Power Processing System

Statement of Federally Sponsored Research and Development

1. This invention was made with government support under 15-C-0176 awarded by the Department of Defense. The government has certain rights in the invention.

TECHNICAL FIELD

1. This invention relates generally to the power processing field, and more specifically to a new and useful variable polarity controllable power processing system in the power processing field.

BRIEF DESCRIPTION OF THE FIGURES

1. FIGURE 1 is a schematic representation of a variation of the power processing system.
2. FIGURE 2 is a schematic representation of a variation of the power processing system with a half-bridge inverter.
3. FIGURE 3 is a schematic representation of a variation of the power processing system with a full-bridge inverter.
4. FIGURE 4 is a schematic representation of an example full-bridge inverter of the power processing system.
5. FIGURE 5 is a schematic representation of an example half-bridge inverter of the power processing system.
6. FIGURES 6A-B are schematic representations of voltage amplification stages of a portion of a variation of the power processing system.
7. FIGURE 7 is a flowchart of data and/or power flows in a variation of the power processing system.
8. FIGURE 8 is a flowchart of data and/or power flows in a variation of an output assembly of the power processing system.
9. FIGURE 9 is a schematic representation of polarity-selectable input stages of a portion of a variation of the power processing system.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

1. The following description of the preferred embodiments of the invention is not intended to limit the invention to these preferred embodiments, but rather to enable any person skilled in the art to make and use this invention.
2. As shown in FIGURE 1, the system includes a control module, a feedback isolator, and an output assembly which includes an inverter, a transformer, and a power rectifier. The system functions to provide polarity-switchable feedback-controlled high voltage power. The system can additionally function to transfer and/or mitigate (e.g., negate) charge buildup of an unpredictable or varying polarity. The system can additionally or alternatively include a power source, housing, primary load, and secondary load. The system can include multiple output assemblies connected to and controlled by a single control module and a single feedback isolator, but there can be any other suitable correspondence between control module(s), feedback isolator(s), and one or more output assemblies (e.g., two control modules connected to and controlling two pairs of output assemblies, each control module and each output assembly connected to a single feedback isolator). Components of the system are preferably radiation-hardened (e.g., operable in a space environment exposed to solar radiation, gamma-ray burst radiation, Van Allen radiation, etc.) but can alternatively be non-radiation hardened.
3. Variants of the system can be operable between several modes. In some variations, the system is operable in a dual output mode (e.g., two output assemblies are operated to generate equal and opposite high voltage outputs by the control module, which receives feedback from the feedback isolator, which receives feedback inputs from the output of each output assembly). In some variations, the system is operable in a single output mode (e.g., a single output assembly is operated to produce either a positive or negative polarity high voltage output, which is switchable and/or controllable during operation without cessation of high voltage power provision). In alternative variations, the system can be configured to operate any suitable number of output assemblies at any suitable output voltage and output polarity.
4. The power processing system can be used with (or include) one or more of the following related systems or components (e.g., as loads, as input power sources): a charged-particle thruster (e.g., an ionic colloid thruster), which can include an electrostatic emitter array and an extractor grid; an ionic particle-removal fluid filter; and/or any other suitable system. The extractor grid of an ionic colloid thruster can be operated by operating the grid at a high voltage (e.g., an extraction potential, 500 volts, 1 kilovolt, etc.) relative to the emitter, which can cause polarized droplets to form at the tip of each electrostatic emitter and to be expelled axially through and past the grid, creating thrust in the opposite direction. Droplets formed from the ionic liquid (e.g., conductive liquid, colloid) have a net charge, and the expulsion of the droplets can lead to charging of the system utilizing the thruster (e.g., spacecraft, aircraft, watercraft, etc.) unless equal and opposite charge is also removed from the system. Accordingly, such a thruster is preferably operated using multiple emitter arrays, with emitter-extractor potential differences energized to achieve equal and opposite extraction currents (e.g., with extractor grids charged at equal and opposite-polarity extraction potentials) to generate and accelerate ions, wherein the total net charge of the system after ion-expulsion is at or near zero (e.g., as near to zero as possible in order to prevent system charging). Such a thruster can additionally or alternatively be operated using a single-polarity array, wherein the charging polarity is periodically switched (e.g., from positive to negative, negative to positive) to mitigate space-charge buildup of the system (e.g., operated for equal time duration in each polarity mode to produce net-zero charge on the system after an even number of positive and negative-polarity operation periods). An ion thruster or electrospray thruster can additionally or alternatively be operated using the power processing system in any other suitable manner, including without switching the charging polarity. Variants of the power processing system as described herein can provide the features for operating ion thrusters in the manner described above, as well as any other suitable systems in any other suitable manner.
5. The power processing system can include circuits and subcircuits, some of which can include ground connections. Such ground connections can include connections to Earth-ground, chassis ground, and/or any other suitable reference potential. The power processing system includes electrical connections to and between active and passive components. Each component in a serial connection has an “upstream” connection point and a “downstream” connection point, wherein the upstream connection point is the point at which current flowing in the conventional current direction would enter the component if a positive polarity voltage source were placed across the component, and wherein the downstream connection point is the point at which conventionally flowing current would exit the component if a positive polarity voltage source were placed across the component. For diodes and other nominally polarity-dependent components, the upstream connection point is defined relative to the direction that current can pass through the component during normal operation (e.g., operation in the designed direction for the diode or similar component).
6. In a specific example, the system includes one control module, one feedback isolator, and two output assemblies. The first output assembly has a first inverter, a first transformer, and a first power rectifier; the first output assembly also generates a positive polarity output sense signal. The second output assembly has a second inverter, a second transformer, and a second power rectifier; the second output assembly also generates a negative polarity output sense signal. The control module receives a voltage magnitude set point (e.g., from an external source, via a direct electrical data connection) and, by way of a direct electrical connection, controls the first and second inverters by way of pulse width modulated (PWM) voltage signals (e.g., transmitted over direct electrical connections between the control module and the inverters) to convert an input direct-current (DC) low power source into a positive polarity (at the first inverter output) and a negative polarity (at the second inverter output) alternating current (AC) waveform at low voltage (e.g., having an RMS voltage magnitude less than one tenth of the desired output voltage magnitude, less than 1/100th, 0.1% of the desired output voltage magnitude, etc.). Parameters of the PWM voltage signals (e.g., magnitude, duty cycles, frequency, etc.) are determined by the control module according to the voltage magnitude set point, based on feedback received (e.g., by way of direct electrical connection) from the feedback isolator. At each output assembly, the low voltage AC waveform is passed through the primary winding of the first and second transformer, respectively, which produces a medium voltage (e.g., a factor of 10 greater than the low voltage, a factor of 2, a factor of 100, a factor of 1000, etc.) AC waveform across the secondary winding of the first and second transformer, respectively. In the first output assembly, which is operated to produce positive polarity high voltage output, the medium voltage AC waveform is directed (e.g., via direct electrical connection) from the first transformer to the positive polarity input of the first power rectifier. In the second output assembly, which is operated to produce negative polarity high voltage output, the medium voltage AC waveform is directed (e.g., via direct electrical connection) from the second transformer to the negative polarity input of the second power rectifier. The medium voltage AC waveform can be directed to either the positive or negative polarity input(s) of the power rectifier by a controllable switch (e.g., a relay) connected to the control module and connecting the output of the transformer to either the positive or negative polarity input of the power rectifier dependent upon the state of the switch, wherein the control module can actuate the switch in order to change its state and thereby switch the output polarity of the associated power rectifier. The first power rectifier converts the medium voltage AC waveform to a positive high voltage DC output (e.g., by way of a series of voltage doubling circuits), which can then power a connected load. The feedback isolator is also directly connected to the output of the first power rectifier by a first sense pathway, such that a first output sense signal proportional to the output voltage of the first power rectifier and of the same polarity (e.g., positive) is transmitted to and received by the feedback isolator. The second power rectifier converts the medium voltage AC waveform to a negative high voltage DC output (e.g., by way of a series of voltage doubling circuits), which can then power a connected load. The feedback isolator is also directly connected to the output of the second power rectifier by a second sense pathway, such that a second output sense signal proportional to the output voltage of the second power rectifier and of the same polarity (e.g., negative) is transmitted to and received by the feedback isolator. The feedback isolator generates two feedback signals: the first feedback signal is generated based on the first output sense signal (e.g., by amplifying, attenuating, filtering, transforming, or performing any other suitable signal processing on the first output sense signal), and the second feedback signal is generated based on a rectified second output sense signal (e.g., based on a positive polarity signal produced upon rectification of the second output sense signal). The two feedback signals are provided to the control module (e.g., via direct electrical connections), which adjusts the output control signals (e.g., the PWM signals) based on deviation(s) of the feedback signals from the output voltage set point (e.g., the PWM duty cycle is increased in order to raise the output voltage when the feedback signals fall below the output voltage set point, a proportional-integral-derivative controller is used with the feedback signals as the inputs and the output control signals as the outputs, etc.); however, the control module can additionally or alternatively adjust the output control signals in any suitable manner to control the output assemblies.
7. In an example implementation of the system, as shown in FIGURE 7, a control module, an output assembly, and a feedback isolator are mutually coupled. The control module can generate control signals and provide the control signals to the output assembly, which receives input power and transforms the input power into high voltage (HV) output power. The output assembly also generates sense signals (e.g., signals encoding data about the output HV power, such as voltage level, current level, etc.) and provides the sense signals to the feedback isolator. In this example, the feedback isolator isolates the feedback polarity (e.g., rectifies negative polarity feedback to generate positive polarity feedback) and generates feedback signals, which the feedback isolator provides to the control module. The control module can generate the control signals based on the feedback signals, external instructions, a combination of feedback signals and external instructions, or based on any other suitable instructions or signals.
8. In an example implementation of an output assembly of the system, as shown in FIGURE 8, an inverter, a transformer, and a power rectifier are mutually coupled. The inverter receives low voltage DC input power and drive signals, and converts the low voltage DC input to a low voltage AC waveform (e.g., an output) under control of the drive signals. The transformer transforms the low voltage AC waveform into a medium voltage AC waveform, and provides current sense signals (e.g., signals encoding data about the output current) to an external signal receiver (e.g., a feedback isolator). The power rectifier converts the medium voltage AC waveform into a high voltage DC output, and provides voltage sense signals (e.g., signals encoding data about the output voltage) to an external signal receiver (e.g., a feedback isolator). The power rectifier of this example implementation is preferably a directional power rectifier (e.g., rectifies current flowing in one direction), but can alternatively be non-directional.
9. Variants of the power processing system can confer several benefits. Some variants can reduce wear on system components (e.g., loads, high-voltage active electrostatically charged components) while enabling efficient high-voltage operation (e.g., operation at high voltage for longer time than using other power sources) by allowing the polarity to be switched. Variants of the system can reduce the weight of weight-sensitive vehicles (e.g., spacecraft) by reducing the weight and/or number of components of the power processing system, because M (e.g., any integer number M) output assemblies can be controlled using a single isolated feedback loop (e.g., instead of using M feedback-enabled control modules). Variants of the system can provide feedback-controlled, equal-magnitude, opposite-polarity high voltage power to two loads (e.g., electrostatic ion accelerators) to generate equal power dissipation (e.g., in generating thrust) without space-charge buildup. Variants of the system can siphon charge buildup from loads that build up static charge of unpredictable and/or varying polarity (e.g., aircraft in flight, vehicles moving through the air and isolated from a charge source/sink, etc.). Variants of the system can apply switchable-polarity high-potential electric fields to the outputs of electrostatic precipitators in order to extract charged particulates from fluid streams (e.g., to extract and thereby reduce emitted pollutants). Variants of the system including adjustable-voltage outputs can enable ion implantation (e.g., for ions having similar charge per ion) at varying depths via electrostatic acceleration, and/or at similar depths (e.g., for ions having varying charge per ion). Variants of the system can provide a robust power processing system that can withstand the rigors of a space environment (e.g., thermal stress, radiation stress, etc.) as well as a launch environment (e.g., acoustic stress, vibration, etc.). Variants of the system can additionally or alternatively provide dual opposite-polarity outputs that cooperatively define a virtual ground, such that other components of the system and related components can be electrically referenced to the virtual ground.
10. The control module functions to set the output voltage, current, and polarity of the output assembly. The control module can additionally function to receive external commands (e.g., manually or automatically generated by a ground control system or team, automatically generated by a command module of a spacecraft). The control module can additionally function to provide operational data (e.g., state information regarding the power processing system, real time performance and/or power consumption of the power processing system, the output current and/or voltage transmitted to a load, etc.) to other related systems (e.g., a spacecraft computer, command module, etc.). The control module is communicatively coupled to (and controls) the inverter of the output assembly, the feedback isolator, and to the secondary side of the transformer of the output assembly. The control module is preferably coupled to the inverter by direct electrical connections (e.g., wires, traces) but can be otherwise coupled. The system preferably includes a single control module, but can alternatively include any number of control modules. The system preferably includes a single control module per output assembly, but can alternatively include a single control module per pair of two output assemblies or any other suitable ratio of control modules to output assemblies and/or other components of the system. The control module preferably includes a microcontroller, a first combiner, a second combiner, a gate driver, and a polarity selector, but can include any other suitable component. The control module can optionally include a PWM controller, as well as any other suitable controller.
11. The control module can be operable between several modes. The control module can be operated in a direct PWM mode, wherein the microcontroller provides PWM control signals directly to the gate driver (e.g., without feedback and without a PWM controller); alternatively, the control module can include the PWM controller and the PWM controller provides PWM control signals (e.g., generated based on feedback) to the gate driver. The control module can be operated in positive (or negative) output polarity mode, wherein the control module selectively completes a circuit (e.g., using a SPST relay, or any other suitable relay or switch) between the secondary side (e.g., output) of the transformer and the positive (or negative) polarity input of the power rectifier, which results in current flow through the power rectifier such that the output potential of the power rectifier is positive (or negative). In one variation, the control module preferably provides 2\*M polarity control signals to 2\*M single-pole single-throw (SPST) relays, where M is the number of output assemblies controlled by the control module. However, the control module can alternatively provide M polarity control signals to M dual-pole single-throw (DPST) relays, or provide any other suitable number of polarity control signals. The control module can be operable in feedback control mode (e.g., voltage controlled, current controlled), wherein the microcontroller provides a voltage command signal to the first combiner, which receives M voltage feedback signals from the feedback isolator and generates and provides a combined voltage command signal to the PWM controller. The microcontroller also generates and provides a current command signal to the second combiner, which receives a current feedback signal from the feedback isolator and generates and provides a combined current command signal to the PWM controller. The PWM controller preferably provides control signals to M gate drivers based on the combined current and/or voltage command signals (e.g., when operated in current-controlled mode and/or voltage-controlled mode), but can alternatively provide control signals to any number of gate drivers. Each gate driver generates P drive signals, wherein P is equal to the number of switches in the inverter (e.g., P = 4 for a full bridge inverter, P=2 for a half bridge inverter), and provides the P drive signals to the gate terminals of the switches (e.g., MOSFETs) of the inverter according to the control signals received from the PWM controller. In variations, each gate driver can alternatively generate a single drive signal (e.g., wherein P=1). Each of the signals described above (e.g., control signals, command signals, feedback signals) can be analog or digital, at any suitable voltage level (e.g., TLL voltage, 3.3 volts, etc.), and can correspond to any suitable data transfer protocol or format (e.g., binary logic levels, I2C, modulated waveform, etc.). Signals are preferably transmitted over direct electrical connections (e.g., wires, conductive pathways, traces) but can alternatively be otherwise transmitted (e.g., wirelessly, such as through inductive coupling).
12. The microcontroller functions to generate control outputs, and to transmit control outputs to other components of the system. The microcontroller can additionally function to receive external instructions, execute preprogrammed instructions, or any combination thereof. The microcontroller is preferably electrically connected to each output assembly by one positive and negative output control pair, to the first combiner by a signal pathway, and to the second combiner by a signal pathway. However, the microcontroller can be otherwise connected. The microcontroller can optionally be directly connected to the gate driver (e.g., for operation in direct PWM control mode) by a signal pathway.
13. The first combiner functions to combine voltage feedback signals and the voltage control command signal to generate the combined voltage command signal, and to provide the combined voltage command signal to the PWM controller. As such, the first combiner is connected to the feedback isolator by a number of signal pathways equal to the number of voltage feedback signals (e.g., one per output assembly) and to the microcontroller by a signal pathway (e.g., over which the voltage command signal is transmitted). In a specific example, the first combiner includes: a first summing junction at which a first voltage feedback signal is summed with an inverted voltage command signal to generate a first residual signal; a second summing junction at which a second voltage feedback signal is summed with the inverted voltage command signal to generate a second residual signal; a comparator junction connected to the outputs of the two summing junctions at which the residual signal (e.g., error signal) with the greatest magnitude is selected and provided as an output (e.g., the combined voltage command signal) to the PWM controller.
14. The second combiner functions to combine the current feedback signal and the current command signal to generate the combined current command signal, and to provide the combined current command signal to the PWM controller. As such, the second combiner is connected to the feedback isolator by a signal pathway and to the microcontroller by a signal pathway (e.g., over which the current command signal is transmitted). In a specific example, the second combiner includes: a summing junction at which the current feedback signal is summed with an inverted current command signal to generate a residual signal which is provided as an output (e.g., the combined current command signal) to the PWM controller.
15. The gate driver functions to control and power (e.g., drive) the inverter (e.g., the switches of the inverter). The gate driver is connected to the PWM controller by one or more signal pathways, to the inverter by a number of signal pathways corresponding to the number of switches of the inverter and can optionally be connected directly to the microcontroller by one or more signal pathways (e.g., for operation in direct PWM control mode). There is preferably a single gate driver per inverter, but can alternatively be any suitable number of gate drivers associated with any suitable number of inverters (e.g., a single gate driver per switch of each inverter, a single gate driver for all switches of multiple inverters, etc.). The gate driver preferably outputs PWM square-wave signals at a voltage level and current capacity at which the switches of the inverter are designed to operate (e.g., according to manufacturer specifications, 3.3 volts peak to peak, 5 volts peak to peak, etc.) but can alternatively output any suitable drive signals at any suitable power levels. The output characteristics (e.g., voltage level, current level, pulse widths, pulse frequency, etc.) are preferably determined by the PWM controller, but can alternatively be determined by the microcontroller or otherwise suitably determined. Drive signals are preferably carried over signal pathways connecting the gate driver and the inverter (e.g., switches of the inverter), but can be otherwise carried or transmitted. Each drive signal is preferably carried over a single signal pathway, but alternatively multiple drive signals may be multiplexed over a single signal pathway and/or a branched signal pathway; however, drive signals can be otherwise suitably carried. The gate driver preferably outputs a number of drive signals equal to the number of switches of the inverter (e.g., two drive signals for an inverter including a half-bridge, four drive signals for an inverter including a full-bridge), but can alternatively output any suitable number of drive signals associated with any suitable number of switches.
16. The polarity selector functions to select the output polarity of the output assembly (e.g., the output polarity of the power rectifier) based on the output control signal generated by the control module. For example, as shown in FIGURE 9, the polarity selector can be a pair of SPST relays that connect the secondary winding of the transformer between ground and either the positive or negative polarity inputs of the power rectifier, respectively, and each SPST is either in a closed or open state based on the output polarity control signal. However, the polarity selector can include any suitable switches for redirecting the output of the secondary winding of the transformer (e.g., solid state relays, MOSFETs, BJT transistors, etc.).
17. The control module can optionally include a PWM controller, which functions to control the gate driver based on combined command signals received from the first and second combiners. The PWM controller can additionally function to control the gate driver based on the operating mode of the system (e.g., current-controlled mode, voltage-controlled mode), which can correspond to different output waveforms of the PWM controller (e.g., fixed frequency and variable duty cycle square-wave output in voltage-controlled mode, fixed duty cycle and variable frequency square-wave output in current-controlled mode, etc.). In a first variation, the PWM controller outputs a control signal to the gate driver with a signal characteristic (e.g., RMS magnitude, frequency) that is selected in response to variation of the current feedback signal away from a current set point (e.g., desired output current magnitude); in a second variation, the control signal characteristic is selected in response to variation of the voltage feedback signal away from a voltage set point (e.g., desired output voltage). In both these variations and related variations, the output of the PWM controller is determined based on (e.g., in response to, in direct relation to) the combined voltage and/or current command signals received from the first and/or second combiners (e.g., the output is feedback-controlled). However, the output of the PWM controller can be otherwise determined.
18. The inverter of the output assembly functions to convert the input power to an AC waveform. The inverter includes a set of switches, each of which is connected to the gate driver by a signal pathway. The inverter is also connected to the input power source, which is preferably a low voltage DC source (e.g., 10 V, 40 V, 100 V, or any other suitable voltage). The output AC waveform of the inverter is preferably a square wave (e.g., equal duty cycle square wave) that alternates between the positive or negative input voltage and ground. Alternatively, the output waveform can alternate between 0V and the input voltage (Vin), between +/- Vin/2, or any other suitable voltages less than or equal to Vin. In further alternatives, the output waveform can be any suitable AC waveform (e.g., sinusoidal, a discrete approximation of a sine wave, unequal duty cycle square wave, etc.).
19. The switches of the inverter function to selectively open and close portions of the inverter circuit to convert the low voltage DC input power to an AC output waveform (e.g., invert the input power). Each switch includes a control input (e.g., gate connection) that is connected to the gate driver by a signal pathway. The gate driver preferably controls (e.g., actuates) the switch to change state (e.g., change between an open and closed state, change between a closed and open state) to conductively connect (or disconnect) an upstream side of the switch with a downstream side of the switch. The switches can be any suitable type of switch (e.g., N-type or P-type transistors, MOSFETs, FETs, high speed solid-state relays, silicon-controlled rectifiers, or any other suitable switch).
20. As shown in FIGURES 2 and 4, a first specific example of the inverter is a full-bridge inverter that includes four switches. In this example, the upstream side of the first switch is connected to the input power and the upstream side of the second switch. The downstream side of the first switch is connected to the high side (e.g., the side closest to the input power connection in the circuit between the input power and ground) of the transformer primary winding and the upstream side of the third switch. The upstream side of the second switch is connected to the input power and the upstream side of the first switch. The downstream side of the second switch is connected to the low side (e.g., the side farthest from the input power connection in the circuit between the input power and ground) of the primary winding of the transformer and the upstream side of the fourth switch. The upstream side of the third switch is connected to the high side of the transformer primary winding and the downstream side of the first switch. The downstream side of the third switch is connected to ground and the downstream side of the fourth switch. The upstream side of the fourth switch is connected to the low side of the transformer primary winding and the downstream side of the second switch. The downstream side of the fourth switch is connected to the downstream side of the third switch and ground. Each switch has a gate connection that is connected to the gate driver of the control module.
21. As shown in FIGURES 3 and 5, a second specific example of the inverter is a half-bridge inverter that includes two switches. The input power is connected to a center tap of the transformer primary winding. The upstream side of the first switch is connected to a first side of the transformer primary winding. The downstream side of the first switch is connected to ground and to the downstream side of the second switch. The upstream side of the second switch is connected to a second side of the transformer primary winding. The downstream side of the second switch is connected to ground and the downstream side of the first switch. Both switches have a gate connection that is connected to the gate driver of the control module.
22. The transformer of the output assembly functions to increase the AC input power voltage to a medium voltage AC waveform. The transformer includes a primary side and a secondary side, which are preferably a primary winding and a secondary winding but can alternatively take any suitable form. The windings can be made of any conductive material (e.g., copper) and can optionally include a ferrous core. Alternatively, the transformer can be a ceramic piezotransduction transformer, or any other suitable step-up transformer. The transformer is preferably connected at the primary side to the inverter, and at the secondary side to the power rectifier (preferably by way of the polarity selector of the control module, but alternatively directly connected or otherwise suitably connected). The transformer can be center-tapped (e.g., input power is connected at a center turn of the primary winding and the inverter is connected at each end of the winding) or end-tapped (e.g., input power and ground are switchably connected to each end of the primary winding), or otherwise tapped in any suitable manner
23. The power rectifier of the output assembly functions to convert the medium voltage AC waveform to a high voltage DC output. The power rectifier can additionally function to provide polarity-selectable (e.g., via the polarity selector of the control module) and magnitude-controllable (e.g., via a variable tap output) output voltage to a load. The power rectifier can additionally function to multiply the magnitude of the input voltage in producing the output voltage (e.g., amplify the voltage, step-up the voltage). The system preferably includes a single power rectifier per output assembly, but can alternatively include any suitable number of power rectifiers (e.g., cascaded/serial power rectifiers, parallel power rectifiers, or any combination thereof). The power rectifier preferably includes one or more voltage doubling stages, and can optionally include a half-doubling stage and a variable-tap output; additionally or alternatively, the power rectifier can include any suitable components for rectification. In a first variation, the power rectifier includes an N-stage (e.g., 3 stage, 5 stage, 50 stage) voltage doubling ladder (e.g., with a maximum output voltage of 2N times the peak output voltage of the transformer secondary side) with a selectable (e.g., variable) tap output, that can be selectively connected (e.g., by the control module in cooperation with a multi-position selectable switch) to a node between any two stages of the ladder, enabling any even integer multiple of the voltage input to the ladder to be obtained at the output. The power rectifier preferably has a positive polarity input and a negative polarity input, each of which can be selectively coupled (e.g., by the polarity selector) to the secondary side of the transformer to enable polarity-selectable output voltage at the output of the power rectifier; however, the power rectifier can have any other suitable inputs, selectable or otherwise.
24. The voltage doubling stage of the power rectifier functions to provide double the output voltage (e.g., relative to ground) as the voltage input to the stage. In a specific example, the voltage doubling stage includes two diodes and two capacitors. As shown in FIGURE 6A, the upstream side of the first capacitor is connected to the input of the stage; the downstream side of the first capacitor is connected to the downstream side of the first diode and the upstream side of the second diode; the upstream side of the first diode is connected to ground and the upstream side of the second capacitor; and the downstream side of the second diode is connected to the downstream side of the second capacitor and the output of the stage. Any number of voltage doubling stages can be placed in series, wherein the output of the stage is the input to the next sequential stage, to achieve a 2N factor increase in the initial input voltage (i.e., where N is the number of stages).
25. The power rectifier can optionally include a half-doubling stage, which functions to enable odd-integer voltage multiplication, when used in combination with a voltage doubling stage. In a specific example, the half-doubling stage includes a third capacitor and a third diode (in addition to the two capacitors and two diodes of a voltage doubling stage). As shown in FIGURE 6B, the upstream side of the third diode is connected to the input to the stage and the upstream side of the first capacitor; the downstream side of the third diode is connected to the downstream side of the third capacitor, the upstream side of the first diode, and the upstream side of the second capacitor; and the upstream side of the third capacitor is connected to ground. There is preferably a single half-doubling stage in sequence with the set of N voltage doubling stages, but there can alternatively be multiple half-doubling stages connected in any suitable manner, or half-doubling stages may not be used in variations of the power rectifier.
26. The power rectifier can optionally include a variable-tap output, which functions to allow the output voltage of the power rectifier to be selected from the available node voltages of the N-stage voltage ladder (e.g., by adjusting which two stages the upstream side of the output connection is electrically connected to). For example, the power rectifier can include a multiposition switch (e.g., a rotary switch, transistor network, relay network, etc.) that is controllable by the control module to connect the output of the power rectifier to any connection between any two stages of the N-stage voltage ladder of the power rectifier.
27. The feedback isolator of the system functions to convert feedback of either positive or negative polarity that originates from the output assembly into feedback of a single polarity, for provision to the control module as a feedback input. The single polarity is preferably positive polarity, but can alternatively be negative. The feedback isolator includes a signal rectifier, one or more voltage sense inputs, one or more current sense inputs, a current feedback output, and one or more voltage feedback outputs. The system preferably includes a single feedback isolator, even for cases in which there are multiple output assemblies, but there can alternatively be any suitable number of feedback isolators. The feedback isolator is connected to sensor outputs of the secondary side of each transformer (e.g., to sense the output current) and to sensor outputs at the output of each power rectifier (e.g., to sense the output voltage) by signal pathways, as well as to the control module by one or more signal pathways (e.g., for transmitting feedback signals); additionally or alternatively, the feedback isolator can be otherwise connected to components of the system in order to receive and/or transmit signals (e.g., feedback signals).
28. The signal rectifier of the feedback isolator functions to rectify the sensed voltage sense input to generate a feedback signal that does not depend on the polarity of the output of the power rectifier. The signal rectifier can additionally function to electrically isolate the output of the power rectifier (e.g., the voltage sense input) from the control module and/or other portions of the system. In a specific example, as shown in FIGURE 2, the signal rectifier includes a first shunt resistor, connected between the power rectifier output and the inputs of two parallel, oppositely-directed diodes, each diode connected to ground across a second and third shunt resistor, respectively. A negative sense output is connected between the second shunt resistor and the voltage sense input of the feedback isolator, and a positive sense output is connected between the third shunt resistor and the voltage sense input of the feedback isolator. Accordingly, a positive voltage sense input is received at the feedback isolator regardless of the output polarity of the power rectifier.
29. The voltage sense inputs of the feedback isolator function to receive the voltage sensor signals from signal rectifier, and thus are preferably connected via signal pathways to the signal rectifier. However, the voltage sense inputs can be otherwise connected.
30. The current sense inputs of the feedback isolator function to receive the current sense signal from the output assembly (e.g., the secondary side of the transformer). In a first specific example, the current sense signal is generated by a voltage across a shunt resistor connected between the low side of the transformer secondary winding and ground, and the current sense input receives the current sense signal as a double-ended voltage signal across the shunt resistor. However, the current sense signal can be otherwise generated.
31. The feedback outputs (e.g., current feedback outputs, voltage feedback outputs) of the feedback isolator function to provide feedback signals to the first and second combiners of the control module. The system preferably includes M voltage feedback outputs, where M is the number of output assemblies connected to the feedback isolator, but the system can alternatively include any suitable number of voltage feedback outputs connected to the first combiner. The system preferably includes a single current feedback output (e.g., for use in controlling a single input power source), but there can alternatively be any suitable number of current feedback outputs connected to the second combiner.
32. The system can optionally include a power source, which functions to provide input power to the inverter for subsequent upconversion to high voltage by the transformer and power rectifier. The power source can additionally function to power the control module (e.g., including DC-DC regulation of the power source to appropriate power levels for the control module). The system preferably includes a single power source, but there can alternatively be multiple (e.g., each connected to the same inverter and/or control module permanently, or controllably by a switch; alternatively they may be connected to different inverters and/or control modules, permanently or controllably by switches). In a first variation, the power source is a rectified DC voltage from an AC source (e.g., an alternator). In a second variation, the power source is a regulated DC source (e.g., a battery, a DC voltage regulator). In a third variation, the power source is a fluctuating and/or uncontrolled DC source (e.g., an unconditioned or partially-conditioned solar panel output). In a fourth variation, the power source is an AC source (e.g., in variations of the system without an inverter, in variations of the system with an additional rectification stage between the power source and the inverter) such as wall power, an alternator, or any other suitable AC source.
33. The system can optionally include a housing, which functions to enclose and shield at least a portion of the power processing system. The housing can additionally function to define throughputs (e.g., feedthroughs) for power transmission lines to pass into and out of the housing and connect to various sources and/or loads. The housing can additionally function to define throughputs (e.g., feedthroughs) for control and/or data transmission lines to pass into and out of the housing and connect to various components of the system. The housing is preferably configured to provide structural support to and an enclosure for components of the power processing system, but can alternatively be otherwise configured. The housing preferably has a form factor configured for integration into a standard satellite bus (e.g., a 1U cubesat, a 3U cubesat, a nanosatellite, a kilowatt-class telecom satellite, etc.), but can additionally or alternatively have any suitable form factor. As such, the housing can include the flanges, bolt patterns, physical layouts, standoffs, and any other suitable features that conform to standards and/or regulations regarding spacecraft integration. The housing preferably provides shielding against solar and other space radiation (e.g., through the use of a radiation-hardened material casing, a specified wall thickness, etc.), but in variations can alternatively provide minimal radiation shielding.
34. The system can optionally include a primary load, which functions to receive and dissipate the output power of the power rectifier. The primary load is electrically connected to the output of the output assembly (e.g., the selected variable-tap output of the N-stage voltage doubler of the power rectifier) between the high voltage output and ground. The system preferably includes a single primary load per output assembly, but can additionally or alternatively include multiple primary loads per output assembly, multiple output assemblies connected to a single primary load, or any other suitable correspondence between any number of primary loads and any number of output assemblies. The primary load can, in variations, have an operating voltage limit (e.g., a breakdown voltage, a voltage above which operational efficiency drops below a threshold), which can, in variations, be less than the maximum output voltage of the output assembly. The operating voltage limit can be prescribed and static in time, but can alternatively change with time (e.g., as components wear). There is preferably a single primary load per output assembly, but there can alternatively be any suitable number of primary loads connected to an output assembly (e.g., via a multiplexer between the output assembly and a plurality of primary loads).
35. In a first specific example, the primary load includes an ion source. The ion source includes a body (e.g., an emitter body) that includes a base and a tip. The body can be made of a porous material (e.g., a microfabricated emitter body formed from a porous metal substrate) compatible with an ionic liquid or a room temperature molten salt (e.g., does not react or result in electrochemical decaying or corrosion). The body can be mounted relative to a source of ionic liquid or a source of a room temperature molten salt. The body can include a pore size gradient that decreases from the base of the body to the tip of the body, such that ionic liquid can be transported through capillarity (e.g., through capillary forces) from the base to the tip; however, ionic liquid can additionally or alternatively be transported through capillarity without a pore size gradient or by any other suitable transport mechanism. The ionic liquid can be continuously transported through capillarity from the base to the tip so that the ion source (e.g., emitter) avoids liquid starvation. An electrode can be positioned downstream relative to the body. The output assembly of the power processing unit can apply high voltage to the body relative to the electrode, thereby emitting a current (e.g., a beam of ions) from the tip of the body. The application of a voltage can cause emission of ions from the tip (e.g., via formation of a Taylor cone at the tip). In a related example, the ion source can include a plurality of emitters in a 1D or 2D array, wherein each emitter is microfabricated substantially as described above. The emitters of the array can have an emitter spacing of less than about 1 mm, or any other suitable spacing; the spacing between emitters may limit the maximum voltage that can be applied due to field-enhancement effects generated at the emitter tips (however, the spacing between emitters may alternatively have no effect on the applicable maximum voltage).
36. The system can optionally include a secondary load, which functions to receive and dissipate voltage(s) produced by the power processing system that are greater than the voltage applied to the primary load. In a first variation, the primary load is connected to the output assembly and receives an output voltage selected by the control module (e.g., using a variable-tap output) that is less than the maximum output voltage of the output assembly (e.g., the primary load is powered at 100\*Vin wherein the output assembly can produce 300\*Vin); the secondary load can then be connected to the output assembly at a secondary output connection that provides the maximum output voltage (e.g., 300\*Vin). In a specific example, the secondary load includes an acceleration electrode (e.g., a grid electrode) positioned downstream of an electrode of an ion source as described above, wherein the electrode is the primary load. Thus, additional momentum can be transferred to the ions as they are accelerated downstream of the primary load without increasing the applied voltage at the primary load. In another variation, the secondary load is a resistive load that can function to dissipate residual charge and thereby increase switching speed (e.g., speed of switching the polarity of the output stage). However, the secondary load can be any other suitable electrical load.
37. As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred embodiments of the invention without departing from the scope of this invention defined in the following claims.

Claims

What is claimed is:

1. The invention as shown and/or described.