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RESEARCH ARTICLE

Protection of battery-powered devices against accidental swap of power supply connections

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Abstract
Objectives. Battery-powered devices (e.g., wireless sensors, pacemakers, watches and other wrist-worn devices, virtual reality glasses, unmanned aerial vehicles, robots, pyrometers, cars, DC/DC converters, etc.) are widely used today. For such devices, it is highly important to ensure safe primary power supply connection, including protection against reverse polarity. The conventional solution to the reverse polarity problem, involving the use of Schottky diodes during system redundancy or increasing power by combining two or more power supplies in the OR-ing circuit due to a large voltage drop, results in significant power losses at high currents, heat dissipation problems, and an increase in the mass and size of the equipment. For this reason, it becomes necessary to develop efficient battery-powered equipment protection against incorrect reverse polarity connection.
Methods. The problem is solved using circuit simulation in the *Electronics Workbench* environment.
Results. When protecting equipment against reverse voltage polarity, it is shown that the minimum level of losses and low voltage drop are provided by "ideal diode" circuit solutions based on discrete components and microcircuits of the "integrated diode" type with external and internal power metal–oxide–semiconductor field-effect transistors (MOSFETs). The circuit simulation of ideal diodes based on *p*- and *n*-channel transistors with superior technical parameters allows the characteristics and voltage and power losses in the protected circuits to be specified along with a presentation of the proposed technical solution simplicity. The contemporary component base of protection devices is discussed in terms of efficiency.
Conclusions. Examples of equipment for protecting against reverse voltage polarity are given along with circuit solutions based on discrete and integrated components. The simulation of the transfer characteristics of protection devices shows the limit for the minimum input voltage value of around 4 V using a MOSFET transistor.

Keywords: protection, battery power, MOSFET, Schottky diode, parasitic diode, ideal diode, connection, voltage, reverse polarity

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НАУЧНАЯ СТАТЬЯ

Защита аппаратуры с батарейным питанием от ошибочного подключения напряжения обратной полярности

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Резюме
Цели. В настоящее время широкое применение находит аппаратура с батарейным питанием (беспроводные датчики, кардиостимуляторы, «умные» браслеты, очки виртуальной реальности, беспилотные летающие аппараты, роботы, пирометры, автомобили, DC/DC преобразователи и др.). Для этих устройств принципиально важным вопросом является безопасное подключение первичных источников электропитания и наличие защиты от напряжения обратной полярности. Традиционное решение проблемы «переполюсовки» (подачи на прибор напряжения питания обратной полярности) с использованием диодов Шоттки при резервировании системы или увеличения мощности путем объединения источников питания по схеме ИЛИ вследствие большого падения напряжения приводит к значительным потерям мощности при больших токах, сложной проблеме теплоотвода и увеличению массогабаритных параметров. Это предопределило реализацию эффективных средств защиты аппаратуры с батарейным питанием от ошибочного подключения напряжения обратной полярности.
Методы. Задача решена с использованием схемотехнического моделирования в среде *Electronics Workbench*.
Результаты. Показано, что минимальный уровень потерь и малое падение напряжения при защите аппаратуры от обратной полярности питающего напряжения обеспечивают схемные решения «идеального диода» на дискретных компонентах и микросхемы типа «интегрального диода» с внешним и внутренним силовым транзистором MOSFET. Схемотехническое моделирование «идеальных диодов» на *p*- и *n*-канальных транзисторах, которые отличаются высокими техническими параметрами, позволило уточнить характеристики, потери напряжения и мощности в защищаемых цепях и показать простоту непосредственно самого технического решения. В статье обсуждены вопросы эффективности и современная элементная база устройств защиты.
Выводы. Приведены примеры элементной базы устройств защиты от «переполюсовки» источников питания, варианты защиты аппаратуры от воздействия напряжения обратной полярности, а также схемотехнические решения на дискретных и интегральных компонентах. Моделирование передаточных характеристик устройств защиты показало ограничение на минимальную величину входных напряжений около 4 В, обусловленную используемым MOSFET транзистором.

Ключевые слова: защита, батарейное электропитание, MOSFET, диод Шоттки, паразитный диод, «идеальный диод», подключение, напряжение, обратная полярность

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INTRODUCTION

In order to provide portability, functionality, and usability of electronic equipment (wireless sensors, pacemakers, “smart” bracelets, virtual reality glasses, unmanned aerial vehicles, robots, pyrometers, cars, DC/DC converters, etc.), a self-contained power supply is required [1–6].

Since battery-powered devices may be damaged by improper connection to the primary power supply, it is advisable to provide protection against reverse polarity. Although the battery compartments and contacts of the battery-powered equipment are typically designed in such a way as to exclude the possibility of misplacing the power supply element, however, it is still possible that battery terminals in automotive electronics, mobile electric vehicles, telecommunications servers, storage systems, server infrastructure equipment, and disk batteries may be misconnected. With polarity reversal or transients occurring during switching of inductive loads, serious failures and damage of electronic systems and units may occur. When the batteries of electric vehicles are incorrectly connected, reverse polarity can be dangerous due to possible generation of significant currents of tens to hundreds of amperes for sustained periods of time.

The use of circuit solutions and auxiliary electronic components to provide protection against power supply with wrong polarity in such cases forms the subject of the analysis presented in this paper.

In order to better understand the processes and factors affecting the characteristics of devices for protection against reverse polarity, circuits are simulated in the *Electronics Workbench* (*EWB*) environment [7]. In addition to conventional Simulation Program with Integrated Circuit Emphasis (SPICE) analysis, *EWB* allows the connection of virtual controls and measuring devices to the investigated circuit, which closely approximate real devices. Along with a significant set of methods for analyzing various characteristics of electronic circuits, *EWB* offers an extensive built-in library of analog and digital electronic components, including powerful *n*- and *p*-channel metal–oxide–semiconductor field-effect transistors (MOSFETs) from International Rectifier (USA) and Zetex Semiconductors (United Kingdom), powerful *p-n* junction diodes, and Schottky diodes (Motorola, USA). Considerable experience of using *EWB* in various fields of analog and digital electronics has been accumulated in extensive literature [7, 8]. *EWB* provides convenient use of two simulation methods supported by the program:

- electronic laboratory simulation implying virtual measuring instruments similar to real devices are installed in the electronic circuit while simulation is started by the Activate Simulation switch on the work panel;
- quasi-professional simulation implying the analysis type is set from the Analysis menu, in which window the analysis type and scheme nodes for which the simulation result is viewed are set.

DIODE PROTECTION AGAINST REVERSE VOLTAGE

The simplest methods of protecting equipment against reverse voltage involve using diode VD1 (Fig. 1a) connected in series with load R1 [9].

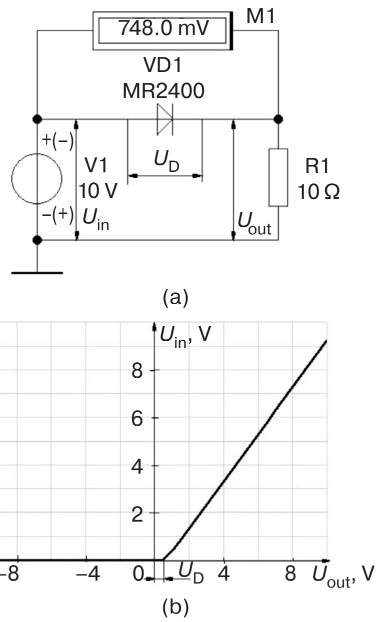

Fig. 1. Diode protection against reverse voltage: (a) circuit, (b) transfer characteristic. MR2400—diode (Infineon Technologies AG, Germany). Here and in following figures, the designations of circuit elements correspond to the designation system adopted by GOST 2.710-81[1]

The transfer characteristic (the dependence of output voltage U_{out} on load R1 on input voltage U_{in}) is shown in Fig. 1b. For convenient estimation of results during simulation in the Analysis/DC Sweep mode, the voltage source V1 determining input voltage U_{in} is varied within the range from −10 V to +10 V. Voltmeter M1 shows voltage drop U_D across diode VD1 in forward direction U_D = 0.748 V with a load current I_l of about 1 A flowing through it. In such a circuit, a power loss of 0.748 W in the protection diode is extremely undesirable for battery-powered devices. Although Schottky diodes slightly improve the diode protection characteristics at voltage drop U_D = 0.3…0.4 V, even such a small voltage drop may be unacceptable for low supply voltages of

[1] GOST 2.710-81. Unified system for design documentation. Alpha-numerical designations in electrical diagrams. Moscow: Izd. Standartov; 1985 (in Russ.).

the order of 3.3 V typically used for powering modern integrated circuits (ICs) and microcontrollers.

In some cases, where special protection IC against reverse polarity is not available, discrete component circuits using cheap and available MOSFETs having low channel resistance in the open state may be applied. These circuits are often called the "ideal diode" or sometimes "smart diode" for their characteristics[2].

IDEAL DIODE BASED ON *p*-MOSFET

The *p*-channel MOSFET circuit performing the function of protection diode is shown in Fig. 2a.[3]

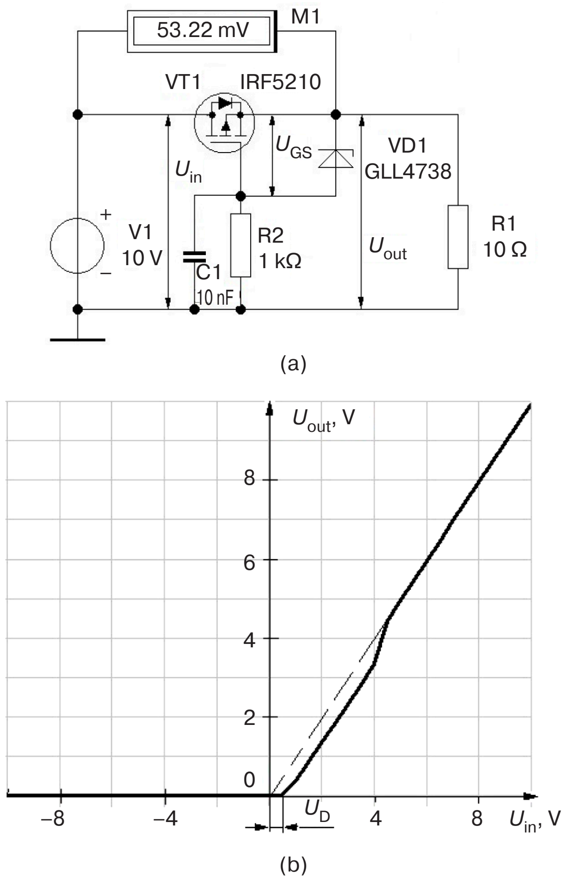

Fig. 2. Protection against reverse polarity based on *p*-MOSFET: (a) circuit, (b) transfer characteristic. GLL4738—zener diode (Vishay, USA)

In the circuit, the drain of transistor VT1 is connected to the positive voltage of the input voltage source V1. Prior to the application of voltage U_{in}, the transistor channel is clamped due to the gate and the source having ground potential along with the voltage U_{GS} between gate and source being zero. When positive input voltage U_{in} is applied, current flows through forward biased parasitic diode (body diode) in the MOSFET system and load R1 resulting in a voltage drop close to U_{in}. The parasitic diode is open until the transistor VT1 channel opens (this occurs at voltage U_{in} about 4.5 V). Due to its low resistance, the open channel shunts the parasitic diode to provide a small voltage drop in it, as can be seen from the transfer characteristic shown in Fig. 2b [10, 11]. Voltmeter M1 measures voltage drop U_{DS} = 53.22 mV across the open transistor. At load current I_1 = 1 A, this corresponds to open transistor channel resistance $r_{DS\ ON}$ = 0.053 Ω being close to the value for the IRF5210 transistor $r_{DS\ ON}$ = 0.06 Ω. When reversing the polarity of input voltage U_{in} generated by source V1, transistor VT1 clamps and blocks the load current (second quadrant of the characteristic shown in Fig. 2b).

Zener diode VD1 protects transistor VT1 against exceeding the permissible gate-source voltage. The value of stabilization voltage is selected equal to U_{st} = 9...10 V, so that the voltage is sufficient for reliable opening of transistor VT1. Capacitor C1 smooths out negative voltage surges across the possible load occurring when the input voltage polarity reverses rapidly.

If input voltage U_{in} does not exceed the permissible voltage of the MOSFET switch (typically about 20V), then protection against exceeding the permissible voltage is not required. The circuit may be simplified by excluding VD1, C1, and R2 with the transistor gate being connected to ground.

In normal operation, the minimum input voltage from which the circuit has minimal losses similar to that of an ideal diode occurs with the unlocking transistor voltage (about 4.5 V). At a lower voltage, the transistor channel is clamped while only the parasitic diode remains open, while the voltage drop across the switch is about U_D = 0.7 V (Fig. 2b). An example of the automotive electronic equipment protection against reverse voltage polarity is given in the relevant literature.[4]

The ideal-diode *p*-MOSFET circuit may be attractive due to its simplicity, low voltage drops across the transistor switch under normal operation and current blocking occur in case of reverse polarity. However, other things being equal, *p*-channel MOSFET is inferior to its *n*-channel analogs in terms of such parameters as open channel resistance, maximum current, input capacitance, and cost.

IDEAL DIODE BASED ON *n*-MOSFET

A similar protection circuit against reverse polarity may be implemented on the basis of *n*-MOSFET provided it is connected to the negative terminal of voltage source V1 as shown in Fig. 3a [12].

[2] *Basics of Ideal Diodes*. Application Note. Texas Instruments Incorporated. SLVAE57B – FEBRUARY 2021. 24 p. https://www.ti.com/lit/an/slvae57b/slvae57b.pdf?ts=1639001451460. Accessed January 10, 2022.

[3] https://www.terraelectronica.ru/news/5444. Accessed January 10, 2022 (in Russ.).

[4] https://www.terraelectronica.ru/news/5446. Accessed January 10, 2022.

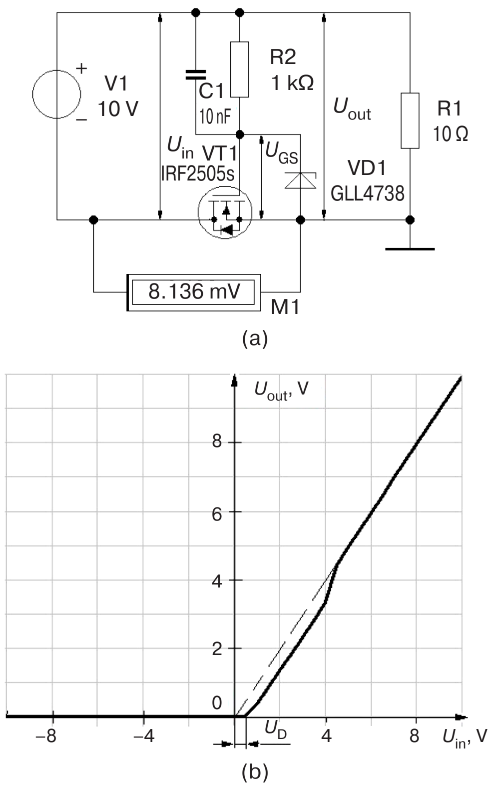

Fig. 3. Protection against reverse polarity based on *n*-MOSFET: (a) circuit, (b) transfer characteristic

As in circuit above, the channel of transistor VT1 is clamped before applying input voltage U_{in}, since $U_{GS} = 0$. When positive input voltage U_{in} is applied, the parasitic diode of transistor VT1 opens, and current flows through load resistance R1. As can be seen from the transfer characteristic (Fig. 3b), the channel of transistor VT1 becomes conductive at voltage U_{in} about +4.5 V. The voltage drop across the open channel of the transistor becomes minimal at 8.136 mV. At load current about 1 A, this corresponds to the open channel resistance $r_{DS\,ON} = 8.136$ mΩ being close to the Datasheet[5] data for the IRF2505S transistor $r_{DS\,ON} = 0.008$ Ω. The scattered power across transistor VT1 is insignificant being about 8 mW.

When the power supply is reverse polarized, transistor VT1 clamps and blocks the reverse current (second quadrant of the transfer characteristic, shown in Fig. 3b). As in the previous circuit, zener diode VD1 protects against exceeding the permissible voltage of transistor VT1. The capacitor C1 ≈ 10 nF is necessary to smooth the negative voltage surge at the output possible of occurring at the moment of reversing polarity of the input voltage and damaging electronic components. Increasing the capacitor C1 capacity, the voltage rise time across the gate voltage may be increased, thus allowing implementing the "soft start" function.

When input voltage U_{in} is less than the voltage permissible for transistor, the overvoltage protection circuit between gate and source may be excluded by eliminating elements VD1, C1, and R2. In this case, the transistor gate is connected to the power supply "plus."

Thus, the *n*-MOSFET circuit provides the most effective protection against reverse polarity. However, it may be someway inconvenient to build a large star ground system due to the protection being included in the ground bus.

INTEGRATED IDEAL DIODE

Electronic component manufacturers offer a fairly wide range of high-efficiency ideal diode solutions. This may be exampled by the LM74610-Q1[6] integrated controller (Texas Instruments, USA) with external *n*-MOSFET VT1 performing the ideal diode functions; its connection circuit is shown in Fig. 4. With the correct (positive) input voltage polarity, the transistor opens to pass current. Here, power dissipation is minimal due to low open channel resistance. In the event of reverse polarity voltage being applied to the circuit input, the controller shuts down the transistor in less than 8 μs. Like a common diode, an ideal diode is connected to the power line via the "Anode" and "Cathode" pins only. The controller has no connection to the common output, thus providing zero self-consumption current. The charge pump circuit with external capacitor V_{cap} is used for controlling the external power transistor.

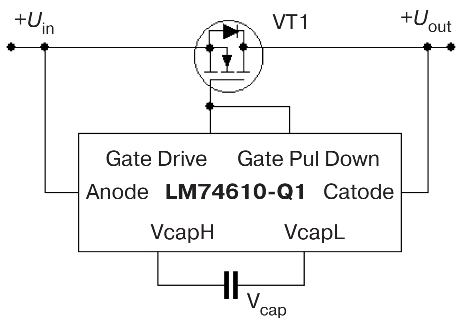

Fig. 4. Connection circuit for the LM74610-Q1 ideal diode

The controller, which is designed for a wide range of automotive applications, is capable of withstanding reverse voltages up to 45 V. Values for current in the circuit and power dissipation are determined by the external transistor characteristics.

[5] Datasheet IRL2505S International Rectifier. https://www.alldatasheet.com/datasheet-pdf/pdf/84685/IRF/IRL2505S.html. Accessed January 10, 2022.

[6] Datasheet LM74610-Q1 Texas Instruments. https://www.alldatasheet.com/datasheet-pdf/pdf/810348/TI1/LM74610-Q1.html. Accessed January 10, 2022.

The LTC4411[7] and LTC4412[8] ideal diodes from Linear Technology (USA) shown in Fig. 5 are oriented towards using *p*-channel MOSFET. However, the LTC4411 model (Fig. 5a) contains a built-in transistor with open state channel resistance $r_{DS\ ON}$ = 0.14 Ω, while the LTC4412 variant has an external transistor, thus extending the range of currents it can control.

In normal operation of ideal diodes, the voltage drop across transistor may be up to 28 mV at a current of no more than 2.6 A with input voltages ranging from +2.6 to +5.5 V. The IC chip has a thermal protection device for blocking the current should the permissible temperature be exceeded. The transistor also switches off when the output voltage exceeds the input voltage with the return current not exceeding 1 μA. The CTL pin can be used to control on/off in response to external commands. The status output STAT indicates the redundant state where power is being supplied from an alternate source, there is voltage across the load, and no current flowing from the main power supply through the ideal diode.

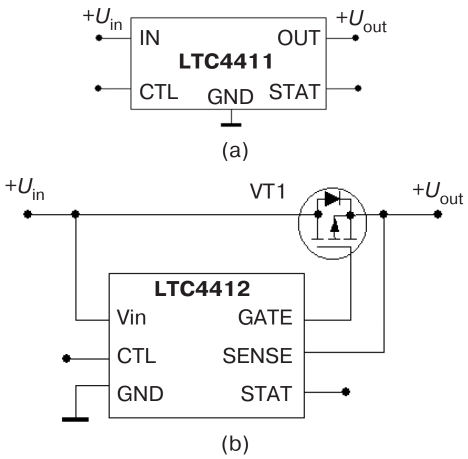

Fig. 5. Ideal diode connection circuit: (a) LTC4411, (b) LTC4412

The LTC4412 controller (Fig. 5b) controls the external *p*-MOSFET (according to established rules, if the transistor is external, then the control circuit is called a controller). The maximum permissible input voltage is up to 40 V, while the switching current is entirely determined by the external transistor characteristics. The SENSE and STAT outputs are used for switching or sharing the load current under operation from multiple power supplies. The gate driver includes an internal voltage clamp for protecting the transistor gate.

Based on the LTC4412, the LTC4412ES[9] power management IC produced by the Linear Technology company comprises an ideal diode with external *p*-channel MOSFET and a built-in Schottky diode to permit efficient OR-ing of multiple power supplies over total load (Fig. 6).

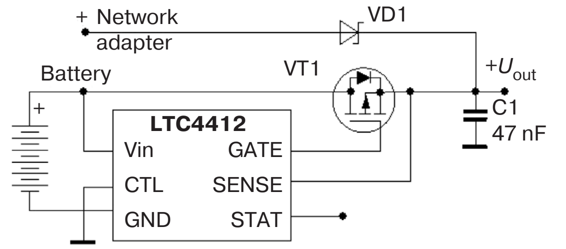

Fig. 6. Redundant power management circuit

In normal operation, the current is brought in contact with the load from the network adapter via the Schottky diode VD1. When external power failure occurs, the current is supplied from the backup battery. The voltage drop across external *p*-channel MOSFET is less than 20 mV.

The IC is designed for use in cellular phones, laptops, digital camcorders, uninterruptible power supplies, powerful USB peripherals, and alternative energy devices. The reverse battery voltage protection circuit based on specialized LTC4359[10] controller (Linear Technology) with external *n*-MOSFET is shown in Fig. 7.

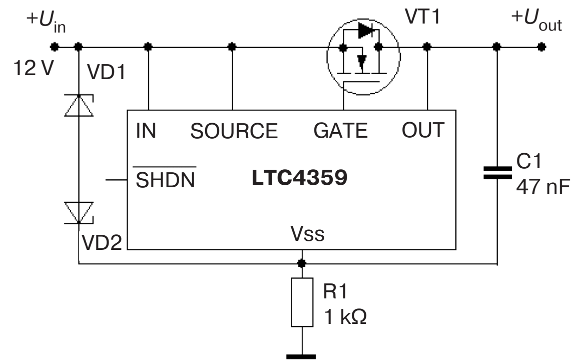

Fig. 7. Automotive equipment protection circuit against the battery reverse polarity

Zener diodes VD1 and VD2 are used in conjunction with resistor R1 to expand the range of possible input voltages. The *n*-channel MOSFET BSC028N06NS[11] (Infineon Technologies AG, Germany) with channel resistance $r_{DS\ ON}$ = 2.8 mΩ and current up to 132 A is

[7] Datasheet LTC4411 Linear Technology. https://www.alldatasheet.com/datasheet-pdf/pdf/94411/LINER/LTC4411.html. Accessed January 10, 2022.

[8] Datasheet LTC4412 Linear Technology. https://www.alldatasheet.com/datasheet-pdf/pdf/82845/LINER/LTC4412.html. Accessed January 10, 2022.

[9] Datasheet LTC4412ES6 Linear Technology. https://www.alldatasheet.com/datasheet-pdf/pdf/82846/LINER/LTC4412ES6.html. Accessed January 10, 2022.

[10] Datasheet LTC4359 Linear Technology. https://www.alldatasheet.com/datasheet-pdf/pdf/1039943/LINER/LTC4359.html. Accessed January 10, 2022.

[11] Datasheet BSC028N06NS Infineon Technologies. https://www.alldatasheet.com/datasheet-pdf/pdf/470560/INFINEON/BSC028N06NS.html. Accessed January 10, 2022.

recommended for use as external VT1 to ensure low heat dissipation, low voltage loss, and small overall dimensions. As well as meeting strict requirements for automotive and telecommunication equipment, the controller allows for redundant power management (SHDN pin).

CONCLUSIONS

The component base of devices providing protection against reverse polarity connection to power supply sources, protection options of devices against reverse voltage polarity has been analyzed along with circuit solutions based on discrete and integrated components. Circuit simulation of ideal diodes based on having high specification *p*- and *n*-channel transistors is used to specify the characteristics and voltage/power losses in protected circuits and demonstrate the simplicity of the technical solution.

Authors' contribution
All authors equally contributed to the research work.

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