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Hybrid IGBT-IGCT Switch

***Abstract**. This paper presents an analysis of a hybrid high-voltage switch based on the parallel connection of IGBT and IGCT. The proposed configuration allows combining the advantages of both semiconductors, resulting in substantially reduced power losses. Such energy efficient switches could be used in high-power systems where decreased cooling system requirements are a major concern. The operation principle of the switch is described and simulated and power dissipation is estimated at different operation conditions.*

***Streszczenie.** Artykuł prezentuje analizę hybrydowego łącznika wysokonapięciowego bazującego na równoległym połączeniu tranzystora IGBT i tranzystora IGCT. Proponowana konfiguracja pozwala na uzyskanie zalet dwóch półprzewodników, w rezultacie czego otrzymano znaczne zmniejszenie strat mocy. Takie energooszczędne łączniki, mogą być używane w systemach dużej mocy, gdzie zmniejszenie urządzeń systemu chłodzenia jest głównym problemem. Opisano i zasymulowano działanie łączników, oraz oszacowano rozpraszanie energii dla różnych warunków pracy. (**Łącznik hybrydowy typu IGBT-IGCT**).*

Keywords: Insulated gate bipolar transistors, insulated gate-commutated thyristors, industrial power systems.
Słowa kluczowe: Tranzystor bipolarny z izolowaną bramką, tyrystor z izolowaną bramką, Przemysłowe systemy energetyczne.

Introduction

High power densities together with a high functionality are the key aspects of modern power electronics. Further requirements are decreased volume and weight of the power systems as well as low cost. In order to fulfil these demands high switching frequencies of the semiconductors are necessary. Insulated gate bipolar transistors (IGBTs) are the major representatives in present day's medium- and high voltage electronics. In terms of blocking voltages (up to 6.5 kV) these devices have reached a level which can satisfy the majority of needs. The major advantages of IGBTs are easy driving and snubberless operation [1]. On the other hand, the switching behaviour of low voltage class IGBTs (<1 kV) is generally slower in comparison to MOSFETs, and high voltage class IGBTs (>3.3 kV) generally have higher conduction losses than GTO and IGCTs. In order to improve the performance of IGBTs, different approaches and methods were introduced and developed. For instance, at lower voltages, increased performance was achieved by a parallel IGBT-MOSFET-combination as shown in [2]. The hybrid integration of a unipolar and a bipolar power semiconductor in parallel allowed combining of their advantages whilst avoiding their disadvantages [3]. However, these positive results were observed only for certain applications and operation parameters.

Similarly, for high power applications the performance of high-power switches could be increased by a parallel connection of IGBT and IGCT switches [4-6]. This paper will focus on 4.5 kV class switches, since both IGBT and IGCT type semiconductors in press-pack type housings are commercially available, allowing easy connection of these devices in series by special cooling systems. The rated permanent DC voltage for both semiconductor devices is generally 2.8 kV. Using two- or three-level topologies, if necessary, this is sufficient to cope with the requirements of many traction and industrial applications with voltage ratings of 2.0-5.6 kV without the need of series connection of several semiconductors. Comparing two 4.5 kV class press-pack semiconductors: T0900EA45A- Westcode (Table 1 [7]) and 5SHY35L4512- ABB (Table 2 [8]), it could be observed that the on-state voltage U_T of IGCT is lower than the corresponding parameter $U_{CE(sat)}$ of IGBT. The turn-on behaviour is similar for both devices, while turn-off behaviour of IGCT is distinctly slower, which results in greatly increased losses during turn-off.

The idea is based on the integration of positive properties of gate-commutated thyristors in terms of low turn-on and on-state power losses as well as high surge current capability and IGBTs with their relatively low losses during turn-off. This may allow creating high-voltage and high-current energy-efficient switches with increased switching frequency, which could be advantageous in high-power (>500 KVA) industrial and railway traction systems [9].

Operation principle

The structure of the proposed hybrid switch (HS) configuration is presented in Fig. 1. The HS consists of a parallel connected asymmetrical press-pack IGCT and press-pack IGBT with an integrated freewheeling diode (FWD).

In the following analysis the HS is assumed to be operated in voltage-source inverter (VSI) circuits. The test circuit shown in Fig. 2 represents the main events that could occur in VSI topologies and includes the clamp circuit, HS, *D1* (representing FWD of the opposite HS) and inductive load. The inductances L_{CL} and L_D represent the stray inductance of the clamp and the stray inductance between the IGCT and IGBT housings, respectively. The clamp circuit typically used in IGCT applications limits the surge reverse-recovery current of the turning-off FWD and generally consists of a *di/dt* limiting inductor L_i, a clamp capacitor C_{CL}, a clamping diode D_{CL} and a resistor R_S.

Table 1. Characteristic values of 900A 4.5kV IGBT (T0900EA45A)

Parameter	Symbol	Value
Collector-emitter voltage	U_{CE}	4500 V
Permanent DC voltage	U_{DC}	2800 V
Collector-emitter saturation voltage (I_C=900 A)	$U_{CE(sat)}$	4.7 V
Turn-on delay time	$t_{d(on)}$	1.6 µs
Rise time	t_r	2.3 µs
Critical rate of rise of diode current	dI_t/dt_{cr}	2000 A/µs
Turn-off delay time	$t_{d(off)}$	1.2 µs
Fall time	t_f	1.2 µs
Turn-off energy (I_C=900 A)	E_{off}	2.6 J

Table 2. Characteristic values of 4.0kA 4.5kV IGCT(5SHY35L4512)

Parameter	Symbol	Value
Peak off-state voltage	U_{DRM}	4500 V
Permanent DC voltage	U_{DC}	2800 V
On-state voltage (I_T=900 A)	U_T	1.15 V
Turn-on delay time	$t_{d(on)}$	3.5µs
Rise time	t_r	1 µs
Critical rate of rise of current	dI_t/dt_{cr}	1000 A/µs
Turn-off delay time	$t_{d(off)}$	11 µs
Turn-off energy (I_T=900 A)	E_{off}	6-8 J

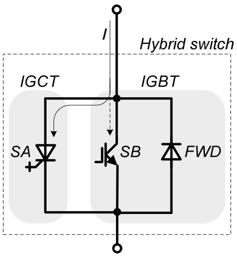

Fig.1. Proposed hybrid switch configuration

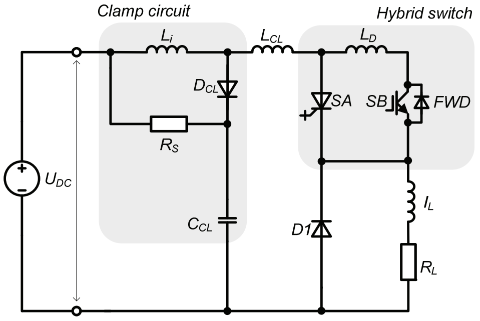

Fig.2. Configuration of the simulation circuit

The generalised HS operation principle is shown in Fig. 3 and the following time intervals during the operation period can be distinguished:

t_0 – the beginning of each switching period of PWM. The thyristor SA of the HS is turned on by the control signal, applying full load current. During this time the transistor of the HS is turned off.

t_0-t_1 – freewheeling diode reverse-recovery process, duration and behaviour are dependent on the diode type and *di/dt*.

t_1-t_2 – thyristor is conducting with low losses. The voltage across the HS determined by the voltage drop across the thyristor U_T.

t_2 – the turn-off control impulse is applied to the thyristor and simultaneously the turn-on impulse is applied to the transistor SB of the HS.

t_2-t_3 – as the turn-on behaviour of the IGBT is faster than the turn-off transient of the IGCT, the thyristor turn-off process occurs when the transistor is already in the on-state. The load current is distributed between both semiconductors.

t_3 – the SA returns to the blocking state, the full load current is applied to the transistor SB. Hence, the turn-off transient of the thyristor occurs when the voltage is limited to the voltage drop $U_{CE(sat)}$ across the conducting transistor SB of the HS. Moreover, during the current transfer to the transistor the voltage across its terminals is limited to the voltage drop across the SA during the on-state. The required duration of the transistor on-state should not be shorter than the turn-off transient of the thyristor.

t_4 – the turn-off of the HS occurs by applying negative gate voltage to the transistor after the thyristor returns to the blocking state. The turn off transient of the HV IGBTs is generally 2…7 µs. After the transistor is switched off, the voltage across HS and all its components become equal to the supply voltage.

Simulation model

To simulate the HS operation the commutation circuit shown in Fig. 2 was modelled in PSpice software. The same diode model was used in the topology for simplicity and the following simulation parameters were assumed: the input voltage is 2800 V, the maximum load current is 750 A. The values of the circuit's passive components are determined according to [10].

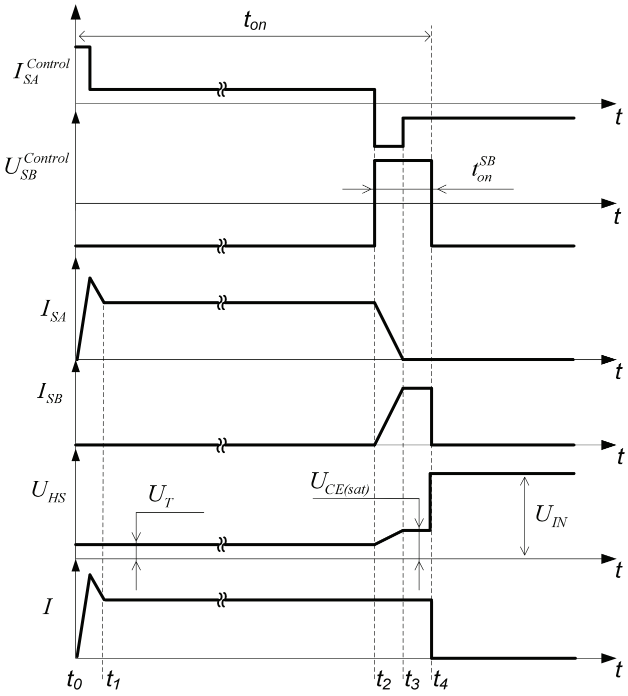

Fig.3. Generalised operation principle and switching waveforms of the proposed HS

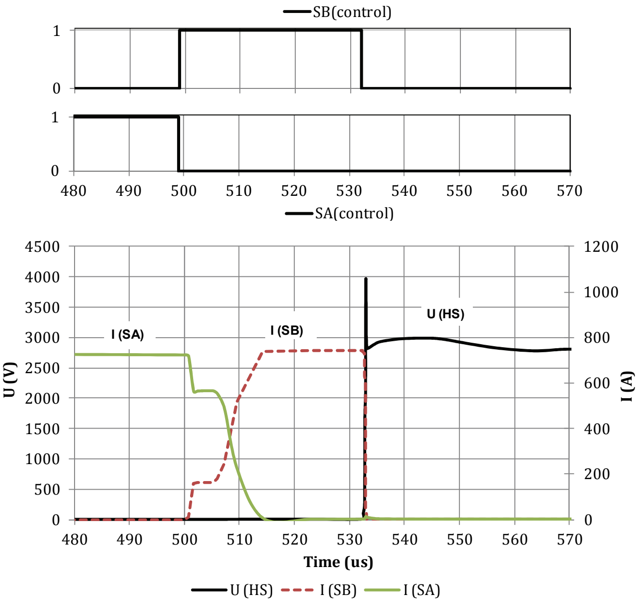

Fig.4. Simulated turn-off behaviour of HS at *I*=750 A, U_{DC}=2800 V

The simulations confirm the estimated behaviour of the proposed switch configuration. At turn-on the HS operates like an IGCT with the *di/dt* clamp, ensuring that *D1* is operating within its SOA. The on-state voltage of the HS is equal to the voltage drop across the thyristor during its conducting period. During turn-off of the HS the transistor is turned on for a short period; the turning-off thyristor current is then transferred to the transistor, which is closed right after the thyristor current becomes zero. The turn-off dynamics of the HS are greatly increased, while the excellent on-state characteristics of IGCT remain (Fig. 4) and all the elements are operated within the SOA.

Generalised loss evaluation

In the simulations of losses, the minimum IGBT switching losses with a very small gate resistances of R_{Gon}=4 Ω and R_{Goff}=2.5 Ω are assumed. In real industrial converters the IGBT gate units are adjusted to generate the desired *di/dt* and *dU/dt* to avoid large voltage and current spikes during transients. However, the use of the gate resistor to control the *di/dt* results in substantially higher switching losses in IGBT [11]. If a *di/dt* limiting turn-on snubber is used with both IGBT and IGCT devices, the turn-on losses would be similar [12]. On the other hand, the turn-off losses of the device may increase slightly [13].

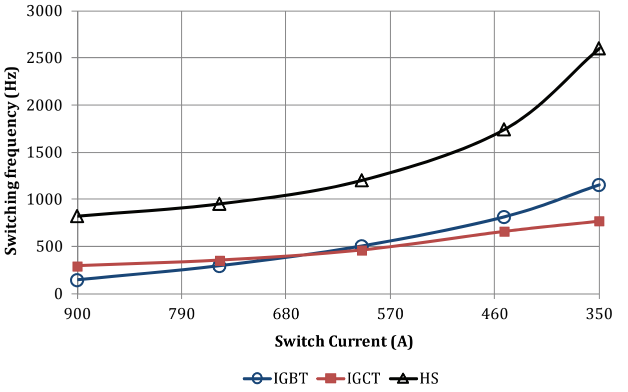

Fig.5. Switch switching frequency vs. current for different semiconductor configurations corresponding to 3 kW total power dissipation at U_{DC}=2800 V, *D*=0.5

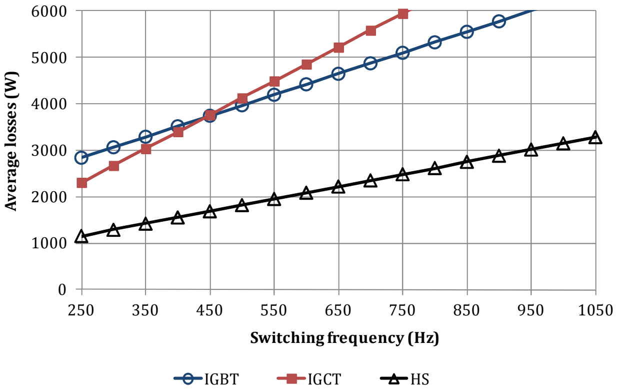

Fig.6. Switch power dissipation vs. switching frequency for different semiconductor configurations at *I*=750 A, U_{DC}=2800 V, *D*=0.5

The turn-off losses of the IGCT were excluded in the simulations; however, according to the test results presented in the previous papers [14], the turn-off losses may not be completely removed due to several factors. Firstly, for a large area device, such as the IGCT, a significant output capacitance must be charged in order to establish the depletion region to support voltage. Another factor is the free carriers which had not recombined being swept from the junction. Nevertheless, an 89% reduction in turn-off losses was reported in [15]. In real conditions, the power losses of industrial applications could be distinctly higher than the simulated values.

After the turn-on of the IGBT, the current distribution between conducting IGBT and IGCT is mainly influenced by different characteristics of the semiconductors, temperature differences and asymmetrically distributed stray inductances in the circuit [16][17]. Assuming both semiconductors in conducting state, the current sharing inside the HS neglecting cell resistances and inductances can be calculated by

(1) $$k_I = \frac{I_{SA}}{I_{SB}} = \frac{U_{CE(sat)}(I)}{U_T(I)}$$

where I_{SA} and I_{SB} are IGCT and IGBT currents respectively

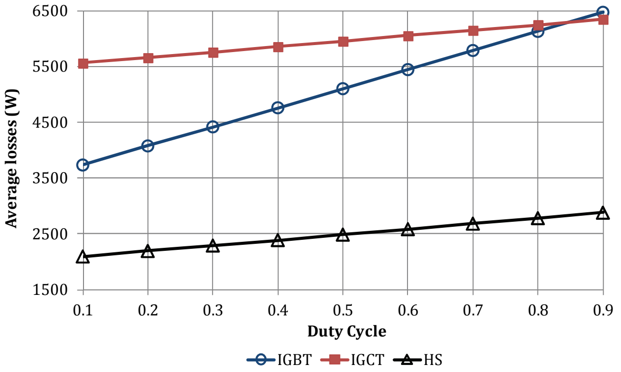

Fig.7. Switch power dissipation vs. duty cycle for different semiconductor configurations at *I*=750 A, U_{DC}=2800 V, f_{sw}=750 Hz

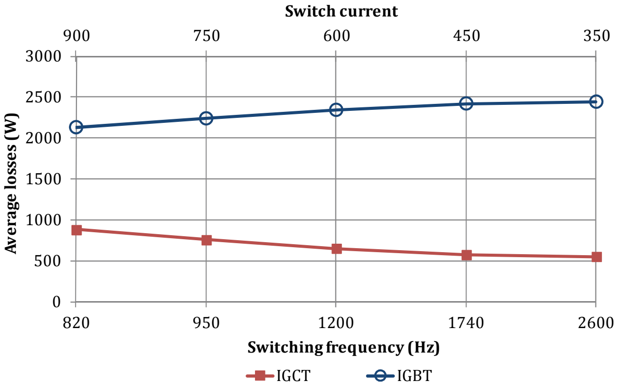

Fig.8. Breakdown of power losses of HS corresponding to 3 kW total power dissipation at U_{DC}=2800 V, *D*=0.5

Using Eq. (1) the IGBT and IGCT currents could be obtained by

(2) $$I_{SB} = I \cdot \frac{1}{1+k_I}$$

(3) $$I_{SA} = I \cdot \frac{k_I}{1+k_I}$$

According to simulations shown of Figs. 5-8 (IGBT-T0900EA45A; IGCT - 5SHY35L4512), the IGCT is showing better dynamics for currents above 650 A, whereas the IGBT is performing better at lower currents (Fig. 5). The proposed switch configuration is estimated to provide 2.3…2.8 times increased switching frequency in comparison to single hard switched IGBT or IGCT exhibiting the same power dissipation of 3 kW. Assuming the same switching frequency in the range of 250…1050 Hz and switch current of 750 A the IGBT performs better than IGCT at frequencies above 450 Hz, whereas the HS provides substantial (1.9…2 times) decrease in power losses in comparison to single semiconductors (Fig. 6). Fig. 7 shows average losses of all considered switch solutions operating in the studied circuit with the wide range of duty cycles. The IGBT performs better than IGCT up to *D*=0.85. Again, the HS shows substantially (1.8…2.2 times) reduced power dissipation in comparison to single semiconductors. As Fig. 8 reveals, the losses of transistor in the HS are essentially (2.4…4.4 times) higher than the losses of thyristor under considered operation parameters. The loss distribution becomes more equal with an increased switch current.

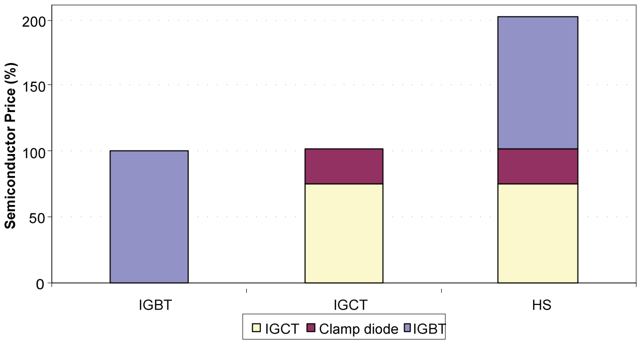

Fig.9. Comparison of semiconductor prices of studied switch configurations

Unlike in the case of the typical parallel connection of identical semiconductors, in the proposed HS both switches are conducting full input current during the operation, thus the current rating of both semiconductors must be sufficient. On the other hand, the overall power dissipation is decreased in comparison with single switches allowing one to increase the switching frequency or reduce cooling system requirements. Moreover, if one of the semiconductors fails, the other one can still continue to operate independently unless sufficient cooling is applied.

The economical feasibility of the HS implementation greatly depends on the application and its operation conditions. The comparison of semiconductor prices of discussed switch configurations is shown in Fig. 9. It should be mentioned, that semiconductor price is only a part of the overall power electronic system. The prices of the passive components greatly vary for different applications and are not considered in this paper.

Conclusions

Using commercially available 4.5 kV class IGBTs and IGCTs in press-pack housings it is possible to create energy efficient switches with essentially decreased power losses. Despite having decreased maximum current capabilities in comparison with parallel connected identical transistors or thyristors and a higher price than single semiconductor switches, the proposed switch configuration could be beneficial in applications where higher switching frequencies are required or decreased cooling system requirements are essential.

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