Static and Dynamic Characteristics of Antiparallel Diode as Part of Switching Power Module

A. V. Gorbatyuk, I. V. Grekhov, D. V. Gusin, and B. V. Ivanov

Abstract—A numerical simulation of the operation of a fast antiparallel diode in the switching power module of an autonomous voltage inverter is carried out. The time of turning off the transient and the static and transient heat losses in the diode are calculated as a function of the electrophysical parameters of the semiconductor diode structure.

Keywords: voltage inverter, antiparallel diode, reverse recovery, carrier lifetime, injection efficiency.

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The development of new designs of switching power devices requires the improvement of the characteristics of fast antiparallel diodes as part of power semiconductor modules. The main application of these modules in the inverter technology is the bridge circuit of a voltage inverter, which makes it possible to gradually adjust the frequency and amplitude of the alternating voltage applied across a load. The load, e.g., one of the windings of the stator of an induction motor with inductance $L_l$ and active resistance $R_l$, is connected across the bridge diagonal of four modules (Fig. 1a, a single-phase version of the circuit). The circuit input is connected to a voltage supply $U$ with an in-parallel capacitive filter, i.e., a capacitor $C_f$. Parasitic inductances of the conductors from the supply rails to the power modules are included in the inductance $L_I \ll L_l$; the inductances associated with element connections in the modules are negligible compared to $L_I$.

The power switches are controlled by the law of pulse-width modulation (PWM). A sinusoidal voltage with a period $T$ must be formed across the load. In one

![Figure 1](image-url)
of the half-periods $T/2$, only the switches of modules $I$ and $3$ operate; the load current varies from the peak value $-I_0$ to $+I_0$. In the second half-period, switches $I$ and $3$ are turned off and the other pair of modules is used. The PWM period $T$ is constant and equal to the sum of two intervals $t_{on}$ and $t_{off}$. At the beginning of each such period, devices $I$ and $3$ are switched on by positive-polarity driving pulses with a width $t_{on}$, the current, which increases with time, flows from the supply sequentially through the turned-on switches of the modules and the load $L$, $R$. After feeding driving pulses that turn off switches $I$ and $3$, the current flows through the diodes of modules 2 and 4 and the inductive load in the same direction. The inductance $L_1$ is now connected to the supply in the reverse polarity, and the current through it decreases. The duration of this phase is equal to $t_{off}$. At the beginning of the next modulation period, switches $I$ and $3$ are switched on again, and the reverse recovery of diodes 2 and 4 occurs.

Antiparallel diodes in an inverter operate under extreme conditions, meaning they must conduct the total operating current and they must recover at a high rate of rise of reverse current. The characteristics of the on state of the diode and the process of recovering its blocking ability depend heavily on the structural parameters of the device, including the thickness of the base, the concentration of the impurity and the diffusion length within it, and the injection efficiency of the anode $p$-emitter). The selection of parameters of the power diode under development is based on the trade-off relationship caused by the following three factors:

1. heat losses in the forward current flow
   \[ W_{st} \approx V_{on} I_{off}, \]
   where $V_{on}$ is the forward voltage drop across a turned-on diode;

2. transient heat losses $W_{off}$ equal to the time integral of $V(t)I(t)$ in the recovery process;

3. limitations of the operating current and voltage with respect to the static and dynamic avalanche breakdown.

In addition, a diode must exhibit soft recovery behavior, which is shown through the limitation in the allowable rate of reverse-current decay. Exceeding this rate leads to high-frequency voltage fluctuations with large amplitudes due to the parasitic inductance of the circuit.

In this work, using a numerical simulation, we discuss the effect of technological parameters of the structure on the characteristics of a diode designed for operating in a power module with a field-controlled integrated thyristor [1] or an insulated-gate bipolar transistor. Similar studies were carried out in several works. For example, in [2], a one-dimensional numerical simulation is used to optimize the reverse recovery behavior by selecting the doping concentration and the thickness of the $p+$ emitter of the diode. The variations in each of these technological parameters were accompanied by the choice of lifetime at a high injection level in the base in order to provide a constant voltage drop across the turned-on diode at a given current density. Based on the simulation results, the reverse recovery time and the amplitude and rate of decay of the reverse current were found. It is pertinent to note that the effect of the above parameters of the device structure on the values of static and transient heat losses, which limit the allowable operating switching frequency of a power module, was not studied in [2]. In addition, the static breakdown voltage of the diode studied in the work was 1200 V. It is of current concern to increase the operating voltage of fast recovery diodes taking into account the fundamental limitations due to avalanche breakdown [3].

**NUMERICAL SIMULATION OF RECOVERY PROCESS**

According to the principle of operation of a PWM voltage inverter, the instantaneous value of load current achieves the peak value $+I_0$ when the ratio of pulses that drive switches $I$ and $3$ is 2. In this case, the diodes of modules 2 and 4 conduct forward current during the time $T_{k}/2$; after that, they recover in the reverse-bias mode with turning on switches $I$ and 3. The value of $T_k$ is low compared to $T/2$, e.g., for high-voltage power switches, the operating frequency $f_k = 1$ kHz, and the frequency of output voltage is 50 Hz. In turn, the reverse recovery of a diode usually occurs within a few microseconds, which is much less than $T_{k}/2$. In the studied period $T_{k}$, the load current change is negligible compared to $I_0$. Therefore, to analyze the transient phenomenon in this PWM period, the inductive load can be replaced with a dc supply $I_0$. The case $I_k \approx I_0$ is the most critical for a diode. This case should be analyzed to determine the effect of the design parameters of the device on its static and dynamic characteristics and to reveal the limitations of operating voltage and load current of the inverter.

To solve the formulated problem, we can pass from the original circuit of Fig. 1a to an equivalent circuit with one diode and a power switch (in fact, they enter the different modules, e.g., 2 and 3). Here, the parasitic inductance $L_1$ is included; the inductance $L_1$ is replaced with a current supply $I_0$; and the active load resistance is negligible. At time $t_{off} = T_{k}/2$, a stationary distribution of injected carrier concentration settles in the diode base. Since the turn-on time of fast semiconductor switches of any type (about 10–20 ns) is significantly shorter than other characteristic times in the circuit ($t_{on}$, $t_{off}$, and the diode reverse recovery time), a perfect switch, which switches on within 10 ns, is used instead of a particular power device in the equivalent circuit (Fig. 1b).

Below, we shall use the example of a fast silicon diode designed for a limiting blocking voltage of 3500 V.