as the energy applicator, extends distally from the

horn. The vibrations of the drivers foster like vibrations in the horn and, by extension, the tip. The motion of a vibrating tip against tissue results in the ablation of, the removal of, the tissue.

[0005] An inherent characteristic many powered surgical tool systems share with other electrically powered assemblies is that parasitic capacitances are present across the components of these systems. A parasitic capacitance is the capacitance present across two components that are at unequal voltages. A consequence of the presence of this capacitance is that a parasitic alternating current can flow through one of the components. For example, when a surgical tool includes a power generating unit to which AC drive signals are applied, due to the parasitic capacitance between the metal structural components of the surgical tool and the power generating components internal to the surgical tool through which current flows, a parasitic current can flow through the metal structural components. This parasitic current contributes to what is known as leakage current. Generally, leakage current is the unintended flow of current through the components of a system to which a current is applied for other purposes. Patient leakage current, more specifically, is the unintended flow of current through a patient.

[0006] There is a possibility that a patient can inadvertently be connected to earth ground during a procedure. If this event does occur, leakage current can flow from the surgical tool into the patient. To avoid danger to the patient, the powered surgical tool system should be designed to minimize leakage current that flows through the patient, such as in a scenario where the patient becomes earth grounded. If a surgical tool through which a leakage current could be present is applied to the patient, the leakage current can, in theory, flow through the patient to this ground. This current can adversely affect the functioning of the patient's organs and tissue.

[0007] For these reasons, a surgical tool system with a surgical tool intended for application to the patient is designed to ensure that the normal leakage current flow is less than 100 μAmps. A surgical tool system with a surgical tool intended for application to cardiac tissue must be designed so the normal leakage current flow is less than 10 μAmps if it will be used in the United States. These requirements are based on the IEC 60601 Medical Design Standards. The IEC 60601 Standards also describe the process for testing a powered surgical tool to ensure the leakage current is below these maximum amounts.

[0008] It is a further requirement that a tool applied to a patient cannot function as a connection to ground. Mainly, if a voltage from another source is somehow applied to the patient, the tool should not function as a connection to ground resulting in a current flow through the patient.

[0009] Powered surgical tool systems may have outputs that are isolated from ground to prevent current leakage. However, isolated output circuits are, by themselves, not enough to reduce leakage to acceptable levels. Some powered surgical tool systems have been designed with the capability of detecting open circuits and being able to lower their peak output voltage accordingly. This leads to several performance problems. Lowering peak output voltage in order to minimize leakage current may degrade the performance of the tool system since the peak output voltage initiates the sparking needed for proper coagulation effect. Further, the amount of time needed by the generator to sense the open circuit condition may lead to momentary voltage spikes, which could allow leakage current to occur.

[0010] One method is to reduce the parasitic capacitance to reduce the parasitic current flow. If the tool is an ultrasonic surgical tool, parasitic capacitance can be reduced by providing electrically insulating impedance disks between the drivers and the horn that the mechanical components of the surgical tool that are intended to be vibrated by the drivers. A disadvantage associated with providing these disks is that they damp the transfer of vibrations from the drivers to the horn and tip. This mechanical damping reduces the efficiency of the surgical tool.

[0011] As such, there is a need to address at least the aforementioned technical deficiencies of prior systems and methods.

SUMMARY

[0012] In one embodiment, a control console for supplying a drive signal to a surgical tool, and methods of operating the same, are provided. The control console comprises a transformer including a primary winding and a secondary winding. The primary winding is configured to receive an input signal from a power source and to induce the drive signal in the secondary winding to supply the drive signal to the surgical tool. The control console further comprises a first current source comprising a leakage control winding coupled to a path of the drive signal and with the primary winding configured to induce a first cancellation current in the leakage control winding to inject into the path of the drive signal to cancel leakage current of the drive signal. The control console also includes a sensor coupled to the path of the drive signal, wherein the sensor is configured to output a sensed signal to provide feedback related to leakage current.

[0013] In another embodiment, a control console for supplying a drive signal to a surgical tool, and methods of operating the same, are provided. The control console comprises a transformer including a primary winding and a secondary winding. The primary winding is configured to receive an input signal from a power source and to induce the drive signal in the secondary winding to supply the drive signal to the surgical tool. The control console further comprises a first current source comprising a leakage control winding coupled to a path of the drive signal and with the primary winding configured to induce a first cancellation current in the leakage control winding to inject into the path of the drive signal to cancel leakage current of the drive signal. A sensor is configured to sense a characteristic of the input signal and to output a sensed signal related to the characteristic of the input signal. A second current source is coupled to the path of the drive signal. A variable gain device is coupled to the sensor and to the second current source. A selection interface is coupled to the second current source and to the variable gain device and is configured to enable selection of one of a plurality of leakage current adjustment settings and to provide selected leakage current adjustment setting to the variable gain device. The variable gain device is configured to receive the sensed signal and to modify the sensed signal based on the selected leakage current adjustment setting. The second current source is configured to generate a second cancellation current based on the modified sensed signal from the variable gain device and to inject the second cancellation current into the path of the drive signal to cancel leakage current of the drive signal.

[0014] In another embodiment, a control console for supplying a drive signal to a surgical tool, and methods of operating the same, are provided. The control console comprises a variable power source, a transformer and a current source. The transformer comprises a primary winding and a secondary winding. The primary winding is coupled to the variable power source and is configured to receive an input signal from the variable power source and to induce a drive signal in the secondary winding to supply the drive signal to the surgical tool. The current source is coupled to a path of the drive signal and is coupled to the variable power source. The variable power source is configured to energize the current source. The current source is configured to generate a cancellation current to inject into the path of the drive signal to cancel leakage current of the drive signal.

[0015] These embodiments offer multiple advantages including enabling the control console to maintain low leakage current without the use of cumbersome additional devices that decrease the output power of the surgical tool, providing the ability to monitor the drive signal for leakage current-which enables the addition of further leakage control and fault detection stages, and/or simplification of the control console by using a single power source to energize the drive signal and leakage control sources. Additional advantages of the control console and methods described herein, as well as the embodiments of the same, will be understood in reference to the description provided herein.

Description

BRIEF DESCRIPTION

[0016] Advantages of the present invention will be readily appreciated as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings wherein:

[0017] FIG. **1** depicts a one embodiment of a powered surgical tool system comprising a control console and a surgical tool.

[0018] FIG. **2** is a diagram of the operation of a feedback loop for measurement and cancellation of leakage current, according to one example.

[0019] FIG. **3** is a schematic representation of two sources for cancelling leakage current for the powered surgical tool system, according to one example.

[0020] FIG. **4** is a schematic diagram of an embodiment of the powered surgical tool system comprising the control console with two leakage current cancellation stages and current-based sensing of leakage current.

[0021] FIG. **5** is a schematic diagram of another embodiment of the powered surgical tool system comprising the control console with two leakage current cancellation stages and voltage-based sensing of a drive signal.

[0022] FIG. **6** is a schematic diagram of an alternative embodiment of another embodiment of the powered surgical tool system comprising the control console with two leakage current cancellation stages and techniques for adjusting leakage current settings.

[0023] FIG. **7** is a schematic diagram of another embodiment of the powered surgical tool system comprising the control console with two leakage current cancellation stages and a fault detection stage for leakage current.

[0024] FIG. **8** is a schematic diagram of circuitry included in the fault detection stage according to one embodiment.

DETAILED DESCRIPTION

I. Overview

[0025] Referring to the Figures, wherein like numerals indicate like or corresponding parts throughout the several views, a powered surgical tool system **20** is provided having a control console **22** configured to supply a drive signal **105** to a surgical tool **28**.

[0026] Reference will now be made to the embodiments illustrated in the drawings and specific language will be used to describe the same. No limitation of the scope of the disclosure is intended by using specific language to describe exemplary embodiments. Any alterations and further modifications of the inventive features illustrated herein, and any additional applications of the principles of the disclosure as illustrated herein, which would normally occur to one skilled in the relevant art and having possession of this disclosure, are to be considered within the scope of the disclosure claimed.

[0027] The powered surgical tool system **20** is now generally described by reference to FIG. **1** and is hereinafter referred to as “the system **20**” for simplicity. The system **20** includes the surgical tool **28**. The surgical tool **28** can be an ultrasonic surgical tool or tool for application of RF or other type of electrosurgical energy. The surgical tool **28** may include a shell or body **30**. The body **30** is the portion of the surgical tool **28** that is actually held by the medical practitioner. The body **30** forms a proximal end **29** of the surgical tool. The term “proximal” is understood to mean closer to the practitioner holding the surgical tool, and further away from the site **33** to which the surgical tool **28** is applied. A distal end **31** of the surgical tool **28** is located opposite the proximal end **29**. The term “distal” is understood to mean further away from the practitioner, and closer to the site **33** to which the surgical tool **28** is applied.

[0028] The control console **22** is part of system **20**. Control console **22** sources drive signals **105** (described below) over a cable **32** to which the surgical tool **28** is connected. In embodiments in which the surgical tool **28** is an ultrasonic surgical tool, it is desirable, but not required, to assemble the cable **32** and the surgical tool **28** as a single unit. The control console **22** includes components that function as a signal generator. These components produce the drive signal **105**, e.g., an AC signal, that is applied to a power generator **27** of the surgical tool **28**. The power generator **27**, also referred to as a transducer, converts the AC signal to the type of surgical energy to be applied to the patient. For example, in an ultrasonic surgical tool **28** the power generator **27** may be a piezo electric stack that converts electrical energy into vibrations. Alternatively, in an RF surgical tool **28** the power generator **27** may not be needed as electrical energy is applied directly to the patient through electrodes. The surgical tool **28** depicted in FIG. **1** is configured to apply ultrasonic or RF energy to the patient through the tip of the surgical tool at the distal end **31**. Surgical energy may also be applied to patient tissue **33** through an electrode or other surgical tools other than those described herein. Regardless of the type of energy applied, the control console **22** is designed to minimize the potential for current leakage into the patient.

[0029] A control interface **24** is connected to control console **22**. In FIG. **1**, the control interface **24** is a foot pedal. A state of control interface **24** is monitored by a processor **35** within the control console **22**. The control interface **24** is a user actuated control member that regulates activation and/or specific control of the surgical tool **28** through the control console **22**. In FIG. **1**, the control interface **24** is shown as being part of a foot pedal assembly that includes several pedals. The added pedals may be used to control devices such as irrigation pump, a suction pump or a light. The control interface **24** may comprise configurations other than the foot pedal as depicted in FIG. **1**.

[0030] The control console **22** may further include a user interface **26**, such as a Graphical User Interface or switch. Like the control interface **24**, the user interface **26** is monitored by the processor **35** within the control console **22**. The user interface **26** is controlled by the practitioner to control operating parameters for the surgical tool **28**. In ultrasonic embodiments, such operating parameters may include the magnitude of the amplitude of the vibrations of surgical tool **28**.

[0031] The control interface **24** and user interface **26** are understood to be general representations of the means of inputting commands to system **20**. In some constructions of the system **20**, a single control unit may perform both functions. For example, the system **20** may be configured so that when a lever or foot pedal is initially first depressed, the system **20** causes a tip head of the surgical tool **28** to undergo a vibration cycle that is of relatively small amplitude. As a result of the continued depression of the lever or foot pedal, the control console **22** resets the drive signal **105** applied to the surgical tool **28** so as to cause tip head to undergo vibration cycles that are of a larger magnitude.

[0032] The control console **22** may include a display **34**. Images on the display **34** may be generated by the processor **35** with the control console **22**. Information depicted on display **34** includes, but is not limited to, information related to the user interface **26**, information identifying the surgical tool **28** and the tip, and any other information describing operation, settings, or notifications of the system **20**. The display **34** may be a touch screen display. In these versions, by depressing images of buttons presented on the display **34**, command can be entered into the processor **35** within the control console **22**. Any suitable interface components between the display **34** and the processor **35** may be provided to facilitate presentation of images on the display **34** and the entry of commands into the processor **35**. Additional details regarding a processor which may be used with the embodiments disclosed are included in in PCT Pat. App. No. PCT/US2016/031651, the contents of which are contained in WO 2016/183084 A1/US Pat. Pub. No. 2018/0056328 A1, the contents of which are herein incorporated by reference in their entirety.

[0033] The processor **35** regulates the outputting of drive signals **105** from the control console **22**. The practitioner-controlled inputs upon which the processor **35** sets the drive signals **105** may be based on the state of the control interface **24** and/or the user interface **26**. Commands entered through the display **34** may also be used to control the setting of the drive signal **105**. The characteristics of the drive signal **105** may also set based on data read from the surgical tool **28** memory. The characteristics of the drive signals **105** are also employed by the control console **22** as feedback signals that further contribute to the setting of the drive signal **105**. Based on these plural inputs, processor **35** outputs the signals that control the drive signal **105**.

[0034] Referring to FIGS. **4-7**, the control console **22** includes, or is otherwise coupled to, a power source **82**. The power source **82** is configured to apply an input signal to a primary winding **84** of a transformer **90**. The input signal from the power source **82** is applied to a center tap of the primary winding **84** of the transformer **90**. Transformer **90** electrically isolates the patient side circuitry from the power source **82**. The transformer **90** blocks any DC component of the signal in primary winding **84** from transferring to secondary winding **88** and may be designed with insulation, shown in FIGS. **4-7** as a core **98**, to minimize capacitive coupling.

[0035] The opposed taps of the primary winding **84** are each coupled to a linear amplifier **86**. Each amplifier **86** applies AC signals that vary in both potential and frequency to the taps of the primary winding **84**. A base signal applied to amplifier **86** as a control signal regulates the frequency and potential of the signals output by the amplifier **86**. In an embodiment in which system **20** includes an ultrasonic surgical tool **28**, the AC signal that is developed across the primary winding **84** may have a frequency between 10 kHz and 100 kHz. This signal may have a peak to peak voltage of at least 200 Volts and more. For other applications, such as RF treatment, the AC signal may have frequency and voltage ranges other than those described herein.

[0036] The structure of the power source **82** and the linear amplifier **86** are not limited to the specific embodiments shown herein, and may include different configurations for generating an AC signal over the primary winding **84**. A further understanding of these sub-assemblies can be found in PCT Pat. App. No. PCT/US2016/031651, the contents of which are contained in WO 2016/183084 A1/US Pat. Pub. No. 2018/0056328 A1, the contents of which are herein incorporated by reference in their entirety.

[0037] The AC signal that develops across the primary winding **84** induces an AC signal across the secondary winding **88** of the transformer **90**. This signal across the secondary winding **88** of transformer **90** is the drive signal **105** applied over cable **32** to the power generator **27** within surgical tool **28**. Cable **32** contains a high voltage conductor **100** with high potential current that flows toward the surgical tool **28** and a low voltage conductor **102** with low potential current that flows away from the surgical tool **28**. A path **104** of the drive signal (also referred to as “drive path”) is defined by these conductors **100**, **102**. The drive signal **105** is the current that runs through the drive path **104**. In an embodiment in which the drive signal **105** is used to actuate ultrasonic drivers, the drive signal has a voltage of at least 500 VAC and can be over 1000 VAC.

[0038] The drive path **104** is surrounded by a shield **99**. The shield **99** prevents parasitic capacitance between the high voltage conductor **100** and earth ground or any objects near the drive path **104**. In addition, the shield may be coupled to the low voltage conductor **102** within the surgical tool **28**. In embodiments where this connection is present, the shield **99** also acts as a secondary path for the return current and protects the patient in the event there is a break in the low-voltage conductor **102**.

II. Techniques for Leakage Current Detection and Cancellation

[0039] According to the techniques described herein, the system **20** may employ leakage cancellation techniques for cancelling patient leakage current (also referred to as “leakage current”). Leakage current is generally the current that flows through a patient connected to the surgical tool **28**. Leakage current can flow from the control console **22**, to the surgical tool **28**, through the patient and to earth ground. As such, the leakage current is generally unintended flow of electrical current through the patient.

[0040] As will be understood from the examples described herein, the system **20** may employ leakage current cancellation using active control, or using a combination of active and passive control. Active controlled techniques employ elements that make determinations based on input or feedback signals. Passive controlled techniques employ elements, such as transformers, resistors, capacitors, inductors, that passively provide leakage current cancellation without active determinations. Active controlled techniques may include passive elements to supplement active devices. One or more of these active and passive leakage current cancellations systems may be included in the control console **22**.

[0041] In one embodiment shown in FIG. **3**, an equivalent circuit is provided illustrating operation of a first source **68′** and a second source **74′** for cancelling leakage current. The first source **68′** is a passive-type and is depicted as an AC voltage source. The second source **74′** is an active-type and is depicted as a variable AC voltage source. The first source **68′** produces a first cancellation current **80′** and the second source **74′** produces a second cancellation current **122′**. Hence, the first and second sources **68′**, **74′** are current sources, in that these sources **68′**, **74′** produce cancellation currents **80′**, **122′**, respectively, as illustrated by FIG. **3**. Sources **68′**, **74′** are referred to herein as current sources.

[0042] A power source representation **56** (comprising the power source **82** and transformer **90**) generates the drive signal **105** for the surgical tool **28**. The cancellation currents **80′**, **122′** are injected by these sources **68′**, **74′** into the drive signal **105**, or into the path **104** of the drive signal **105**.

[0043] In this equivalent schematic, the first current source **68′** is illustrated in series with capacitor **70** and the second current source **74′** is in series with capacitor **76**. Impedance **58** represents a known impedance of the surgical tool **28**, resistor **66** represents a variable impedance through the surgical site **33**, and capacitors **60** and **64** represent capacitances for the high and low side voltage conductors **100**, **102**, respectively. Such capacitances may be parasitic, thereby resulting in generation of the leakage current **62′**. In this example, leakage current **62′** in the drive signal **105** is traveling through capacitor **60**.

[0044] According to IEC 60601 Medical Design Standards, the powered surgical tool system **20** shall maintain the leakage current at 100 μAmps or less. If the powered surgical tool system **20** is designed for use on or near cardiac tissue, a maximum leakage current is 10 μAmps.

[0045] In some embodiments, the first current source **68′** is designed to cancel a majority (e.g., 50%-90%) of the leakage current **62′**. The second current source **74′** generates the second cancellation current **122′** to cancel at least some of the residual leakage current **62′** that remains after cancellation by the first cancellation current **80′**. Such residual leakage current **62′** may be 1-40% of the total leakage current **62′**, for example. In one example, the first current source **68** may be designed to cancel up to ±500 μA patient leakage current cancellation, while leaving a small amount of residual leakage current, e.g. ±40 μA patient leakage current. In other examples, the second current source **74′** may cancel a majority of the leakage current **62′**.

[0046] In an ideal control console **22**, leakage current **62′** of the drive signal **105** will be equal to the first cancellation current **80′** plus the second cancellation current **122′**. Alternative embodiments may use a single active or passive current source, any combination of active and/or passive current injection sources, or any pluralities thereof.

[0047] As will be appreciated from the embodiments described herein, the second (active) current source **74** may comprise additional components beyond those components that actually generate the second cancellation current **122**. Such additional components, may, for example, aide in determining how or when to produce the second cancellation current **122**. As such, the phrase “second current source” as described herein, is not limited solely to current generating components.

[0048] Referring now to FIGS. **4-7**, further aspects of the first current source **68** and second current source **74** are described. The first current source **68** may also be referred to as a matched current source. The first current source **68**, according to one embodiment, comprises a leakage control winding **92**. The leakage control winding **92** may also be referred to as tuned winding or a sense winding. The leakage control winding **92** may be integrated with the transformer **90** such that the transformer **90** includes the leakage control winding **92**. Examples of how the leakage control winding **92** and capacitor **94** can both be made integral with the transformer **90** are described in PCT App. No. PCT/US2017/034437 the contents of which are published in PCT Pub. No. WO

2017/210076 A2/US Pat. Pub. No. 2019/0291135 A1, the contents of which are hereby incorporated by reference in their entirety. The first current source **68** may also include a capacitor **94**.

[0049] Current is induced across the leakage control winding **92** by the primary winding **84**. Induction of this current facilitates generation of the first cancellation current **80** by the first current source **68**. The first cancellation current **80** is injected into the low side voltage conductor **102** of the drive signal path **104**. While FIG. **4** shows the first cancellation current **80** injected into the low-side voltage conductor **102**, cancellation current of opposite polarity could be injected into the high-side voltage conductor **100** to offset leakage current **62**′. In embodiments where the control console **22** includes the transformer **90** across which the drive signal **105** is generated, one or all of the components forming the first current source **68** may be built into a single unit with the transformer **90**.

[0050] Additional details regarding the structure of the transformer **90** and the first current source **68** may be found in PCT App. No. PCT/US2017/034437 the contents of which are published in PCT Pub. No. WO 2017/210076 A2/US Pat. Pub. No. 2019/0291135 A1, the contents of which were previously incorporated by reference.

A. Closed Loop Leakage Current Cancellation Control

[0051] Referring to FIGS. **2**, **4**, **5** and **7**, embodiments of second current sources **74** employed by the control console **22** to cancel at least some of the leakage current **62** are described. In one example, the second current sources **74** utilize feedback signals, which can be a measurement of current or voltage of the drive signal **105**, to cancel at least some of the leakage current **62**.

[0052] Cancellation of leakage current **62** through the use of a feedback signal is illustrated in the control loop shown in FIG. **2**. One or more sensors **36** measure a characteristic the drive signal **105** and output a sensed signal **110**′ related to leakage current **62**. The sensed signal **110**′ may be current, voltage, or any property bearing a known or determinable relationship to leakage current **62**. A target value **114**′ is set and may be 0 or any other positive or negative value. The target value **114**′ may be a target signal including a current amplitude, or a voltage. The target value **42** may include both AC and DC components. The difference between the sensed signal **110**′ and the target value **114**′ is determined to produce an error signal **44**. In an embodiment, the error signal **44** is calculated by a summation stage **40** by summing the positive target value **114**′ with the negative of the sensed signal **110**′. Many additional ways to determine the difference between a sensed signal **110**′ and target value **114**′ could be substituted for this summing process.

[0053] The error signal **44** is multiplied by a gain device **46**. The gain device **46** may increase, decrease, or allow the error signal **44** to remain the same. The gain device **46** may be circuitry, software, or a combination of the two. The gain device **46** outputs the cancellation current **122**′ that is injected into the drive signal **105**′ to offset the leakage current **62**. The human body model **50**, which represents the surgical tool **28** applied to a patient, is powered by the drive signal **105**, which includes the cancellation current **122**′. The transfer function of the control loop may be represented as: TF=G/(1+S*G). Where G represents the gain **46** and S is the sensed signal **110**′. The principles illustrated by FIG. **2** are implemented in embodiments of the surgical system **20** shown in FIGS. **4**, **5** and **7**.

[0054] Components of the surgical system **20** relevant to reducing or eliminating leakage current **62** are depicted in FIGS. **4-7**. FIGS. **4**, **5** and **7** depict embodiments with passive (first) and active (second) leakage current cancellation sources **68**, **74**, respectively.

[0055] The second current source **74** receives two inputs, namely, a sensed signal **110** and a target value **114**. In one embodiment, shown in FIG. **4**, a transformer **106** is used to sense residual leakage current **62** in the drive signal **105** and generate the sensed signal **110**. Transformer **106** comprises the drive path **104** as a primary winding. In other words, the primary winding of the transformer **106** comprises the high-side voltage conductor **100** and the low-side voltage conductor **102**. Transformer **106** has a secondary winding implementing a sensor **108**.

[0056] The sensor **108** senses common mode current in the drive path **104** and outputs the sensed signal **110** indicative of the common mode current to the second current source **74**. The common mode current provides some indication or relationship to the leakage current **62**. Mainly, the high-side voltage conductor **100** conducts current to the surgical device and the low-side voltage conductor **102** conducts current away from the surgical tool **28**. These currents **100** and **102** are ideally, equal in magnitude and opposite in polarity. When leakage current **62** is present, the magnitude of the current on the high-side voltage conductor **100** will be different from the magnitude of the current on the low-side voltage conductor **102**. This difference in current is the common mode current. Common mode current is a measurement of the current flowing in a single direction. When a common mode current is present across the drive path **104**, it generates a magnetic field that is sensed by the secondary winding, i.e., sensor **108**. In this embodiment common mode current is directly related to leakage current **62** of the drive signal **105** because common mode current will only be present when some amount of current is lost between the high-side voltage conductor **100** and the low-side voltage conductor **102**. If no leakage current **62** exists, the high-side voltage conductor **100** will have current that is equal and opposite to the current across the low-side voltage conductor **102**. In this instance both common-mode current and leakage current **62** in the powered surgical tool system is 0 or substantially 0.
[0057] In FIG. **5**, the sensor **108** is replaced by sensor **126**, which is shown as a capacitor. Sensor **126** senses voltage on the low-side voltage conductor **102** of the drive path **104**. When no leakage current **62** is present the voltage on the low-side conductor will be 0 volts, or approximately 0 volts, relative to power source **82**.
[0058] In an embodiment where the shield **99** is also electrically connected to the low-voltage conductor **102** in the surgical tool **28**, common mode current is instead the difference between the current on the high-voltage conductor **100** and the low voltage conductor **102** plus the shield **99**.
[0059] In FIGS. **4**, **5** and **7**, leakage current **62** is illustrated as a small current opposing the portion of the drive signal **105** on the low-voltage conductor **102** in order to represent current that has escaped the drive signal **105** and passed to ground through another path. This leakage current **62** is the result of current that may be lost in a number of ways and locations throughout system to, including capacitive coupling between elements of the system **20** and/or leakage of current through the patient. The leakage current **62** could be illustrated anywhere that unintended flow of current is occurring. In some instances the first cancellation current **80** and second cancellation current **122** may result in leakage current **62** that flows in a opposite direction to the direction of the leakage current **62** shown in the Figures.
[0060] The sensed signal **110** may be modified by one or more gain devices, depicted in FIGS. **4**, **5** and **7** as amplifier **112**. The sensed signal **110** is inputted to the second current source **74** for determining the second cancellation current **122**.
[0061] A second input to the second current source **74** is the target value **114**, shown to the right in FIGS. **4**, **5** and **7**. The sensed signal **110** and the target value **114** are fed into the summing amplifier **118** with amplification **120** to output the second cancellation current **122**. In FIGS. **4** and **7**, the target value **114** is a target current for comparing to the sensed signal **110**, which is used to determine the second cancellation current **122**. In this example, the target current may be, for example, 0 amps, representing ideal conditions for elimination of leakage current. In FIG. **5**, the target value **114** is a target voltage, which may be set to 0 volts, for example, also representing ideal conditions for elimination of leakage current. Other target values **114** besides those described herein are contemplated and may be utilized.
[0062] As shown in FIGS. **4**, **5** and **7**, a power source drives the second current source **74**. In the examples shown, this is the same power source **82** that energizes the transformer **90**. Additional aspects of the power source **82** as it relates to the second current source **74** are described below. Alternatively, the power source that powers the second current source **74** may be different from power source **82**. The target value **114** may have some amount of DC offset because DC power

source **82** is used to energize the second cancellation current **122**. The target value **114** may be modified by gain device **116** and then used as an input into summing amplifier **118** with additional amplification stage **120**. The summing amplifier **118** with amplification **120** determines the difference between the target value **114** and the sensed signal **110**. The summing amplifier **118** with amplification **120** then outputs the second cancellation current **122**.

[0063] Before the second cancellation current is injected into the drive path **104**, a capacitor **124** may be used to block any DC component of the second cancellation current **122** from entering the drive path **104**. In some embodiments, the capacitor **124** uses low capacitance.

[0064] This second cancellation current **122** cancels at least some of the residual leakage current **62** that remains when the first leakage current cancellation **80** is injected. Regardless of the type of sensor **106**, **126** used, the second cancellation current **122** will both modify the magnitude of the current on the low-side voltage conductor **102** so that it more closely matches the magnitude of the current on the high-side voltage conductor **100**, and will bring the voltage relative to the power source **82** closer to 0 volts.

[0065] Non-disclosed equivalents of the active current leakage cancellation techniques shown in FIGS. **4**, **5** and **7** are fully contemplated. The schematic representations shown in FIGS. **4**, **5** and **7** may include additional or different components from those specifically shown while still producing suitable cancellation currents, as contemplated.

B. Open Loop Control Current Cancellation Control

[0066] FIG. **6** shows another embodiment of the second current source **74** used to generate the second current cancellation current **122**. In this embodiment, a measurement from the drive signal **105** is not utilized. Instead, a sensor **130** is included to measure the AC signal generated by transformer **90**. In one example, the AC signal is a voltage of the surgical tool **28** hand piece. The sensor **130** could be part of or in addition to transformer **90**. In the embodiment in FIG. **6**, the sensor **130** is transformer winding.

[0067] Sensor **130** measures the AC signal generated across transformer **90** and sends the sensed signal to a gain stage **132** that is configured to scale the AC signal from the sensor **130**. The variable gain device **132** may be part of the second current source **74**, or may be separate therefrom.

[0068] A selection interface **134** is coupled to the second current source **74** and to the gain stage **132**. The selection interface **134** is configured to enable selection of one of a plurality of leakage current adjustment settings. The leakage current adjustment settings provide user-selectable fine-tuning cancellation of the leakage current **62**. The leakage current adjustment settings can be saved in a look-up table in the control console **22** memory.

[0069] In the example shown in FIG. **6**, the selection interface **134** is a potentiometer, which may be adjustable circuitry or a digital potentiometer controlled by software. The selection interface **134** may also be implemented by a user interface on the display **34** of the control console **22**. Other types of selection interfaces for enabling selection of leakage current adjustment settings are contemplated.

[0070] The selection interface **134** enables easier adjustment of positive or negative leakage currents. Adjustments may be made to enable the control console **22** to meet the IEC 60601, or any additional or different standard for leakage current.

[0071] The selection interface **134** is coupled to the sensor **130** through the first gain stage **132**. The selection interface **134** receives a scaled version of the AC signal from the first gain stage **132**. The selection interface **134** is coupled to a variable gain amplifier **138** that can adjust the gain from −1 to +1 based on the selection interface **134** adjustment setting. In instances where the selection interface **134** is a potentiometer, the variable gain amplifier **138** comprises an output **136** interfacing with the potentiometer to variably operate the same.

[0072] In one embodiment, the selection interface **134** is adjusted as part of the manufacturing process. This enables greater manufacturing tolerances and ensures that each control console **22** meets requirements to minimize leakage current.

[0073] The output of amplifier **138** is then fed to a power amplifier **140** that makes use of a power source, such as the power source **82** that powers the drive signal **105**. In the alternative, the second current source **74** could use a separate power source. Amplifier **140** outputs the second cancellation current **122** into the drive signal path **104**. The second cancellation current **122** is DC blocked by capacitor **124** before being injected into the drive signal path **104**.

[0074] As with the embodiments described in the previous section in relation to FIGS. **4**, **5** and **7**, the second cancellation current **122** generated in the embodiment of FIG. **6** may be utilized in conjunction with the first cancellation current **80** generated by the first current source **68** to thereby provide fine tuning for cancellation of the leakage current **62**.

[0075] Non-disclosed equivalents of the active current leakage cancellation techniques shown in FIG. **6** are fully contemplated. The schematic representation shown in FIG. **6** may include additional or different components from those specifically shown while still producing suitable cancellation currents, as contemplated.

C. Variable Power Source for Second Current Source

[0076] For any of the embodiments described herein, and shown in FIG. **4-7**, the power source **82** coupled to the primary winding **84** of the transformer **90** may be a variable power source. According to one example, the power source **82** has a variable output DC voltage level that can be set. In one embodiment, this voltage is between 25 and 250 VDC. Other types of power sources with or without variable voltage levels may also be used. The voltage of the signal out of the power source **82** is set based on a power source control signal applied to the power source **82**. The power source **82** may apply a DC input signal to a center tap of the primary winding **84** of the transformer **90**. The DC input signal from power source **82** may have a potential that varies. Specifically, the potential of this input signal may be set to vary as a function of the potential of the drive signal **105** that is to be applied to the power generator **27** of the surgical tool **28**.

[0077] This variable power source **82** may be utilized to energize, drive or otherwise provide input to any of the second current sources **74** shown throughout the Figures. The second current source **74** may be coupled to the path of the drive signal **104** and coupled to the variable power source **82**. The variable power source **82** is configured to energize the current source **74** and the current source **74** (energized by the variable power source **82**) is configured to generate the cancellation current **122** to inject into the path **104** of the drive signal to cancel leakage current of the drive signal.

[0078] Specifically, the DC input signal from power source **82** applied to the primary winding **84** may also be used as an input into one or more of the amplifiers **120** or **140** of the second current source **74**, shown in FIGS. **4**, **5**, and **7**. Specifically, this DC input signal may be used as the positive voltage to facilitate the amplification of the signal produced by the second current source **74** to ensure the signal is at the correct voltage. In these versions, this DC signal may also be applied to the second current source **74** as an input signal, shown in FIGS. **4**, **5**, and **7** as Power Source **82** feeding into the stage that generates target value **114**. The second current source **74** includes a feedback sub-circuit that adjusts the target value **114** from this variable power source **82** so the signal does not drift as a result of changes in the DC positive voltage applied to the one or more amplifiers. In the embodiment shown in FIG. **6**, the second current source **74** is energized by the variable power source **82** connected to amplifier **140**.

[0079] The variable power source **82** drives the second cancellation current **122**. In one embodiment, this is the same power source **82** that energizes the drive path **104** for the surgical tool **28**. Using the same power source **82** provides benefit because the power needed to drive the second cancellation current **122** varies in proportion to the power of the drive signal **105**. Alternatively, a separate power source may be used to drive the second leakage current source **74**.

[0080] While reusing the variable power source **82** to energize the leakage current cancellation sources is advantageous, embodiments may include a separate power source to generate the second cancellation currents **122**.

[0081] The variable power source **82** may have configurations and capabilities other than those shown in the Figures and described herein. Moreover, the variable power source **82** may be coupled to components of the control console **22** other than those shown in the Figures.

D. Fault Detection Techniques for Leakage Current

[0082] FIG. **7** shows the same components as FIG. **4** with the addition of a fault detection stage **144**, which can be implemented by circuitry and/or software.

[0083] The fault detection stage **144** is coupled to the sensor **106** or alternatively sensor **126** from FIG. **5**. The fault detection stage **144** is configured to receive the sensed signal **110** from the sensor **106**, **126** and to generate a fault detection signal **158** for detection of a fault condition related to leakage current **62**.

[0084] If the sensed signal **110** indicates levels of leakage current **62** beyond a specified threshold, it could be due to a fault in the system **20**, such as a short or a connection of the patient to ground. When leakage current **62** is excessive, the fault detection stage **144** triggers the fault detection signal **158** at a GPIO (general purpose input/output) line.

[0085] A controller **160** is coupled to the fault detection stage **144**, e.g., at the GPIO line, and is configured to receive the fault detection signal **158** from the fault detection stage **144** and to determine the fault condition related to leakage current **62**. The controller **160** may have one or more microprocessors for processing instructions or for processing an algorithm stored in memory to control operation of the control console **22**. Additionally or alternatively, the controller **160** may comprise one or more microcontrollers, field programmable gate arrays, systems on a chip, discrete circuitry, and/or other suitable hardware, software, or firmware that is capable of carrying out the functions described herein. The fault detection stage **144** and controller **160** may be combined or separate elements.

[0086] The fault detection stage **144** is configured to sense presence of the fault detection signal **158** for a predetermined period of time and to send the fault detection signal **158** to the controller **160** when the predetermined period of time is reached. The fault detection stage **144** may do so to ensure that persistent fault is detected and to avoid false alarms based on negligible or intermittent signal spikes.

[0087] The controller **160** receives the fault detection signal **158** from the GPIO line and is configured to compare the fault detection signal **158** to a target value to determine the fault condition. The controller **160** can decrease or terminate power to the surgical tool **28** in response to determination of the fault condition. The controller **160** may trigger other responses for the control console **22** or surgical tool **28** other than those described herein.

[0088] FIG. **8** shows one embodiment of the fault detection stage **144**. In certain embodiments, the fault detection stage **144** only becomes active when the sensed common mode current or the low-side voltage surpasses a specified level. The sensed signal **110** may be modified by amplifier **112**. This amplifier **112** may be the same as the first gain stage used to generate the second cancellation current **122** or it may be a separate gain device. The sensed signal **110** is then fed to low pass filter **146** and rectifier **148**. The low pass filter **146** will remove higher frequency signals beyond a specified threshold. Low pass filter **146** may also attenuate the signal, if it is relatively close to the filter frequency. A gain device, depicted as amplifier **148**, may be used to change the amplitude of the sensed signal **110** in response to any attenuation. During a fault condition, sensed signal **110** will pulse every drive cycle (e.g. when the drive signal **105** is at maximum amplitude the common mode current sensed by sensor **108** will be as a maximum, when the drive signal **105** is at a minimum common mode current will approach 0). A filter comprising capacitor **150** and resistor **152** is put in place to hold the fault condition at its maximum level between pulses. The RC time constant of the filter is the capacitance of capacitor **150** multiplied by the resistance of resistor **152**. The fault signal is then output to an inverter **154**, which inverts the applied signal to output the fault signal **158** to controller **160**. The controller **160** monitors the signal and when fault condition exists for a specific period controller **160** can take appropriate action with the system as necessary.

Actions taken by controller **160** include alerting the operator of the surgical tool **28** via the display **34**, reducing the power output by power source **82**, and/or shutting off power to the surgical tool **28**.

[0089] The fault detection stage **144**, controller **160**, and components thereof may be different from that described herein while still realizing the capabilities for detecting leakage current faults, as described herein.

[0090] Several embodiments have been described in the foregoing description. However, the embodiments discussed herein are not intended to be exhaustive or limit the invention to any particular form. The terminology, which has been used, is intended to be in the nature of words of description rather than of limitation. Many modifications and variations are possible in light of the above teachings and the invention may be practiced otherwise than as specifically described.

[0091] The many features and advantages of the invention are apparent from the detailed specification, and thus, it is intended by the appended claims to cover all such features and advantages of the invention which fall within the true spirit and scope of the invention. Further, since numerous modifications and variations will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation illustrated and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

Claims

1. A control console for supplying a drive signal to a surgical tool, the control console comprising: a transformer comprising a primary winding and a secondary winding, the primary winding being configured to receive an input signal from a power source and to induce the drive signal in the secondary winding to supply the drive signal to the surgical tool; a first current source comprising a leakage control winding coupled to a path of the drive signal, wherein the primary winding is configured to induce a first cancellation current in the leakage control winding to inject into the path of the drive signal to cancel at least a portion of leakage current of the drive signal; a sensor coupled to the path of the drive signal, wherein the sensor is configured to output a sensed signal to provide feedback related to the leakage current; and a fault detection stage coupled to the sensor and being configured to receive the sensed signal and to generate a fault detection signal responsive to detection of a fault condition related to the leakage current.

2. The control console as claimed in claim 1, wherein the fault detection stage comprises a low pass filter, a rectifier, and a filter configured to alter the sensed signal to generate the fault detection signal.

3. The control console as claimed in claim 1, further comprising a controller coupled to the fault detection stage and being configured to receive the fault detection signal from the fault detection stage and to determine the fault condition related to leakage current.

4. The control console as claimed in claim 3, wherein the fault detection stage is configured to sense presence of the fault detection signal for a predetermined period of time and to send the fault detection signal to the controller when the predetermined period of time is reached.

5. The control console as claimed in claim 3, wherein the controller is configured to compare the fault detection signal to a target value to determine the fault condition and to decrease or terminate power to the surgical tool in response to determination of the fault condition.

6. The control console as claimed in claim 1, wherein the sensor is configured to sense a current of the drive signal and to output the current of the drive signal as the sensed signal.

7. The control console as claimed in claim 1, wherein the sensor is configured to sense a common-mode current of the drive signal and to output the common-mode current of the drive signal as the sensed signal.

8. The control console as claimed in claim 7, wherein the path of the drive signal comprises a high voltage conductor and a low voltage conductor and wherein the sensor is further defined as a transformer winding disposed around both the high and low voltage conductors.

9. The control console as claimed in claim 1, wherein the path of the drive signal comprises a high voltage conductor and a low voltage conductor, and the sensor is coupled to the low-voltage conductor and is configured to sense voltage from the low voltage conductor and output the voltage as the sensed signal.

10. The control console of claim 9, wherein the sensor is a capacitor.

11. The control console as claimed in claim 1, wherein the first cancellation current is configured to cancel a first portion of the leakage current, and further comprising: a second current source coupled to the path of the drive signal; and a selection interface coupled to the second current source and being configured to enable selection of one of a plurality of leakage current adjustment settings, wherein the second current source is configured to generate a second cancellation current based on the selected leakage current adjustment setting to inject into the path of the drive signal to cancel a second portion of the leakage current.

12. The control console as claimed in claim 9, wherein the power source is a variable power source that also energizes the second current source.

13. The control console as claimed in claim 1, wherein the primary winding, the leakage control winding, and the secondary winding are configured to collectively generate a capacitance between the leakage control winding and the secondary winding.

14. A control console for supplying a drive signal to a surgical tool, the control console comprising: a variable power source; a transformer comprising a primary winding and a secondary winding, with the primary winding coupled to the variable power source and configured to receive an input signal from the variable power source and to induce a drive signal in the secondary winding to supply the drive signal to the surgical tool; a sensor configured to sense a characteristic of the input signal and to output a sensed signal related to the characteristic of the input signal; a variable gain device coupled to the sensor; a selection interface coupled to the variable gain device and being configured to enable selection of one of a plurality of leakage current adjustment settings and to provide selected leakage current adjustment setting to the variable gain device, wherein the variable gain device is configured to receive the sensed signal and to modify the sensed signal based on the selected leakage current adjustment setting; and a current source coupled to a path of the drive signal and the variable gain device, wherein the variable power source is configured to energize the current source, and the current source is configured to generate a cancellation current to inject into the path of the drive signal to cancel leakage current of the drive signal based on the modified sensed signal from the variable gain device.

15. The control console as claimed in claim 14, further comprising: a second sensor coupled to the path of the drive signal, wherein the second sensor is configured to output a second sensed signal to provide feedback related to the leakage current; and a fault detection stage coupled to the second sensor and being configured to receive the second sensed signal and to generate a fault detection signal responsive to detection of a fault condition related to the leakage current.

16. The control console as claimed in claim 15, wherein the fault detection stage comprises a low pass filter, a rectifier, and a filter configured to alter the second sensed signal to generate the fault detection signal.

17. The control console as claimed in claim 15, further comprising a controller coupled to the fault detection stage and being configured to receive the fault detection signal from the fault detection stage and to determine the fault condition related to leakage current.

18. The control console as claimed in claim 17, wherein the fault detection stage is configured to sense presence of the fault detection signal for a predetermined period of time and to send the fault detection signal to the controller when the predetermined period of time is reached.

19. The control console as claimed in claim 17, wherein the controller is configured to compare the fault detection signal to a target value to determine the fault condition and to decrease or terminate power to the surgical tool in response to determination of the fault condition.

20. A method of operating a control console for supplying a drive signal to a surgical tool, the control console comprising a transformer comprising a primary winding and a secondary winding, a first current source comprising a leakage control winding coupled to a path of the drive signal, a sensor coupled to the path of the drive signal, and a fault detection stage coupled to the sensor, the method comprising: receiving, with the primary winding, an input signal from a power source; inducing, with the primary winding, the drive signal in the secondary winding; supplying, with the secondary winding, the drive signal to the surgical tool; inducing, with the primary winding, a first cancellation current in the leakage control winding; injecting, with the first current source, the first cancellation current into the path of the drive signal to cancel the leakage current of the drive signal; outputting, with the sensor, a sensed signal to provide feedback related to the leakage current; receiving, with the fault detection stage, the sensed signal; and generating, with the fault detection stage, a fault detection signal responsive to detection of a fault condition related to the leakage current.
