Optoelectronics and optoelectronic devices

Application of active diodes to enhance the efficiency and reliability of switching power supplies

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Abstract. The paper deals with use of active (‘ideal’) diodes to improve the efficiency and reliability of switching power supplies. Traditional semiconductor diodes have significant energy losses due to forward voltage drop and reverse currents, which negatively affects the overall efficiency of systems, especially in low-voltage high-efficiency devices. Active diodes that use transistors and control circuitry enable achieving a low forward bias voltage drop and minimize reverse currents. Theoretical analysis and graphical dependences show significant reduction in power losses in rectifier elements using active diodes. Active diodes have significant potential for applications in various fields of electronics, especially in renewable energy and energy-efficient lighting, and are a promising area for further research and implementation in modern electronic systems.

Keywords: switching power supply, diode, forward bias voltage, reverse currents.

https://doi.org/10.15407/spqeo28.01.077
PACS 84.30.Le, 84.32.Ff, 84.32.Tt, 84.60.Ve, 85.30.De, 85.30.Kk, 88.05.Bc

Manuscript received 30.12.24; revised version received 31.01.25; accepted for publication 12.03.25; published online 26.03.25.

1. Introduction

Switching voltage converters [1, 2] play a key role in modern electronics. One of the critical components of these systems is diodes, which are used to rectify, switch and protect electrical circuits. Traditional semiconductor diodes, including Schottky diodes [3], have significant drawbacks, such as power losses due to voltage drop at forward switching and reverse currents during switching to the closed state caused by diffusion capacitance of the *p-n* junction. This has a negative impact on the overall efficiency and reliability of switching power supplies and is particularly significant for low-voltage high-efficiency devices [4].

One of the ways to overcome these shortcomings is to use active diodes, or so-called ‘ideal diodes’, in electronic power supplies [5]. Such diodes employ semiconductor switches, such as metal-oxide-semiconductor field-effect transistors (MOSFETs), to achieve a minimal voltage drop during forward bias. Additionally, they incorporate a controller that generates signals for rapid switching of the transistor, effectively minimizing reverse currents during the transition between the open and closed states.

Fast and Schottky diodes have a forward voltage drop in the range of 0.5 to 1.2 V. In low-voltage systems, where saving energy is critical, these voltage drops result in significant energy losses. In modern voltage conversion systems based on switching power supplies, such as solar power conversion controllers [6], light-emitting diode (LED) drivers [7], battery charging systems [8] and other electronic devices, where reduction of rectification losses is important, use of active diodes increases the overall system efficiency, reduces heat generation and improves the reliability of electronic components [9, 10].

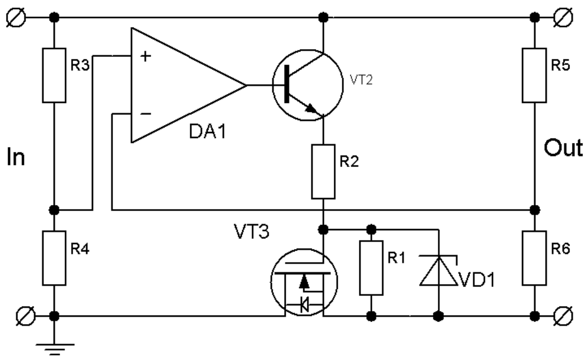
Modern switching power supplies with various topologies (forward [11, 12], reverse [13–15], resonant [16, 17], or quasi-resonant [18, 19]) use traditional diodes in both alternating current voltage rectification circuits and reverse voltage protection links. Significant forward voltage drops across the diodes lead to a significant reduction in the efficiency of a power supply as a whole. Reducing forward voltage drop of the rectifier element is especially effective for systems with low operating voltages (in particular, liquid crystal, LED, and other types of displays [20–22]), as well as for modern powerful LED light sources and systems with large numbers of LED control channels [23, 24].

The purpose of this work is to demonstrate the possibility of a significant improvement of the efficiency of voltage converters when active diodes are used in their design. It is expected that the results of this study will show the advantages of using active diodes instead of traditional ones and the prospects of the former for improving the efficiency and reliability of switching power supplies.

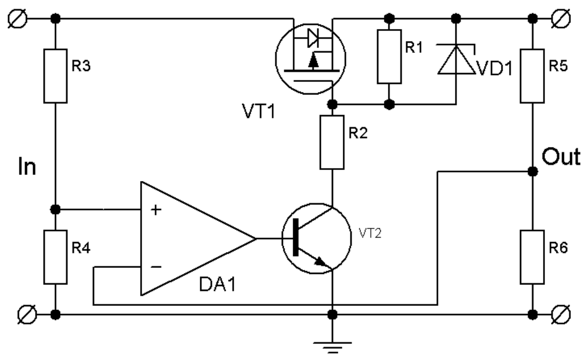
2. Principle of operation of active diodes

The main advantage of an active diode is that it provides current rectification with minimal forward voltage drops and power losses. Unlike conventional diodes, which have a significant voltage drop (at least 0.5 V), an active diode uses a transistor and a control circuit to provide almost perfect conductivity in forward direction and effective blocking in reverse direction. Fig. 1 shows schemas of the simplest active diodes.

As can be seen from Fig. 1, an active diode is based on transistors, usually MOSFETs, which have low channel resistance. In the case of low voltage switching, most of these transistors have conductive channel resistance of 1 to 15 mOhm, which allows them to achieve low voltage drops and thus significantly reduces power losses at high switching currents. This is especially important in applications where it is necessary to minimize energy losses and reduce heat generation. The control circuit of such transistors detects voltage differences between the input and output of the active diode and opens or closes the transistor accordingly. This allows the device to respond to voltage polarity reversal and let current flow in only one specific direction with minimal losses. When the input voltage is higher than the output voltage, the control circuit opens the transistor, allowing current to flow across the active diode with a minimal voltage drop. If the input voltage drops below the output voltage or reverses polarity, the control circuit closes the transistor.



(a)



(b)

Fig. 1. Diagram of an active diode (a) with N-channel transistor and (b) with P-channel transistor.

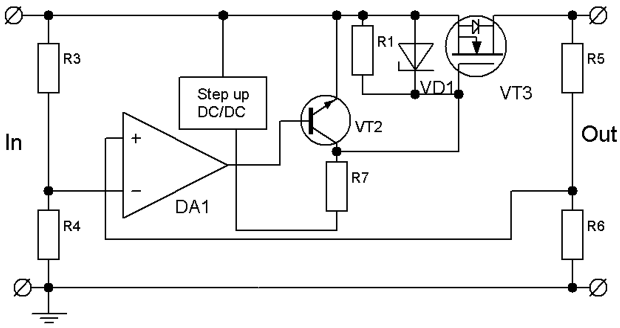


Fig. 2. Diagram of an active diode with an N-channel MOSFET transistor in the ‘+’ line.

In this state, the transistor blocks the reverse current, preventing undesirable effects and possible damage to the equipment. This approach allows for fast and efficient switching between conductive and non-conductive states, bringing the device behavior closer to that of an ideal rectifier diode.

In the simplest schemes for implementing an ‘ideal’ diode (Fig. 1), two types of MOSFET transistors can be used: P- and N-channel ones. The advantage of N-channel transistors over P-channel transistors is a significantly lower channel resistance, which reduces losses compared to the use of P-channel transistors. However, the circuit with a P-channel transistor (Fig. 1b) does not break the earth conductor relative to the load, which is important because low-impedance shunts are often mounted on the earth conductor to measure current. To mount the N-channel transistor in the ‘+’ line, it is necessary to provide an additional voltage that is 12…15 V higher than the input voltage and can be applied to the transistor gate, ensuring opening the transistor (Fig. 2). To realize this, an additional step-up converter is introduced, which can be implemented using different topologies or specialized microcircuits (*e.g.* LM5050).

When designing devices in electronic circuits that use ‘ideal’ diodes, attention should be paid to the maximum frequency of the diode, which sets the minimal switching time from the open to the closed state of the ‘ideal’ diode. This time determines the amount of current required to recharge the gate-source capacity. It is also necessary to pay attention to the consumption by the transistor control circuit in the ‘ideal’ diode, which sets the limit of feasibility for use in low-power systems.

3. Efficiency of active diodes

Comparing the efficiency gained by using active diodes in switching power supplies, the power losses of conventional and active diodes at a given current or voltage should be compared.

To compare the power loss of a conventional diode and an active diode at a certain current I, the following must be taken into account:

1. The forward voltage drop (V_f) across the diode remains constant in the main region of its current-voltage characteristics (within its operating range). The power losses in the diode (P_{loss-D}) can be calculated as:

$$P_{loss-D} = V_f \times I . \quad (1)$$

2. When an active diode circuit is used for transistors with a channel resistance R, the power loss P_{loss-T} is calculated according to the Joule–Lenz law:

$$P_{loss-T} = I^2 \times R . \quad (2)$$

Fig. 3 shows the dependence of power losses on current for conventional diodes with a forward voltage drop of 0.5 to 1.2 V and active diodes that use transistors with a channel resistance of 1...15 mOhm.

Fig. 3 shows the ratios of power losses on conventional and active diodes *versus* current through them. These dependences demonstrate a clear advantage of using active diodes based on MOSFET transistors compared to traditional diodes, especially at high switching currents. Power losses in the diodes with a voltage drop of 0.5 to 1.2 V increase linearly with current, which causes significant energy losses. On the other hand, the losses in the transistors have quadratic dependence, but remain significantly lower even at a channel resistance of 15 mOhm. Use of transistors with a channel resistance of 1 mOhm ensures minimal losses, making such transistors an optimal choice for low-voltage and high-efficiency power supplies to reduce heat generation and increase overall system efficiency.

Comparison of the values for the worst-case conventional and active diodes (curves *1* and *3*, Fig. 3) allows us to build the dependences presented in Fig. 4, which show the ratio of the power losses on conventional diodes to the losses on active diodes. We considered the cases with both maximum possible power losses (curve *1*, black) and minimal losses (curve *2*, red).

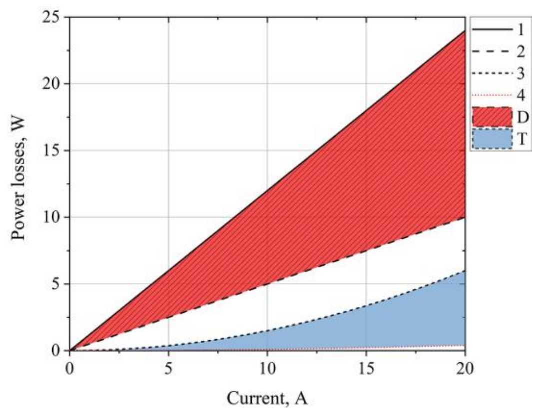


Fig. 3. Dependence of power losses on current through a diode and a transistor, where *1* is for a diode with a voltage drop of 1.2 V, *2* is for a diode with a voltage drop of 0.5 V, *3* is for a transistor with a channel resistance of 15 mOhm, and *4* is for a transistor with a channel resistance of 1 mOhm. The shaded areas show the power losses of power supplies using *D* – diodes and *T* – transistors, the corresponding parameters of which lie within the indicated ranges.

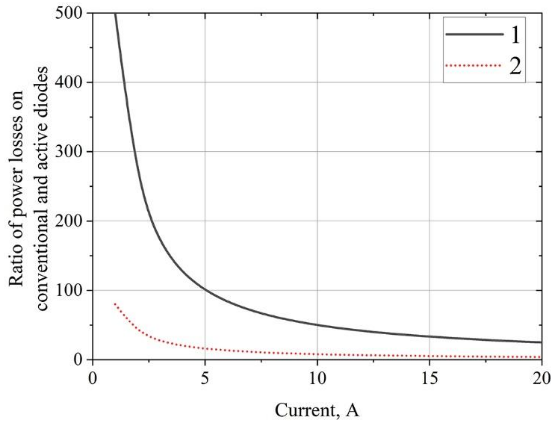


Fig. 4. Dependence of the ratio of power losses on an active and conventional diode on the current: *1* – for the maximum possible power losses and *2* – for the minimum possible power losses.

It can be seen from Fig. 4 that the power losses for the power supplies using conventional diodes are much higher compared to the case of active diodes. Use of transistors with low conductive channel resistance in the structure of active diodes ensures significantly lower losses compared to conventional diodes, especially at high currents.

The presented dependences emphasize the efficiency of active diodes compared to that of conventional diodes and demonstrate the hundreds of times greater advantage of using the former. Even in the best-case scenario for conventional diodes (curve *2*), active diodes show significantly lower losses, which makes them an optimal solution for energy-efficient power supplies, particularly for low-voltage and high-current applications. The effectiveness of using active diodes in low current circuits may not be practical because the supply of the transistor control circuit may exceed the losses compared to using a fast diode or Schottky diode.

To estimate the part of the power lost on switching elements at different voltages V and currents I, it is necessary to determine the ratio of the power loss (Fig. 3) to the total power, which is defined as

$$P = V \times I . \quad (3)$$

In our case, the part of the lost power is calculated by the following expression:

$$\eta = \frac{V_f \times I}{V \times I} = \frac{V_f}{V} . \quad (4)$$

Taking into account Eq. 2 for the case of an active diode, the part of the lost power is calculated as

$$\eta = \frac{I^2 \times R}{V \times I} = \frac{I \times R}{V} . \quad (5)$$

Fig. 5 compares the relative power losses when using conventional or active diodes at common voltages of 18, 36 and 72 V, which occur at a switching current of 20 A.

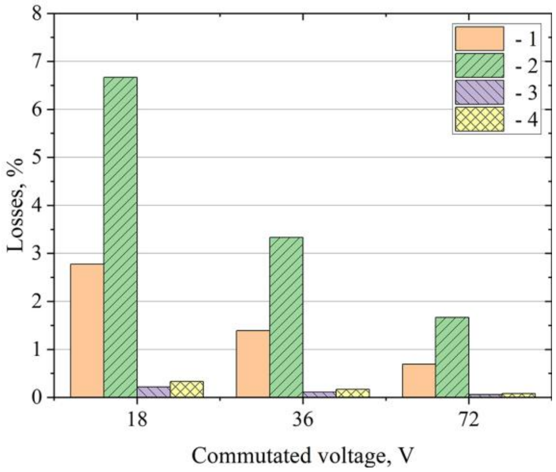


Fig. 5. Comparison of energy losses on diodes (with voltage drops of 0.5 (*1*) and 1.2 V (*2*)) and transistors (with channel resistance of 1 (*3*) and 15 mOhm (*4*)) at a current of 20 A.

Figs. 4 and 5 show obvious advantage of using active diodes in low-voltage power supplies. It should be noted that at low currents and voltages, the relative losses of conventional diodes increase, and the advantage of active diodes becomes even greater, until the point when the losses in the control system of active diodes start to exceed the losses of conventional diodes. In some cases (when the source voltage is very low), use of active diodes is unavoidable. When active diodes replace conventional diodes in modern power supplies, a sharp increase in the efficiency of a power supply as a whole is ensured.

4. Conclusions

Use of 'ideal' diodes significantly increases the efficiency of power supplies by reducing power losses in rectifier components. This is important for systems operating at high currents, where losses on conventional diodes are quite high. The advantage of active diodes becomes greater as the power of the device increases. Reduction of power losses is primarily achieved by using MOSFET transistors with low conductive channel resistance and special control circuits that ensure fast and efficient switching between conductive and non-conductive states.

Use of active diodes helps to reduce heat generation, which has a positive impact on the reliability and durability of electronic components. This is especially important for modern electronic devices, where power efficiency and thermal management are critical.

The obtained results indicate prospects for introducing active diodes into various topologies of switching power supplies. Such diodes can improve the overall system efficiency, which is an important step in the development of energy-saving technologies.

Introduction of active diodes makes it possible to create new types of modern reliable and efficient electronic systems, especially in growing areas of renewable energy and energy-efficient lighting.

Acknowledgements

This work was supported by the National Research Foundation of Ukraine (project No 2022.01/0037).

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Korkishko R.M.: writing – review & editing, validation, investigation.

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Застосування активних діодів для підвищення ефективності та надійності імпульсних джерел живлення

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Анотація. Розглянуто застосування активних («ідеальних») діодів для підвищення ефективності та надійності імпульсних джерел живлення. Традиційні напівпровідникові діоди мають значні втрати енергії через падіння напруги при прямому включенні та зворотні струми, що негативно впливає на загальну ефективність систем, особливо в низьковольтних високоефективних пристроях. Активні діоди, що використовують транзистори та схему керування, дозволяють досягти низького падіння напруги при прямому зміщенні та мінімізувати зворотні струми. Теоретичний аналіз та графічні залежності показують значне зменшення втрат потужності на випрямних елементах при використанні активних діодів. Застосування активних діодів має значний потенціал у різних галузях електроніки, особливо в сферах відновлюваної енергетики та енергоефективного освітлення, і є перспективним напрямком для подальших досліджень та впровадження в сучасні електронні системи.

Ключові слова: імпульсне джерело живлення, діод, напруга при прямому зміщенні, зворотні струми.