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INTRINSICALLY SAFE ENERGY HARVESTER FOR POWERING MULTI-SENSOR APPLICATIONS

Abstract

An electrical circuit for protecting an electronic device, and a method of operating the electric circuit, can involves the use of a protection circuit that includes a group of diodes and one or more field effect transistors, along with an energy storage device associated with the electronic device. The field effect transistors are electrically connected to the group of diodes, and reference voltage associated with the protection circuit is tunable to trigger the protection circuit at a threshold voltage, which when triggered activates the field effect transistor(s) to protect the energy storage device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present.

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Background/Summary

CROSS-REFERENCE TO RELATED PATENT APPLICATION

[0001] This patent application claim priority to Indian Provisional Patent Application No. 202411011499, filed Feb. 19, 2024, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

[0002] Embodiments are generally related to the field of energy harvesting devices. Embodiments further relate to intrinsically safe energy harvesters for use with power multi-sensor applications.

BACKGROUND

[0003] Photovoltaic-based energy harvesting, also known as solar energy harvesting, is a sustainable and increasingly popular method for generating electrical energy from sunlight. This technology can convert sunlight into electrical energy using photovoltaic cells or solar panels. Photovoltaic energy harvesting plays a crucial role in reducing our dependence on fossil fuels and mitigating climate change. Solar panels include numerous photovoltaic cells configured from semiconductor materials such as silicon. When sunlight strikes these cells, it excites electrons, creating an electric current.

[0004] To make use of the direct current (DC) generated by solar panels, the current needs to be boosted and stored for downstream use. This is where an energy harvester module can come into play. An energy harvester module can be utilized as a part of an energy harvesting device or energy harvesting system to efficiently extract power ranging from microwatts (μW) to milliwatts (mW) from various DC energy harvesting sources, such as photovoltaic (solar), without destabilizing those sources. The energy harvester module can also include battery management features to prevent overcharging of secondary rechargeable batteries and ensure that the voltage is boosted without exceeding safe limits or depleted excessively by the system load.

[0005] A challenge arises in storing this extracted energy from the energy harvester module. The extracted energy needs to be preserved in energy storage devices such as rechargeable batteries, supercapacitors, hybrid layer capacitors, etc. Typically, these energy storage devices can operate in a voltage range of 3V to 4.4V. Users can select the appropriate voltage source based on the output voltage of the energy harvester module for general-purpose applications.

[0006] In hazardous area applications, the boosted output voltage needs to be protected to match the voltage rating of the energy storing source. Various protection techniques exist in electrical circuits to prevent overcharging of the energy storing source. However, each method has its pros and cons. Some meet the overvoltage protection requirement, while others meet functional performance requirements, but not both.

[0007] In hazardous location (HAZLOC) applications, protection methods vary based on the deployment location. In North America, they are classified into Class I Division 1 and Class I Division 2, with Class I Division 1 being more stringent. Similarly, in EMEA (Europe, Middle East, Africa) regions, they are classified into Zones like Zone 0, Zone 1, and Zone 2, with Zone 0 being the most stringent. Depending on the classes and zones, the protection circuits may incur up to two countable faults and unlimited uncountable faults. This can lead to duplicates and triplicates of protection circuits, which come with limitations such as, for example, increased circuit leakage currents, potentially leading to draining of energy storage devices.

[0008] FIG. **1**, FIG. **2**, and FIG. **3** illustrate schematic diagrams of different prior art protection circuits, which can be used with energy harvesting systems. The configurations shown in FIG. **1** to FIG. **3** are depicted herein to demonstrate problems with current protection circuit solutions. Note that in FIGS. **1-3**, similar or identical components may be indicated by identical reference numerals.

[0009] FIG. **1** illustrates a schematic diagram of an electrical circuit **100** that includes an energy harvesting circuit **104** that is connected electrically to a prior art shunt protection circuit **102**. The energy harvesting circuit **104** includes an energy harvester **106** and the prior art shunt protection circuit **102** includes a duplet of Zener diodes **108** as part of the prior art shunt protection circuit **102** and in association with an energy storing device that includes a capacitor **110**.

[0010] The prior art shunt protection circuit **102** shown in FIG. **1** meets functional requirement with very low reverse leakage current in the order of 5 μA. However, the duplet of Zener diodes **108** does not comply with a maximum super capacitor voltage of 4.1 V. Lowering the Zener voltage to 4.1V can enable compliance with the super capacitor voltage rating, but this can result in a very large reverse leakage current up to 20 mA/Zener which will drain the battery and thus does not meet functional requirements. In addition, there are no energy storage devices available with a miniature form-factor with such high voltage, for example, 5.6V.

[0011] The Zener diodes **108**, while functioning as important components for the prior art shunt protection circuit **102**, fail to adhere to the maximum super capacitor voltage of 4.1 V. Although reducing the Zener voltage to 4.1V would align with the super capacitor voltage rating, this adjustment leads to a substantial increase in reverse leakage current, reaching up to 20 mA/Zener. Consequently, this heightened leakage current poses a severe threat, as it could rapidly deplete the battery, rendering it non-compliant with functional requirements. Additionally, integrating energy storage devices within the context of a miniature battery rated at, for instance, 5.6V, has not been addressed in this setup.

[0012] FIG. **2** illustrates a schematic diagram of the electrical circuit **100** including the energy harvesting circuit **104** and the prior art shunt protection circuit **102**. The configuration shown in FIG. **2** is slightly different from that shown in FIG. **1**. That is, the prior art shunt protection circuit **102** depicted in FIG. **2** uses a duplet of Zener diodes **11** in association with an N-channel metal-oxide semiconductor field-effect transistor (MOSFET) switch **113**. The Zener voltage associated with the prior art shunt protection circuit **102** is 4.1V, with the N-channel MOSFET switch **113** having a gate threshold set to nominal 3.9V in a series arrangement, and which complies with the super cap voltage rating but with a lower reverse leakage current. N-Channel MOSFET gate thresholds generally can begin at 1V with a worst-case maximum voltage of 2.8V, which means that the N-channel MOSFET switch **113** can turn on at a lower voltage and start leakage with the reverse current up to 10 mA/Zener through the Zener diode. Although this configuration may solve certification problems, it will not meet performance requirements.

[0013] In FIG. **2**, the electrical circuit **100** exhibits a slight deviation from the configuration shown in FIG. **1**, featuring the prior art shunt protection circuit **102** equipped with a pair of Zener diodes **111** alongside an N-channel MOSFET switch **113**, set with a gate threshold of nominal 3.9V in series, meeting the super cap voltage rating but with reduced reverse leakage current, however, the gate thresholds of the N-channel MOSFET switch **113** may potentially lead to activation at lower voltages and subsequent leakage currents up to 10 mA/Zener through the Zener diode, which, although addressing some certification concerns, falls short of meeting performance standards.

[0014] FIG. **3** illustrates a schematic diagram of the electrical circuit **100** with the prior art shunt protection circuit **102** based on a series protection configuration using a triplet of three Schottky diodes **117** in association with diodes **114** and **116**. The configuration of the prior art shunt protection circuit **102** includes a series protection arrangement that uses the three Schottky diodes **117** between a boost output and the energy storage device (capacitor **110**) to drop the voltage from 5.6V to 4.1V but requires two more diodes in series to make it total of 5 (the three diodes **117** and the diodes **114** and **116**) as they apply two countable faults for Zone 0. This approach may meet certification requirement but introduces a great deal of forward voltage drop at the booster output, which in turn leads to performance issues. Furthermore, a diode forward drop is a function of temperature and increases exponentially with high temperatures.

[0015] There is a clear need for an energy harvesting system that can broaden the scope of existing solutions while improving update rates and avoiding the problems with prior art solutions such as shown in FIG. **1**, FIG. **2**, and FIG. **3**. Furthermore, existing solutions on the market, however, are bulky and heavy due to their energy harvesting methods. In addition, for retrofitting applications where size and weight matter, there is a crucial need for a solution that can boost the efficiency of energy harvesting while maintaining a compact form factor.

BRIEF SUMMARY

[0016] The following summary is provided to facilitate an understanding of some of the features of the disclosed embodiments and is not intended to be a full description. A full appreciation of the various aspects of the embodiments disclosed herein can be gained by taking the specification, claims, drawings, and abstract as a whole.

[0017] It is, therefore, one aspect of the embodiments to provide for improved energy harvesting systems, devices, and methods.

[0018] It is another aspect of the embodiments to provide for improved energy harvesting systems, devices, and methods that prevent energy storing sources from overcharging.

[0019] It is also an aspect of the embodiments to provide for improved energy harvesting systems, devices, and methods that meet energy storing source over voltage protection and functional performance requirements.

[0020] It is a further aspect of the embodiments to provide for intrinsically safe energy harvesters for powering multi-sensor applications.

[0021] Is yet another aspect of the embodiments to provide for an improved electrical circuit that can protect an electronic device through the implementation of shunt protection circuitry.

[0022] It is also an aspect of the embodiments to provide for an electrical circuit and associated electronic components and devices that can facilitate the use of a shunt protection circuit that can meet functional requirements while exhibiting a very low reverse leakage current.

[0023] The aforementioned aspects and other objectives can now be achieved as described herein. In an embodiment, an electrical circuit for protecting an electronic device, can include a protection circuit comprising a plurality of diodes and at least one field effect transistor. An energy storage device is associated with the electronic device, and the field effect transistor is electrically connected to the plurality of diodes. A reference voltage of the protection circuit is tunable to trigger the protection circuit at a threshold voltage, which when triggered activates the at least one field effect transistor to protect the energy storage device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present.

[0024] In an embodiment of the electrical circuit, the protection circuit can protect the energy storage device and enhance the performance and the life of the electronic device by maintaining a low reverse leakage current consumption.

[0025] In an embodiment of the electrical circuit, the protection circuit can comprise a shunt regulator circuit.

[0026] In an embodiment of the electrical circuit, the plurality of diodes can include a triplet of diodes, shunt regulators and MOSFET switches for Zone 0/Class I Division 1 deployments in hazardous location (HAZLOC) areas.

[0027] In an embodiment of the electrical circuit, the plurality of diodes can comprise a duplet of diodes, shunt regulators and MOSFET switches for Zone 1/Class I Division 1 deployments in HAZLOC areas.

[0028] In an embodiment of the electrical circuit, the plurality of diodes can comprise a single set of diodes, shunt regulators and MOSFET switches for Zone 2/Class I Division 2 deployments in HAZLOC areas.

[0029] In an embodiment of the electrical circuit, the electronic device can comprise an energy harvesting device.

[0030] In an embodiment of the electrical circuit, the field effect transistor may be a MOSFET.

[0031] In an embodiment of the electrical circuit, the protection circuit can include a semiconductor switch comprising one or more of: a MOSFET, a PNP/NPN transistor, or an electronically controlled load switch.

[0032] In an embodiment of the electrical circuit, the MOSFET may be a P-Channel MOSFET.

[0033] In an embodiment, a shunt protection circuit can include a diode configured to shunt excess voltage above a predetermined threshold; an energy storing device connected in parallel with the diode; and a triplet circuit situated between the diode and the energy storing device, the triplet circuit comprising a semiconductor switch and a shunt regulator with a reference voltage set to activate the regulator at a predetermined threshold voltage, wherein the shunt regulator conducts when the voltage across the diode reaches the predetermined threshold voltage, thereby activating the semiconductor switch to protect the energy storing device.

[0034] In an embodiment of the shunt protection circuit, the shunt regulator can maintain a low reverse leakage current in the order of tens of microamps when not triggered.

[0035] In an embodiment of the shunt protection circuit, the overall system leakage current can be maintained below, for example, 10 microamps, thereby minimizing drainage of the energy storing device and meeting performance requirements of an end application.

[0036] In an embodiment of the shunt protection circuit, the semiconductor switch can comprise one or more of: a MOSFET, a PNP/NPN transistor, or an electronically controlled load switch.

[0037] In an embodiment of the shunt protection circuit, the MOSFET may be a P-Channel MOSFET.

[0038] In an embodiment, a method of protecting an electronic device can involve: electronically connecting a protection circuit to an electronic device, wherein the protection circuit includes a plurality of diodes and at least one field effect transistor, wherein the field effect transistor is electrically connected to the plurality of diodes; and tuning a reference voltage associated with the protection circuit to trigger the protection circuit at a threshold voltage, which when triggered activates the at least one field effect transistor to protect an energy storage device associated with the electronic device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present

[0039] In an embodiment of the method, the protection circuit can protect the energy storage device and enhance the performance and life of the electronic device by maintaining a low reverse leakage current consumption.

[0040] In an embodiment of the method, the plurality of diodes can comprise a triplet of diodes, shunt regulators and MOSFET switches for Zone 0/Class I Division 1 deployments in hazardous location (HAZLOC) areas.

[0041] In an embodiment of the method, the plurality of diodes can comprise a duplet of diodes, shunt regulators and MOSFET switches for Zone 1/Class I Division 1 deployments in HAZLOC areas.

[0042] In an embodiment of the method, the plurality of diodes can comprise a single set of diodes, shunt regulators and MOSFET switches for Zone 2/Class I Division 2 deployments in HAZLOC areas.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0043] The accompanying figures, in which like reference numerals refer to identical or functionally-similar elements throughout the separate views and which are incorporated in and form a part of the specification, further illustrate the present invention and, together with the detailed description of the invention, serve to explain the principles of the present invention.

[0044] FIG. **1** illustrates a schematic diagram of a prior art shunt protection circuit using a duplet of Zener diodes;

[0045] FIG. **2** illustrates a schematic diagram of a prior art shunt protection circuit using a duplet of Zener diodes with a MOSFET switch;

[0046] FIG. **3** illustrates a schematic diagram of a protection circuit based on a series protection configuration using a triplet of three Schottky diodes;

[0047] FIG. **4** illustrates a schematic diagram of an electrical circuit including an energy harvesting circuit and a protection circuit that includes a sub-circuit, which can incorporate the use of a shunt voltage regulator with a MOSFET switch, in accordance with an embodiment

[0048] FIG. **5** illustrates a schematic diagram of a sub-circuit, which may be implemented in accordance with an embodiment;

[0049] FIG. **6**A and FIG. **6**B illustrate respective cut-away side and perspective views of an application circuit that can be implemented in the context of a signal scout gas detector system, in accordance with an embodiment;

[0050] FIG. **7**A and FIG. **7**B illustrate respective cut-away side and perspective views of an application circuit, which can be implemented in a multi-variant transmitter system, in accordance with an embodiment;

[0051] FIG. **8**A and FIG. **8**B illustrate layout diagrams of a signal scout energy harvester incorporating a shunt protection circuit and a super capacitor, in accordance with an embodiment; and

[0052] FIG. **9**A and FIG. **9**B illustrate layout diagrams of a transmitter energy harvester, which may be implemented in accordance with an embodiment.

[0053] In the drawings described and illustrated herein, identical or similar parts and elements are generally indicated by identical reference numerals.

DETAILED DESCRIPTION

[0054] The particular values and configurations discussed in these non-limiting examples can be varied and are cited merely to illustrate one or more embodiments and are not intended to limit the scope thereof.

[0055] Subject matter will now be described more fully hereinafter with reference to the accompanying drawings, which form a part hereof, and which show, by way of illustration, specific example embodiments. Subject matter may, however, be embodied in a variety of different forms and, therefore, covered or claimed subject matter is intended to be construed as not being limited to any example embodiments set forth herein; example embodiments are provided merely to be illustrative. Likewise, a reasonably broad scope for claimed or covered subject matter is intended. Among other issues, subject matter may be embodied as methods, devices, components, or systems. Accordingly, embodiments may, for example, take the form of hardware, software, firmware, or a combination thereof. The following detailed description is, therefore, not intended to be interpreted in a limiting sense.

[0056] Throughout the specification and claims, terms may have nuanced meanings suggested or implied in context beyond an explicitly stated meaning. Likewise, phrases such as “in one embodiment” or “in an example embodiment” and variations thereof as utilized herein may not necessarily refer to the same embodiment and the phrase “in another embodiment” or “in another example embodiment” and variations thereof as utilized herein may or may not necessarily refer to a different embodiment. It is intended, for example, that claimed subject matter include combinations of example embodiments in whole or in part.

[0057] In general, terminology may be understood, at least in part, from usage in context. For example, terms such as “and,” “or,” or “and/or” as used herein may include a variety of meanings that may depend, at least in part, upon the context in which such terms are used. Generally, “or” if used to associate a list, such as A, B, or C, is intended to mean A, B, and C, here used in the inclusive sense, as well as A, B, or C, here used in the exclusive sense. In addition, the terms “one or more” or “at least one” as used herein, depending at least in part upon context, may be used to describe any feature, structure, or characteristic in a singular sense or may be used to describe combinations of features, structures, or characteristics in a plural sense. Similarly, terms such as “a,” “an,” or “the”, again, may be understood to convey a singular usage or to convey a plural usage, depending at least in part upon context. In addition, the term “based on” may be understood as not necessarily intended to convey an exclusive set of factors and may, instead, allow for existence of additional factors not necessarily expressly described, again, depending at least in part on context. Furthermore, the term “at least one” as utilized herein can refer to “one or more”. For example, “at least one widget” may refer to “one or more widgets”.

[0058] The terms “energy harvesting module,” “energy harvesting device,” “energy harvesting system” and “energy harvester” may be used interchangeably with one another, but in some situations may offer subtle differences in meaning depending on the context in which they are used. Before proceeding to a description of the embodiments, a breakdown of each term is outlined below.

[0059] The term “energy harvesting module” can relate to a discrete component or subsystem within a larger system that can be specifically designed to capture, convert, and store ambient energy from the environment. An energy harvesting module can include components such as energy harvesting transducers (e.g., photovoltaic cells, thermoelectric generators, piezoelectric materials), power management circuits, energy storage elements (e.g., supercapacitors, batteries), and possibly control or monitoring circuitry. The energy harvesting module may be integrated into a larger electronic system or device to supplement or replace traditional power sources, enabling self-sustainability or extended operation without external power input.

[0060] The term “energy harvesting device” can be used interchangeably with “energy harvesting module” in some contexts, referring to a device or component that can be designed for harvesting ambient energy. The term may also refer to a standalone device that can incorporate energy harvesting capabilities as its primary function, such as a solar-powered calculator or a self-powered sensor node. In some cases, “energy harvesting device” can emphasize the functionality of harvesting energy rather than the specific components or subsystems involved.

[0061] The term “energy harvester” can relate to a core component or subsystem responsible for capturing and converting ambient energy into usable electrical power. It may encompass the entire energy harvesting module or device, including all associated components and subsystems, or it may specifically refer to the transducer or mechanism responsible for energy conversion (e.g., a solar panel, a piezoelectric material, a thermoelectric generator). The term “energy harvester” may also be used to emphasize the action of harvesting energy rather than the complete system or device.

[0062] While there may be slight nuances in usage, these terms generally can refer to components or systems involved in the process of capturing, converting, and storing ambient energy for powering electronic devices. The choice of terminology may vary based on the specific context, emphasis on certain aspects of the technology, or conventions within a particular industry or field.

[0063] As will be discussed in greater detail below, the embodiments relate to an electrical circuit and associated electronic components and devices that can facilitate the utilization of a Zener shunt protection circuit, such as a 5.6V Zener shunt protection circuit, which can meet functional requirements while exhibiting very low reverse leakage current, on the order of around 5 uA.

[0064] A triplet circuit can be integrated between the Zener and an energy storing device, incorporating a shunt regulator circuit with a P-Channel MOSFET Switch. The reference of the shunt regulator can be set to activate the regulator at, for example, 3.9V. When the fault voltage reaches 3.9V, the shunt regulator can conduct, turning on the MOSFET switch to safeguard the Energy Storing Device. This action can ensure that the leakage current remains very low, in the range of, for example, a few tens of uA. The overall system leakage current, including the triplet circuit, can be kept under 10 uA. This design feature can prevent significant draining of the energy storing device, thereby contributing to meeting the performance requirements of the end application.

[0065] FIG. **4** illustrates a schematic diagram of an electrical circuit **101** that includes an energy harvesting circuit **101** and a protection circuit **107** that can include a sub-circuit **151**, which can incorporate a shunt voltage regulator with a MOSFET switch (e.g., P-Channel MOSFET), in accordance with an embodiment. The energy harvesting circuit **101** includes an energy harvester **109** and the protection circuit **107** can incorporate sub-circuits **151**, **153**, and **155** (also respectively labeled as CW**1**, CW**2**, and CW**3**) in FIG. **4**.

[0066] As shown in FIG. **4**, the energy harvester **109** can be electrically connected to a group of capacitors including capacitors **120**, **122**, **124**, **126**, **128** and capacitors **130**, **132**, and **134**. The energy harvesting circuit **101** can connect to the protection circuit **107** through a switch **140** (also labeled as F**1** in FIG. **4**). The protection circuit **107** can include a group of switches (also labeled as PWR SWITCHES in FIG. **4**) composed of diodes **144** and **146** and a resistor **138** that electrically connects to diode **144**. A resistor **136** connects electrically to diode **144** and diode **146**. A resistor **148** can connect electrically to the diode **146**. Protection circuit **107** also includes a resistor **142** that can connect electrically to a diode **150** and a diode **152**. In the electrical circuit **101** shown in FIG. **4**, diodes **150** and **152** can be connected in parallel with one another.

[0067] The sub-circuit **151** can include a resistor **154** that can be connected electrically in series with a resistor **156**. The sub-circuit **151** also can include a resistor **158** that can connect electrically to a resistor **160**, which in turn can electrically connect to a diode **162**. In addition, a P-Channel MOSFET **166** can connect electrically to the resistor **160** and the resistor **166**, and to a resistor **164** and a diode **168**.

[0068] The sub-circuit **153** can include a resistor **170** that can connect electrically to a resistor **171**. A diode **176** can connect electrically to the resistor **170** and the resistor **171** and further to a resistor **174**. A resistor **172** connects electrically to resistor **174** and a P-Channel MOSFET **180**. The sub-circuit **153** additionally includes a diode **182** that connects to the P-Channel MOSFET **180** and to a resistor **178**.

[0069] The sub-circuit **155** includes a resistor **184** that can connect electrically to a resistor **186**. A diode **192** connects electrically to the resistor **184** and the resistor **186**. A resistor **190** connects electrically to the output of diode **192** and to a resistor **188**. A P-Channel MOSFET **195** connects electrically to a resistor **194** and a diode **198**. The diode **198** in turn connects to a capacitor **196** through a switch **199**.

[0070] Note that in FIG. **4**, the shunt voltage regulator comprises components within sub-circuit **151** including the series of resistors **154**, **156**, **158**, **160**, the diode **162**, and the P-Channel MOSFET **166**. Additionally, within sub-circuit **153**, the P-Channel MOSFET **180** can function as part of the shunt voltage regulator. These components can work together to regulate the voltage across the energy harvesting circuit **101** and ensure that it remains within a safe range, protecting it from overvoltage conditions.

[0071] FIG. **5** illustrates a schematic diagram of the sub-circuit **151**, which may be implemented in accordance with an embodiment. As discussed above, the sub-circuit **151** can include two diodes **150** and **152**, which are also labeled respectively as D**1** and D**2** in FIG. **5** and shown as electrically connected in parallel with one another. The diodes **150** and **152** can electrically connect to a resistor **154** and to a resistor **156**. The resistor **154** and the resistor **156** can be connected in series with one another and can connect electrically to a diode **162**. The resistor **160** can connect electrically to the diode **162** and to a resistor **158** and can further connect electrically to P-Channel

MOSFET **166**. The resistor **158** and the P-Channel MOSFET transistor **166** can electrically connect to diode **168**. The P-Channel MOSFET **166** further can connect electrically to a resistor **164**.

[0072] The approach can streamline the use of a 5.6V Zener shunt protection circuit, with a low reverse leakage current of approximately 5 uA, effectively meeting functional requirements. To bolster protection, a triplet of shunt regulator circuits (sub-circuits **151**, **153**, **155**), each incorporating a P-Channel MOSFET switch, can be introduced between the Zener and the energy storing device. The shunt regulator's reference is finely tuned to trigger at 3.9V, ensuring timely activation. Upon reaching this threshold, the shunt regulator initiates, promptly deactivating the MOSFET switch to shield the energy storing device from harm.

[0073] Prior to activation, the system maintains minimal reverse leakage current, typically in the range of a few 10s of uA. With the addition of the triplet circuit, the overall system leakage current remains below 10 uA, effectively safeguarding the energy Storing device and maintaining optimal performance for the end application. Note that the term 'Zener' as utilized herein relates to a Zener diode, which is a silicon pn junction device that allows current to flow not only in the forward direction like a typical silicon or germanium diode, but also in the reverse direction if the voltage is greater than the breakdown voltage known as Zener knee voltage or simply Zener voltage (named after Clarence Melvin Zener, the discoverer of this electrical property).

[0074] FIG. **6**A and FIG. **6**B illustrate respective cut-away side and perspective views of an application circuit **105** that can be implemented within a signal scout system **200**, in accordance with an embodiment. Note that the signal scout system **200** can include an upper portion **202**, a middle portion **203**, and a lower portion **204**. One or more photovoltaic cells such as photovoltaic cell **206** may be positioned on top of the upper portion **202** of the signal scout system **200**.

[0075] In FIG. **6**A, the application circuit **105** is shown a located within the upper portion **102**. The application circuit **105** may be implemented as an energy harvester PWA (Printed Wiring Assembly) with an super capacitor. The energy harvester PWA may be implemented as a circuit board assembly that can harvest and store energy from ambient sources, such as light, heat, or vibration, using a super capacitor as an energy storage device. Note than an example of a device, which can be utilized to implement the signal scout system **200**, is disclosed in the document "Honeywell Versatilis™ Signal Scout™ Release 100, Installation and User's Guide, 34-VT-25-02, February 2023," which is incorporated herein by reference in its entirety.

[0076] The signal scout system **200** can be implemented with an energy harvesting module that can generate up to 100 mW of power with a sunlight of 50K Lux and a minimum of 30 mW with 10K Lux. The Honeywell Versatilis™ Signal Scout™ can be equipped with a D-Cell Battery having a battery life of 4 months in continuous operation mode and 1.5 years in 25% duty cycle mode with 5 sec sensor sampling and 2 min LoRa publish rate. The addition of the disclosed energy harvesting solution can enhance the battery life up to 7-10 years depending on geography it deployed if the unit receives at least 4 hrs sunlight.

[0077] Note that the acronym "PWA" stands for "Printed Wiring Assembly," which relates to a circuit board populated with electronic components and wiring to perform a specific function. In the context of an energy harvester, the PWA can contain components such as energy harvesting circuitry, a super capacitor, voltage regulation components, and additional circuitry for monitoring and managing the harvested energy.

[0078] FIG. **7**A and FIG. **7**B illustrate respective cut-away side and perspective views of an application circuit **105**, which can be implemented in a transmitter system **210**, in accordance with an embodiment. As shown in FIG. **7**A, the transmitter system **210** can include the application circuit **105**. As discussed above, the application circuit **105** can function as an energy harvester PWA with a super capacitor **212** (e.g., super capacitor/battery). A photovoltaic cell **206** may be located at the top of the transmitter system **210**. A lower portion **214** of the transmitter system **210** can include an interface board **216** along with a thermal isolator **218**, a PCM heat exchanger **220**, a heat sink **222**, and a temperature sensor **224**. FIG. **7**B shows a pictorial perspective view of the transmitter system **210**.

[0079] Note that a non-limiting example of a device, which can be adapted for use as or with the transmitter system **210** is shown and described in the document, "Honeywell Versatilis Transmitter, Multi-Variant Sensing, 34-VT-03-01|Rev 6|June 2023," which is incorporated herein by reference in its entirety."

[0080] The embodiments can be tailored to meet specific requirements, including, for example, HAZLOC approval, wherein the energy harvesting solution can be designed to support deployment in hazardous locations, meeting standards such as IECEx Zone0 and Class I Division 1. Other specific requirements may include size and power. For example, the embodiments can be implemented in a compact design and can integrate energy harvesting capabilities with sensors, communication, and processing functionalities into a single device. Embodiments can also feature a highly efficient and ultra-low leakage energy harvesting system capable of extracting power ranging from microwatts (μW) to milliwatts (mW) from various DC energy sources, including photovoltaic (solar) and thermoelectric generators (TEG), without disrupting their operations.

[0081] FIG. **8**A and FIG. **8**B illustrate layout diagrams of the signal scout system **200** shown in FIG. **6**A and FIG. **6**B, in accordance with an embodiment. The signal scout system **200** can function as a signal scout energy harvester and can incorporate the shunt protection sub-circuit **151** and super capacitor **212**. The signal scout system **200** can serve a dual role as both a signal scout and an energy harvester. The signal scout system **200** can incorporate essential components such as the shunt protection sub-circuit **151** and the super capacitor **212**. The layout diagrams shown in FIG. **8**A and FIG. **8**B offer a comprehensive view of how these components are arranged within the system, highlighting their spatial relationships and connections. This design ensures optimal functionality and efficiency for the signal scout system, enabling it to effectively harvest energy while performing its scouting duties.

[0082] FIG. **9**A and FIG. **9**B illustrate layout diagrams of the transmitter system **210** shown in FIG. **7**A and FIG. **7**B, in accordance with an embodiment. The transmitter system **210** can function as a transmitter energy harvester as discussed previously. As shown in FIG. **9**A, a super capacitor connection **304** is shown along with a shunt protection sub-circuit **151**.

[0083] It can be appreciated that the embodiments offer a number of advantages and features. For example, by incorporating the shunt voltage regulator with MOSFET switches (P-Channel MOSFET) in the protection circuit, the embodiments can provide robust protection against overvoltage conditions. The sub-circuit **151**, along with sub-circuits **153** and **155**, for example, can effectively regulate the voltage across the energy harvesting circuit, thereby ensuring it remains within a safe range, while safeguarding it from potential damage due to voltage spikes or surges. Furthermore, the integration of the protection circuit with the energy harvesting module can ensure efficient energy utilization. By maintaining the voltage within a specified range, the invention can maximize the energy harvesting capabilities of the system, allowing it to effectively capture and store energy from ambient sources such as light, heat, or vibration.

[0084] The disclosed energy harvesting solution also significantly extends the battery life of devices such as the signal scout system and transmitter system. By supplementing the primary power source (e.g., D-cell battery) with harvested energy, the invention can prolong the operational lifespan of these devices, reducing the frequency of battery replacements and maintenance requirements. In addition, the embodiments can be tailored to meet specific requirements, including hazardous location (HAZLOC) approvals and standards such as IECEx Zone0 and Class I Division 1. Additionally, the compact design and integration capabilities enable the invention to meet size, power, and efficiency demands across various applications, ensuring compliance with industry standards and regulations.

[0085] The signal scout system and transmitter system, equipped with the disclosed energy harvesting solution, serve a dual role, functioning both as scouts or transmitters and as energy harvesters. This versatility enhances the overall utility and value proposition of the systems, allowing them to perform their primary functions while simultaneously harnessing ambient energy for sustained operation.

[0086] Overall, the embodiments offer a comprehensive solution for efficient energy management and protection in electronic devices, enabling prolonged operation, enhanced reliability, and compliance with industry standards.

[0087] It should be appreciated that although the operations of the devices, systems and/or method(s) herein are shown and described in a particular order, the order of the operations may be altered so that certain operations may be performed in an inverse order or so that certain operations may be performed, at least in part, concurrently with other operations. In another embodiment, instructions or sub-operations of distinct operations may be implemented in an intermittent and/or alternating manner.

[0088] At least some of the steps or operations described or features herein can be implemented using software instructions stored on a computer useable storage medium for execution by a computer. As an example, an embodiment of a computer program product includes a computer useable storage medium to store a computer readable program.

[0089] The computer-useable or computer-readable storage medium can be an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system (or apparatus or device). Examples of non-transitory computer-useable and computer-readable storage media include a semiconductor or solid-state memory, magnetic tape, a removable computer diskette, a random access memory (RAM), a read-only memory (ROM), a rigid magnetic disk, and an optical disk. Current examples of optical disks include a compact disk with read only memory (CD-ROM), a compact disk with read/write (CD-R/W), a digital video disk (DVD), Flash memory, and so on.

[0090] Alternatively, embodiments may be implemented in hardware or in an implementation containing hardware and software elements. In embodiments that do utilize software, the software may include firmware, resident software, microcode, etc.

[0091] In some alternative implementations, the functions noted in the blocks may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that the blocks of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

[0092] Based on the foregoing, it can be appreciated that a number of varying embodiments are disclosed herein. For example, in an embodiment an electrical circuit for protecting an electronic device, can include a protection circuit for an electronic device, wherein the protection circuit includes a plurality of diodes and at least one field effect transistor; and an energy storage device associated with the electronic device, wherein the field effect transistor is electrically connected to the plurality of diodes, wherein a reference voltage of the protection circuit is tunable to trigger the protection circuit at a threshold voltage, which when triggered activates the at least one field effect transistor to protect the energy storage device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present.

[0093] In an embodiment, the protection circuit can protect the energy storage device and can enhance the performance and life of the electronic device by maintaining a low reverse leakage current consumption.

[0094] In an embodiment, the protection circuit can include a shunt regulator circuit.

[0095] In an embodiment, the plurality of diodes can comprise, for example, a triplet of diodes, shunt regulators and MOSFET switches for Zone 0/Class I Division 1 deployments in hazardous location (HAZLOC) areas.

[0096] In an embodiment, the plurality of diodes can comprise, for example, a duplet of diodes, shunt regulators and MOSFET switches for Zone 1/Class I Division 1 deployments in HAZLOC

areas.
[0097] In an embodiment, the plurality of diodes can comprise, for example, a single set of diodes, shunt regulators and MOSFET switches for Zone 2/Class I Division 2 deployments in HAZLOC areas.
[0098] In an embodiment, the electronic device can be an energy harvesting device.
[0099] In an embodiment, the field effect transistor can comprise a MOSFET.
[0100] In an embodiment, the protection circuit can comprise a semiconductor switch including one or more of, for example: a MOSFET, a PNP/NPN transistor, or an electronically controlled load switch.
[0101] In an embodiment, the MOSFET can comprise a P-Channel MOSFET.
[0102] In an embodiment, a shunt protection circuit can include: a diode configured to shunt excess voltage above a predetermined threshold; an energy storing device connected in parallel with the diode; and a triplet circuit situated between the diode and the energy storing device, the triplet circuit comprising a semiconductor switch and a shunt regulator with a reference voltage set to activate the regulator at a predetermined threshold voltage, wherein the shunt regulator can conduct when the voltage across the diode reaches the predetermined threshold voltage, thereby activating the semiconductor switch to protect the energy storing device.
[0103] In an embodiment of the shunt protection circuit, the shunt regulator can maintain a low reverse leakage current in the order of, for example, tens of microamps, when not triggered.
[0104] In an embodiment of the shunt protection circuit, the overall system leakage current can be maintained below, for example, 10 microamps, thereby minimizing drainage of the energy storing device and meeting performance requirements of the end application.
[0105] In an embodiment of the shunt protection circuit, the semiconductor switch can comprise one or more of: a MOSFET, a PNP/NPN transistor, or an electronically controlled load switch.
[0106] In an embodiment of the shunt protection circuit, the MOSFET can comprise a P-Channel MOSFET.
[0107] In an embodiment, a method of protecting an electronic device, can involve: electronically connecting a protection circuit to an electronic device, wherein the protection circuit includes a plurality of diodes and at least one field effect transistor, wherein the field effect transistor is electrically connected to the plurality of diodes; and tuning a reference voltage associated with the protection circuit to trigger the protection circuit at a threshold voltage, which when triggered activates the at least one field effect transistor to protect an energy storage device associated with the electronic device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present
[0108] In an embodiment of the method, the protection circuit can protect the energy storage device and can enhance the performance and life of the electronic device by maintaining a low reverse leakage current consumption.
[0109] In an embodiment of the method, the plurality of diodes can comprise, for example, a triplet of diodes, shunt regulators and MOSFET switches for Zone 0/Class I Division 1 deployments in hazardous location (HAZLOC) areas.
[0110] In an embodiment of the method, the plurality of diodes can comprise, for example, a duplet of diodes, shunt regulators and MOSFET switches for Zone 1/Class I Division 1 deployments in HAZLOC areas.
[0111] In an embodiment of the method, the plurality of diodes can comprise, for example, a single set of diodes, shunt regulators and MOSFET switches for Zone 2/Class I Division 2 deployments in HAZLOC areas.
[0112] It will be appreciated that variations of the above-disclosed and other features and functions, or alternatives thereof, may be desirably combined into many other different systems or applications. It will also be appreciated that various presently unforeseen or unanticipated

alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

Claims

1. An electrical circuit for protecting an electronic device, comprising: a protection circuit for an electronic device, wherein the protection circuit includes a plurality of diodes and at least one field effect transistor; and an energy storage device associated with the electronic device, wherein the field effect transistor is electrically connected to the plurality of diodes, wherein a reference voltage of the protection circuit is tunable to trigger the protection circuit at a threshold voltage, which when triggered activates the at least one field effect transistor to protect the energy storage device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present.
2. The electrical circuit of claim 1 wherein the protection circuit protects the energy storage device and enhances a performance and a life of the electronic device by maintaining a low reverse leakage current consumption.
3. The electrical circuit of claim 1 wherein the protection circuit comprises a shunt regulator circuit.
4. The electrical circuit of claim 1 wherein the plurality of diodes comprises a triplet of diodes, shunt regulators and MOSFET switches for Zone 0/Class I Division 1 deployments in hazardous location (HAZLOC) areas.
5. The electrical circuit of claim 1 wherein the plurality of diodes comprises a duplet of diodes, shunt regulators and MOSFET switches for Zone 1/Class I Division 1 deployments in HAZLOC areas.
6. The electrical circuit of claim 1 wherein the plurality of diodes comprises a single set of diodes, shunt regulators and MOSFET switches for Zone 2/Class I Division 2 deployments in HAZLOC areas.
7. The electrical circuit of claim 1 wherein the electronic device comprises an energy harvesting device.
8. The electrical circuit of claim 1 wherein the field effect transistor comprises a MOSFET.
9. The electrical circuit of claim 1 wherein the protection circuit further comprises a semiconductor switch comprising at least one of: MOSFET, a PNP/NPN transistor, or an electronically controlled load switch.
10. The electrical circuit of claim 1 wherein the MOSFET comprises a P-Channel MOSFET.
11. A shunt protection circuit, comprising: a diode configured to shunt excess voltage above a predetermined threshold; an energy storing device connected in parallel with the diode; and a triplet circuit situated between the diode and the energy storing device, the triplet circuit comprising a semiconductor switch and a shunt regulator with a reference voltage set to activate the regulator at a predetermined threshold voltage, wherein the shunt regulator conducts when the voltage across the diode reaches the predetermined threshold voltage, thereby activating the semiconductor switch to protect the energy storing device.
12. The shunt protection circuit of claim 11 wherein the shunt regulator maintains a low reverse leakage current in the order of tens of microamps when not triggered.
13. The shunt protection circuit of claim 11 wherein an overall system leakage current is maintained below 10 microamps, thereby minimizing drainage of the energy storing device and meeting performance requirements of an end application.
14. The shunt protection circuit of claim 11 wherein the semiconductor switch comprises at least one of: a MOSFET, a PNP/NPN transistor, or an electronically controlled load switch.
15. The shunt protection circuit of claim 14 wherein the MOSFET comprises a P-Channel MOSFET.

16. A method of protecting an electronic device, the method comprising: electronically connecting a protection circuit to an electronic device, wherein the protection circuit includes a plurality of diodes and at least one field effect transistor, wherein the field effect transistor is electrically connected to the plurality of diodes; and tuning a reference voltage associated with the protection circuit to trigger the protection circuit at a threshold voltage, which when triggered activates the at least one field effect transistor to protect an energy storage device associated with the electronic device from an over voltage condition or an over charging condition until the over voltage condition or the overcharging condition is no longer present.
17. The method of claim 16 wherein the protection circuit protects the energy storage device and enhances a performance and a life of the electronic device by maintaining a low reverse leakage current consumption.
18. The method of claim 16 wherein the plurality of diodes comprises a triplet of diodes, shunt regulators and MOSFET switches for Zone 0/Class I Division 1 deployments in hazardous location (HAZLOC) areas.
19. The method of claim 16 wherein the plurality of diodes comprises a duplet of diodes, shunt regulators and MOSFET switches for Zone 1/Class I Division 1 deployments in HAZLOC areas.
20. The method of claim 16 wherein the plurality of diodes comprises a single set of diodes, shunt regulators and MOSFET switches for Zone 2/Class I Division 2 deployments in HAZLOC areas.